UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, DC 20555 – 0001

January 23, 2015

MEMORANDUM TO: ACRS Members

FROM: Christopher L. Brown, Senior Staff Engineer **/RA/**
Technical Support Branch, ACRS

SUBJECT: CERTIFICATION OF THE MINUTES OF THE ACRS METALLURGY AND REACTOR FUELS SUBCOMMITTEE MEETING, DECEMER 2, 2014 - ROCKVILLE, MARYLAND

The minutes of the subject meeting were certified on January 9, 2015, as the official record of the proceedings of that meeting. A copy of the certified minutes is attached.

Attachment: As stated

cc w/ Attachment: E. Hackett
M. Banks

UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, DC 20555 – 0001

January 7, 2015

MEMORANDUM TO: Christopher L. Brown, Senior Staff Engineer
Technical Support Branch, ACRS

FROM: Pete Riccardella, Meeting Chairman
Metallurgy and Reactor Fuels Subcommittee, (for proposed revision 1 to Regulatory Guide 1.207)

SUBJECT: CERTIFICATION OF THE MINUTES OF THE ACRS METALLURGY AND REACTOR FUELS SUBCOMMITTEE MEETING, DECEMBER 2, 2014 - ROCKVILLE, MARYLAND REGULATORY GUIDE (RG) DRAFT REGULATORY GUIDE DG-1309, "GUIDELINES FOR EVALUATING THE EFFECTS OF LIGHT WATER REACTOR COOLANT ENVIRONMENTS IN FATIGUE ANALYSES OF METAL COMPONENTS."

I hereby certify, to the best of my knowledge and belief, that the minutes of the subject meeting on December 2, 2014, are an accurate record of the proceedings for that meeting.

______________RA____________1/ 9 /2015
Pete Riccardella, Meeting Chairman,
Metallurgy and Reactor Fuels
Subcommittee

Certified by: Peter Riccardella
Certified on: January 9, 2015

**ADVISORY COMMITTEE ON REACTOR SAFEGUARDS**
**MINUTES OF THE ACRS METALLURGY AND REACTOR FUELS SUBCOMMITTEE MEETING**

Regulatory Guide (RG) Draft Regulatory Guide DG-1309, "Guidelines for Evaluating the Effects of Light Water Reactor Coolant Environments in Fatigue Analyses of Metal Components."

December 2, 2014
ROCKVILLE, MD

The ACRS Metallurgy, and Reactor Fuels Subcommittee held a meeting on December 2, 2014, in T2B1, 11545 Rockville Pike, Rockville, MD. The meeting convened at 1:00 p.m. and adjourned at 3:13 p.m.

ATTENDEES

ACRS Members/Staff

| | |
|---|---|
| Pete Riccardella, Chairman | Gordon Skillman, Member |
| Dana Powers, Member | Steve Schultz, Member |
| Joy Rempe, Member | Ron Ballinger, Member |
| Bill Shack, Consultant | Dennis Bley, Member |

Christopher Brown, Designated Federal Official

Dave Gerber, Structural Integrity
Bob Hardies, NRR
Robert Hardies, NRR
K. R. Hsu, NRR
Gary Steven, RES
David Rudland, RES

SUMMARY

The staff has revised the guidance for environmentally assisted fatigue (EAF) Regulatory Guide (RG) Draft Regulatory Guide DG-1309, "Guidelines for Evaluating the Effects of Light Water Reactor Coolant Environments in Fatigue Analyses of Metal Components." The staff has also developed the supporting technical basis NUREG Draft, NUREG/CR-6909, Revision 1 (ANL-12/60), "Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials." The staff discussed the background, reasons for revising Reg. Guide 1.207, provided a summary of Revisions to Reg. Guide 1.207, and discussed the revisions to $F_{en}$ equations.

The meeting transcript and slides are attached and contains an accurate description of each matter discussed during the meeting.

| SIGNIFICANT ISSUES | |
|---|---|
| Issue | Reference Pages in Transcript |
| 1. Discussions on cumulative usage factor (CUF). For nuclear plant design, cumulative fatigue damage due to applied cyclic loading is estimated using cumulative usage factor (CUF): CUF= = $U_1 + U_2 + U_3 + \ldots + U_Z < 1.0$. | 8 - 10 |
| 2. Discussion on what is EAF and why guidance is needed. Discussion on why laboratory testing of specimens tested in water indicated that the air design curves may not adequately define fatigue life for materials exposed to water environments. | 8 - 17 |
| 3. Discussion on $F_{en.}$ $F_{en}$ is defined as the ratio of fatigue life in air at room temperature to the fatigue life in water at the service temperature. Staff presented and discussed an example. | 18 - 22 |
| 4. Discussion on subsequent license renewal and the calculations for CUF as it relates to the regulatory guide. | 24 - 34 |
| 5. Discussion of scope of applicability, which is modified to include all metal components exposed to the LWR environment that have a CUF calculation required by the plant's current licensing basis | 23 -32 |
| 6. Discussion on revisions to $F_{en}$ equations. Review of updated fatigue data. Staff discussed and reviewed air fatigue curves. Members questioned the plotted data depicted on the curves. | 33 - 38 |
| 7. Review of air fatigue curves for carbon steels, low-alloy steels, austenitic stainless steels, and Ni-Cr-Fe alloys. Discussion on how the Monte Carlo simulations were done. | 39 - 50 |
| 8. Review of changes to $F_{en}$ equations for carbon steels, low-alloy steels, austenitic stainless steels, and Ni-Cr-Fe alloys. Discussion and comparisons of $F_{en}$ vs. strain rate, R and $F_{en}$ vs. temperature, T from different organizations including JNES. | 50 - 75 |
| 9. Discussion on validation calculations that were performed by estimating life using ASME Code methods (i.e., calculate CUF) and comparing the results to the experimental (i.e., measured) fatigue life. Changing strain rate, changing strain rate and temperature, spectrum loading, complex loading, U-bend tests, and stepped pipe were discussed. | 75 - 87 |
| 10. Discussion of sample problem in Appendix C of NUREG/CR-6909, Rev. 1. | 88 - 89 |
| 11. No public Comments | |

# Official Transcript of Proceedings

# NUCLEAR REGULATORY COMMISSION

Title: Advisory Committee on Reactor Safeguards
Metallurgy and Reactor Fuels Subcommittee

Docket Number: (n/a)

Location: Rockville, Maryland

Date: Tuesday, December 2, 2014

Work Order No.: NRC-1259 Pages 1-108

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NUCLEAR REGULATORY COMMISSION

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

(ACRS)

+ + + + +

METALLURGY AND REACTOR FUELS SUBCOMMITTEE

+ + + + +

TUESDAY

DECEMBER 2, 2014

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ROCKVILLE, MARYLAND

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The Subcommittee met at the Nuclear Regulatory Commission, Two White Flint North, Room T2B1, 11545 Rockville Pike, at 1:00 p.m., Peter C. Riccardella, Chairman, presiding.

COMMITTEE MEMBERS:

PETER RICCARDELLA, Subcommittee Chairman

RONALD G. BALLINGER, Member

DENNIS C. BLEY, Member

DANA A. POWERS, Member

JOY REMPE, Member

GORDON R. SKILLMAN, Member

ACRS CONSULTANT:

WILLIAM J. SHACK

DESIGNATED FEDERAL OFFICIAL:

CHRISTOPHER L. BROWN

ALSO PRESENT:

CHAKRAPANI BASAVARAJU, NRR
DAVE GERBER, Structural Integrity Associates
BOB HARDIES, NRR
ALLEN L. HISER, JR., RES
K.R. HSU, NRR
PAT PURTSCHER, NRR
DAVE RUDLAND, RES
GARY STEVENS, RES
ALEXANDER TSIRIGOTIS, NRO

A-G-E-N-D-A

P R O C E E D I N G S

1:03 p.m.

CHAIRMAN RICCARDELLA: Meeting will now come to order. This is a meeting of the Metallurgy and Reactor Fuels Subcommittee. I'm Pete Riccardella. I'm chairing the meeting.

ACRS members in attendance are Dick Skillman, Dennis Bley and Joy Rempe. We also have our consultant, Bill Shack, Chris Brown of the ACRS staff is a designated federal official for this meeting and I am expecting Ron Ballinger and Dana Powers to come in shortly.

The purpose of this meeting is to receive a briefing on the regulatory guidance for evaluating the effects of light water reactor coolant environments on the fatigue analysis of metal components, proposed Reg. 1 to Reg. Guide 1.207.

We'll hear presentations from the representative of the Office of Nuclear Regulatory Research. The subcommittee will gather information, analyze relevant issues and facts and formulate a proposed position and action as appropriation for deliberation by the full committee.

This meeting is open to the public. The rules for participation in today's meeting were announced as part of the meeting notice previously published in the Federal Register on November 25th, 2014.

We received no written comments or requests for time to make oral statements from members of the public regarding today's meeting. A transcript of the meeting is being kept and will be made available as stated in the Federal Register notice.

Therefore, we request that participants in the meeting use the microphones located throughout the room.

When addressing the subcommittee participants should first identify themselves and speak with sufficient clarity and volume so that they can be readily heard.

A bridge line has been set up and I understand there are several people on the bridge line. It will be in listen-in mode only but we will open it up after the briefing for public comments.

I request that everybody silence their cellphones and other devices so as to not interrupt the meeting.

We will now proceed with the meeting and I call upon Gary Stevens from Research to make introductory remarks. David, unless you want to make some introductory remarks.

Okay. It's all yours, Gary. We are scheduled to have a break. I don't see a break schedule. We're scheduled to adjourn at 3:30 so maybe we don't need a break.

MR. STEVENS: All right. Thank you. I'm Gary Stevens, Office of Research Division of Engineering Component Integrity branch. Dave Rudland is the chief. Brian Thomas is the division director.

So when this was first presented to me it was advertised as you wanted to know what's changing in the Reg. Guide and with that I have one slide. But I assumed at - because there aren't that many changes to the Reg. Guide.

But we have done extensive updating and revision to the technical basis, assuming that you want to see what happened to the technical basis.

And then the other part that was a little uncertain to me is I don't know the level of proficiency I'll have with this topic. So I put this together. You need only a little background of the topic. So it's pretty basic.

So if I'm too slow for you just speed me along. So I'm here at your request and we're revising the guidance for environmentally assisted fatigue, EAF.

By the way, the last page of your presentation I tried to do my diligence and provide you a hit list of acronyms because we overuse those here.

CHAIRMAN RICCARDELLA: This is the one place where I don't need that.

MR. STEVENS: The very last page of your PowerPoint is a cheat sheet for acronyms here. The guidance consists of the Reg. Guide and a supporting technical basis NUREG.

In both cases, we're incrementing the documents to Reg. 1. The Reg. Guide - all Reg. Guides when they go out for public comment as drafts get a DG number and this one's been assigned DG-1309.

It went out for public comment last Monday the 24th. The NUREG is still a draft. It went out for public comment last spring. I'll detail that for you on the forthcoming slides.

It was out for a 45-day review period. So this is kind of the outline. I have a lot of background where I'm going to try to get everybody on the same playing field with the terminology and what this methodology does and then I'm going to explain to you why we revised the Reg. Guide, what we revised in it and in particular these environmental multiplier equations we have were the major change and I'll go through those and then give you an estimated schedule moving forward with this work.

Okay. So here's another acronym - CUF - cumulative usage factor. What is cumulative usage factor? A cumulative usage factor is really ASME's way of estimating fatigue damage, calculating it, and it's with this equation that you see here, a summation, and what it is is if you look at the curve down here, which is a typical fatigue curve in the lower right, otherwise called an SN curve for being stress or strain versus cycles.

That's a material dependent property curve and it defines at any given stress level the number of cycles that you would theoretically could tolerate before you would initiate fatigue failure of a test vessel.

So very simply, if we were at a stress level here of - this is in KSI - 100 KSI, we could tolerate just over a thousand cycles, which in theory would mean if we applied the thousand cycles we would then initiate a fatigue failure and a specimen.

What the summation does is it simply does that ratio for all applied loads, given that most of our components don't have one load applied to them -

they have many applied loads.

And what it says is that that ratio of the applied cycles to the allowed cycles from this curve must be less than 1.0. N is a function of the alternating stress and here is the allowed number of cycles, and as I mentioned these curves are material - they are material properly. They are like yield strength or ultimate. They belong to each material.

I'll probably throughout this talk refer to the fatigue curves as SN curves and they are defined in ASME Code Section 3, Mandatory Appendix I.

They have several different curves in there, primarily two. There's one for ferritic materials and one for austenitics.

These curves are design curves. They're usually in log-log form and what they are they're best fits of laboratory test data of test performed in air with design factors applied to make them a design curve.

And I'll go through what those design factors are intended to cover and what they aren't intended to cover. So what you see there is one of the design curves out of Section 3.

If I had my glasses I'd be able to tell you what material that is. It looks like it's austenitic materials.

CHAIRMAN RICCARDELLA: Austenitic - you know, should you maybe mention the pseudo nature of the stress? I mean, obviously, this goes to a million psi.

MR. STEVENS: Right. So the - as Pete pointed out, you'll see the stress on the vertical access can go quite high, which is well above the material yield strength.

These curves are based on elastic stress analysis. There's factors applied for stresses over yield and it's - the stresses we're talking about here are highly localized surface stresses not to be confused that we're taking a through section stress well above yield.

So what is EAF? Again, environmentally assisted fatigue. As you heard me mention on the prior slide, these curves were developed from laboratory tests of small-scale polished specimens in air - laboratory air.

That air test data were used to develop these fatigue curves and they're based on best fit log-log curves for each different material type. Those curves are adjusted to account for mean stress effects, primarily at the high cycle end.

Then they have factors applied on them to develop design curves, which are intended to be conservative lower-bound fatigue design curves for each material.

The factors that ASME originally used for these were two on strain or 20 or cycles, whichever was more severe. We'll go into what the current factors in our work as well as in the code. But this is how the code initially established those curves.

And how EAF came about is more recent and actually and I guess it's not so recent anymore but in the 80s and 90s laboratory testing of specimens now in water actually plotted out to be below the design curve and what's on this figure here maybe this is the best fit of the data in error and then when that curve gets adjusted for environmental effects - I'm sorry, gets adjusted to be a design curve with factors of two and 20, this would be the design curve, and what some of the laboratory tests in water showed is the points were coming below the design curve and what the conclusion that came out of that was is in some cases for some environments the design curves could potentially be nonconservative.

What are the - why is there a guidance on EAF? So, basically, we all - we always tie back to 10 CFR 50 and Appendix A in particular with the two general design criteria about structure systems and components designed, fabricated, erected and tested to quality standards and the reactor pressure coolant boundary being tested, erected and fabricated and all that to the highest practical standards.

In addition, 50.55a(c) endorses ASME code for use in design of safety-related systems and components class one and that's where these fatigue curves are included in Section 30 for class one components.

The fatigue curves, and this is specifically noted in Section 3 of the code, they do not address the impact of the reactor coolant system environment.

They were based on air with design factors that apply to account for other things like surface finish size effects, temperature of the laboratory, environment, et cetera, but not for water.

CHAIRMAN RICCARDELLA: The code - I think the code states that addressing environment is the responsibility of -

MR. STEVENS: That's right. I'm flashing it real quick. I thought I - yes, I have that NB-3121. So these curves that are in Section 3, now, they've been modified recently but they were originally developed in the late 60s and early 70s and, like I say, air environment at ambient temperatures margin of two on strain and then 20 on cycle of life.

In NB-3121 in Section 3 of the code for class one components identifies that the data used to develop the fatigue design curves did not include tests in environments that might accelerate fatigue failure.

I happen to be one of those that reads that very clearly that the effects of the LWR environments are not included. There are others in the code committees that don't agree with me. But that's the way I read it.

Now, in the 1980s the NRC initiated a fatigue action plan and these were in response to a lot of - there was some plant life extension which we now call license renewal studies that occurred in the early 80s and there was various findings that came out of those studies that - on a variety of topics, one of which was fatigue and so there's fatigue action plan undertaken.

Research in Japan as well as Argonne National Laboratory identified these potentially significant effects of the water environment and that's back to that curve I showed you where some of the points were plotting below the design curve.

The fatigue action plan was closed down in

1995 and by the way on all these slides I footnoted you the appropriate references for these NRC actions that I'm citing if you want to look at those.

They closed out the fatigue action plan and they resolved the generic safety issue which had to do with the adequacy of fatigue life of metal components and included in that is that the risk to core damage from fatigue failures for 40 years was very small and, however, there was a potential for increased leaks beyond 40 years into license renewal.

So they said that needed to be looked at. So what you'll see throughout this presentation is EAF is not considered for the current operating 40-year term for the fleet but it is addressed for operation beyond 40 years and all of our guidance has been set up with that in mind. It was not back fit to the 40.

Where this all culminated is in 1999 the various generic safety issues that captured all these were closed out, the final one being the GSI 190, fatigue evaluation of metal components for 60-year plant life and that led to our guidance for license renewal for EAF effects which we say meet the provisions of 5421 aging management programs for license renewal.

Now, in December of 1999 the NRC wrote a letter to the ASME Board of Nuclear Codes and Standards requesting the ASME to revise the code to include EAF effects and so embarked a long, long history of task groups and committees and what not that continue to this day.

There are two code cases that tried to adopt some environmental effects but in the code itself there are no rules for these effects yet.

ASME, in response to that letter, initiated a steering committee with PVRC to look at this and ultimately that committee published a WRC bulletin, 487, where they were recommended - they recommended revising the code in fatigue design curves and pretty much at that time it was consistent with Argonne's work but there was an argument over how much conservatism there was embedded in the existing code curves and whether you could account for that.

So bottom line is ASME code has really struggled on this issue now for more than 20 years. There still are no rules in Section 3 that are acceptable to the staff, although these two code cases I've listed here have been published.

We have not endorsed those yet and so based on the closeout of fatigue action plan the NRC developed our own guidance for this issue, and there was a couple of reports that were published in the 1999 time frame that were applied to license renewal applicants and eventually this Reg. Guide 1.207 was published in 2007 for new reactors.

All right. Here are the two reports that were published in 1998 and 1999 respectively that many of the earlier license renewal applicants used to evaluate EAF effects. Dr. Shack here is one of the co-authors on one of those.

One is for, basically, ferritic materials and the other was for austenitics. The GALL report for license renewal basically adopted the use of those NUREGs for license renewal applicants and that's contained in Chapter X.M1 of the GALL report and that goes back to the original GALL report in 2001 that that guidance was in there.

Effectively, these NUREGs they do remain in the current revision two of GALL and the - that was in 2010 when the GALL report was last issued and that version of the GALL report also allows use of the Reg. Guide which, again, is intended for new reactors but it does allow its use for operating reactors.

So the guidance for new reactors, again, is in this Reg. Guide 1.207, Rev. 0 issued in March 2007. That's the Reg. Guide we're revising here - proposing to revise, and the technical basis for that NUREG is this NUREG CRC 6909, which is the technical basis we're revising and I'll be talking to you about today.

Again, these were issued in the 2007 time frame. Near as I can tell, they adopted the - all of the environmental fatigue data through about the 2003 or 2004 time frame that was available.

The guidance for operating reactors - the 40-year fleet there is no requirement to address EAF so there is no guidance for that and the license renewal applicants follow the guidance in NUREG 1801 Rev. 2 and here's kind of how it reads.

It says that for carbon steel they have a choice of using the 1999 NUREG or the 6909 that was associated with Reg. Guide 1.207. Same for stainless steel and for nickel alloy. They were directed to use the methods in 6909.

In all three cases, the licensee, since this is only guidance, can use an NRC-approved alternative of their own choice should they so choose.

The early - the 1999 and 1998 NUREGs did not address methods for nickel alloys. That is why for the nickel alloys the GALL report does not allow the use of the earlier NUREGs.

So what is Reg. Guide 1.207 and 6909? Well, it defines this fatigue multiplier Fen. I'll refer to that as Fen and it's just a multiplier and you'll see how that multiplier fits back into the CUF calculation I showed you back on slide two.

MEMBER SKILLMAN: Gary, what does the EN stand for?

MR. STEVENS: Environmental.

MEMBER SKILLMAN: Oh. Gotcha.

MR. STEVENS: This is EAF guidance, again, for new reactors and what you'll be hearing here is when we revise it we're trying to consolidate everything into a Rev. 1 that applies to everybody.

As I mentioned, the GALL report allows license renewal applicants also to use the this Reg. Guide which is for new reactors and, really, these two documents are the best vehicle we at the NRC have to update and consolidate our guidance.

So if we're going to update and put everything in one place revision of these is the place to do it.

MEMBER BLEY: Is there anything likely to be needed if we go beyond six years with a subsequent?

MR. STEVENS: Yes. The intent - you know, there's internal activities underway working on the GALL for subsequent license renewal, which is basically operation beyond 60 years and that document, which will be a GALL specifically aimed at SLR is - I think the schedule shows it's going out for public comment next year and the intent is that document will refer to the Revision 1 of these two documents.

Okay. So what is this Fen? That's a factor - environmental factor and now you can see down below the CUF calculation on slide two of these factors tied in.

On the first slide, you know, each - we had each of these views were just the ratio of the cycles - the point loads to allowable and you can kind of see now the attractiveness of Fen.

What we've done is for each of those summation factors we can come up with a multiplier to just insert into that calculation. So this method is a really nice way and easy way to adopt these factors into the current structure for CUF calculations.

In the beginning, NRC looked at two approaches. One was to revise the fatigue curves themselves and the other was to use this factor approach, and we used this factor approach because the primary reason was that there are conditions in power plants where fatigue effects don't apply.

This factor allows you to turn on and off environmental effects easy, whereas if you revised the fatigue curve these effects would always be there. So you'd either have to have multiple fatigue curves -

MEMBER BLEY: Multiple fatigue curves, right.

MR. STEVENS: So this was considered at the time to be the easier way to adopt these methods and that's what was adopted and what it is defined as is the ratio of the fatigue life - fatigue life is the number of allowed cycles for a material - the ratio of the fatigue life in air to water.

So it kind of makes sense that if this CUF calculation I showed you on slide two was based on air then if you have a factor that's based on the ratio of air to water that's where the multiplier comes from.

So it is the allowable number of cycles in air room temperature to those in water at the surface temperature.

All right. Now, this is an example of what those factors look like and it's a relatively simple equation that you could plug into a spread sheet. These are the - this is an equation for stainless steel out of the Rev. 0 of 6909. So I don't want you to think this is what the equation looks like today. I'm going to show you that in a few slides.

And what these - what these equations are it's an exponential term that in this case had a constant and then it has three variables which basically have temperature, oxygen content of the fluid and strain rate.

MEMBER SKILLMAN: And that was a product, fatigue?

MR. STEVENS: Those are - yes, those are product of fatigue terms, yes. Now, the one thing that's not intuitive here, and you'll see this throughout, is, you know, a lot of folks look at the minus sign and say wow, these terms actually subtract off.

But what happens if you look at this last term here on strain rate, it's a logarithm and it's a logarithm of a ratio that's less than one so it ends up being a negative number.

So even though that's a minus sign the product is negative so it's actually a plus. So what you have here, and it kind of makes sense, you know, the effects are based on how you load the - how you load the component in terms of strain rate and then the conditions of the environment - temperature and oxygen.

This is stainless. Ferritic materials for carbon and alloy steel are similar but they have the introduction of a sulfur term. The sulfur is the sulfur content of the metal.

And I'm going to go into - this I just wanted to show you so now you kind of know what an Fen is and how it's calculated and I'll go into new expressions, how they're developed and these parameters how they're determined.

Okay. So the real question is for the brief is why are you revising Reg. Guide 1.207. I have one slide for that. There's actually three reasons.

We're trying to consolidate all the EAF guidance in one place so that we don't have a set for new reactors, another set for license renewal applicants and they're different. So we're trying to consolidate. We are trying to update the guidance based on stakeholder feedback as well as our own.

There have been some issues - some practical issues with applying the EAF rules in the past and I'll show you what those are and so we're revising it to try and take care of those issues, and then we are updating the guidance based on more recent research data available since that 2003-04 time frame when the Reg. Guide was first written.

So shortly after I arrived here at the agency in 2010, the Office of New Reactors and Nuclear Reactor Regulation both prepared a user need for research to work on this and update the guidance and that's been a three-year research effort and follow-on activities to get these documents published.

It's noteworthy that also as a part of this we did embark on an MOU - memorandum of understanding - with EPRI to tie their research efforts in with ours and EPRI co-funded the research on this project to the tune of about 45 percent.

That was very helpful to get the research done that we wanted to do. Okay. So that's why we embarked on it. We had a request from the program offices and here's all we did to the Reg. Guide.

The title of the Reg. Guide used to have new reactors in it so we removed it. It's applicable to everybody.

The guidance was clarified to apply to all metal components exposed to the LWR environment - I'm reading this carefully because the words are carefully chosen - that have a CUF calculation required by the plant's current licensing basis and what that says is we are not mandating or we are not providing guidance to licensees that they have to create CUF calculations to address the environment.

If they have them and they're part of their current licensing basis then these effects need to be addressed for operation beyond 60 years and for new reactors.

CHAIRMAN RICCARDELLA: For operation beyond 60 years.

MR. STEVENS: Sorry. Forty.

CHAIRMAN RICCARDELLA: Forty.

MR. STEVENS: Beyond 40.

