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UNITED STATES OF AMERICA

NUCLEAR REGULATORY COMMISSION

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

SUBCOMMITTEE ON MATERIALS, METALLURGY, AND

REACTOR FUELS

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WEDNESDAY,

December 6, 2006

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The meeting was convened in Room T-2B3 of Two White Flint North, 11545 Rockville Pike, Rockville, Maryland, at 1:30 p.m., Dr. J. Sam Armijo, Chairman of the subcommittee, presiding.

MEMBERS PRESENT:

J. SAM ARMIJO, CHAIRMAN

MARIO V. BONACA, ACRS MEMBER

SAID ABDET KHALIK, ACRS MEMBER

SANJOY BANERJEE, ACRS MEMBER

THOMAS S. KRESS, ACRS MEMBER

JOHN D. SIEBER, ACRS MEMBER

GRAHAM WALLIS, ACRS MEMBER

CHARLES G. HAMMER, DESIGNATED FEDERAL OFFICIAL

CAXETANO SANTOS, ACRS STAFF

I N D E X

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

1:31 P.M.

CHAIRMAN ARMIJO: The meeting will now come to order. This is a meeting of the Materials, Metallurgy and Reactor Fuels Subcommittee. My name is Sam Armijo, Chairman of the Committee. ACRS Members in attendance are Dr. Mario Bonaca, Mr. Jack Sieber, Dr. Bill Shack is sitting as a member of the audience or staff at this point, Dr. Thomas Kress and Dr. Graham Wallis are also present.

Gary Hammer of the ACRS staff is the Designated Federal Official for this meeting.

The purpose of this meeting is to discuss Regulatory Guide 1.207, guidelines for evaluating fatigue analyses incorporating the life reduction of metal components due to the effects of light-water reactor environments for new reactors. We will hear presentations from the NRC's Office of Nuclear Regulatory Research and their contractor, Argonne National Laboratory.

We will also hear presentations from representatives of the American Society of Mechanical Engineers and AREVA.

The Subcommittee will gather information, analyze relevant issues and facts, and formulate proposed positions and actions, as appropriate for deliberation by the Full Committee.

The rules for participation in today's meeting have been announced as part of the notice of this meeting previously published in the Federal Register. We have received no written comments 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 this meeting use the microphones located throughout the meeting when addressing the Subcommittee.

Participants should first identify themselves and speak with sufficient clarity and volume so that they may be readily heard.

We will now proceed with the meeting and I call on Mr. Hipolito Gonzales of the Office of Nuclear Regulatory Research to begin.

MR. GONZALEZ: Thank you. I am Hipolito Gonzalez. I'm the Project Manager for Regulatory Guide 1.207. I'm from the Corrosion and Metallurgy Branch and with me, Omesh Chopra. He's from Argonne National Lab. He's going to be presenting part of the regulatory basis, technical regulatory basis.

I would like to acknowledge William Cullen from the Office of Research and John Ferrer, NRR, for their helpful reviews and comments on this project.

Next slide.

The agenda today, we're going to be discussing Regulatory Guide 1.207. I'm going to give a quick historical perspective and then we're going to go over an overview the reg. guide. And then Omesh will present the technical basis which is the NUREG report CR, NUREG CR 6909, Revision 1.

I'm going to give a summary of the regulatory positions. And the last presentation is going to be the resolution of public comments.

The ASME Section 3, fatigue design curves were developed in the late 1960s and the early 1970s. The tests conducted were in laboratory environments at ambient temperatures. And the design curves included adjusted factors of 2 constraint and 20 on cyclic life to account for variations in materials, surface finish, data scatter and size.

Results from the studies in Japan and others in ANL, Argonne National Lab, as illustrated. Potential significant effects of the light-water reactor coolant environment on the fatigue life of the steel, steel components.

Next slide.

Since the late 1980s, the NRC staff has been involved in the discussion with ASME co-committees, the PVRC and Technical Community to address the issues related to the environmental effects on fatigue.

In 1991, the ASME Board of Nuclear Code and Standards requested the PVRC to examine worldwide fatigue strain versus like data and develop recommendations.

In 1995, it was resolution for GSI 166 which established that the risk to core damage from fatigue failure of the reactor coolant system was small. So no action was required for current plant design life of 40 years. Also, the NRC staff concluded that fatigue issues should be evaluated for extended period of operation for license renewal and this is under GSI-190.

In 1999, we had GSI-190 and the fatigue evaluation of metal components for 60-year life plant, plant life. Staff concluded that consistent with requirements of 10 CFR 54.21, that aging management programs for license renewal should address components of fatigue including the effects of the environment.

On December 1, 1999, by letter to the

Chairman of the ASME Board of Nuclear Code and Standards, the NRC requested ASME to revise the code to include the environmental effects on the fatigue design components.

Next slide.

ASME initiated the PVRC Steering Committee on cyclic life and environmental effects and the PVRC Committee recommended revising the code for design fatigue curves. This was to WRC Bulletin 487.

After more than 25 years of deliberation, there hasn't been any consensus regarding environmental effects on fatigue life on the light-water reactor environments.

The NRR requested research under user need requests to 504 to develop guidance for determining the acceptable fatigue life of ASME pressure boundary components with consideration of the light water reactor environment and this guidance will be used