CHAIRMAN RICCARDELLA: It seems though that there's a significant change here because the GALL report and the prior work said pressure boundary, right? And this doesn't say pressure boundary. This says example reactor internals or -

MR. STEVENS: Yeah. It actually - although it may cite an example of internals it doesn't use that terminology and it says components exposed to the environment that had a CUF calculation as part of their licensing basis. You are correct. That's a change.

CHAIRMAN RICCARDELLA: So I understand that for subsequent license renewal. But now how does this affect plants that have already done an initial license renewal by the old rules?

MR. STEVENS: Doesn't affect them in the sense that we're not - we're not back having them change anything like that.

CHAIRMAN RICCARDELLA: So it's similar to the last one.

MR. STEVENS: Right.

CHAIRMAN RICCARDELLA: So we don't have to do it for a 40-year -

MR. STEVENS: Right.

CHAIRMAN RICCARDELLA: - projected to do it for 40 or 60. Now we're saying that you don't have to do this new stuff if you're already licensed. What about a plant that's coming up now for 40 to 60, if there are still a few?

MR. STEVENS: They would be subject - well, they're following GALL Rev. 2. All current - the current fleet is going to continue to follow GALL Rev. 2 so they would need to meet those requirements, which is Rev. 0 of this Reg. Guide or the old NUREGs.

CHAIRMAN RICCARDELLA: Okay.

MR. STEVENS: Now, obviously, with - before the Reg. Guide addressed new reactors and now we're bringing in the operating fleet for license renewal so the background had to be expanded quite a bit to bring in the relevant content for the operating reactors and license renewal and that's really the most significant change to the Reg. Guide if you were to do a side by side comparison. There's a lot of background that we brought in.

But the guidance itself really didn't - the guidance section of the Reg. Guide didn't change that much. The Fen equations were revised based on a research on all the stakeholder feedback.

The Fen equations actually are not contained in the Reg. Guide. They're in the NUREG document. So when you look at the Reg. Guide the guidance says use the equations in the NUREG. It still says that. It's really not much of a change. But the equations have changed in the NUREG and the NUREG has more than doubled in size.

CONSULTANT SHACK: Just coming back to Pete's question, I mean, why does this renewal treat the aging management programs as sort of living documents? We've certainly seen plants go back and address buried piping as the considerations for buried piping have changed with submerged cables. Why wouldn't this be like any other aging management program?

MR. STEVENS: I'm looking at Mr. Hiser. So I would say that - all right, go ahead.

MR. HISER: This is Alan Hiser at license renewal. Actually, these - the calculations of CUF, CUF EN are time limited aging analyses so they're not

ANPs.

So once they've been demonstrated to be, you know, the prior analysis is still - well, actually, and see, these are even more bizarre. The environmental effects are not time limited aging because they're not in the COV for the first operating period.

But plants treat them like a TLAA. So they evaluate them - evaluate the environmental effects like it's a TLAA. So, for example, they say that the calculations are still valid or they update them and show they're less than one or they do aging management which sometimes they end up having to do for pressurized or surge lines and things like that that have a high usage and a fairly high Fen as well. So it's a little bit different from EG management programs in that perspective because they are time limited aging analyses.

And I guess the one other thing I'd comment on the internals for PWR plants that use MRP-227-A for aging management there is a provision at staff SC that if plants have CUF values for internals that they need to incorporate environmental effects for those internals. For DWR plants that doesn't apply but for PWR they should be including environmental effects for internals.

CHAIRMAN RICCARDELLA: They've already been doing it in accordance with Rev. 0. Is that what you're saying?

MR. HISER: No, they haven't been but if there's NRP 227 didn't exist at that point so that what they would do is use GALL Rev. 2 guidance on how to do environmental effects. Then they would use the MRP 227 provision that they had to do environmental effects for internals and that would be included in their license renewal application.

CHAIRMAN RICCARDELLA: Then what's the logic for having a different set of rules for BWRs versus PWRs? What difference does it make?

MR. HISER: We have not updated GALL to incorporate internals at this point in time. There are many inconsistencies. You know, as Dr. Shack mentioned, you know, if you update the Reg. Guide should that go back and apply to all plants. That's not the licensing - that's not the way we regulate plants. If we felt that it was necessary then we would go to the measures of doing a back fit. But we haven't made that determination at this point.

CONSULTANT SHACK: But, again, most of those license renewals, since you didn't have MRP 227 said that we would base our aging management program for the internals on the updated guidance when it became available.

So that MRP 227 then would apply to virtually all of the plants - all the PWRs, at any rate, because they neither directly cited it or they said they would follow it when it became available.

MR. HISER: Yeah, I think that's correct. In the industry, MRP 227-A, the implementation of it is through an industry initiative and so all PWRs should be implementing that so they should be, if they have CUF calculations for internals, which is a critical piece, they may not have been a part of the original design in many cases if a plan came in for a power upgrade or some other modification then we in some cases wanted them to consider fatigue effects through a CUF calculation for internals, in that case they would - they should update the calculation for environmental effects. But if there are - there's no need to generate new CUF values.

CHAIRMAN RICCARDELLA: But if they've been doing it in accordance with Rev. 0, my understanding is that Rev. 1 actually of these documents actually makes the adjustments a little less onerous.

MR. STEVENS: It depends. Yes, in general. There is a case where that might not be true and if the Rev. 0 guidance was interpreted by some applicants to allow the use of average temperature and if an applicant used average temperature that could be nonconservative most of the applicants that we saw that we've seen used maximum temperature. So your comment is correct.

CHAIRMAN RICCARDELLA: And what is the new guidance required?

MR. STEVENS: The new guidance says you need to - you can use average temperature but you need to evaluate the appropriateness of doing that for - and justify it.

CHAIRMAN RICCARDELLA: Okay.

MR. STEVENS: My expectation is a lot of the applicants may just end up using maximum temperature to get around that. But we don't - we don't mandate that.

The other thing I was going to say, at least with regard to the BWRs, I mean, whenever this conversation has come up about internals with them it's generally recognized that their aging management programs are inspection based and that those inspections are driven more by SEC, which is much more limiting than fatigue would be. And so generally the inspections address fatigue concerns.

CHAIRMAN RICCARDELLA: Yeah. And so is temperature. I mean, shouldn't you be addressing the temperature at the time that the peak stress occurs?

MR. STEVENS: Yes.

CHAIRMAN RICCARDELLA: Which, I mean, if -

MR. STEVENS: Well -

CHAIRMAN RICCARDELLA: - this peak stress in the cycle or, you know -

MR. STEVENS: Yeah, it's - it depends on what method, how you're calculating your Fen. It could be an integrated average of the temperature between adjacent peaks.

But, generally speaking, you would evaluate in the load pair you're looking at at the two temperatures of the peak stresses and take the higher of the two. In some cases, the applicants based on what - how Rev. 0 was worded maybe is the average temperature, which would be less conservative than the maximum temperature because the temperature term is lower for the lower temperature.

So what you just said would be correct if they were taking the temperatures of where the peak stress occurred and they were using the maximum of the two -

CHAIRMAN RICCARDELLA: Of the two.

MR. STEVENS: - in a loaded pair, that would be correct.

CHAIRMAN RICCARDELLA: But I keep thinking of, like, you know, like a thermal shock type stress where you hit it with cold water, when the time the peak stress develops it's - the surface is fairly cool.

MR. STEVENS: Yeah.

CHAIRMAN RICCARDELLA: But then you're saying you'd also have to look at where you started?

MR. STEVENS: Well, the temperature that's in here is the metal temperature.

CHAIRMAN RICCARDELLA: Yeah, but the metal temperature at what time during the transient?

MR. STEVENS: When those peak stresses occur.

CHAIRMAN RICCARDELLA: Okay. But if you have another - if that's just one part of the load pair and then you've got a compressive part of the load pair, say, where the temperature is higher you'd have to use that.

MR. STEVENS: Right.

CHAIRMAN RICCARDELLA: Okay.

MR. STEVENS: Or if you wanted to use something else like an average and you could justify it then we're all open for it.

Okay. So what did we change in - you know, the real crux of what we did it was all background and title.

We changed these Fen equations and we expanded the technical basis to clarify, to explain, to - you know, to provide more details, et cetera, and that's why the NUREG more than doubled its size.

So what did we do to these equations? Initially, when Argonne and RES embarked on this our intent was to collect all publically available fatigue data published since the time of Reg. Guide 1.207.

That was published in 2007 but, as I mentioned, the fatigue data captured was through the 2003 or 2004 time frame.

So in 2010 we thought there was six or seven years of fatigue data out there we can capture and, like with Reg. Guide 1.207, there were some informal exchanges.

But most of the data that was provided was taken out of the publically available literature. So our intent was to do that again and update and whatever was out there we would incorporate that into this work.

At the start of this research this wasn't really a part of this program and on the side Office of Research embarked on negotiations with JNES, which is the research organization in Japan for the regulator and they're now known as JNRA, to formally obtain all of their research data.

They were the largest researcher - not the largest, the researcher with the largest amount of data available in the world. And so we embarked upon trying to get that information with them and our pursuit of that was under the Cooperative Materials Research Agreement that NRC has with them.

And basically what this led to is the Japanese recompiled and published their information and gave it to us in October of 2011. I've noted the report here.

Now, I can't say enough good things about the Japanese and providing us the information they did, as you'll see, and what it - how it expanded our database.

You have to look at the date and understand that they had a lot bigger issues ongoing in their country at the time and yet they still took the time to embark on this exchange with us and were very gracious about that so -

CHAIRMAN RICCARDELLA: The date was 2007?

MR. STEVENS: No, 2011 is when we got their report.

CHAIRMAN RICCARDELLA: After March?

MR. STEVENS: October is when they provided us their report. So I can't say enough good things and have a lot of respect for that organization, that culture and that country and what they've done for us.

And here's a summary of the air fatigue data. On the next slide I'll show you the water data, and what I've done is I've showed you the - I've given you reference to the specific figures in Rev. 0 of 6909 and in the draft of Rev. 1 and what they did.

The expansion of the data in air was, you know, as much as 74 percent in terms of the number of data points.

Dr. Chopra at Argonne and I were actually astonished when we did get our hands on the data. We expected an increase but never of this magnitude. The 20 percent or 10 percent was what we expected.

So when we got - and as you'll see in the water data in some cases a doubling of the amount of data available we truly were astonished.

It also allowed us to - I don't want to say correct but much of the data that was taken out of publications - publicly available publications in the past were digitized off log-log plots, which was - you can get within 10 percent but with the transmittal of this data we were able to refine the database significantly as well.

CHAIRMAN RICCARDELLA: In tabular form?

MR. STEVENS: Yes.

MEMBER REMPE: So just out of curiosity you had an existing agreement. You didn't have to provide funding - they just - you said hey, we'd like it as part of our existing agreement without having - they didn't ask for anything in return?

MR. STEVENS: Correct.

MEMBER REMPE: That's interesting.

MR. STEVENS: They didn't ask for anything in return but it means an awful lot to them that we're using their data and citing it as such in our guidance.

But you're right, this is - this represents more than $100 million worth of testing on their behalf that they literally handed over to us. Now, that the -

CHAIRMAN RICCARDELLA: They used the ASME codes too so to the extent that this gets recognized an ASME code that -

MR. STEVENS: Yeah, and you'll see as we go through this, I mean, there was a benefit to them in the sense that our research was done independent of theirs and effectively going through two different methods of whatever you want to call it - processing - we've now come to agreement in terms of - general agreement and what our predictions are versus theirs.

And I think in their - in their efforts to get the SNE code to adopt work and all that they've done many presentations and for us to be in alignment is - it adds to their credibility and their ability to get ASME convinced of their work.

In terms of the water data, it's a drastic increase - 64 percent up to as much as 150 percent. I couldn't quantify nickel-chrome alloys because I don't really - I probably have it somewhere but I wasn't able to look at the data that Argonne had available at the time the Reg. Guide was written but it was a substantial increase still.

MEMBER SKILLMAN: Gary, is there a reason why they did so much research?

MR. STEVENS: To quantify these effects. I mean, they believed that these effects are real and so they were doing so much research to quantify and come up with a methodology that would accommodate it.

They continue to do some amount of research to now, I'll say, hone the methodology. There's areas that haven't been addressed in the research in terms of particular effects and parameters and their testing is aimed at looking at some of those, and I'll talk about some of those a little bit.

So what I have here are - I'm going to show you the air curves for each of the materials. So on the left is the curve and the data that we published in Rev. 0 of 6909 and on the right are the curves we published in Rev. 1, and really here's the short one-liner version of this.

What you see here is more data on the right and I just showed you why there's more data on the right, and when you do a best fit through the data you basically get the same answer.

Some folks, when I put that result out, were disappointed - wow, we got all that data and nothing happened. I said, well, that's actually a pretty good message because my message to the industry is it's time to quit testing small specimens.

We saturated the result now. We've proven that when we doubled the data our answers didn't change that much. So let's move on to more important things like maybe testing real components.

CHAIRMAN RICCARDELLA: But also what's significant, though there was a significant change from the original code best fit to this best fit.

MR. STEVENS: That's right.

CHAIRMAN RICCARDELLA: And it shows that the code best fit was very conservative.

MR. STEVENS: The - yeah, and we're going to talk about this as we go on and remember the code factors were two and twenty and in Rev. 0 we adopted factors of two and twelve and the work we've done now were factors of two and ten.

So we've improved upon what's in the code. So what you see here is - you know, take away from this. On the right, a lot more data points. The same best fit curve goes through it.

As I note at the bottom, it's the same best fit curve on both sides. We didn't change it. And what really happened is if you do the statistics of the curve on the left and you get the curve fits for it and you do the same thing with the one on the right, they do change but it leads to less than a 10 percent difference in fatigue life, and a 10 percent difference in fatigue life is truly in the noise.

So we did not change the coefficients for the curves because effectively for the purposes of what we have here they did not change.

CHAIRMAN RICCARDELLA: Is the data on the left included in the data on the right?

MR. STEVENS: Yes. Well -

(Simultaneous speaking.)

CHAIRMAN RICCARDELLA: -- cycles.

MR. STEVENS: Well, I don't really know - yeah, no. It's supposed to be but these are the curves I took out of the report. So I have - I have difficulty resurrecting exactly which points were used in the Rev. 0 work.

So but the point is I do have all the data from Rev. 0 and Rev. 1 and when we do the statistics on them there is no meaningful difference between the two, and this is true for all the materials in air.

It's the same for low alloy steel and -

CHAIRMAN RICCARDELLA: Wait. Go back to the previous one. I mean, there's data on the left hand -

MR. STEVENS: That's not on the right. Correct.

CHAIRMAN RICCARDELLA: No. Go back to the carbon - the carbon steel. There's significant data above - at least three data points above ten to the sixth and on the right there's nothing above ten to the sixth, and it seems to me that those data points should have to be significant in driving the tail of that curve.

MR. STEVENS: Yeah. So just consider it - that all that data was considered is just not reflected on these plots.

CHAIRMAN RICCARDELLA: Just not showing the plots. Okay.

MR. STEVENS: And, unfortunately, it was very difficult for me to go back and get a one to one plot between these two pieces of work. This is low alloy steel.

Okay. So all I'm trying to show here is give you some more detail on the curve fits. These curve fits are fit to the - using the Langer fit, as shown at the bottom, where there's three constants - A, B and C - and then you have the variables.

N is the fatigue life and the epsilon sub A is the strain amplitude. And basically what I'm showing you here is the difference in the constant A between the Rev. 0 analysis and the Rev. 1 analysis and for now just focus on the statistics.

The median value here before we got 6.583 and in the new data when we doubled the data we got

6.592. So when I say that the curve fits didn't change, you know, it had - it had an impact in the third decimal point in the coefficients of the fit. It was not significant enough for us to change.

So in Rev. 1 we documented this but we maintained the curve fits that were developed in Rev. 0. Same curve for low alloy steel. So before we had a median of 6.449. Now it's 6.513. Again, very small. We maintained the curve fit.

CHAIRMAN RICCARDELLA: These aren't log plots so that -

MR. STEVENS: No.

CHAIRMAN RICCARDELLA: - does that imply that it's a normal as opposed to log normal?

MR. STEVENS: Correct. So we also developed design curves consistent with that Section 3 does, yes.

CHAIRMAN RICCARDELLA: Okay. But it's log of N so -

MR. STEVENS: Right.

CHAIRMAN RICCARDELLA: - so it is log normal.

MR. STEVENS: And log of epsilon. So we came up with design curves consistent with what Section 3 does. Remember that originally the ASME's curves were based on factors of two and twenty.

So what we did is, and this is another interesting point that we've been questioned on, but we maintained a factor of two on strain amplitude and then we determined through Monte Carlo simulations what the factor - what should be the appropriate factor on life.

Now, the factor of twenty that's built into the code as you see here is meant to address material availability and scatter about a factor of two, size effects factor of two and a half, surface finish a factor of four, and when you multiply those four numbers together you get the factor of twenty that Section 3 adopted originally, and these come out of the Section 3 basis criterion document.

For our work, based on research and available data we looked at, what you see is the range of values we saw for each of these various parameters and what we did is we assumed log normal distributions for those and did these Monte Carlo simulations to determine what the factor on life would be to bound 95 percent of the data with 95 percent confidence.

And when we did that we come up with a factor of 10.2. So what that says is for carbon steel factors of two and ten are supported by the statistics for building the design curve.

Before I comment on what we're using that's different than Rev. 0, in Rev. 0 we determined that factor to be twelve - two and twelve.

So here our research is supporting factors of two and ten and I'm going to run through the other materials and then I'll describe to you what we recommended.

CHAIRMAN RICCARDELLA: How did you do a Monte Carlo - maybe Bill can help me with this - to address size effect? Arguably, you'd have to have tests on different sizes - on larger sizes. I can see you could account for the scatter - the material variability.

MR. STEVENS: Right.

CONSULTANT SHACK: It's just that when we looked at things for the size effect we really couldn't find a big effect when you actually look at the data where people made the things. So we - you know, we just sampled from those ranges we found for the effects in the literature and decided that they - you know, they wouldn't apply - you know, you didn't get the worst case every time. So we sampled and -

CHAIRMAN RICCARDELLA: You did use data from the literature from -

CONSULTANT SHACK: Yeah. So, you know, we looked for data on surface finish effects in the literature, you know, and that -

CHAIRMAN RICCARDELLA: And what is the loading history?

MR. STEVENS: Loading history has to do with, you know, the specimens are tested under uniform R ratio minus one loading versus in power plants, you know, you could go for days or weeks or months without a load and then you have a load. So just the sequence effects.

CHAIRMAN RICCARDELLA: Okay.

MR. STEVENS: Okay. So we get ten - roughly, ten for carbon steel and now, when we drafted the NUREG 6909 Rev. 1 and we put it out for public comment we maintained factors of two and twelve to be consistent with Rev. 0 and to be consistent with past work because we didn't want to, I'll just say, perturb the system.

However, we said and we showed the data that supported the factor of ten and ten in the Federal Register notice we requested specific feedback from the public on that and we said we put in twelve. The research supports ten.

We kept twelve because it's consistent

with what we did in the past. We don't want to change but give us your feedback. So that's the way we are now and we haven't - as we work through the comments on both the NUREG and the Reg. Guide we'll make a decision as to which one we finally adopt or recommend.

But, clearly, even if we stayed with a factor of twelve a factor of ten is supported technically. So it's something you want to -

MEMBER POWERS: Geometric mean of ten and twenty, almost exactly.

MR. STEVENS: So right now that's the way the revised NUREG reads.

CONSULTANT SHACK: But, I mean, you should point out that when they did 792 they kept the twenty.

MR. STEVENS: That's right. The code still uses - they did adopt a factor of twelve for austenitics in 2009 but they have not changed from the factor of twenty on ferritic materials.

So, you know, I'll point out that whether we use ten or twelve - ten or twelve or whatever we recommend for ferritics our curves are inconsistent with the code right now. It's been our recommendation to ASME to change the ferritic curve.

CHAIRMAN RICCARDELLA: But also out in the high - out in the high cycle range it's controlled by the factor of two -

MR. STEVENS: That's right.

CHAIRMAN RICCARDELLA: - on stress and yet you're still way above the original code curve. I'm looking at the solid curve versus -

MR. STEVENS: That's right.

CHAIRMAN RICCARDELLA: - the lowest of the curves.

MR. STEVENS: You know, keep in mind that - so we're conservative, we are - however you want to say - we're less conservative in the code for two reasons.

Well, in this particular case it's really one. They maintain the factor of twenty versus our twelve.

CHAIRMAN RICCARDELLA: Not at the high cycle end. At the high cycle end the factor of twenty doesn't come into play. It's that your mean curve is higher and therefore a factor of two below the mean curve is higher.

MR. STEVENS: That's correct.

CHAIRMAN RICCARDELLA: Right?

MR. STEVENS: In that end, that's right.

CHAIRMAN RICCARDELLA: And, now, is the Fen intended to apply to your design curve or the code curve?

MR. STEVENS: Well, either.

CHAIRMAN RICCARDELLA: But it's -

MR. STEVENS: I mean, we - logistically our curve. But if they want to use their curve and be conservative then more power to them.

CHAIRMAN RICCARDELLA: Okay. So -

MR. STEVENS: And in fact our guidance says that. For ferritic we say use our curve and alternatively you can use the code curve and that would prevent them from having to change their fatigue calculation.

And low alloy steel - now, here the difference is we have the twelve and twenty but, you know, we have a separate curve defined for low allow steel compared to carbon steel and the code combines the two.

CHAIRMAN RICCARDELLA: Yeah.

MR. STEVENS: And when you combine the two it's really controlled by carbon steel and that makes that curve conservative for low alloy steel applications.

So another comment we would have to the code to remove conservatism is to separate those two curves into carbon and low alloy steel. They have not done that.

Here, when we did the Monte Carlo simulation for low alloy steel we got that factor of nine. So, again, we're about in the factor of ten range. Two and nine would be supported versus two and twelve.

Austenitics the same kind of results and here I show the factor went from 6891 to 6913 - again, a very small change. And here what you see is that we matched the code curve.

It was actually to a curve that's shown there just for reference is the old ASME code curve prior to the 2009 edition.

The current code matches the Argonne design curve for austenitics. Factors of two and twelve. In our Monte Carlo simulation for austenitics we got a factor of 9.6. So, again, we're down around the ten range.

And then nickel, chrome, iron, steel here there was - there is a different relationship for nickel chrome iron alloys for Fen. They make use of the austenitic fatigue curve for the CUF calculations.

Now, one area of improvement we see here and we saw this with the data we looked at for nickel chrome iron steels is that, you know, there is a difference.

In grouping all the austenitics into one curve there is conservatism in doing that for some of those materials. Based on the research and the amount of data we had, you know, the - we used the austenitics stainless steel design curve.

That's consistent with what's in the code. An area of further improvement, in my opinion, would be to separate the austenitic materials into different curves and that's been our recommendation to the industry to look into.

Okay. So the changes to the Fen equations, what I tried to do here is I tried to put the old equations on the left, old equations being what's in 6909 Rev. 0 and the new equations on the right, Rev. 1, I tried to color code the variables so you can tie them into the definitions below. So you remember the Fen example I gave you back on slide ten or whatever it was was for austenitics.

So here's for the carbon steel material and as you can see it has a similar form but there's another term here, the sulfur term based on the sulfur content of the material, and one of the biggest comments we got from the stakeholders was the constant in these expressions - the point - in this case the .632 and the expression on the left.

And what happens there is if you zero out - if you say - you're in a situation where you have no environmental effects that is the second term with the S, the T, the O and the R zero out. Your Fen is still non - you get a value greater than one.

CHAIRMAN RICCARDELLA: The .632 is about two, isn't it?

MR. STEVENS: Right. Even if .632 comes out for this case to be about two. So what that means is even when you don't have environmental conditions present you would hit it with a factor of two, which, you know, kind of doesn't make technical sense.

CHAIRMAN RICCARDELLA: Over and above the existing factor of twelve or twenty or whatever it is.

MR. STEVENS: Right. This would say - if you didn't have environmental - if environmental conditions didn't apply for the component you're looking at you'd still have to double the CUF, just by using these rules and that, you know, technically just was a little bit inconsistent.

And what that was a function of really was the constraints that were used to fit the environmental data. So when we redid the fits in Rev. 1 we basically put a constraint in it and had to go down to one - one environmental condition.

Now, it's hard to see out here but here you have a leading constant in the new term .003 but, see, it's multiplied by - so if environmental effects go away -

CHAIRMAN RICCARDELLA: Yeah. Yeah.

MR. STEVENS: - you basically go to a Fen of one.

CHAIRMAN RICCARDELLA: E to the zero is one.

MR. STEVENS: This was the significant feedback that we received from stakeholders as well as ourselves. But so this was the most significant change and, again, it just amounted to when you do the fit of the data to put an extra constraint on it to force it through an Fen of one.

So the new equation has the same kind of form, the same variables but it just comes up with a different value when environmental conditions don't apply. And for low alloy steel, the previous equation - the lead coefficient which I kind of outlined in yellow instead of being .632 was 702, otherwise it was the same.

We use the same Fen for both carbon and low alloy steel. There's no difference there. They have different fatigue curves but the environmental multiplier is identical.

Okay. These plots - you know, you can never put these on one plot and get everything because of all the terms. So, you know, anytime you want to know what's the Fen you have to do it as a function of something.

So on the left is a plot of Fen as a function of strain rate, given a sulfur content of temperature and there's several curves for a family of dissolved oxygen content.

The solid lines represent the Rev. 1 expressions and the dotted lines represent the Rev. 0 expressions and basically what you see, and this is consistent with your comment, Pete, the new expressions come with better - all other things pretty equal they give you a lower Fen.

CHAIRMAN RICCARDELLA: Yeah.

MR. STEVENS: And what you see at the lower end where they come down and bottom out is the old expressions - the dotted line came out about two and now they're coming out to be one. And then on the right is the same plot except now instead of strain rate being the variable you have temperature for a fixed strain rate.

CHAIRMAN RICCARDELLA: But their - for low strain rates they're -

MR. STEVENS: Low strain rates are the -

CHAIRMAN RICCARDELLA: High temperatures - I mean, you're talking factors of twenty.

MR. STEVENS: They're large.

CHAIRMAN RICCARDELLA: That's huge.

MR. STEVENS: They can be large.

CHAIRMAN RICCARDELLA: I didn't realize that.

MR. STEVENS: And where that's coming from is, you know, back in the expression you're down here into this, the low strain rates. This term becomes a large - this is small. The logarithm is a large negative number which causes the Fen to go up.

CHAIRMAN RICCARDELLA: Well, what are the strain rates for typical transient? Where do you fall on that in that range?

MR. STEVENS: So for this ten to the minus - boy, I'm drawing a blank on, like, a start up event. But that's on the order of, like, ten to the minus five, ten to the minus four percent a second.

But the issue is though where you can get the high Fen you don't get much stress. The transient is so slow and, you know -

CHAIRMAN RICCARDELLA: Like 100 degrees per hour?

MR. STEVENS: Right.

CHAIRMAN RICCARDELLA: Heat up would be -

MR. STEVENS: You might get a very large multiplier but your component may not have this - you know, you may be below the endurance limit and you're not getting any fatigue contributions. So if you get a factor of twenty times, basically, zero it's zero.

The transients that drive the fatigue are very high strain rate transients and those typically have much lower Fen multipliers.

But that's what's caused a bit of the issue because your intuition of in the past stepped - changed transients always caused the highest fatigue. That's true, but they caused the lowest Fen multipliers.

CHAIRMAN RICCARDELLA: Okay.

MR. STEVENS: And in - let's see, these are, again, some - I guess I showed you this one, and then okay. So now what we did is we took all the data and we plotted our estimated fatigue life with our expressions versus those using Japan's expressions.

If they were perfectly equal you would get on a 45-degree line and you see here within the scatter of the data they match. So back to the question of why would they gives us the data.

This plot right here shows two independent research organizations who did take a different approach to how they fit the data basic and come up with equations that look similar but are different are basically getting the same answer, and this is - this is a very important - a very powerful plot for them. We do still see some deviations and in this case - so for some of the lower cycle and, you know, we don't know what's causing all of those other than in the backup slides I've showed you we do have a different approach to how we fit the data.

We minimize - basically when we do the best fit we minimize each point with its distance - perpendicular distance to the best fit curve and the Japanese minimize only on life.

MEMBER BLEY: Just my eye arguing with the curves I see because up at the high cycle the points are above the lines and at the low cycle they're below the lines. So you kind of expect your fit would have twisted some to account for that.

MR. STEVENS: Yeah, and we - it's hard to chase down some of these differences with that. I mean, we did that - to us, this plot within the scatter of the data looked really good. The Japanese looked really good. But specifics get down to - you know, we kind of deviate from the get-go on how we did our fits.

CHAIRMAN RICCARDELLA: Is the fit - the dashed line -

MR. STEVENS: It's not a fit but it's -

CHAIRMAN RICCARDELLA: - it's not a fit.

MEMBER BLEY: That's where it is. That's just the 45-degree line. So the fits -

MR. STEVENS: Oh, I'm sorry. I misunderstood your -

MEMBER BLEY: - the fit's not really shown on here.

MR. STEVENS: The 45-degree - the dotted line is the 45-degree where their prediction would exactly equal our prediction.

MEMBER BLEY: Okay.

CONSULTANT SHACK: So they have two different formulas for predicting but they have the - I mean, it's pretty close, especially in the middle.

CHAIRMAN RICCARDELLA: No, but if you - but if you had a fit it would be some line that would be different than or slightly different than that.

MR. STEVENS: Right. So you see, yeah, the - our prediction versus theirs does have a little bit of a slant to it like what you observed.

CHAIRMAN RICCARDELLA: So.

MR. STEVENS: And it really comes down to how we started the fitting process in the beginning, at least near as I can conclude from this work. They fit it differently than we do.

CHAIRMAN RICCARDELLA: So we're more conservative for low cycle fatigue and less conservative for high cycle or vice versa? I'm having trouble figuring that out.

MR. STEVENS: So for lower cycles - okay, let's look at the plot for low alloy steel one on there.

CHAIRMAN RICCARDELLA: Low cycles - they would predict the shorter lives than us.

MR. STEVENS: They predict a shorter life than us.

CHAIRMAN RICCARDELLA: And for high cycles -

MR. STEVENS: Be opposite.

CHAIRMAN RICCARDELLA: - they'd be longer - longer ones.

MR. STEVENS: And given -

MEMBER POWERS: Your basic approach to fitting is pretty sound.

MR. STEVENS: Yeah. I mean, given that the quantity of data, the fact that there's a scatter of two, the fitting process used in all that, I mean, but given enough time and resources we would chase this down and get it to be perfect and we just - at this -

CHAIRMAN RICCARDELLA: But you know things always look good on log-log. I mean, if the low cycle ends some of those data points are off by a factor of five.

MR. STEVENS: Yeah, and there are some that - and I think some of these -

MEMBER POWERS: Well, they're not off. I mean, it's really that he's basically fitting two things for the variable and he's taking a -

MR. STEVENS: Yeah.

MEMBER POWERS: - an approach in which he has minimized the variance in both directions.

MR. STEVENS: And my recollection is some of the deviations were occurring under, like, BWR water conditions - normal water chemistry conditions.

CHAIRMAN RICCARDELLA: Oh, I see.

MR. STEVENS: And given that there was another reason we kind of abandoned chasing this too much is because there aren't really that many plants following that anymore.

So what was the merit of chasing differences in conditions that plants don't really operate in. So -

MEMBER POWERS: Before I chased anything I would say let's look and see how the prediction does against the data, not against somebody else's correlation.

MR. STEVENS: Right.

MEMBER POWERS: I mean, that's what's misleading about this is people say well, you're off. Well, no, no - you're not off. You're - you have to look at the data -

MR. STEVENS: Right. It's them versus us kind of prediction.

MEMBER POWERS: And I think the approach you've taken in your fitting is very defensible - very defensible.

MR. STEVENS: They were happy with this. I think we're generally happy with it. There are some areas that, you know, again, if we had more time and resources we would pursue further as good researchers. But -

CHAIRMAN RICCARDELLA: But fatigue is that kind of a animal too. I mean, you take ten identical specimens and put them on a fatigue - on a fatigue - on an identical fatigue test and you'll get one of them that'll fail a factor of ten shorter cycles than another, and then the longest one. That's the nature of the phenomenon of -

MEMBER POWERS: Because the metallurgists can't make good materials.

MR. STEVENS: Metallurgy is a black art.

MEMBER POWERS: It still is. They say the wrong incantations, you know.

(Laughter.)

MR. STEVENS: Okay. So then in - here we have the austenitics stainless steel. We basically got rid of the constant out front. However, the transformed variables definitions changed a bit.

The other thing you'll note is before in Rev. 0 we allowed this to go above 325 degrees C. The data doesn't support that because the data we used was 325 degrees C and below. So we did limit it to that and in the NUREG we noted that and we said that we don't really know of any applications with the current fleet where a higher temperature is needed than that. I mean, and if somebody were to use it we need to - I don't know that we would argue against a use of this beyond that temperature but we're probably going to ask some questions about that and its applicability.

We didn't want to put validity on these equations that wasn't true is what it amounted to. So, again, we got rid of the constant terms. Before I think the exponent of .734 came out to be about two and a half when no environmental conditions applied and that's disappeared.

And, again, similarly, here's the plot of the prior Fens and RFens and I think what we have here the solid lines are the new expression. I don't know if I called this out. We also have the Japanese expressions on here. The Japanese expressions are the chain dashed line whereas the dotted line are the Rev. 0 of the NUREG.

So you can see that we do have some differences still with the Japanese in terms of, like, cutoffs and things like that. And, again, at the lower end we now go down to one as opposed to before it was two or two and a half.

So we have a lot more data. Didn't really change things much but we changed a constraint to get the equations to bottom out at one and that's really what happened. That's the differences we made.

Here, the Japan expressions versus ours for stainless steel - again, pretty good agreement. You see a little bit more deviation from that 45-degree line.

Again, we could have pursued more but

everybody looked at this and thought this was pretty good, especially compared to what some of these comparisons were like before.

MEMBER POWERS: I think it would be really interesting to see comparison against the database for some of these areas where there are differences, recognizing you had this problem and it's a multidimensional space.

MR. STEVENS: Right.

MEMBER POWERS: It's kind of hard to plot -

MR. STEVENS: Right.

MEMBER POWERS: - on a two-dimensional plot.

MR. STEVENS: Right.

MEMBER POWERS: But you can - you can plot predicted versus observed on a two-dimensional plot.

MR. STEVENS: Right.

MEMBER POWERS: And that one would be very interesting at the tails because just to see if - I mean, if you're within the scatter bounds on things you can fit until your eyes fall out. You're just fooling yourself.

MR. STEVENS: Right. Yeah, it does get kind of wacky to try and chase some of this down and

-

MEMBER POWERS: I mean, people do this all the time. They end up fitting noise.

MR. STEVENS: Right.

MEMBER POWERS: And it was if you have a very nicely defensible approach to this thing I think you'd be congratulated for using that kind of approach because it's appropriate.

MR. STEVENS: Well, thanks.

MEMBER POWERS: And for two different approaches giving you this kind of agreement the real surprising thing is it's all on one plot.

MR. STEVENS: Right.

CHAIRMAN RICCARDELLA: Let me understand the previous point better. So the dashed curve is the old -

MR. STEVENS: Rev. 0.

CHAIRMAN RICCARDELLA: - Rev. 0 and the solid curve is the new -

MR. STEVENS: Rev. 1.

CHAIRMAN RICCARDELLA: - Rev. 1 and there's really not that much of a difference in those, at least the two blue curves.

MR. STEVENS: No. Mainly at the bottom end.

CHAIRMAN RICCARDELLA: Yeah. And but the - and then the chain link curves are Japanese?

MR. STEVENS: Japanese. That's right.

CHAIRMAN RICCARDELLA: So therein you see the big difference in the -

MR. STEVENS: So there you can see, for example, in the BWR normal water chemistry -

CHAIRMAN RICCARDELLA: Yeah.

MR. STEVENS: - going way up, yeah.

CHAIRMAN RICCARDELLA: Huge difference in that low strain area.

MR. STEVENS: And that's why I was saying, like, in that one curve - well, this is austenitic but I think a lot of the places on that comparison plot where we deviated were there and, you know, we just didn't delve into pursuing that condition.

CHAIRMAN RICCARDELLA: But one of the - I mean, it's just at that low end we're a lot more - at that low strain rate end they're a lot more conservative then.

MR. STEVENS: Right. They're also making changes. They continue to tweak on their model a bit and I know that difference in particular kind of bothered them.

CHAIRMAN RICCARDELLA: So do I understand

- forgetting about the Japanese, from the dashed curve versus the solid curves that we're now distinguishing between dissolved oxygen while the old - while the Rev. 1 only had one curve for all the oxygen levels.

MR. STEVENS: Correct.

CHAIRMAN RICCARDELLA: Okay. And that difference is - that difference is huge.

MR. STEVENS: Right.

CHAIRMAN RICCARDELLA: And is the - is the load dissolved oxygen typical of, I assume, PWRs and the new BWR water chemistry?

MR. STEVENS: Mm-hmm.

CHAIRMAN RICCARDELLA: Oh, okay. Good.

MR. STEVENS: Yeah, in fact that's - for that lower range on that is 40 PPB and that's - you know, what I'm used to seeing is more like 10 PPB and below.

So it's close but it's - yeah, definitely covers their normal dissolved oxygen levels at the lower end and you see it's - you know, in terms of that variable it's about a factor of three from the bottom end to the top, almost.

CHAIRMAN RICCARDELLA: Yeah.

MR. STEVENS: Okay. So nickel chrome iron alloys, we have an expression which is, as you see, the same as - well, it has the same equation as austenitic material.

I'll flash back to that real quick. But the definitions below for the transformed parameters are a little bit different. So even though it has the same equation you get a different value.

Fen was not specified in Rev. 0. It was noted in there that alloy 600 and 690, you know, in their welds that the updated model at the time for austenitic was either consistent or conservative for use with those alloys.

Now, some licensees we noted used an Fen of 1.49, a constant Fen of 1.49 for nickel chrome iron alloys and this was based on an FRE report where they recommended a nonmandatory appendix for inclusion into Section - I don't remember if it was Section 3 or 11 of the code, and in there they came up with 1.49 and they got that by ratioing a couple of curve fits that Argonne had published for air and water.

And anyway, we don't subscribe to that value and anybody that's used it we would expect them to correct that.

CHAIRMAN RICCARDELLA: Significant differences though if you look at the curves. You know, for carbon steel you were seeing factors as high as in the twenties - twenty to, you know, between twenty and twenty-five. In stainless steel you see factors on the order of ten.

MR. STEVENS: Right.

CHAIRMAN RICCARDELLA: And for the inconel stuff you get, like, three. Huge difference.

MR. STEVENS: And that was consistent with the old - I mean, if you were - so even with Rev. 0 if you had ferritic material and you were BWR under normal water chemistry for a slow transient you would be calculating very high Fens. Whereas the old expressions for austenitics have been peaked at about eight.

CONSULTANT SHACK: But, yeah. Someplace where fatigue is demanding that alloy 600 and crew were pretty good.

CHAIRMAN RICCARDELLA: Which is interesting contrast to stress curves and cracking. Can a metallurgist give us some insights into that?

MEMBER POWERS: Into what now?

CHAIRMAN RICCARDELLA: It seems like the -

MEMBER POWERS: Presume that they understand source corrosion cracking that's a big mistake.

CHAIRMAN RICCARDELLA: The alloy 600,

which has been very sensitive to stress corrosion cracking in these environments shows a much less effect of environment on fatigue. I would think the two would somehow be related. But that's my mechanical engineering mind.

CONSULTANT SHACK: Well, look at the austenitics thing with steels where the PWR is worse than the BWR.

MR. STEVENS: But yet it's just the opposite on Ferritic.

CONSULTANT SHACK: The first time Omesh and I said that out loud -

CHAIRMAN RICCARDELLA: But that's - but you got sensitization, you know.

CONSULTANT SHACK: No, no. There's no sensitization here. This is for unsensitized things.

CHAIRMAN RICCARDELLA: I understand. So in the BWR environment unsensitized stainless steel doesn't crack. It's the sensitized stuff that cracks, right?

CONSULTANT SHACK: Still, anything in the PWR - the PWR people didn't believe it at first.

MR. STEVENS: It'd be interesting to hear -

MEMBER POWERS: Why don't you just say

that gee, Westinghouse is crappier than GE? Then we'd get a controversy going.

MEMBER BALLINGER: See, I'm more used to seeing cracked growth data plotted as opposed to SN data because we're - what we're seeing here is a combination of things that you have very high stresses and strains that were - that are focusing on - they're focusing the initiation. It's what's happening when the cracks are actually growing where you see a big difference.

CHAIRMAN RICCARDELLA: That was going to be one of my questions at the end is how does this stuff all correlate with what we see in fatigue crack growth behavior in the environments. Has anybody taken a look at that?

MEMBER BALLINGER: Because what I was - we were talking earlier we're doing some test right now for the Navy people and at high sulfur - that is sulfur at the high end of the band in the spec for stainless steel -

CHAIRMAN RICCARDELLA: Are you sure you can say this on the record?

MEMBER BALLINGER: Yeah. You shut down cracked growth rate. Goes right down to the air line. For large - for - a trapezoidal loading pattern for long hold - long rise times, 500 seconds and higher, in fatigue crack growth with sulfur at the high end at the band the crack growth rate is down - right down on the air line. If you drop the sulfur down to the low levels which normally you would buy you get an acceleration factor.

MEMBER POWERS: Your precipitating on the crack there.

MEMBER BALLINGER: Yeah. What you're doing is you're cropping up the crack dip and what you're doing is you're lowering the decay at the crack and so it's basically shutting it down. So you see big effects and it's opposite on low alloy steel.

MR. STEVENS: Mm-hmm. Yeah, I think - you can correct me, Bill, if I characterize this wrong - you know, Omesh would say that the observations of environmental effects are consistent between initiation and growth.

But I don't know that the magnitude of the effect from, like, these Fens versus growth rates is entirely consistent.

CHAIRMAN RICCARDELLA: Like, what about the trends like the carbon steel versus stainless steel versus inconel? You would think that if one is significantly worse than the other for crack growth you would think it would be something --

MEMBER BALLINGER: Well, but crack growth rate in nickel-based alloy, especially 625 or 690 they're extremely slow - extremely slow, much slower than 600 even and 600 is pretty slow.

CHAIRMAN RICCARDELLA: Yeah. Okay. Environmental.

MEMBER BALLINGER: Yeah, we're right - also right now we're setting up to do a test at pure D2O. So we're going to do a crack growth test in stainless steels and pure D2O and then go find the hydrogen - deuterium. It's all over the place.

CHAIRMAN RICCARDELLA: Is an acceptable alternative for all this to do some sort of a flaw tolerance analysis for you to say I'll give up the initiation and I'll just look at how the cracks grow, assume I have a small crack. I mean, this is - this is initiation of what, I think I saw three millimeter cracks as the assumption?

MEMBER BALLINGER: Yeah. This is an assumption that you have - that you can get initiation.

MR. STEVENS: Our definition of CUF 1 is that it equates to a 3 millimeter crack in the component.

CHAIRMAN RICCARDELLA: And in evaluating the fatigue lives, right? The 25 percent load drop or whatever it was?

MR. STEVENS: Right.

CHAIRMAN RICCARDELLA: Evaluating the data. So, I mean, isn't it an acceptable alternative to say well, I've got a 3 millimeter crack at day one and I'll grow that - and I'll grow that crack.

Is that counted - is 3 millimeters mechanically large enough to apply fracture mechanics? I think it is.

MEMBER BALLINGER: Oh, yeah.

CHAIRMAN RICCARDELLA: Yeah. So -

MR. STEVENS: So my only comment on that would be I think your starting crack is going to be consistent with what you can detect by NDE, which is probably quite a bit bigger.

But flaw tolerances we've approved at least one instance of that in license renewal space as an alternative to doing these calcs.

CHAIRMAN RICCARDELLA: Why does it have to be bigger than what you assume for the initiating crack in your - in these studies?

MR. STEVENS: Well, most folks are applying Section 11 to Appendix L which requires as an initial flaw size it be compatible with what you can detect by NDE and so we - but to your point, there's some work going on in the code and Steve Goslin is doing it where he's - the other conservatism here is, you know, we have small specimens and they're tested basically under membrane loading and most of our - most of the components in the real world aren't under membrane loading.

We have a gradient loading and there's an effect of that as well, and he's doing some work to address that difference and he's starting with 3 millimeter cracks trying to equate CUF equal one values and then into growth and all that.

I think it's a promising approach. He's got a ways to go. So this is what he Fens look like for nickel chrome iron alloys.

CHAIRMAN RICCARDELLA: Somebody's running a fatigue test upstairs.

MR. STEVENS: Sounds like it.

MEMBER POWERS: But they're hoping it fails up there.

MR. STEVENS: I didn't have the same plots for the nickel chrome iron alloys where I predicted, you know, I could show our prediction versus the Japanese predictions.

Here what you see is the prediction versus the experimentally observed values and basically what you get here is you reproduce within the scatter of the data which is what you'd expect if you did the curve fitting right.

So these - you know, basically within about a factor of two is the scatter on the data.

MEMBER POWERS: You know, if you had a real problem on high cycle you're way conservative.

MR. STEVENS: Yeah. Some of that here may be - well, no, I won't say that. Some of that may be the fact that we're using the austenitic curve still for the nickel alloys.

MEMBER POWERS: But where are the tests that the experimental life tests that you're applying this to?

MR. STEVENS: It's the laboratory tests.

MEMBER POWERS: But I read in the NUREG something about laboratory tests on big pipe samples and things like that. Is that what this is or is this the actual small samples?

MR. STEVENS: No. This would be the test specimen. It is basically -

MEMBER POWERS: Okay.

MR. STEVENS: - predicting the test you use to come up with the predictions which, by some standard, wouldn't be a, you know, an independent assessment.

MEMBER POWERS: Yeah. So it's just - the scatter you see is the scatter in the data.

MR. STEVENS: And I have a slide. I'll talk a little bit. We tried to do some of the things you're talking about in NUREG on big pipes and all that and, you know, there were some - there were some good parts of that and some more not so good parts -

MEMBER POWERS: Okay.

MR. STEVENS: - where we get into and know where what we start getting into is the difference between these small specimens and real components. So here we are, a good lead-in - validation calculation.

MEMBER POWERS: Okay.

MR. STEVENS: So I had this idea in this NUREG of, you know, so we got all this. We ought to be able to - so if we have tests where we essentially got failure in a specimen we could calculate CUF for the specimens and then test how well this methodology works on those.

So if we got failure then theoretically if they're in an environment the CUFen should have been 1.0 for those tests. So we came up with a series of six tests and what we wanted to do, and I highlighted these in the blue font, we wanted to come up with different types of testing to test the - or try to validate the Fen and what you see is the last two are more like real components.

We had the U-bend test that EPRI did over in Germany and we also did the step pipe test that Bettis did, which was these are both starting to get into where they are real components whereas the first four tests were just testing of specimens but under different types of conditions.

The first one is changing the strain rate and the second one was changing strain rate and temperature and spectrum loading and complex loading. So whereas, you know, these - so these tests start to exercise, you know, the methodology - predictive methodology kind of off from just doing straight fully reversed uniform loading.

And so what we did in these is we took the tests. We got the load. We calculated the stress in the specimen. We calculated CUF. We calculated a Fen with a predictive methodology for those test conditions and we then calculated a CUFen and basically said did we get 1.0 because the specimen failed.

And, you know, in theory we should get 1.0 plus or minus a factor of two, which is a scatter of the data, and the short of it is we did through at least the first five.

We did not do so well on number six, and I'll go into that a little bit more. But the idea here was trying to get some kind of a validation of real world type of calcs against this methodology and we were very limited, especially with real component tests because there's not many of those out there.

We looked at - and another place where you get into is how you calculate Fen and primarily how you calculate the strain rate in these expressions can be different and so we looked at three different - we assessed three different ways of calculating the strain rate where, you know, in one case we had the peak and the valley and we just drew a straight line and calculated the average strain rate, which is item two here.

In another case, we broke it up into - instead of one ramp into as many as four ramps and that would be the multi linear strain-based approach three. And the other one is we did a very detailed integration which the NUREG calls the modified rate approach as the first one.

And we calculated Fen using all three methods and we calculated CUFen and basically all our validation calculations, certainly for the small-scale specimens, agreed within a factor of about two. So I guess, you know, we - again, we kind of - we reproduced the data we used to create the expressions. You would kind of expect that.

Now, in - when we got to the component test -

CHAIRMAN RICCARDELLA: But wait, wait, wait. The data you used to create the expressions didn't have all these changing strain rates, changing strain rate and temperatures -

MR. STEVENS: That's right.

CHAIRMAN RICCARDELLA: - spectrum loading, things like that. So you did more than - you did more than just analyze the data you used to create - you analyzed data that was tested under different loading conditions.

MR. STEVENS: That's right.

CONSULTANT SHACK: You didn't go from small specimen to component, though.

CHAIRMAN RICCARDELLA: Not in the first pool. In the last two you did.

MR. STEVENS: Well, in the last two.

CHAIRMAN RICCARDELLA: Yeah.

MR. STEVENS: In the last two. So and that's where then we got mixed results. Basically, on the U-bend tests out of the seven tests they ran we got five of them within the factor of two and the other were not.

We conservatively predicted life, meaning that we predicted failure prior to when the actual component failed. And then for the step pipe test results, the results were even more mixed and I say that because, you know, we tried to get details behind that test and there were some other papers written to document analysis that was done on that step pipe, and we made use of those and in going through the fine element analyses associated with those, you know, I found problems with that and we tried to sort that out with the authors and just couldn't get there.

We tried to do our own independent analysis and we couldn't get agreement with what they had. So it became difficult because these - some of the results they had we just didn't think the analysis supporting them was consistent.

Bottom line is that we weren't very good at - we were way overly conservative in those - most of those tests at predicting.

CHAIRMAN RICCARDELLA: That's okay. That's -

MR. STEVENS: And this leads to the last

one.

CHAIRMAN RICCARDELLA: Well, at least we were on the - way overly conservative and not on the opposite - not on the other side.

MR. STEVENS: We recognize that the use of small-scale polished specimens fatigue test data for real components may be conservative and in some cases overly conservative, and I'll just - I'll just say that, you know, all of our work was done on specimens to align with the code curves and come up with this environmental factor.

We think there's been enough testing and data available for those specimens. Our input to the industry is you're right - you should go pursue component testing, and we're fully amenable to review of that data and open to adjustments for accommodating the real components.

CHAIRMAN RICCARDELLA: But this sounds like this is just the opposite of that size correction factor, if you go back to the very beginning.

CONSULTANT SHACK: Well, no -

CHAIRMAN RICCARDELLA: This says that -

CONSULTANT SHACK: Yeah, but the one thing that we didn't correct in all those design factors is this nonmembrane loading, which I think is a large part

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MR. STEVENS: That's right.

CONSULTANT SHACK: - of the - of the -

MR. STEVENS: You're right. We got into sequence but the gradient, and we're getting - we're getting some work now - the gradient load or, you know, a three-wall variation in stress versus a membrane stress I think -

CHAIRMAN RICCARDELLA: Even on the initiation of a three millimeter crack? I mean, that - I'm surprised it's that important up to three millimeters. I could see on the cracked growth beyond that certainly it is but up -

MR. STEVENS: Not so much there but, you know, I think this - the crack growth beyond there, yeah, it is significant.

CHAIRMAN RICCARDELLA: Oh, for sure. But when you - when you evaluated these real components I'm assuming the tests were - failure was based on crack initiation, not on actual failure of the component.

MR. STEVENS: That's right. That's right.

CHAIRMAN RICCARDELLA: So -

MR. STEVENS: Step pipe it was, you know, cracks and, you know, the problem is is they didn't always measure, you know, the number of cycles at a three millimeter crack depth.

They might have stopped the test and looked and it was a tenth of an inch deep or two-tenths or whatever it might have been.

CHAIRMAN RICCARDELLA: Yeah. And then they -

MR. STEVENS: And there was no, you know -

CHAIRMAN RICCARDELLA: - and then they did test them all the way to failure or -

MR. STEVENS: No.

CHAIRMAN RICCARDELLA: No?

MR. STEVENS: Not in that case.

CHAIRMAN RICCARDELLA: Okay.

MR. STEVENS: And in some of the component tests the majority of them, you know, it's a 25 percent load drop. They weren't tested to failure either. Some of them were, other ones weren't.

CHAIRMAN RICCARDELLA: Was that - was that Bettis work that -

MR. STEVENS: Yes.

CHAIRMAN RICCARDELLA: Dave Jones?

MR. STEVENS: Yes. I think here -

CHAIRMAN RICCARDELLA: The last one, item six.

MR. STEVENS: Yeah.

CONSULTANT SHACK: So this is thermal fatigue, though, I mean, so you could have a nongrade - I mean, a gradient term is going to be important here.

MR. STEVENS: Right. That's the thing about the Bettis test is there you do have the gradient. That test has the gradient effect in it.

CONSULTANT SHACK: I mean, you may have a gradient in the U-bend test but it's a gradient that's a whole lot gentler -

MR. STEVENS: Plus, it's a real thin wall, too. The Bettis test was the thick-walled pipe of varying thicknesses and it does - and you may have thermal shocks in it representing safety injection transients.

So you definitely got gradient loading there and, you know, none of our work - none of the fatigue curve work is based on gradient loading. The work that Steve Goslin has done to date, you know, with his kind of calculation shows that if you take account for gradient loading you get another factor of two or three on CUF, and some of our results differed, you know, when we were conservative by a factor of three.

CHAIRMAN RICCARDELLA: Even to crack

initiation?

MEMBER BALLINGER: Well, I mean, the kicker - the killer on this is the Japanese have been doing some - looking at pipes and residual stresses near welds just eat the prediction alive because the residual stress pattern in the heat affected zone in the weld is so different than what they're doing in these tests.

CHAIRMAN RICCARDELLA: But that's our ratios.

MEMBER BALLINGER: Huh?

CHAIRMAN RICCARDELLA: But that's our ratio. I mean, it's not cyclic. It's - I mean, the stress -

MR. STEVENS: I guess - yeah, the mean stress adjustment at the upper end depending on how many - how much load you're applying.

CHAIRMAN RICCARDELLA: Yeah. But, you know, the mean stress effect is important at real high cycle fatigue but when you get down to low cycle fatigue you wash that out for a few cycles. That's -

MR. STEVENS: So if I were to - if I were to summarize, you know, where the action could be at in the fatigue weld is, you know, okay, in some cases we doubled our data - specimen data and it didn't change anything.

Okay. So if I were doing testing I wouldn't waste a whole lot of more money testing specimens other than to maybe pursue some of the adjustment factors like surface finish and Omesh and I think hold time appropriately applied makes a big difference.

A lot of the hold time calculations were done at the highest strain level and we're thinking a more - a better one would be to put a hold time in at zero strain level in the middle of the cycle.

And so - and that could be - those kind of effects could be measured through specimens. But generally speaking, in terms of the strain environmental effect, enough's enough - test components. And then separation of the materials we're getting enough data now.

For example, you could dissect the austenitic curve into the various types of materials. That would be a benefit. On the ferritic side of things, doing the same thing in terms of ultimate strength we see an effect of that.

That would be worthwhile to pursue. Those are the areas we see as the recommendations for moving forward here.

And then the last one would be - at least, I believe that Section 3 after 40 years could look at the way they calculate CUF and maybe consider updating that because we also have - you know, another thing we haven't talked about - we talked about the gradient loading versus the membrane but another thing here is the specimens are basically uniaxial and our components have triaxial stress dates. Somebody could look at that and how CUF is calculated. There could be something there.

So between the curves and that methodology that's not our jurisdiction. That's for the code to take on. We've encouraged them for four years now to look at that.

The last thing I did to the appendix and this probably added the most number of pages, I added Appendix C sample problem. This was not meant to be exhaustive or anything.

It was meant to give out an example to the industry, a typical one based on finding element analysis of how this approach would be applied. Meant to give - just kind of give general direction and on how these things were to be applied and eliminate the low-hanging fruit in terms of questions and all that and to provide enough detail in there that any of the users could reproduce the calculation on their own.

So all of the gory detailed stresses and everything are provided in that appendix so that someone could reproduce that calculation on their own from scratch and dissect it any which way they want.

The sample problem actually came from the industry. EPRI had a couple of round robin sample problem solutions they funded and we took one of those problems and basically solved it ourselves and put it in Appendix C. So that's one example application of the Fen but not meant to be exhaustive.

It's common but it still is relative -

CHAIRMAN RICCARDELLA: What type of a component was it?

MR. STEVENS: It's basically a stepped pipe -a very simple stepped pipe -bimetallic pipe with transients and thermal fatigue, yeah.

So it was relatively simple. It wasn't a surge line.

CHAIRMAN RICCARDELLA: Did the Fen have a huge effect in this?

MR. STEVENS: It had about a factor of - I can't remember what the final factor was. I don't have it here with me. Yes, it was on - it was well above 1.0. It was designed to be that way.

CHAIRMAN RICCARDELLA: Okay.

MR. STEVENS: I think the usage without Fen was up around .75. It was designed that with Fen it would go over 1.0. So we took their problem that they designed and we basically solved it.

We're trying to promote consistency and all that so when applicants use it they kind of get the idea of how to do it.

Feedback that I've received from a lot of the stakeholders on that sample problem through code meetings and whatever has been very positive.

They said that was a great aid to them, and I even got - I got one set of comments that came in one month after the close of comments on the NUREG where a guy solved it and said, I basically got your same answer - you know, I took the problem, I solved it without looking and I got the same answer - this is great. So I think it was a very useful thing for us to do.

So what's our schedule? As I mentioned, the Reg. Guide went out for public comment last Monday, a 60-day review. The public comment period closes on January 23rd. The NUREG - the NUREG went out for public comment 45 days last spring. I had more than 200 individual public comments received on that which was a surprise.

The reason it was a surprise is because two years prior to that Dr. Chropra and I did a very detailed presentation at code on here's everything that's going to be in this NUREG when it comes out, and we received over a hundred comments on and we treated that as a public meeting and put it on the docket and said you have 90 days to comment and encouraged everybody around the world to comment.

We received over a hundred comments on that presentation, which we responded to, and addressed in the NUREG before we released it for public comment. So we thought we had vetted the comments and we got 200 more so you never know.

The comments that are on this slide and, you know, these - we got ten sets of comments from, basically, the worldwide leaders that are invested in this research so they're very good comments.

Still working through that. I really - you know, once those comments are documented and addressed the size of that document is probably going to rival the size of the NUREG itself.

It's going to take me a while to get those. Right now, I'm hoping to have those addressed by the end of next summer.

CHAIRMAN RICCARDELLA: The 200 comments came from these ten - MR. STEVENS: Right. There's one set of public comments I didn't include on here that came in about a month and a half after the public comment period closed and that was mainly, like I said, the guy solved the sample problem.

I didn't include those here. I don't think there's anything in there that would lead to any changes in the NUREGs so I didn't list them here.

CHAIRMAN RICCARDELLA: In any of these? I mean -

MR. STEVENS: No, no. Just in that one.

CHAIRMAN RICCARDELLA: So you think there are things in these that would lead to changes in the methodology or -

MR. STEVENS: Not the methodology. You know, there will be changes - there were some typos identified in all that and that's one of the things we looked at. I think there's probably going to be some change in some of the discussion of the document.

I don't see any changes in methodology. A lot of the comments that I saw were looking at well, you guys didn't do this or, you know, you didn't separate, like, for example - an example that would be on the ferritic curve you didn't separate out by ultimate strength.

That has an effect. And my response is going to be you're right but we chose not to and we're not going to and if you wanted to do that feel free. You know, that kind of response.

MEMBER POWERS: That's the screw you, strong letter to follow up.

MR. STEVENS: We got comments on you know what you didn't do. We know there's a lot we didn't do. We got to say when at some point and if we were invested in this topic as a high priority moving forward and funding more research for sure we'd pursue those.

But what I have found in worldwide application of this, everybody in the world is using it and can successfully - can show successful results for 60 years.

Nobody has ever yet given me an example of a case where they couldn't pencil whip it if they chose to. In the case - in some cases what we've seen, like, in one licensee they chose - rather than pencil whip it they chose to do flaw tolerance and they did that.

CHAIRMAN RICCARDELLA: This argues for why we didn't back fit it.

MR. STEVENS: And even two weeks ago at code the Koreans came and said, we just did our AP 1400 or whatever reactor it was and they said and here's the results we got for 60 years, and nobody could read the chart.

So when he was finished I said, can you back up to that slide and magnify it and all his usage factors with environmental effects were less than one. The Japanese, in all the discussions I've had with them, apply this regularly for 60 years and in all cases they are able to show acceptable results.

So for 60 years this methodology is sufficient. Now, beyond that for 80 years I suspect there will be challenges. But that's what we've seen.

I - you know, in the all the meetings I've gone to in the code I've - for the vendors that have complained about the methodology I said bring me an example of where you're having hardship and no one's ever been able to produce that.

CHAIRMAN RICCARDELLA: So they just have to do more sophisticated analyses, I assume?

MR. STEVENS: That's what it comes down to. They have to do more detailed analysis but in all cases with - they're not doing anything different but doing more refined calculations. They're not going to plastic analysis or anything like that.

CHAIRMAN RICCARDELLA: I mean, we have had a number of notable fatigue failures in plants and they're summarized very nicely in the NUREG. But I guess by and large those occurred because we didn't define - not because of the - not because we didn't know but we just - there were loads that we didn't know about or we didn't find, right? Thermal stratification, lightning, all those -

MR. STEVENS: I still don't know of any failures caused by environmental effects as opposed to - maybe a better way to say it is there could have been environmental effects at work there but like what you said the failures we've seen have been caused by loads not considered by the design or vibration.

CHAIRMAN RICCARDELLA: Yeah.

MR. STEVENS: So we expect the comment period to close in late January on the Reg. Guide addressing comments into next summer.

I expect to probably come before you all in the fall with the final drafts of the documents and the public comments addressed and all that and I'm hoping to issue both by the end of next year, and that schedule supports the needs of subsequent license renewal so they can reference the documents in their new GALL report when it gets published.

That's all I have.

CHAIRMAN RICCARDELLA: I've got a question, Gary. Has anybody done a trial calc to push beyond 60 to 80? Pick a couple of what you consider to be the most sensitive components and just try it and see what the CUF would look like?

MR. STEVENS: Actually, a couple. In my prior life I actually did one because the licensee asked for - happened to be one of the licensees who was sort of thinking out like that and so they asked for calculations to be done at 60 and 80 years. And they didn't ask for the 80-year calculations to be shown to be acceptable.

They just wanted to see what they were. So I'm aware of a few calculations like that and, you know, some of those - it's what you'd expect. If you take the 60 years numbers and scale them up some of them work and others don't and so I've seen those types of assessments.

I don't think the - to my knowledge I haven't seen any here at the NRC that have been formally submitted.

So I - you know, I expect that 25 percent of the components are going to require further analysis of some sort or to switch over to flaw tolerance.

I'll just note that the one application we saw of flaw tolerance was applied to the surge line and there the licensee elected not to pursue acceptable CUF calculations and they went to flaw tolerance and that analysis supported a ten-year inspection interval, which is what Section 11 would require you to do.

MEMBER SKILLMAN: I would expect in a lot of cases that there is a significant amount of margin because the early functional specifications require including in the CUF a large number of fatigue cycles and plants are not operated that way.

They're basically not quite base loaded by pretty close. So you've got a lot of margin in the -in the cycles that are not used to allow those components to stretch out quite a bit in the future.

MR. STEVENS: Right. So generally speaking the PWRs have shown the number of cycles that were postulated for 40 years remain valid for 60 years. I imagine there will be some subset of those that might be able to show the same for 80.

MEMBER BALLINGER: I mean, a lot of these - a lot of these plants nowadays and new plants are doing stress improvements on the build and so they're compressive on the surface to start with from the stress load cracking point of view. But it's got to help on the fatigue side.

MR. STEVENS: Well, it's interesting - and Section 3 is also pursuing a flaw tolerance approach and basically what they're advocating is they really want to depart from the CUF calculation and go straight to an inspection-based method.

You know, where we - the devil's in the details on that and we're not quite sure how that fits within the structure of Section 3 and all that and everything. But anyway, that is being pursued. They got a code case. In fact, there's a conference call tomorrow.

CHAIRMAN RICCARDELLA: That's a big change.

MR. STEVENS: It is.

CHAIRMAN RICCARDELLA: When we put flaw analysis into Section 11 only Section 3 has what cracks - you can't analyze cracks - cracks are unacceptable. Of course, the inspections they did - the inspections they did didn't find the - didn't find cracks but they were there. But if you find them they're unacceptable.

MR. STEVENS: And those - you know, those approaches are based on the premise that you - that you do an inspection and you don't find anything. I mean, that -

CHAIRMAN RICCARDELLA: And the bottom

line is don't look for the cracks?

CONSULTANT SHACK: I mean, some - you know, cask stainless is always going to be a problem from that point of view.

CHAIRMAN RICCARDELLA: Yeah.

CONSULTANT SHACK: It's going to be very difficult to convince anybody with the inspection.

MR. STEVENS: Dave and I are laughing about cask because aside from fatigue there's a whole another issue on that going on right now. And yes, at the - at the heart of it is inspection.

CHAIRMAN RICCARDELLA: Okay. Well, thank you again.

MR. GERBER: Oh, I'm going to - hi, I'm Dave Gerber, Structural Integrity Associates. We did - we've taken a quick look.

First - the first plant we've been taking a look at for SLR and so PWR and we have been discovering on a first cut basis that not only was 40 equal to 60 but 40 is equal to 80 also, as far as numbers of cycles that they'd look at.

It's not all the cycles there are but it's the ones in their FSARs. So that will be, I think, an approach that will work for PWRs for most transients.

CHAIRMAN RICCARDELLA: Thank you. Okay.

So let's first go around the table and start with Joy. Is there any further comments?

CONSULTANT SHACK: Excellent presentation, brilliant work.

MR. STEVENS: I figured if I - I figured if I didn't show today you could have just done the presentation.

CHAIRMAN RICCARDELLA: Ron?

MEMBER BALLINGER: Same thing. Brilliant work.

CHAIRMAN RICCARDELLA: Good.

MEMBER SKILLMAN: Excellent presentation. I apologize for my cold but I've been completely tuned in. I'm fighting through it. But excellent. Thank you.

MR. STEVENS: Thank you.

CHAIRMAN RICCARDELLA: Dana?

MEMBER POWERS: Well, I would say excellent presentation and brilliant work but that would be agreeing with Shack and I'm constitutionally ill disposed to doing that.

But it really is quite good on your, certainly, calculations but come away a little confused about the ranges that you've used in your Monte Carlo sampling.

Not too concerned about distribution but the ranges are the ones that I - I did not come away with a warm and fuzzy feeling for their - in the course of making modifications to your documentation if you can make that a little clearer that would have helped me a lot on that.

MR. STEVENS: Okay.

MEMBER POWERS: I don=t have a problem with your methodology, and like I say, your methods are excellent. I really like what you've done there.

MR. STEVENS: Okay. Thank you.

CHAIRMAN RICCARDELLA: Dennis?

MEMBER BLEY: Nothing additional from me.

CHAIRMAN RICCARDELLA: Okay. I have a few but I think most of them have been answered. Are you going to seek a code case? Is it your desire to get a code case on this?

MR. STEVENS: So - okay, regarding code cases, as I mentioned on slide - I know that was pretty early -there's two code cases -

CHAIRMAN RICCARDELLA: And there are some code cases that -

MR. STEVENS: There's two code cases out and a few more being developed, okay, and one of them is a flaw tolerance code case for Section 3 and I'll just not talk about that right now.

So the other three code cases there's seven - N-761 which is environmental fatigue curves. I'm going to point you to the right slide here. Right here - slide number ten.

N-761 is environmental fatigue curves and, you know, we didn't approve that because this was a curve put together by the subgroup on the fatigue strength for Section 3 where Bill O'Donnell was the chair.

CHAIRMAN RICCARDELLA: Yeah.

MR. STEVENS: And, you know, we asked how they developed the curves and, frankly, they haven't provided a technical basis that allows us to understand that, and I'm now under discussions with folks at Bettis to try and get that.

Section 3 has been basically ordered to try and get us to get a code case that's amenable to us because they believe - Section 3 members believe the Fen is too complicated.

They just want to use curves so far and the curves as we see them are not consistent with our work and we need to understand that and we're trying to work through that process. So that code case is issued.

We have not endorsed it and we won't and we're trying to work through with that committee now to come up with something that's acceptable.

The other code case you see here is N-792. N-792 is an Fen code case. Effectively, it adopts Rev. 0 of the NUREG with the exception of it does not have a strain threshold below where the environmental effects don't apply.

So as I've stated, the ASME, for the first time in the history of the industry, the code is more conservative than the regulator.

We didn't approve that code case because at the time we had an agreement we had started on this research and we said do you think it's better if you hold off on the code case and then make it match our work and then issue it.

CHAIRMAN RICCARDELLA: Make it match Rev. 1?

MR. STEVENS: Yeah. Fundamentally, we're okay with that code case. The fact that it doesn't have a strain amplitude threshold is conservative. So we would vote for it. But what we're going to say is they need to revise it now to match this and they have plans to do that.

The third code case is a strain rate code case that the Japanese are putting together and it has intricate detail on how to calculate strain rate, and I haven't really evaluated that but, frankly, it carries the science way beyond anything that's - that can be - I mean, that can be proven.

You know, they're getting into so much detail and they have nothing to benchmark what is recommended. So I don't necessarily have any complaints with it and we haven't evaluated it in detail but the issue I'll have is in the end, you know, they're trying to evaluate triaxial stress dates and all these other things and I don't have anything to benchmark it up against.

So whether they're right or, you know, they have ten guys on the committee and they've all recommended a way, whose way is right and there's no way to know.

So I recommended to them that they need to tie in with EPRI's longer term efforts and come up with a test where they can benchmark it. So we don't have, and I don't remember the number on that code case offhand - I know we don't have a problem with that approach. It's just that it'll be difficult for them to technically justify it.

And so those are the three things and my understanding there's a working group now devoted to environmental fatigue effects in the code, which I try and attend quarterly.

What they want to do is get these three code cases done and out and approved and then they want to put them into a nonmandatory appendix in Section 3.

CHAIRMAN RICCARDELLA: 761 and 792, they're not issued - they're just being worked on?

MR. STEVENS: They're both issued. It's just that we haven't endorsed them in the Reg. Guide.

CHAIRMAN RICCARDELLA: But they're working on a rev to 792? MR. STEVENS: They're working on a rev to 792. Well, actually - I believe right now 792-1 is issued. The next thing they would do is issue a dash two that would incorporate Rev. 1 and they're waiting to do that until we issue Rev. 1.

CHAIRMAN RICCARDELLA: All right.

MR. STEVENS: The code case for flaw tolerance I don't know if it's been assigned a number yet. It's not been approved. That one's got a long ways to go, in my opinion, because, you know, fundamentally they made a match in Section 11 Appendix L.

CHAIRMAN RICCARDELLA: Yeah.

MR. STEVENS: And they just said, you

know, go to the Section 11 and NDE qualification and acceptance standards tied into all that. Section 3 hasn't figured out how to do that part of it yet. So the flaw tolerance analysis part is okay.

But what they're postulating for initial flaw size and where it comes from and how it ties into the NDE world and all that, they haven't figured that out yet.

So in my opinion, that's probably going to be harder than the technical flaw tolerance part of the code case and they just haven't done that. So it's probably got a ways to go. The strain rate code case I think I just saw a presentation two weeks ago that's up to draft rev 18 or something ridiculous. It's still going through the working group.

I expect it'll probably be issued in, like, a year - something like that, and then I think their fatigue action plan that they have for Section 3 says once we get all these done we want to get the regulator to endorse them.

Then we're going to put them in a nonmandatory appendix in Section 3 in which case then they're - the other issue with these code cases is there's nothing that would point you to use them. There would have to be - if they put it in a nonmandatory appendix now they'd have to put some invoking words into Section 3 as to what would ever get you that appendix, and I think where it's NB-3121 or whatever the section was I cited here you just add a sentence there and say one way to address these effects is in the appendix and then they have it covered. But that's quite a ways off.

CHAIRMAN RICCARDELLA: Okay. Thank you. So do we have any comments from anybody else in the room? Okay. Could we get the - it's open. Okay. So we do have, I understand, some people on the bridge line.

I wonder if we have any comments from people on the bridge line. Would somebody out there just say hello so I can confirm that it's open?

PHONE PARTICIPANT: Hello. No comment.

CHAIRMAN RICCARDELLA: Thank you. Okay. So I guess with that the topic is closed. I think we're going to - this is kind of a preliminary review in parallel with it going on for public comment.

I think we'll be addressing the issue when we get any comments back and I don't know if we'll take any full committee action on it.

But we will certainly hear from you again once you have the comments back. Okay. Thank you.

MR. STEVENS: Thank you.

CHAIRMAN RICCARDELLA: Meeting is

adjourned.

(Whereupon, the above-entitled meeting concluded at 3:13 p.m.)

U.S.NRC
United States Nuclear Regulatory Commission
*Protecting People and the Environment*

# Advisory Committee on Reactor Safeguards Metallurgy and Reactor Fuels Subcommittee Meeting

# Technical Brief on Regulatory Guidance for Evaluating the Effects of Light Water Reactor Coolant Environments in Fatigue Analyses of Metal Components

***(Proposed Revision 1 to Regulatory Guide 1.207)***


**Gary L. Stevens, Sr. Materials Engineer**

*Office of Nuclear Regulatory Research*
*Component Integrity Branch*


**Tuesday, December 2, 2014**
**NRC Headquarters**
**Rockville, MD**

# Objective

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

- **At ACRS's request, the staff is providing this brief**
- **NRC is revising the guidance for environmentally assisted fatigue (EAF)**
  - **Regulatory Guide (RG)**
    - **Draft Regulatory Guide DG-1309, "Guidelines for Evaluating the Effects of Light Water Reactor Coolant Environments in Fatigue Analyses of Metal Components"**
  - **Supporting technical basis NUREG**
    - **Draft NUREG/CR-6909, Revision 1 (ANL-12/60), "Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials"**
- **Both draft documents were released for public comment**
  - **The draft RG was published for 60-day public comment on 11/24/2014**
  - **The draft NUREG was published for public comment during the time period of 4/17/2014 – 6/2/2014**

# Outline

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- Background
  - What is cumulative usage factor (CUF)?
  - What is EAF?
  - Why is there NRC guidance on EAF?
  - What is the NRC guidance on EAF?
  - What is Reg. Guide 1.207 and NUREG/CR-6909?
  - What is $F_{en}$?
- Reasons for Revising Reg. Guide 1.207
- Summary of Revisions to Reg. Guide 1.207
- Revisions to $F_{en}$ Equations
  - Review of updated fatigue data
  - Review of air fatigue curves
  - Review of changes to $F_{en}$ expressions
- Estimated Schedule for RG and NUREG Publication

# BACKGROUND

What is cumulative usage factor (CUF)?

What is EAF?

Why is there NRC guidance on EAF?

What is the NRC guidance on EAF?

What is Reg. Guide 1.207 and NUREG/CR-6909?

What is $F_{en}$?

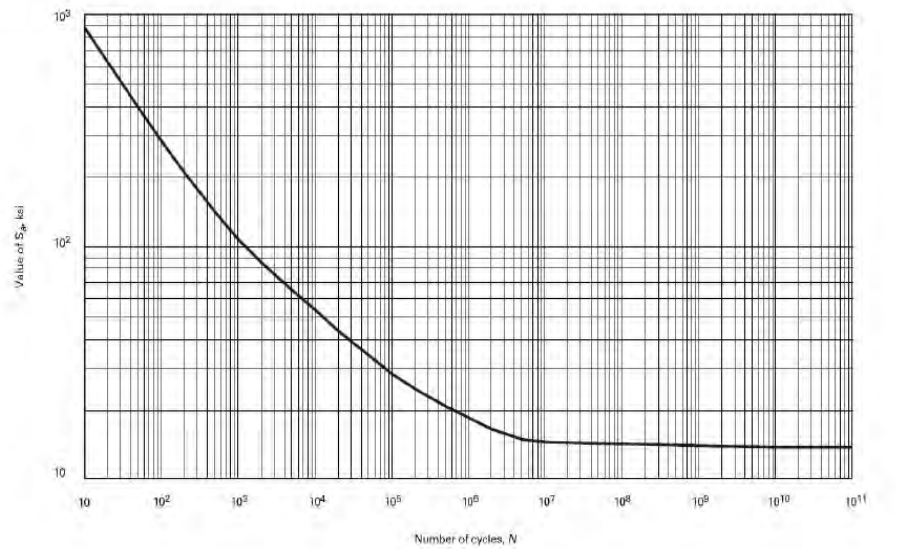
# What is cumulative usage factor (CUF)?

- **For nuclear plant design, cumulative fatigue damage due to applied cyclic loading is estimated using cumulative usage factor (CUF):**

$$\mathbf{CUF} = \sum_{i}^{Z} \frac{n}{N} = U_1 + U_2 + U_3 + \ldots + U_Z < 1.0$$

*where: n is the applied number of cycles for load i*
*N is the allowable number of cycles for the stress associated with load i*
*Z is the number of applied loads*

- **N is a function of the alternating stress, $S_a$, applied to a component, and is material dependent (i.e., it is a material property)**
- **S-N curves ("fatigue curves") are given in ASME Code, Section III, Mandatory Appendix I for different materials**
- **Design fatigue curves are based on best fits of air test data with design factors applied**




GENERAL NOTES:
(a) $E = 28.3 \times 10^6$ psi
(b) Table I-9.2 contains tabulated values and a formula for an accurate interpolation of this curve.

FIG. I-9.2M DESIGN FATIGUE CURVES FOR AUSTENITIC STEELS, NICKEL–CHROMIUM–IRON ALLOY, NICKEL–IRON–CHROMIUM ALLOY, AND NICKEL–COPPER ALLOY FOR TEMPERATURES NOT EXCEEDING 425°C

***S-N curves are usually defined in log-log form***

# What is EAF?

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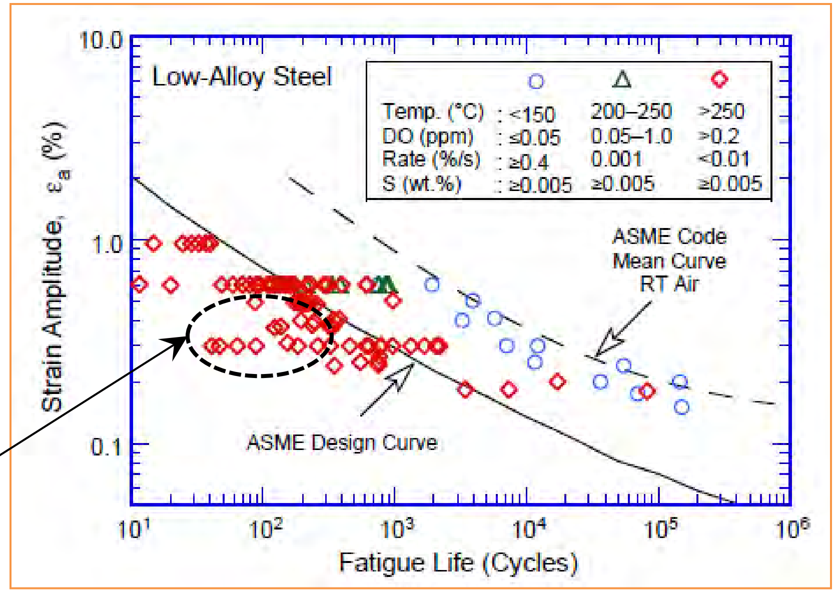
- **The fatigue curves in Section III of the ASME Code were developed from laboratory test data from small-scale, polished specimens tested in AIR**
- **The AIR test data were used to develop design fatigue curves suitable for design:**
  - **Develop best fit log-log curves for the AIR data for each material type**
  - **Adjust the best fit curves to account for worst-case mean stress effects using the Modified Goodman relationship**
  - **Apply factors* of 2 on strain amplitude ($\varepsilon_a$) or 20 on cycles (N), whichever is more conservative, to develop AIR design curves for each material**
- **More recent laboratory testing of specimens tested in WATER indicated that the AIR design curves may not adequately define fatigue life for materials exposed to WATER environments:**

*Note how some of the points for tests in WATER fall below the AIR design curve.*




* Factors to account for data scatter, size effects (i.e., small laboratory specimens vs. large power plant components), surface finish, atmosphere, etc.

# Why is there NRC guidance on EAF? (1/4)

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## Related Regulatory Requirements

- **Title 10 of the Code of Federal Regulations (10 CFR) Part 50, "Domestic Licensing of Production and Utilization Facilities, Appendix A, "General Design Criteria for Nuclear Power Plants"**
  - **General Design Criterion 1**

    *Safety related SSCs must be designed, fabricated, erected, and tested to quality standards commensurate with the importance of the safety function performed*
  - **General Design Criterion 30**

    *Components included in the reactor pressure boundary must be designed, fabricated, erected, and tested to the highest practical quality standards*
  - **10 CFR 50.55a (c), endorses ASME Code for design of safety-related systems and components (Class 1)**
    - **ASME Code, Section III includes fatigue design curves**
    - **Fatigue design curves do not address the impact of the reactor coolant system environment**

# Why is there NRC guidance on EAF? (2/4)

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- **ASME Section III fatigue design curves developed in the late 1960s and early 1970s**
  - **Air environments at ambient temperatures**
  - **Margin of 2 on strain and a margin of 20 on cyclic life**
  - **ASME Section III, NB-3121 identifies that the data used to develop the fatigue design curves did not include tests in environments that might accelerate fatigue failure**
- **In the 1980s, the NRC initiated the Fatigue Action Plan (FAP) in response to findings primarily from early Plant Life Extension Studies**
- **Research in Japan (Higuchi and Iida, 1991) and those at ANL (NUREG/CR-4667, 1990) identified potentially significant effects of light water reactor (LWR) coolant environment on fatigue lives of steels**

# Why is there NRC guidance on EAF? (3/4)

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- **In 1995, closeout of the FAP* and resolution of Generic Safety Issue (GSI) 166, "Adequacy of Fatigue Life of Metal Components," established that**:**
  - Risk to core damage from fatigue failure of RCS very small; no action required for current plant design life of 40 years
  - NRC staff concluded that fatigue issues should be evaluated for extended period of operation for license renewal (under GSI 190)
- **In 1999, resolution of GSI 190, "Fatigue Evaluation of Metal Components for 60-Year Plant Life" *****
  - 10 CFR 54.21, Aging Management Programs for license renewal should address component fatigue including addressing the effects of the LWR coolant environment

* SECY-95-245, "Completion of the Fatigue Action Plan," September 25, 1995, ADAMS Accession No. ML031480210.

** NUREG/CR-6674 (PNNL-13227), "Fatigue Analysis of Components for 60-Year Plant Life," June 2000.

*** Thadani, Ashok C., Director of the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, memorandum to William D. Travers, Executive Director for Operations, U.S. Nuclear Regulatory Commission, "Closeout of Generic Safety Issue 190, 'Fatigue Evaluation of Metal Components for 60 Year Plant Life'," August 26, 1999, ADAMS Accession No. ML003673136

# Why is there NRC guidance on EAF? (4/4)

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- **On December 1, 1999, by letter to the Chairman of the ASME Board on Nuclear Codes and Standards (BNCS), the NRC requested that ASME revise the Code to include environmental effects in the fatigue design of components**
- **ASME initiated the Pressure Vessel Research Council (PVRC) Steering Committee on Cyclic Life and Environmental Effects**
- **PVRC recommended revising the Code design fatigue curves (Welding Research Council (WRC) Bulletin 487)**
- **ASME Code has struggled with this issue for more than 20 years; still no acceptable rules to address EAF in Section III**
  - **Two Section III Code Cases have been published (N-761 and N-792), but these have not been endorsed by NRC**
- **Based on NRC's FAP efforts, guidance was developed for operating plants* to address EAF (1999) and new reactors to address EAF (2007)**



*** License renewal applicants only (i.e., only applicable for operation beyond the 40-year design life of operating plants).**

# What is the NRC guidance on EAF? (1/3)

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- **In the late 1990s, NRC published the results of their research efforts related to the impact of LWR coolant environments on the fatigue lives of steels:**
  - Chopra, O. K., and W. J. Shack, "Effects of LWR Coolant Environments on Fatigue Design Curves of Carbon and Low–Alloy Steels," NUREG/CR–6583, ANL–97/18, 1998.
  - Chopra, O. K., "Effects of LWR Coolant Environments on Fatigue Design Curves of Austenitic Stainless Steels," NUREG/CR–5704, ANL–98/31, 1999.
- **Based on the direction of the FAP closeout, these NUREGs were adopted for use in guidance for license renewal applicants in the initial release of NUREG-1801, "Generic Aging Lessons Learned (GALL) Report" (2001)**
  - Chapter X.M1, "Metal Fatigue of Reactor Coolant Pressure Boundary"
- **These NUREGs remain in the current license renewal guidance documented in NUREG-1801, Rev. 2 (2010)**

# What is the NRC guidance on EAF? (2/3)

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## GUIDANCE FOR NEW REACTORS

- **EAF guidance for new reactor design was issued in 2007:**
  - RG 1.207, "Guidelines for Evaluating Fatigue Analyses Incorporating the Life Reduction of Metal Components Due to the Effects of the Light Water Reactor Environment for New Reactors" March 2007.
- **The technical basis document for RG 1.207 is NUREG/CR-6909:**
  - NUREG/CR–6909, ANL–06/08, Chopra, O. K., and W. J. Shack, "Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials – Final Report," February 2007.

# What is the NRC guidance on EAF? (3/3)

U.S.NRC
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## GUIDANCE FOR OPERATING REACTORS

- **Currently, operating reactors that are not in the license renewal period have no guidance or requirements for considering EAF**
- **Recent license renewal applicants follow the guidance of NUREG-1801, Rev. 2:**
  - **For carbon steel: May use either NUREG/CR-6583 OR NUREG/CR-6909 OR an NRC-approved alternative**
  - **For stainless steel: May use either NUREG/CR-5704 OR NUREG/CR-6909 OR an NRC-approved alternative**
  - **For Ni-Cr-Fe alloys: May use NUREG/CR-6909 OR an NRC-approved alternative.**

# What is Reg. Guide 1.207 and NUREG/CR-6909?

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- Defines fatigue multiplier, $F_{en}$, methodology
- EAF guidance for new reactors
- May also be used by license renewal applicants
- These documents provide the best vehicle for the NRC to consolidate and update EAF guidance

# What is $F_{en}$? (1/2)

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- Initially, the NRC reviewed two methods for incorporating EAF effects; the second method was adopted:
  - 1. Develop new environmental fatigue curves
  - 2. Use of an environmental correction factor, $F_{en}$
- $F_{en}$ is defined as the ratio of fatigue life in air at room temperature to the fatigue life in water <u>at the service temperature</u>:

$$F_{en} = N_{air}/N_{water}$$

- $F_{en}$ is multiplicative to the calculated CUF in air:

$$CUF_{en} = U_1 F_{en,1} + U_2 F_{en,2} \ldots\ldots U_Z F_{en,Z}$$

# What is $F_{en}$? (2/2)

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- **How is $F_{en}$ computed?**
- **For example, from Revision 0 of NUREG/CR-6909 for stainless steel materials:**

$$F_{en} = \exp[0.734 - T' \, O' \, R']$$

**where:**

**T' = transformed temperature:**

| | |
|---|---|
| $T' = 0$ | for temperature, $T \leq 150^{o}C$ |
| $T' = (T - 150)/175$ | for $150 < T < 325^{o}C$ |
| $T' = 1$ | for $T \geq 325^{o}C$ |

**O' = transformed oxygen:**

| | |
|---|---|
| $O' = 0.281$ | for all fluid dissolved oxygen levels |

**R' = transformed strain rate:**

| | |
|---|---|
| $R' = 0$ | for strain rate, $R \geq 0.4\%/s$ |
| $R' = \ln(R/0.4)$ | for $0.001 \leq R < 0.4\%/s$ |
| $R' = \ln(0.001)$ | for $R < 0.001\%/s$ |

# REASONS FOR REVISING REG. GUIDE 1.207

# Reasons for Revising Reg. Guide 1.207

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- **There are three reasons the NRC is revising the EAF guidance in RG 1.207:**
  1. **To consolidate all EAF guidance**
  2. **To update the guidance based on stakeholder feedback**
  3. **To update the guidance based on all available research data**
- **In 2010, the Office of New Reactors (NRO) and the Office of Nuclear Reactor Regulation (NRR) prepared a joint User Need Request (UNR)**
  – **Requested the Office of Nuclear Regulatory Research (RES) to perform research activities to update EAF guidance and revise RG 1.207 and NUREG/CR-6909**
  – **NRC also implemented an addendum to the NRC/EPRI Memorandum of Understanding (MOU) that authorized EPRI participation and co-funding of the NRC's EAF research activities**

# SUMMARY OF REVISIONS TO REG. GUIDE 1.207

# Summary of Revisions to Reg. Guide 1.207

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- **The following revisions were made to RG 1.207:**
  1. **The title was revised to remove "New Reactors" (i.e., the RG was made applicable to all LWRs)**
  2. **The guidance was clarified to apply to all metal components exposed to LWR environments that have a CUF calculation required by a plant's current licensing basis (CLB)**
  3. **The background section was revised to incorporate the relevant content for operating reactors, license renewal, etc.**
  4. **The $F_{en}$ equations were revised based on stakeholder feedback and the updated research documented in NUREG/CR-6909, Rev. 1**

# REVISIONS TO $F_{EN}$ EQUATIONS

Review of updated fatigue data

Review of air fatigue curves

Review of changes to $F_{en}$ expressions

Validation calculations

Sample problem

# Review of Updated Fatigue Data (1/3)

U.S.NRC
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- **Initially, RES planned to gather and incorporate all publically available fatigue data published since the initial release of RG 1.207 (2007)**
- **At the start of NRC research efforts, negotiations were undertaken with the Japan Nuclear Energy Safety Organization (JNES), now the Japan Nuclear Regulatory Authority (JNRA), to formally obtain all EAF data from Japanese research programs**
  - **Pursued under the NRC/JNES Cooperative Materials Research Agreement**
  - **Led to formal release of Japanese EAF data to NRC in October 2011***

* RES gratefully acknowledges the release of the Japanese EAF research data, as documented in Report No. JNES-SS-1005, "Environmental Fatigue Evaluation Method for Nuclear Power Plants," Nuclear Energy System Safety Division, Japan Nuclear Energy Safety Organization, March 2011, ADAMS Accession No. ML113010189.

# Review of Updated Fatigue Data (2/3)

United States Nuclear Regulatory Commission
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## Summary of air fatigue data in Rev. 0/Rev. 1 of NUREG/CR-6909:

| Material | Data Available for Rev. 0 | Data Available for Rev. 1 | Increase* |
|---|---|---|---|
| Carbon Steels | 153 points<br>(8 heats)<br>[Figure 7(a) of Rev. 0] | 254 points<br>(19 heats)<br>[Figure 32(b) of Rev. 1] | 66 % |
| Low-Alloy Steels | 358 points<br>(19 heats)<br>[Figure 7(b) of Rev. 0] | 430 points<br>(22 heats)<br>[Figure 32(d) of Rev. 1] | 20 % |
| Austenitic Stainless Steels | 357 points<br>(38 heats)<br>[Figure 35 of Rev. 0] | 622 points<br>(40 heats)<br>[Figure 45(b) of Rev. 1] | 74 % |
| Ni-Cr-Fe Alloys | Not quantified<br>[Figures 56 & 57 of Rev. 0] | 559 points<br>(45 heats)<br>[Section 3.3 of Rev. 1] | N/A |

* The majority of the increase in data is attributed to the additional data reported in Report No. JNES-SS-1005.

# Review of Updated Fatigue Data (3/3)

United States Nuclear Regulatory Commission
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## Summary of water fatigue data in Rev. 0/Rev. 1 of NUREG/CR-6909:

| Material | Data Available for Rev. 0 | Data Available for Rev. 1 | Increase* |
|---|---|---|---|
| Carbon Steels | 318 points<br>(12 heats)<br>[Figure 27 of Rev. 0] | 638 points<br>(21 heats)<br>[Figure 79 of Rev. 1] | 100 % |
| Low-Alloy Steels | 327 points<br>(13 heats)<br>[Figure 27 of Rev. 0] | 536 points<br>(20 heats)<br>[Figure 79 of Rev. 1] | 64 % |
| Austenitic Stainless Steels | 276 points<br>(14 heats)<br>[Figure 52 of Rev. 0] | 683 points<br>(32 heats)<br>[Figure 110 of Rev. 1] | 147 % |
| Ni-Cr-Fe Alloys | Not quantified<br>[Figures 58 & 59 of Rev. 0] | 162 points<br>(13 heats)<br>[Section 4.3 of Rev. 1] | N/A |

* The majority of the increase in data is attributed to the additional data reported in Report No. JNES-SS-1005.

# Review of Air Fatigue Curves (1/12)

U.S.NRC
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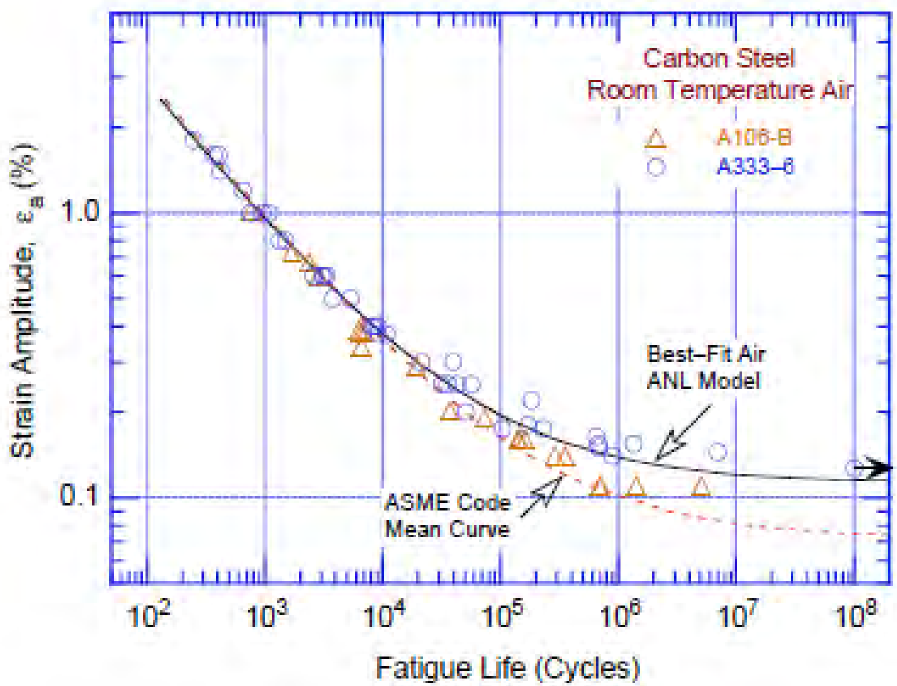
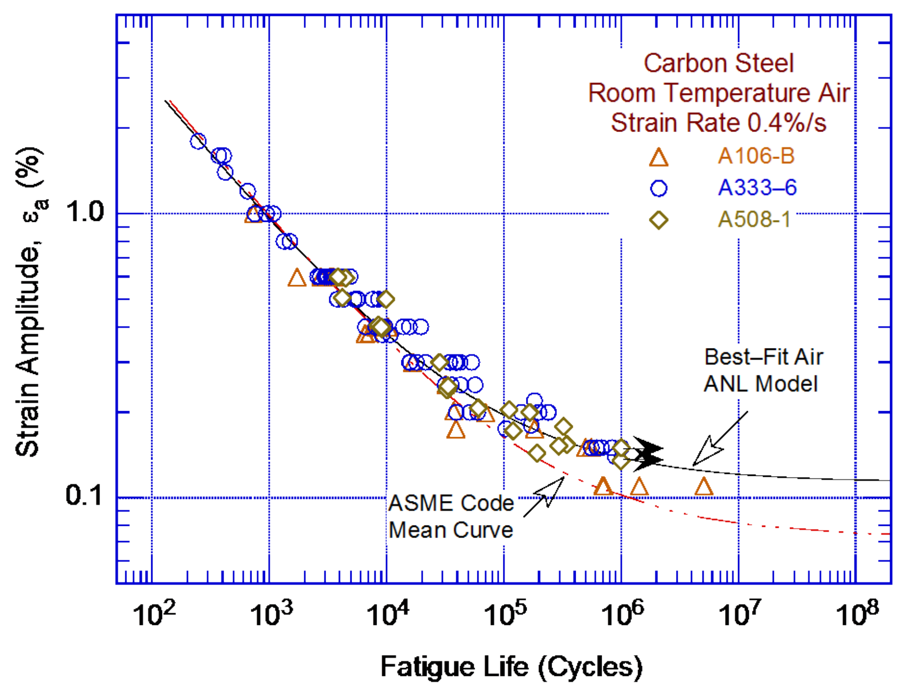
## Best Fit AIR Curves for Carbon Steel

**From NUREG/CR-6909, Rev. 0:**




**From NUREG/CR-6909, Rev. 1:**




**NOTE: The ANL best-fit air curves are identical in both of the above figures.**

# Review of Air Fatigue Curves (2/12)

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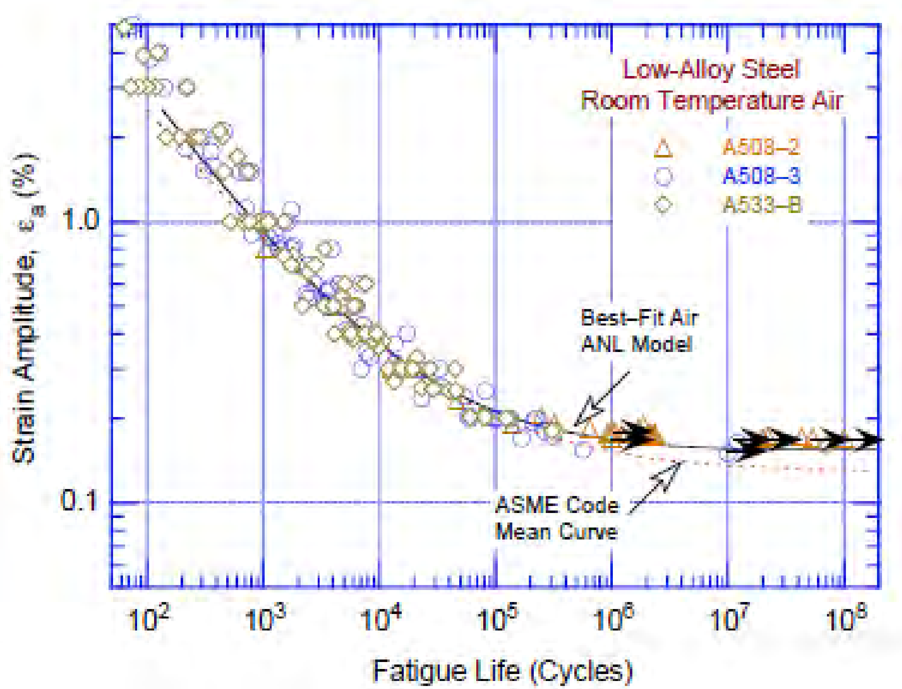
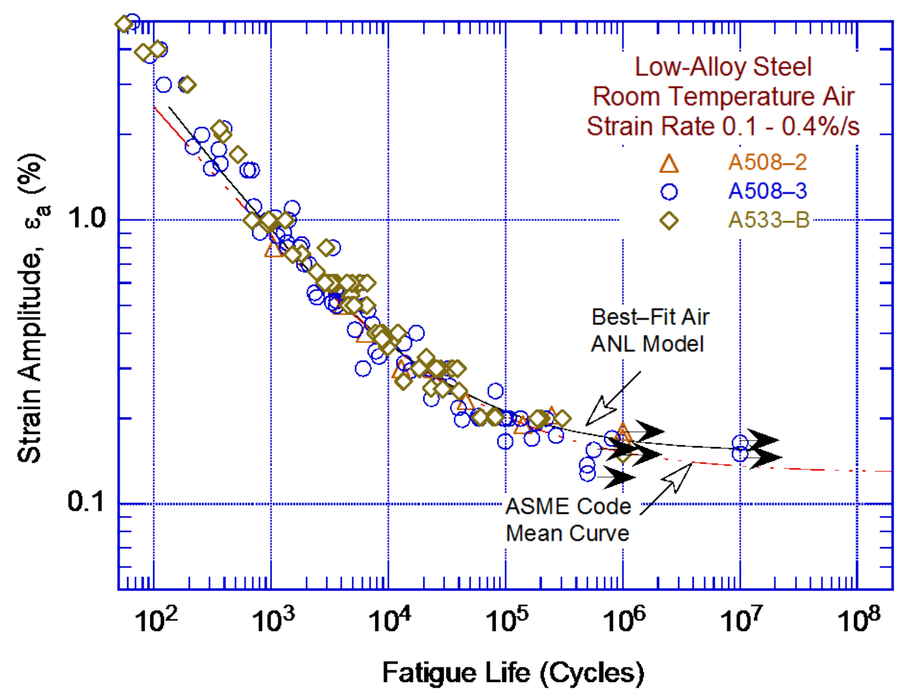
## Best Fit AIR Curves for Low Alloy Steel

### From NUREG/CR-6909, Rev. 0:




### From NUREG/CR-6909, Rev. 1:




**NOTE: The ANL best-fit air curves are identical in both of the above figures.**

# Review of Air Fatigue Curves (3/12)

U.S.NRC
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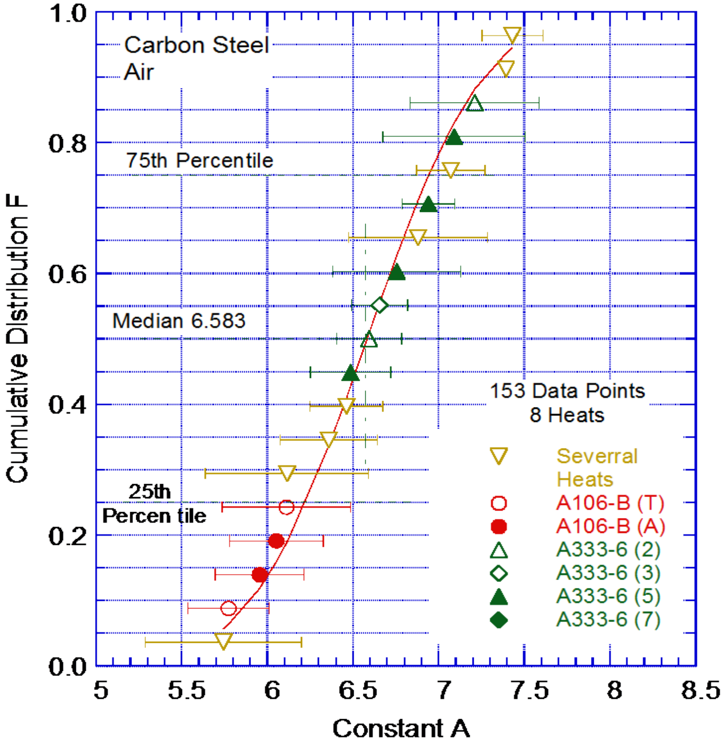
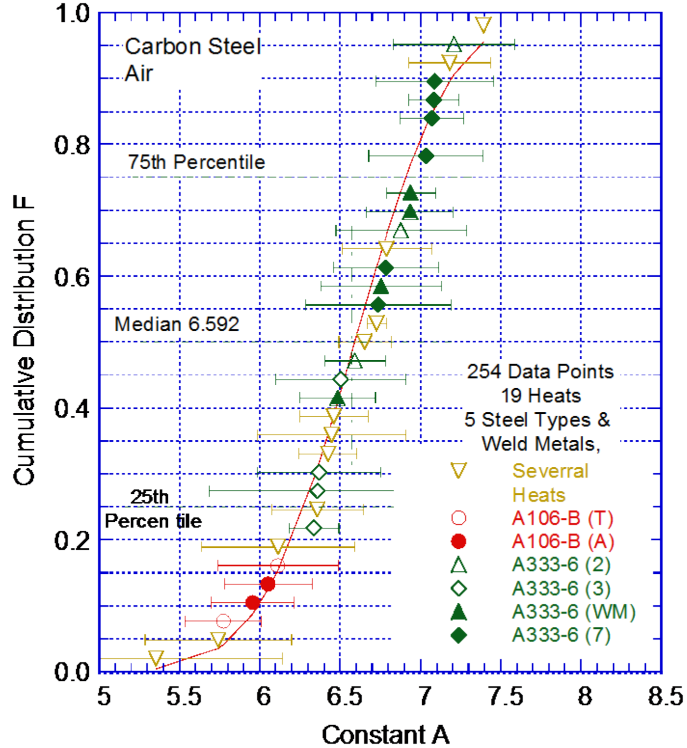
## Distribution of Constant A for AIR Curves for Carbon Steel

**From NUREG/CR-6909, Rev. 0**




**From NUREG/CR-6909, Rev. 1**




**Curve fits are made using a Langer fit of the form:**

$$\ln(N) = A - B \ln(\varepsilon_a - C)$$

**where:** A, B, C are constants

$\varepsilon_a$ is the strain amplitude

N is the fatigue life (cycles)

# Review of Air Fatigue Curves (4/12)

United States Nuclear Regulatory Commission
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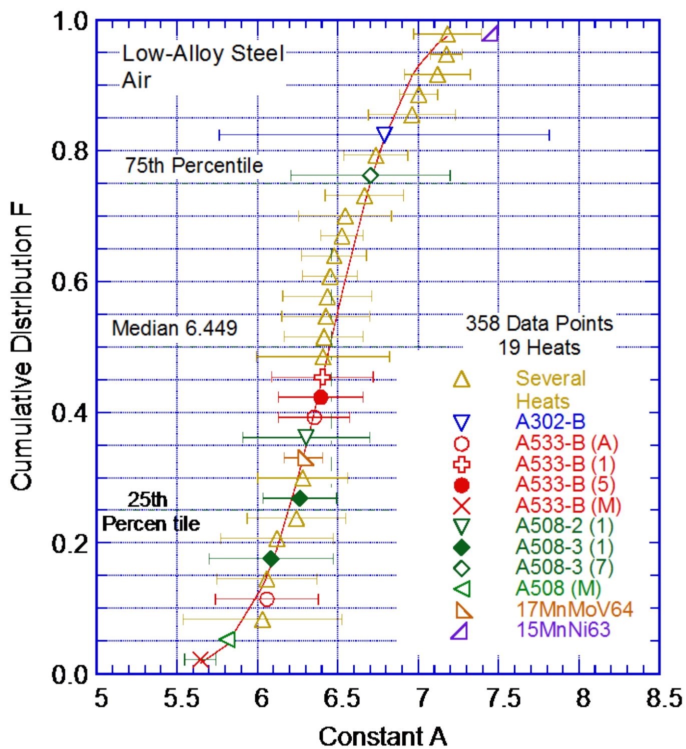
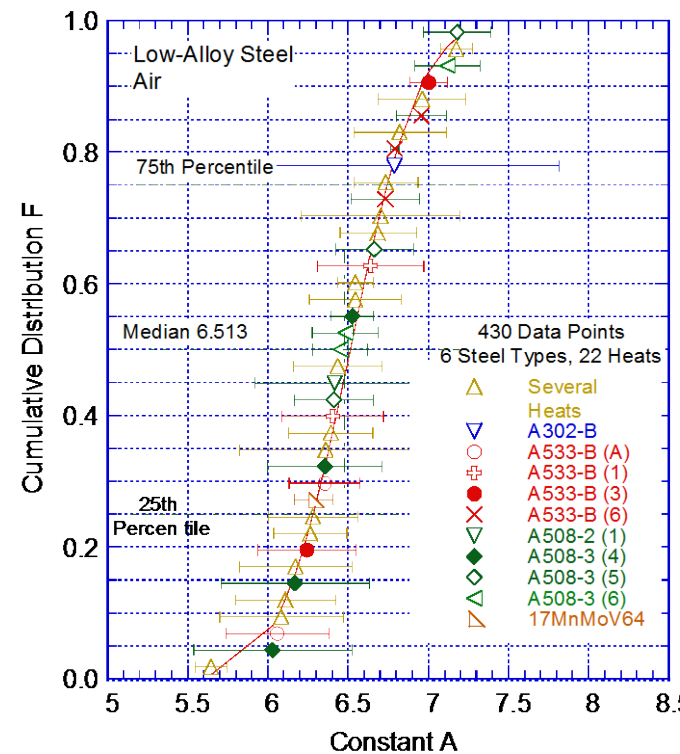
## Distribution of Constant A for AIR Curves for Low Alloy Steel

**From NUREG/CR-6909, Rev. 0**




**From NUREG/CR-6909, Rev. 1**




**Curve fits are made using a Langer fit of the form:**

$$\ln(N) = A - B \ln(\varepsilon_a - C)$$

**where:** A, B, C are constants

$\varepsilon_a$ is the strain amplitude

N is the fatigue life (cycles)

# Review of Air Fatigue Curves (5/12)

U.S.NRC
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## Design AIR Curve for Carbon Steel

- Consistent with the ASME Code Section III Design Curve, adjustment factors must be applied to best-fit air curves to accommodate various material, loading, and environmental parameters
- ASME's factor of 2 on strain amplitude was maintained
- To determine the most appropriate value for the adjustment factor on fatigue life, 25,000 Monte Carlo simulations were performed using the following factors:

| Parameter | Section III Criterion Document | Present Report |
|---|---|---|
| Material Variability and Data Scatter (minimum to mean) | 2.0 | 2.1–2.8 |
| Size Effect | 2.5 | 1.0–1.4 |
| Surface Finish, etc. | 4.0 | 1.5–3.5 |
| Loading History | – | 1.0–2.0 |
| Total Adjustment | 20 | 4.7–27.4 |

- Lognormal distributions were used, and the 5$^{th}$ and 95$^{th}$ percentile values were assumed as the minimum and maximum values for each factor
- The 95$^{th}$ percentile value for the adjustment factor was calculated as 10.2

# Review of Air Fatigue Curves (6/12)

U.S.NRC
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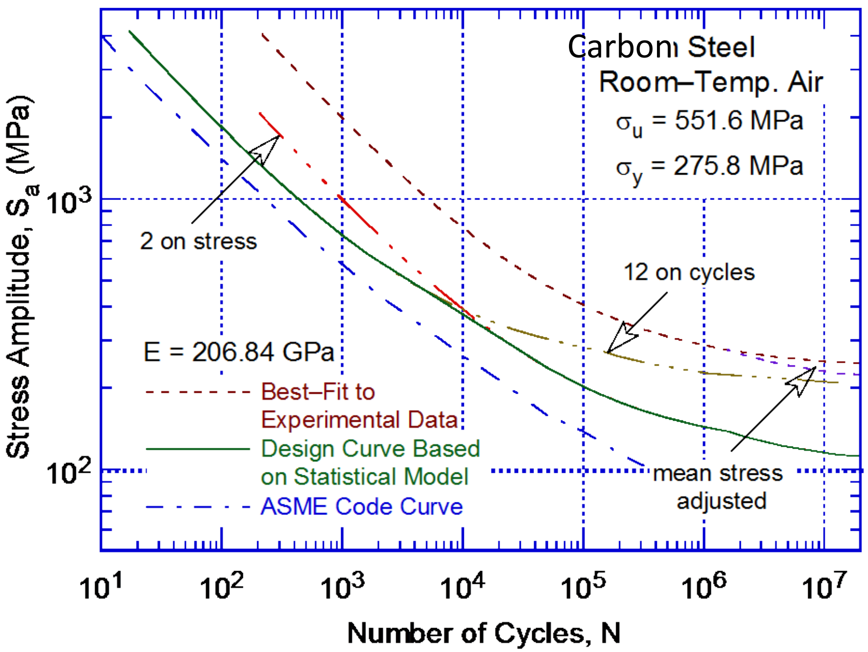
## Design AIR Curve for Carbon Steel

- Although a factor of ~10 was supported by the Monte Carlo evaluation, adjustment factors of 2 and 12 were used to provide consistency with Rev. 0 work
- Therefore, there is no change in the carbon steel design air curve between NUREG/CR-6909, Rev. 0 and NUREG/CR-6909, Rev. 1
- NRC requested feedback on maintaining a factor of 12 vs. changing to a factor of 10 when the draft of NUREG/CR-6909, Rev. 1 was released for public comment last spring




**NOTE: Existing ASME Code Section III design air curve is conservative compared to NUREG/CR-6909, Rev. 1 (because of factor of 20 vs. 12)**

# Review of Air Fatigue Curves (7/12)

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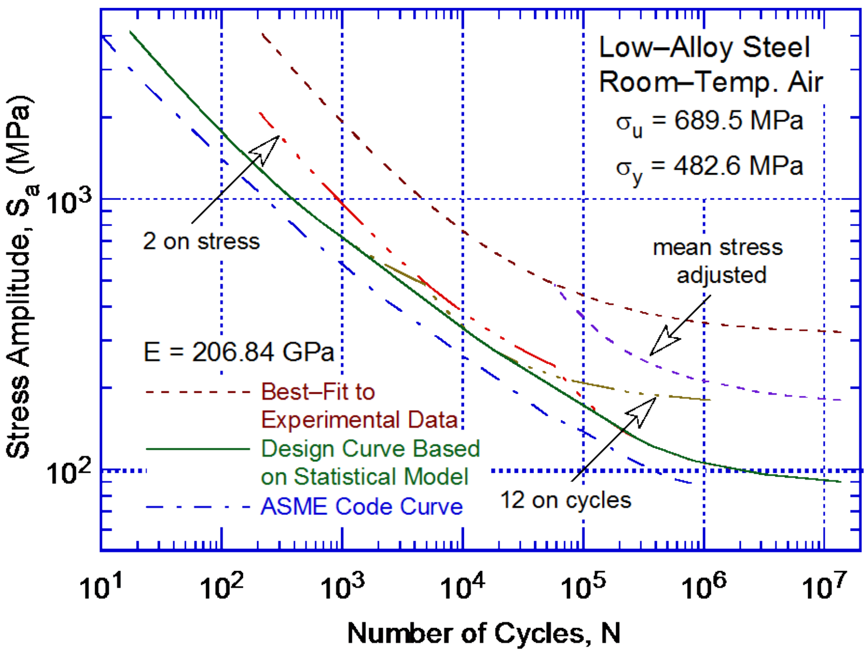
## Design AIR Curve for Low Alloy Steel

- **A factor of 9.0 was obtained from the Monte Carlo simulations; again, adjustment factors of 2 and 12 were used to provide consistency with Rev. 0 work**
- **Therefore, there is no change in the low alloy steel design air curve between NUREG/CR-6909, Rev. 0 and NUREG/CR-6909, Rev. 1**
- **NRC requested feedback on maintaining a factor of 12 vs. changing to a factor of 10 when the draft of NUREG/CR-6909, Rev. 1 was released for public comment last spring**




**NOTE: The existing ASME Code Section III design air curve is conservative compared to NUREG/CR-6909, Rev. 1 (because of factor of 20 vs. 12 and the combining of the carbon steel and low alloy steel curves into one curve in Section III)**

# Review of Air Fatigue Curves (8/12)

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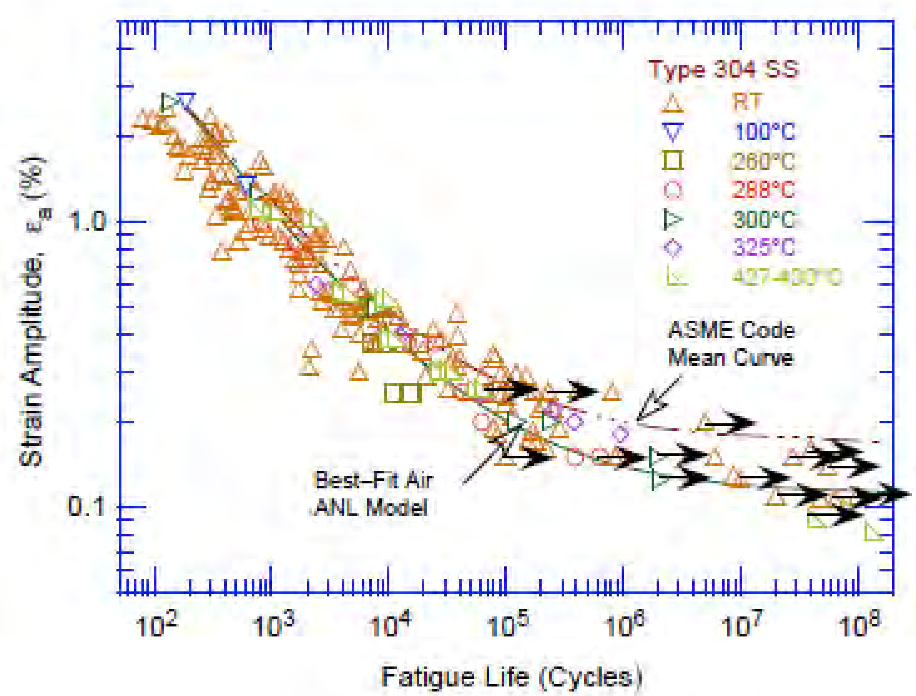
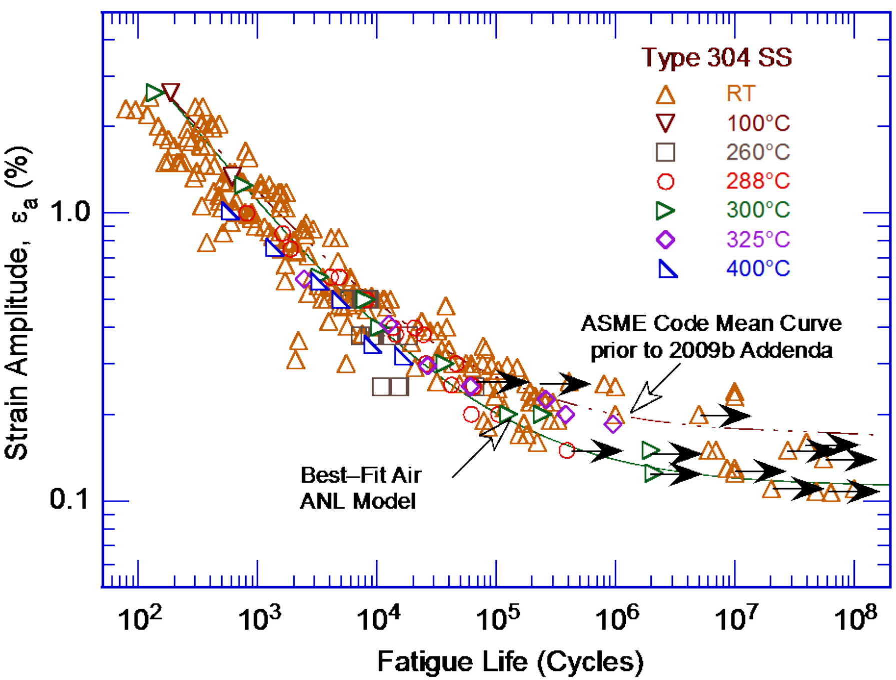
## Best Fit AIR Curves for Austenitic Stainless Steel

**From NUREG/CR-6909, Rev. 0:**




**From NUREG/CR-6909, Rev. 1:**




**NOTE: Only Type 304 materials are shown; the ANL best-fit air curves are identical in both of the above figures.**

# Review of Air Fatigue Curves (9/12)

U.S.NRC
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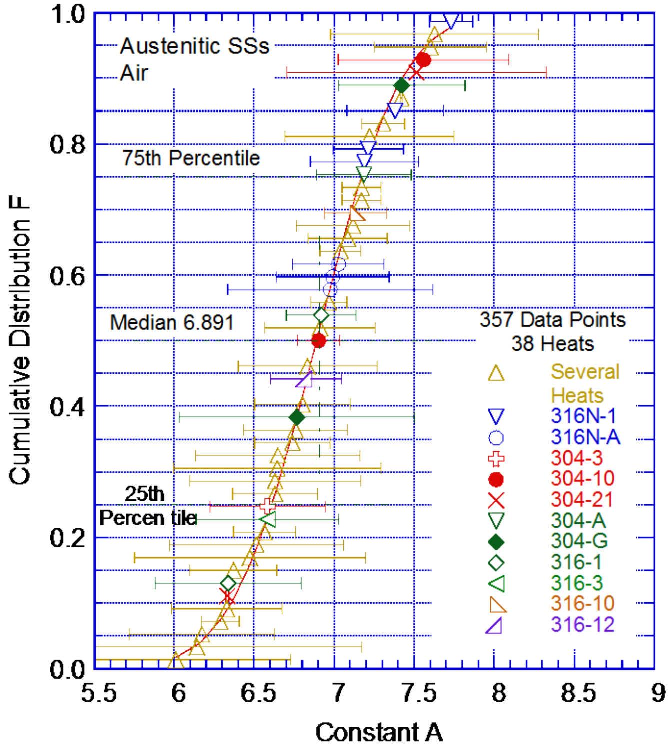
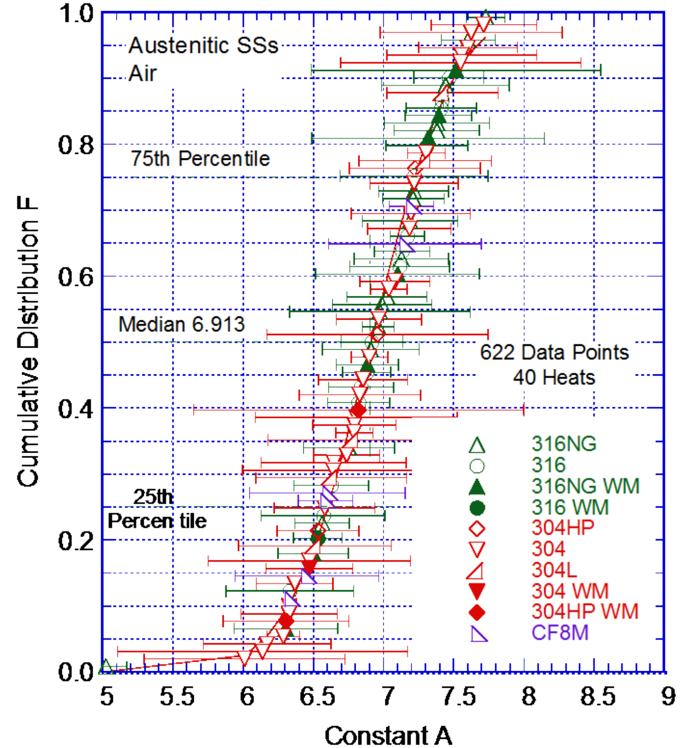
## Distribution of Constant A for AIR Curves for Austenitic Stainless Steel

**From NUREG/CR-6909, Rev. 0**




**From NUREG/CR-6909, Rev. 1**




**Curve fits are made using a Langer fit of the form:**

$$\ln(N) = A - B \ln(\varepsilon_a - C)$$

where: A, B, C are constants

$\varepsilon_a$ is the strain amplitude

N is the fatigue life (cycles)

# Review of Air Fatigue Curves (10/12)

U.S.NRC
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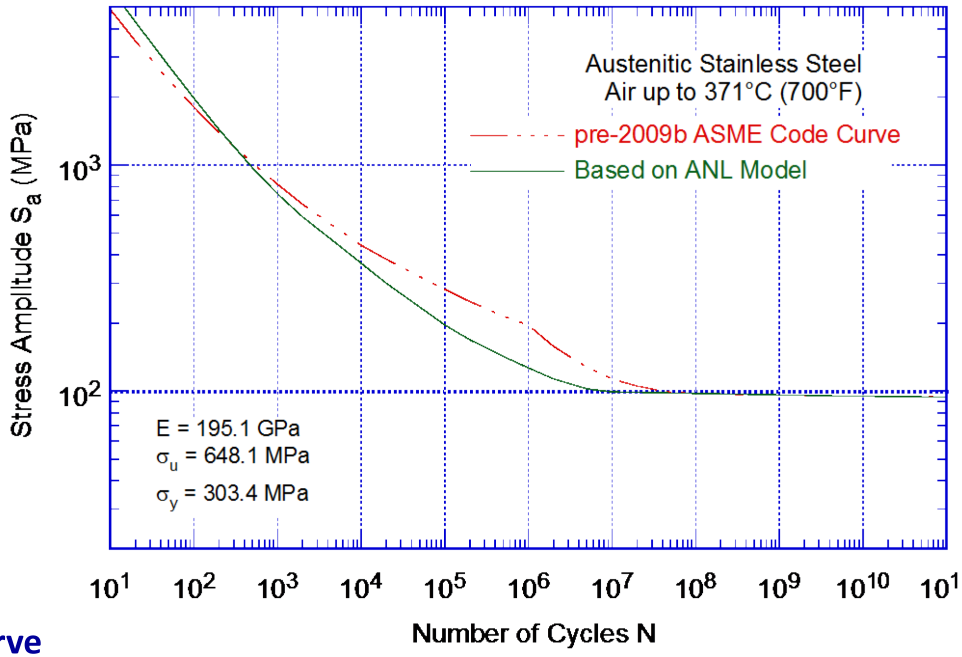
## Design AIR Curve for Austenitic Stainless Steel

- A factor of 9.6 was obtained from the Monte Carlo simulations; again, adjustment factors of 2 and 12 were used to provide consistency with Rev. 0 work
- Therefore, there is no change in the austenitic stainless steel design air curve between NUREG/CR-6909, Rev. 0 and NUREG/CR-6909, Rev. 1
- NRC requested feedback on maintaining a factor of 12 vs. changing to a factor of 10 when the draft of NUREG/CR-6909, Rev. 1 was released for public comment last spring

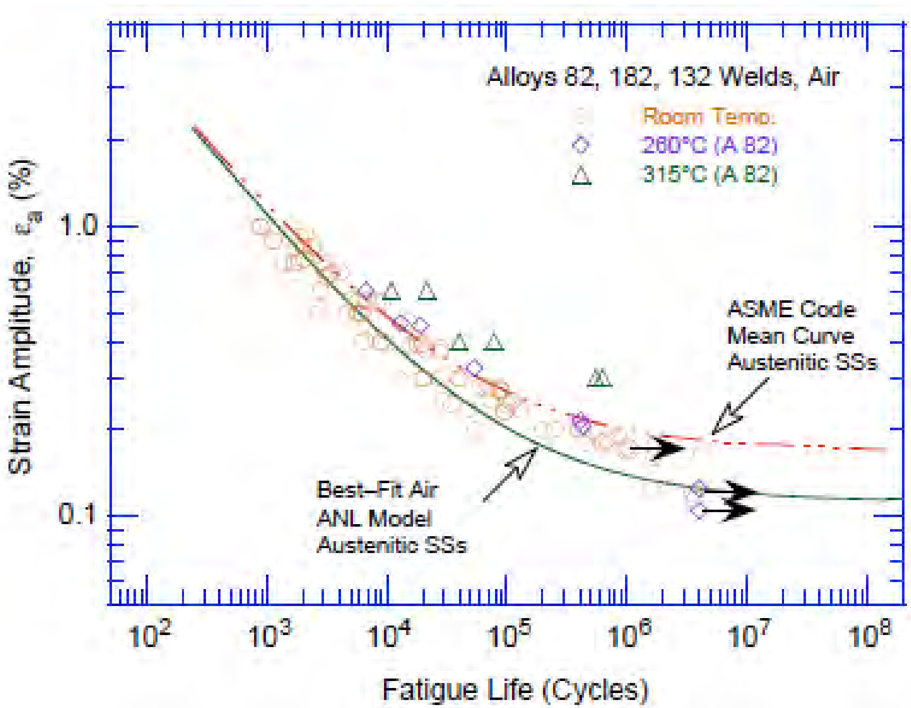



**NOTE: The existing ASME Code Section III design air curve is identical to the ANL design air curve shown.**

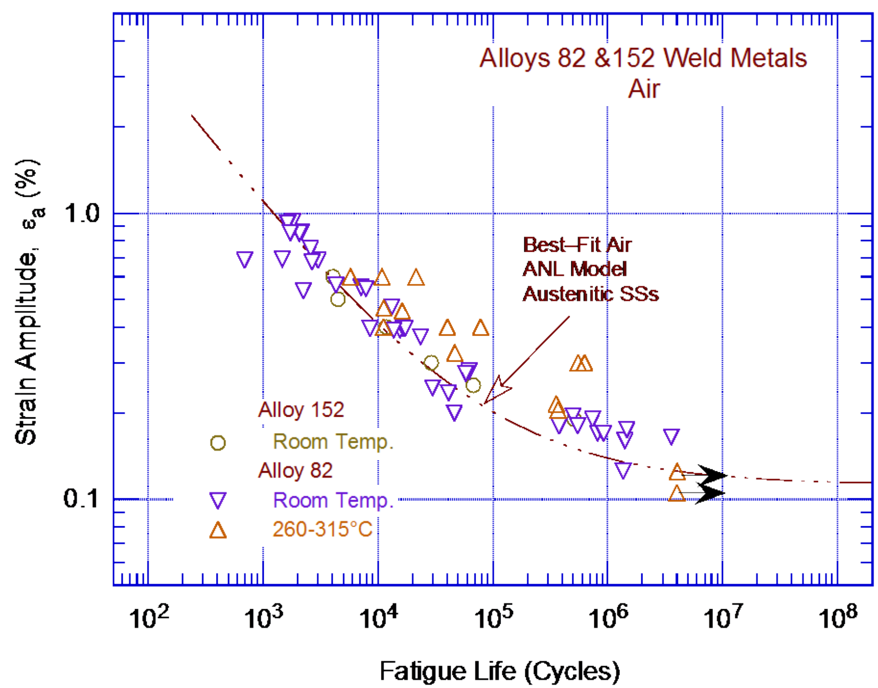
# Review of Air Fatigue Curves (11/12)

## Best Fit AIR Curves for Ni-Cr-Fe Steel

### From NUREG/CR-6909, Rev. 0:




### From NUREG/CR-6909, Rev. 1:




**NOTE: Only Ni-Cr-Fe weld metals are shown; the ANL best-fit air curves are identical in both of the above figures.**

# Review of Air Fatigue Curves (12/12)

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## Design AIR Curve for Ni-Cr-Fe Steel

- Estimates of the cumulative distribution of Constant A in the fatigue ε–N curve for the various heats of Ni-Cr-Fe steels and their associated weld metals yielded a median value of 7.129
- This value is slightly greater than the value of Constant A derived for austenitic SSs (6.891)
- In other words, the fatigue lives of these Ni-Cr-Fe steels are approximately 25% greater than those for austenitic stainless steels
- Based on these findings, the design air curve for austenitic stainless steel is used for Ni-Cr-Fe steel

**NOTE: The existing ASME Code Section III design air curve for stainless steel is also used for Ni-Cr-Fe steel.**

# Review of Changes to $F_{en}$ Equations (1/10)

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## $F_{en}$ equations for Carbon Steel

**From NUREG/CR-6909, Rev. 0**

$F_{en} = \exp[0.632 - 0.101\, S^* T^* O^* R^*]$

where:

Transformed sulfur, $S^*$:

| | |
|---|---|
| $S^* = 0.001$ | $(S \leq 0.001$ wt.%) |
| $S^* = S$ | $(S \leq 0.015$ wt.%) |
| $S^* = 0.015$ | $(S > 0.015$ wt.%) |

Transformed temperature, $T^*$:

| | |
|---|---|
| $T^* = 0$ | $(T < 150°C)$ |
| $T^* = (T - 150)$ | $(150 < T \leq 350°C)$ |

Transformed dissolved oxygen, $O^*$:

| | |
|---|---|
| $O^* = 0$ | $(DO \leq 0.04$ ppm) |
| $O^* = \ln(DO/0.04)$ | $(0.04 < DO \leq 0.5$ ppm) |
| $O^* = \ln(12.5)$ | $(DO > 0.5$ ppm) |

Transformed strain rate, $R^*$:

| | |
|---|---|
| $R^* = 0$ | $(R > 1\%/s)$ |
| $R^* = \ln(R)$ | $(0.001 \leq R \leq 1\%/s)$ |
| $R^* = \ln(0.001)$ | $(R < 0.001\%/s)$ |

**From NUREG/CR-6909, Rev. 1**

$F_{en} = \exp[(0.003 - 0.031R^*)\, S^* T^* O^*]$

where:

Transformed sulfur, $S^*$:

| | |
|---|---|
| $S^* = 2.0 + 98\, S$ | $(S \leq 0.015$ wt.%) |
| $S^* = 3.47$ | $(S > 0.015$ wt.%) |

Transformed temperature, $T^*$:

| | |
|---|---|
| $T^* = 0.395$ | $(T < 150°C)$ |
| $T^* = (T - 75)/190$ | $(150 < T \leq 325°C)$ |

Transformed dissolved oxygen, $O^*$:

| | |
|---|---|
| $O^* = 1.49$ | $(DO < 0.04$ ppm) |
| $O^* = \ln(DO/0.009)$ | $(0.04 \leq DO \leq 0.5$ ppm) |
| $O^* = 4.02$ | $(DO > 0.5$ ppm) |

Transformed strain rate, $R^*$:

| | |
|---|---|
| $R^* = 0$ | $(R > 2.2\%/s)$ |
| $R^* = \ln(R/2.2)$ | $(0.0004 \leq R \leq 2.2\%/s)$ |
| $R^* = \ln(0.0004/2.2)$ | $(R < 0.0004\%/s)$ |



**NOTE: For Rev. 0, $F_{en} > 1.0$ even when environmental effects do not apply.**

# Review of Changes to $F_{en}$ Equations (2/10)

U.S.NRC
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**$F_{en}$ equations for Low Alloy Steel**

**<u>From NUREG/CR-6909, Rev. 0</u>**

**$F_{en}$ = exp[0.702 – 0.101 S*T*O*R*]**

where:

S*, T*, O*, R* are defined the same as for carbon steel

**<u>From NUREG/CR-6909, Rev. 1</u>**

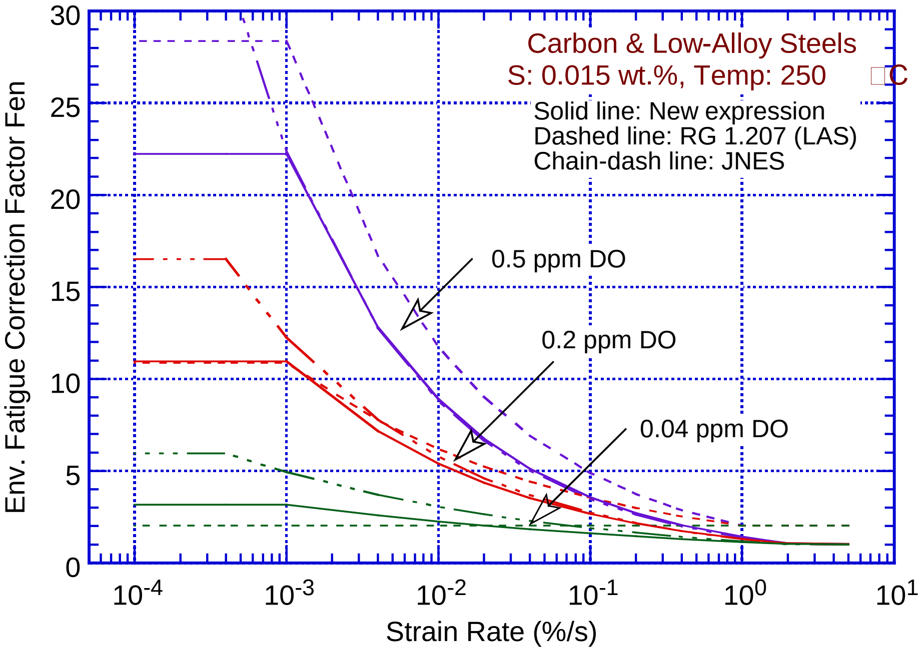
**$F_{en}$ = same expression as for carbon steel**

**NOTE: For Rev. 0, $F_{en}$ > 1.0 even when environmental effects do not apply.**

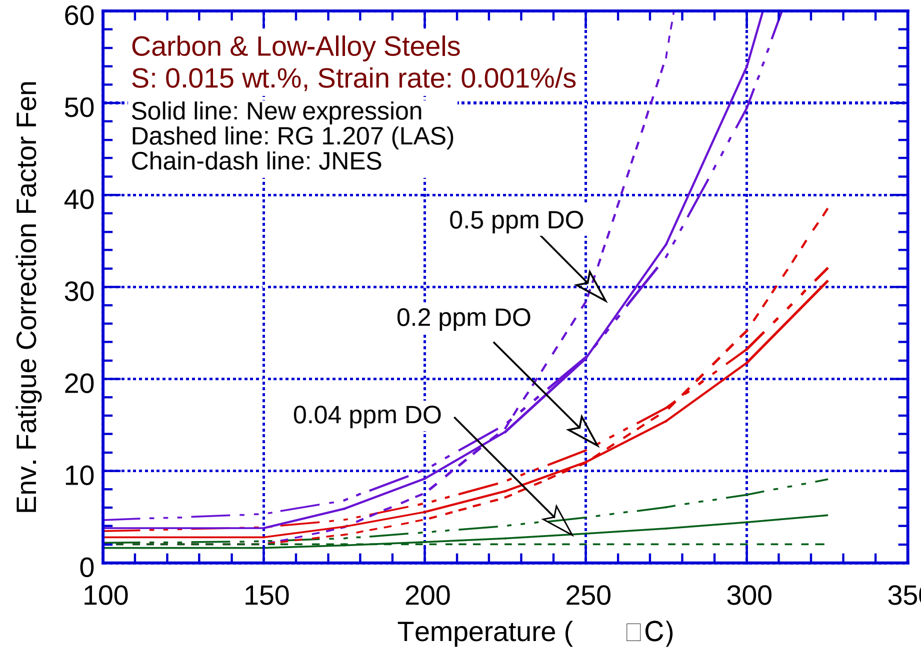
# Review of Changes to $F_{en}$ Equations (3/10)

## $F_{en}$ plots for Carbon and Low Alloy Steels

### $F_{en}$ vs. strain rate, R:



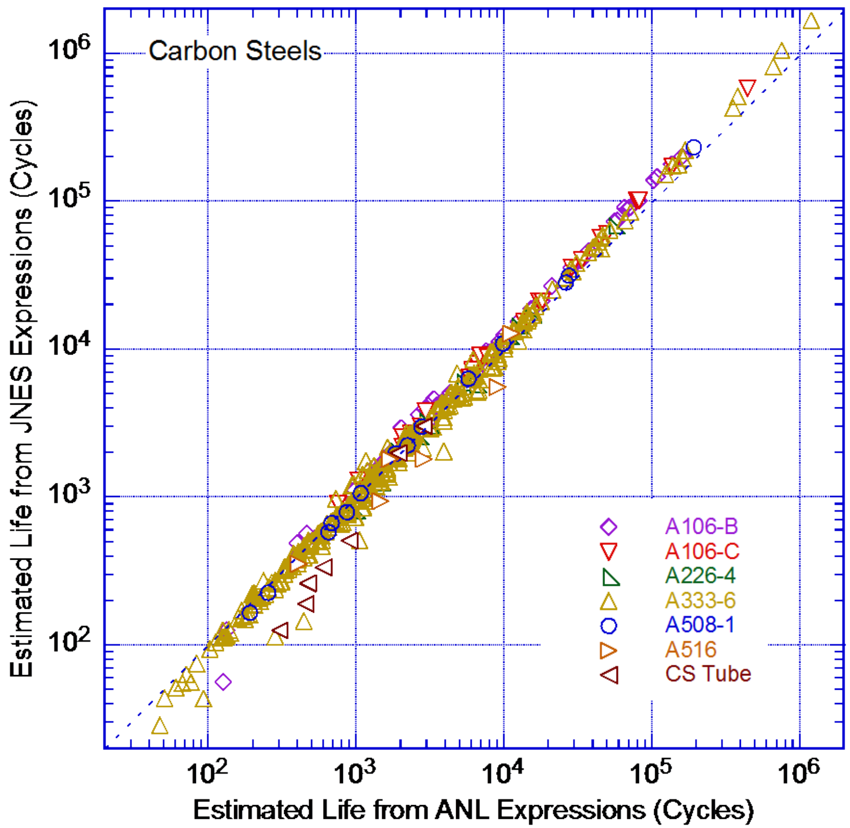

### $F_{en}$ vs. temperature, T:

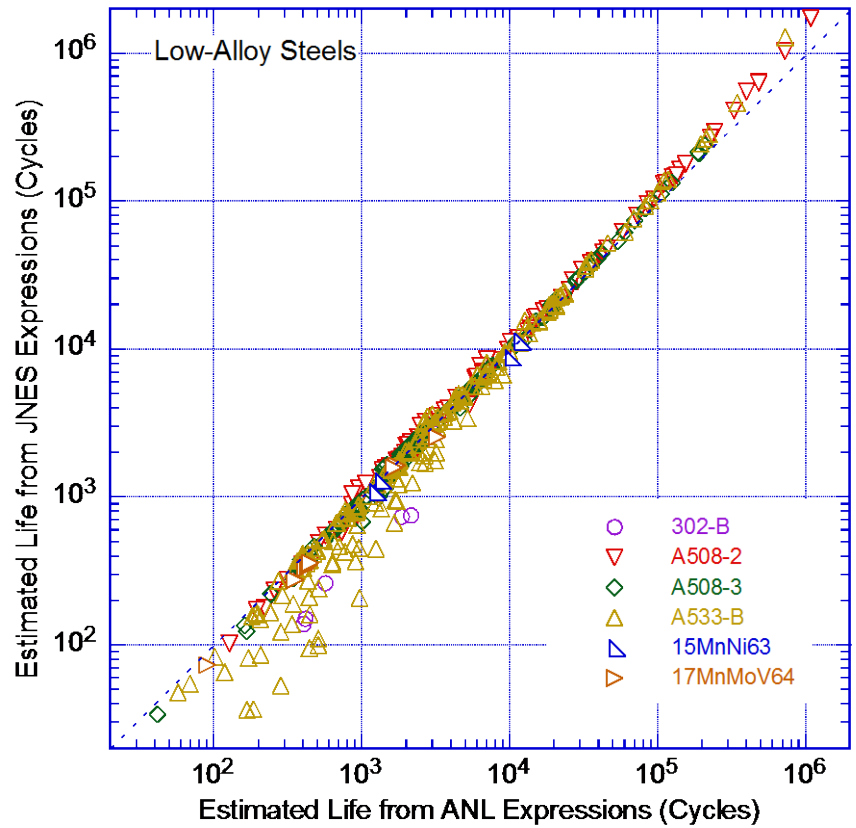


# Review of Changes to $F_{en}$ Equations (4/10)

## Life predictions for Carbon and Low Alloy Steels

### The NRC and JNES predictions are in good agreement:



# Review of Changes to $F_{en}$ Equations (5/10)

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## $F_{en}$ equations for Austenitic Stainless Steel

**From NUREG/CR-6909, Rev. 0**

$F_{en}$ = exp[0.734 – T*O*R*]

where:

Transformed temperature, T*:

| | |
|---|---|
| T* = 0 | (T < 150°C) |
| T* = (T – 150)/175 | (150 < T ≤ 325°C) |
| T* = 1 | (T > 325°C) |

Transformed dissolved oxygen, O*:

| | |
|---|---|
| O* = 0.281 | all DO levels |

Transformed strain rate, R*:

| | |
|---|---|
| R* = 0 | (R > 0.4%/s) |
| R* = ln(R/0.4) | (0.001 ≤ R ≤ 0.4%/s) |
| R* = ln(0.001) | (R < 0.001%/s) |

**From NUREG/CR-6909, Rev. 1**

$F_{en}$ = exp[-T*O*R*]

where:

Transformed temperature, T*:

| | |
|---|---|
| T* = 0 | (T < 100°C) |
| T* = (T – 100)/250 | (100 < T ≤ 325°C) |

Transformed dissolved oxygen, O*:

For PWR or BWR HWC (DO < 0.1 ppm):
O* = 0.29

For BWR NWC (DO ≥ 0.1 ppm):
O* = 0.29 (sensitized high-C wrought and cast)
O* = 0.14 (all wrought except sensitized high-C)

Transformed strain rate, R*:

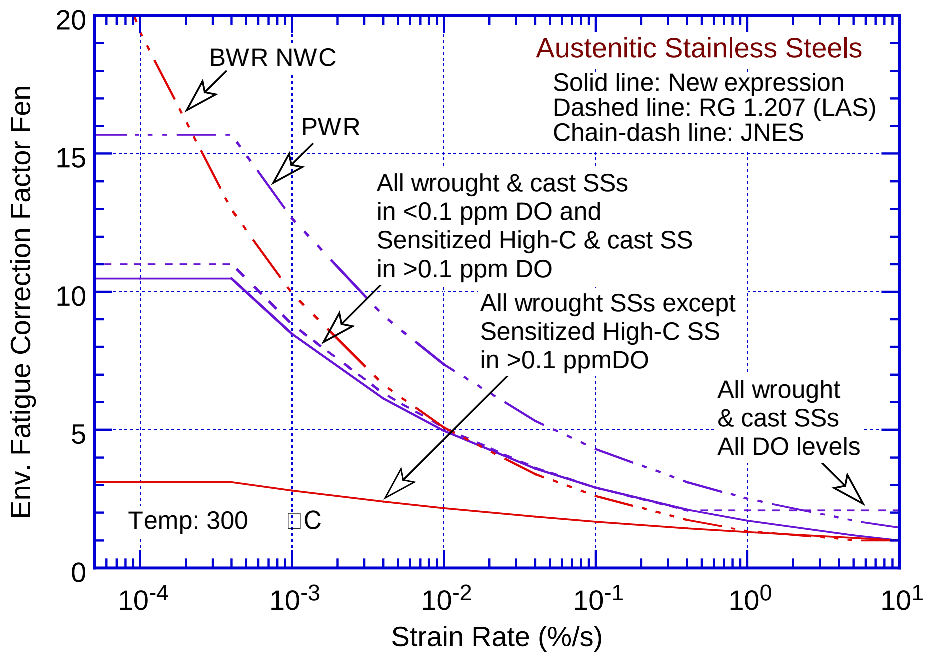
| | |
|---|---|
| R* = 0 | (R > 10%/s) |
| R* = ln(R/10) | (0.0004 ≤ R ≤ 10%/s) |
| R* = ln(0.0004/10) | (R < 0.0004%/s) |

**NOTE: For Rev. 0, $F_{en}$ > 1.0 even when environmental effects do not apply.**

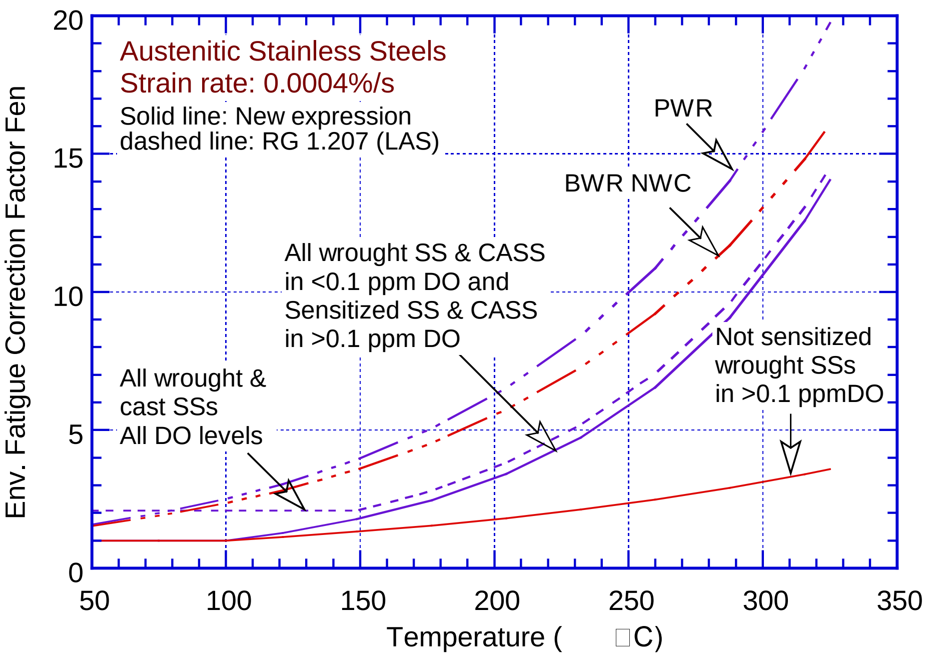
# Review of Changes to $F_{en}$ Equations (6/10)

## $F_{en}$ plots for Austenitic Stainless Steel

### $F_{en}$ vs. strain rate, R:



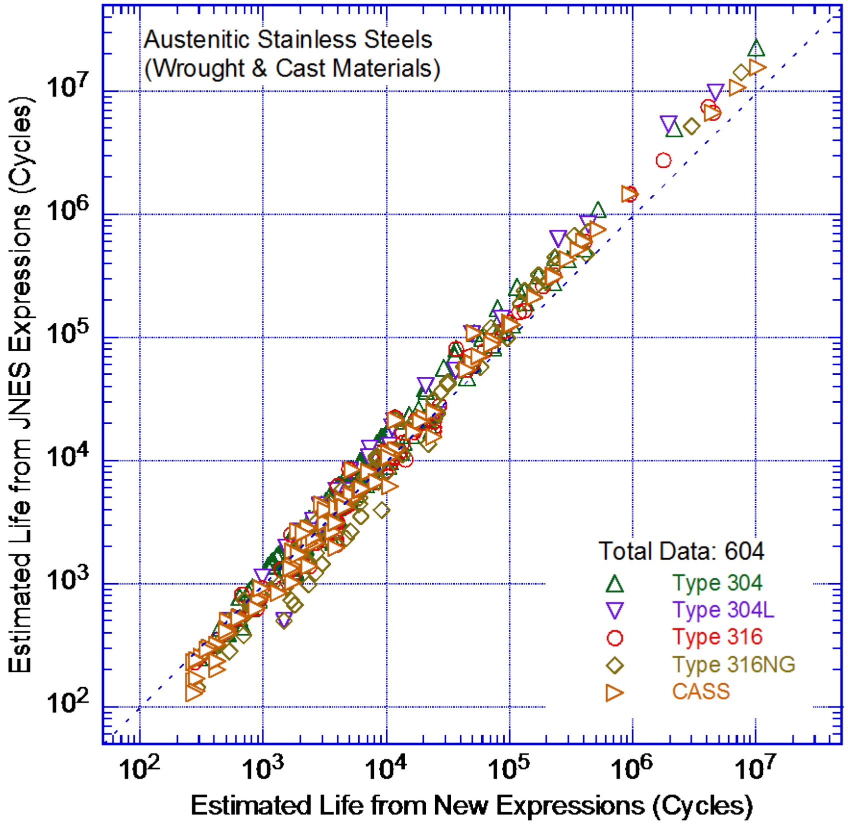

### $F_{en}$ vs. temperature, T:



# Review of Changes to $F_{en}$ Equations (7/10)

## Life predictions for Austenitic Stainless Steel

**The NRC and JNES predictions are in good agreement:**



# Review of Changes to $F_{en}$ Equations (8/10)

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## $F_{en}$ equations for Ni-Cr-Fe Steel

**From NUREG/CR-6909, Rev. 0**

**$F_{en}$ not specified**

It was noted that for Alloys 600 and 690 and their welds, the updated ANL fatigue life model proposed for austenitic stainless steel was either consistent or conservative with respect to the fatigue ε–N data.

Some licensees used a constant $F_{en}$ of 1.49 based on earlier recommendations made by EPRI*; this value is not supported by the available test data.

**From NUREG/CR-6909, Rev. 1**

**$F_{en} = \exp[-T^*O^*R^*]$**

where:

Transformed temperature, T*:

| | |
|---|---|
| $T^* = 0$ | $(T < 50°C)$ |
| $T^* = (T - 50)/250$ | $(50 < T \leq 325°C)$ |

Transformed dissolved oxygen, O*:

| | |
|---|---|
| $O^* = 0.06$ | (BWR NWC, DO ≥ 0.1 ppm) |
| $O^* = 0.14$ | (BWR HWC/PWR, DO < 0.1 ppm) |

Transformed strain rate, R*:

| | |
|---|---|
| $R^* = 0$ | $(R > 5.0\%/s)$ |
| $R^* = \ln(R/5.0)$ | $(0.0004 \leq R \leq 5.0\%/s)$ |
| $R^* = \ln(0.0004/5.0)$ | $(R < 0.0004\%/s)$ |

*** EPRI TR-105759, "An Environmental Factor Approach to Account for Reactor Water Effects in Light Water Reactor Pressure Vessel and Piping Fatigue Evaluations," August 1996.**

# Review of Changes to $F_{en}$ Equations (9/10)

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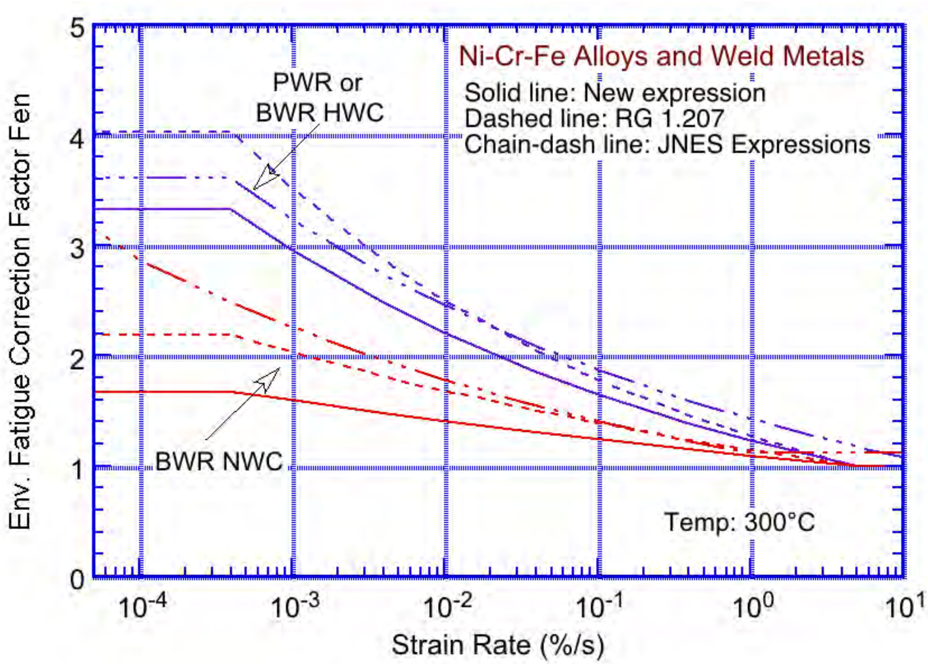
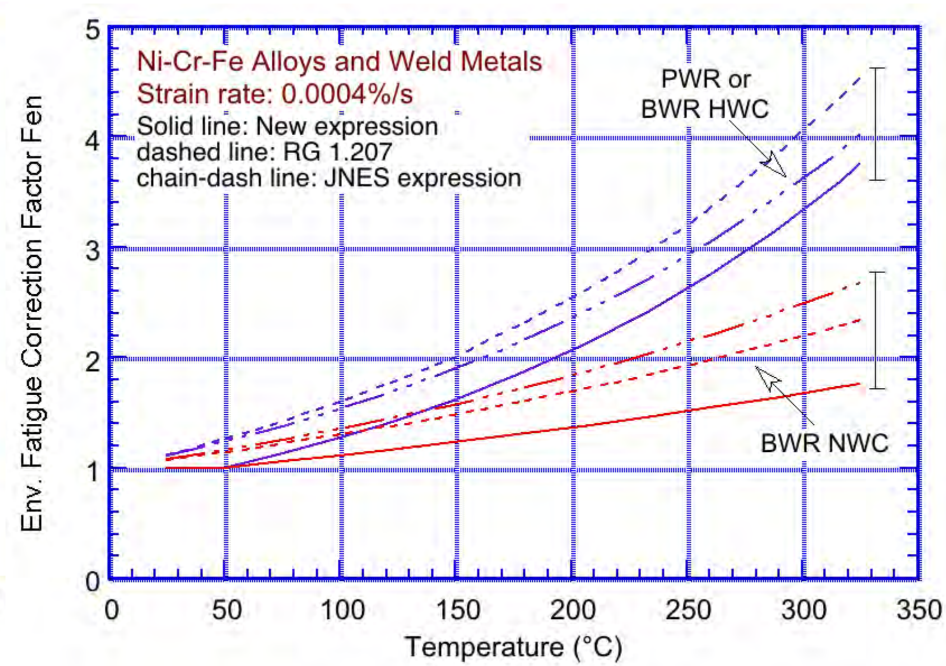
## $F_{en}$ plots for Ni-Cr-Fe Steel

### $F_{en}$ vs. strain rate, R:




### $F_{en}$ vs. temperature, T:



# Review of Changes to $F_{en}$ Equations (10/10)

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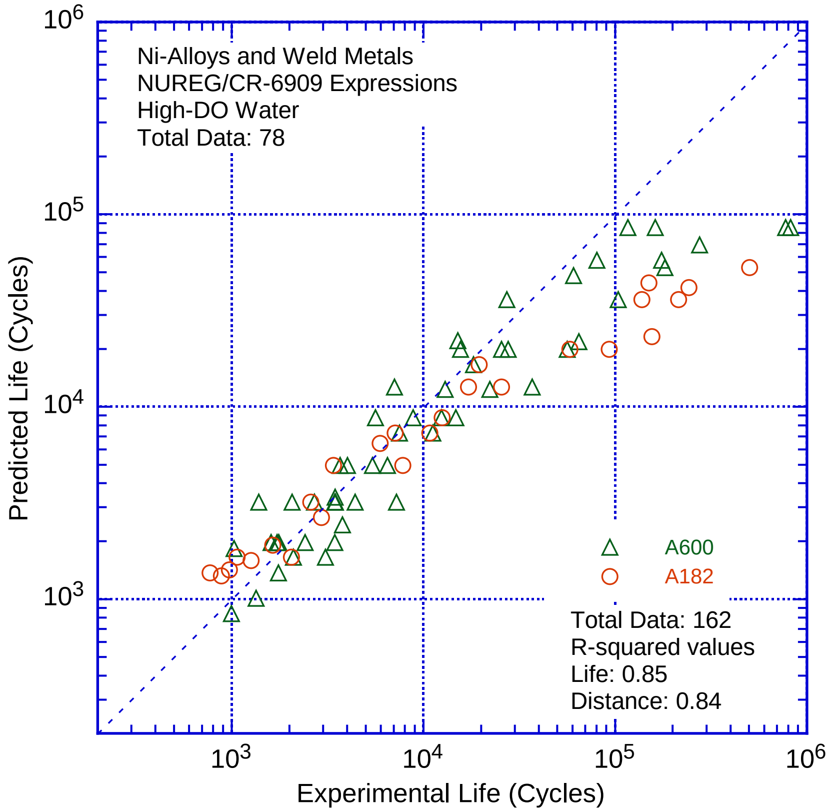
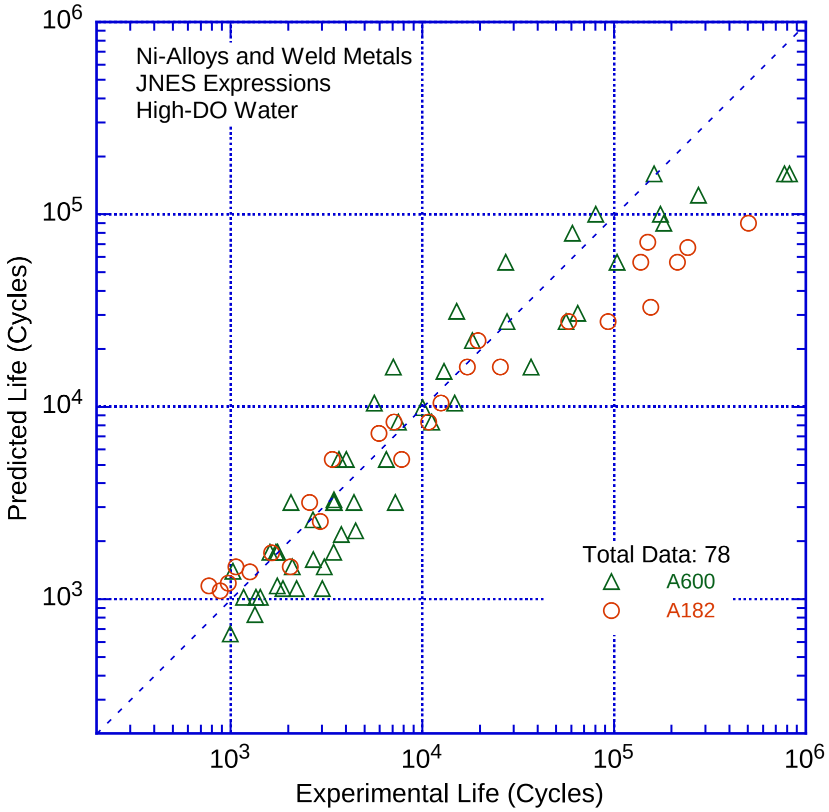
## Life predictions for Ni-Cr-Fe Steel

### The NRC and JNES predictions are in good agreement:



# Validation Calculations (1/2)

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- Several validation calculations were performed by estimating life using ASME Code methods (i.e., calculate CUF) and comparing the results to the experimental (i.e., measured) fatigue life
  - Since the experimental data sets selected were tested to failure (i.e., CUF = 1.0+), the goal of these evaluations was to benchmark the $F_{en}$ methodology and make adjustments, if warranted
- The results of the following experimental data sets were compared with estimates of fatigue life based on the $F_{en}$ methodology to validate the revised $F_{en}$ expressions
  1. Tests with changing strain rate within a strain cycle (Higuchi, Iida, and Asada, ASTM STP 1298, 1997; Higuchi, Iida, and Sakaguchi, ASME PVP-419, 2001; Higuchi, Sakaguchi, and Nomura, ASME PVP2007-26101, 2007)
  2. Tests with changing strain rate and temperature within a strain cycle (Nomura, Higuchi, Asada, and Sakaguchi, ASME PVP-480, PVP2004-2679, 2004; Sakaguchi, Nomura, Suzuki, and Kanasaki, ASME PVP2006-ICPVT-11-93220, 2006)
  3. Tests with spectrum loading (random strain amplitudes, Solin, ASME PVP2006-ICPVT-93833, 2006)
  4. Tests with complex loading (actual PWR transient – cold and hot thermal shock, Le Duff, Lefrancois, and Vernot, ASME PVP2009-78129, 2009)
  5. EPRI U-bend tests in inert and PWR environment (Hickling, Kilian, Spain, and Carey, ASME PVP2006-ICPVT-11-93318, 2006)
  6. Thermal fatigue test of a stepped pipe (Jones, Holliday, Leax, and Gordon, ASME PVP-482, PVP2004-2748, 2004)

# Validation Calculations (2/2)

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- Three $F_{en}$ methods were used
  1. Modified rate (strain-integrated) method
  2. Simplified (average strain rate)
  3. Multi-linear strain-based method
- The validation calculations for specimens agreed within the data scatter (i.e., factor of 2)
- The validation calculations for components had mixed results
  - For the EPRI U-bend tests, 5 out of 7 tests fell within the data scatter; the remaining 2 tests were conservatively predicted
  - For the stepped pipe tests, results were mixed; however, NRC found issues with finite element analysis and did not pursue corrected analysis
- NRC recognizes that use of small-scale specimen fatigue test data to predict the fatigue lives of actual components may be conservative under certain conditions

# Sample Problem

- Appendix C of NUREG/CR-6909, Rev. 1 contains a detailed sample problem
  - Same as sample problem developed and solved by industry under EPRI guidance and funding
  - Finite element based
- Intent was to demonstrate one example application of the $F_{en}$ methodology
  - A common but relatively simple problem
  - Promote consistency in the application of EAF methods
- Not intended to be an exhaustive treatment for EAF evaluation
- Feedback from public stakeholders has been very positive

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# ESTIMATED SCHEDULE FOR RG AND NUREG PUBLICATION

# Estimated Schedule

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- **RG 1.207, Rev. 1**
  - All internal reviews completed; comments addressed
  - Published for public comment on 11/24/2014 (79 FRN 69884)
  - Public comment period closes on 01/23/2015
- **NUREG/CR-6909, Rev. 1**
  - All internal review completed; comments addressed
  - Published for public comment 4/17/2014 – 6/2/2014
  - More than 200 individual public comments were received from 10 commenters (see next slide)
  - Responses are under development
- **Best-Estimate Publication Schedule**
  - Address all public comments on both documents – Summer 2015
  - Reviews (including ACRS) – Fall 2015
  - Publish final documents – December 2015

# Public Comments on NUREG/CR-6909, Rev. 1

U.S.NRC
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| No. | ADAMS Accession No. | Commenter Affiliation | Commenter Name |
|---|---|---|---|
| 1 | ML14157A322 | Consultant, Japan | Makoto Higuchi |
| 2 | ML14157A323 | Consultant – CF Int. Engineering, France | Claude Faidy |
| 3 | ML14157A324 | AMEC, United Kingdom | David Tice |
| 4 | ML14157A325 | Westinghouse Electric Company, USA | James Gresham |
| 5 | ML14157A326 | Mitsubishi Heavy Industries, Japan | Seiji Asada |
| 6 | ML14157A327 | Rolls Royce PLC, United Kingdom | Keith Wright |
| 7 | ML14157A328 | Electricite de France, France | Thomas Metais |
| 8 | ML14157A330 | Hitachi, Japan | Akihiko Hirano |
| 9 | ML14157A331 | AREVA, Inc., USA | Devin Kelley |
| 10 | ML14157A332 | Kansai Electric Power Company, Republic of Korea | June-soo Park |

# Questions or Comments?

# BACKUP SLIDES

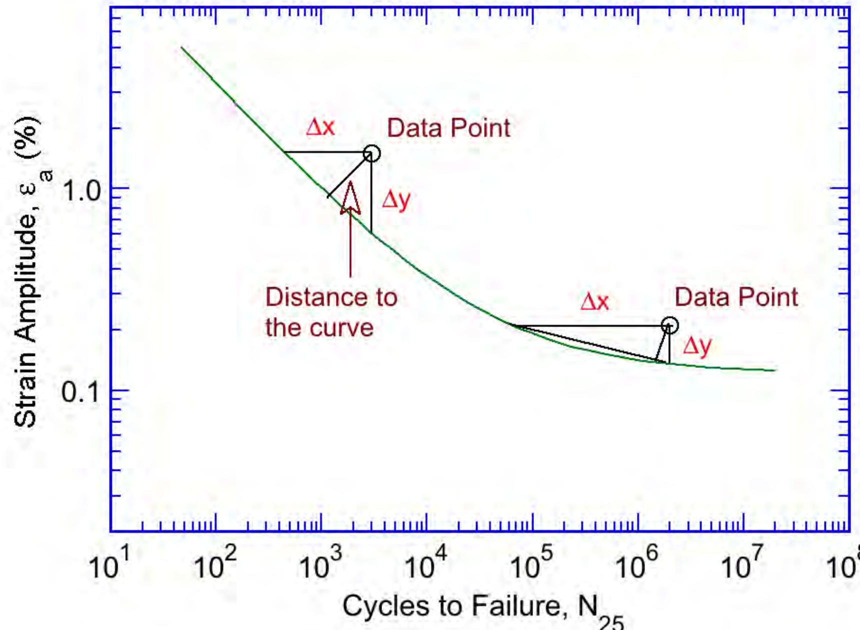
# Method for Best Fit of Experimental Data

- Fatigue strain amplitude ($\varepsilon_a$) vs. life ($N_{25}$) data are expressed as:

  $$\ln(N_{25}) = A - B \ln(\varepsilon_a - C)$$

- Constants determined from a best-fit of the fatigue $\varepsilon_a$-N data

  **NUREG/CR-6335 (1995) gives rigorous statistical analysis to estimate probability of initiating a fatigue crack**




- Ideally, a best-fit of the experimental data should be determined for:
  - low-cycle fatigue by minimizing the error in life
  - high-cycle fatigue by minimizing the error in strain
- NRC used a best-fit of the experimental S-N data determined by minimizing the error in the distance between the data point and the curve
- However, both of these analyses may be biased depending on the heats of material used in obtaining the fatigue $\varepsilon_a$-N data

# Possible Mechanisms for Fatigue Crack Initiation

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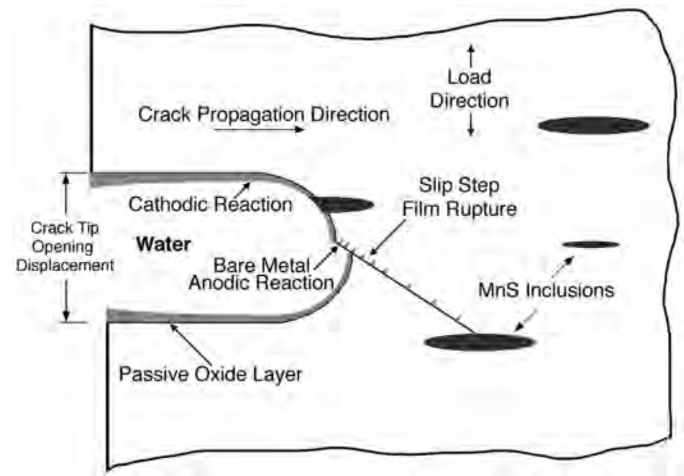
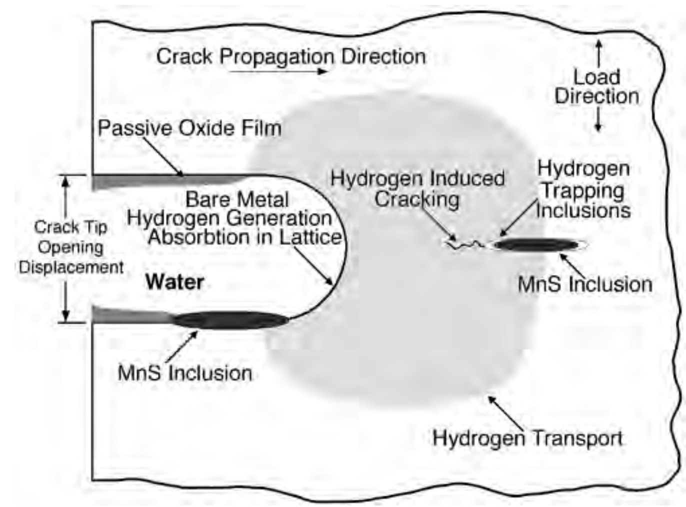
- *Film Rupture/Slip Dissolution*:
  - Incremental strain ruptures the protective surface oxide film
  - Crack extension occurs by dissolution/oxidation of the freshly exposed surface
  - Critical concentration of sulfide / hydrosulfide ions is required at the crack tip




- *Hydrogen-Induced Cracking*:
  - Hydrogen and vacancies produced by corrosion reaction enter the steel
  - Hydrogen diffuses to strong trapping sites (manganese-sulfide inclusions) ahead of the crack tip, which act as initiation sites for local quasi-cleavage cracking as well as void formation
  - Crack advances by linking of these microcracks with the main crack



# Fatigue Crack Initiation - Significant Results

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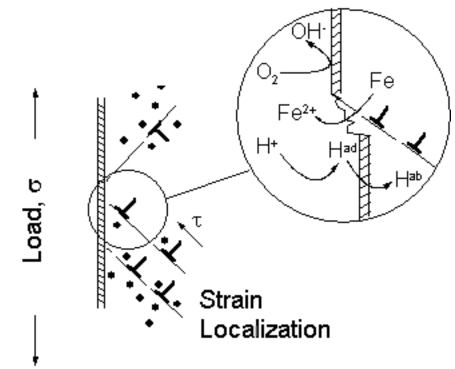
- Fatigue data show very strong strain-rate dependence of life in LWR environments
- For low-alloy steels, fatigue data suggest that cracking occurs by hydrogen-induced cracking at high strain rates and by film rupture/slip dissolution at slow strain rates
  - At high strain rates, surface cracks are inclined to the stress axis and grow in a tortuous manner; fracture surface exhibits the typical fan-like or quasi-cleavage cracking
  - At slow strain rates, surface cracks are absolutely straight, perpendicular to stress axis; fracture surface is flat with evidence of crack arrest
- Fatigue crack initiation and crack growth may be enhanced in LWR environments by a combination of the two mechanisms
  - Hydrogen produced by the oxidation reaction diffuses into the steel ahead of the crack tip, thereby changing the stacking fault energy, which results in more localized deformation
  - Strain localization leads to increased film rupture frequency, and crack extension occurs by dissolution/oxidation of the freshly exposed surface
- Dynamic strain aging may play an important role in the cyclic deformation process
  - Dynamic strain aging occurs in alloys containing solutes that segregate strongly to dislocations resulting in strong elastic interactions between the solute and dislocation stress-strain field
  - Depends on temperature and strain rate

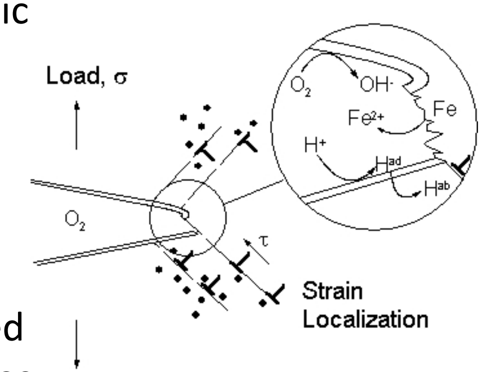
# Effect of Dynamic Strain Aging



- In high-temp water, the synergistic interactions between environmentally assisted corrosion and dynamic strain aging in a fatigue environment may be rationalized as follows:
  - Hydrogen and vacancies produced by the corrosion reaction at the crack tip enter the steel and hydrogen diffuses to strong trapping sites inside the crack tip maximum hydrostatic stress region (e.g., manganese-sulfide inclusion) ahead of the crack tip
  - According to hydrogen-induced cracking, these sites act as initiation sites for local quasi-cleavage cracking and void formation, and these microcracks link with the main crack
  - According to an alternative mechanism, at a given macroscopic strain, the microscopic strain in a steel that is susceptible to dynamic strain aging is higher because of strain localization to small areas, which leads to higher rates and larger steps of oxide film rupture. Therefore, the film rupture/slip dissolution process would enhance crack initiation or crack growth rates
  - Such processes occur under certain conditions of temperature, strain rate, and DO level, and may enhance environmentally assisted corrosion and increase fatigue crack initiation and crack growth rates




From Devrient et al. Env. Degradation Conf., 2007



# Abbreviations and Symbols Used in this Presentation

U.S.NRC
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| Abbreviation | Definition |
|---|---|
| ANL | Argonne National Laboratory |
| ASME | American Society of Mechanical Engineers |
| BNCS | Board on Nuclear Codes and Standards |
| CFR | Code of Federal Regulations |
| CLB | Current Licensing Basis |
| CUF | Cumulative Usage Factor |
| DO | Dissolved Oxygen Content |
| EAF | Environmentally Assisted Fatigue |
| FAP | Fatigue Action Plan |
| GALL | Generic Aging Lessons Learned |
| GSI | Generic Safety Issue |
| JNES | Japan Nuclear Energy Safety Organization |
| JNRA | Japan Nuclear Regulatory Authority |
| LWR | Light Water Reactor |
| MOU | Memorandum of Understanding |
| NRO | Office of New Reactors |
| NRR | Office of Nuclear Reactor Regulation |

| Abbreviation | Definition |
|---|---|
| PNNL | Pacific Northwest Nuclear Laboratory |
| PVRC | Pressure Vessel Research Council |
| RES | Office of Nuclear Regulatory Research |
| RG | Regulatory Guide |
| WRC | Welding Research Council |

| Symbol | Definition |
|---|---|
| A, B, C | Constants for Langer Curve Fit |
| $\varepsilon_a$ | Strain Amplitude (%) |
| $F_{en}$ | Environmental Fatigue Multiplier |
| O<br>O* | Fluid Dissolved Oxygen Content<br>Transformed Oxygen Content |
| R<br>R* | Strain Rate (%/s)<br>Transformed Strain Rate |
| S<br>S* | Metal Sulfur Content (wt. %)<br>Transformed Sulfur Content |
| T<br>T* | Temperature (°F or °C)<br>Transformed Temperature |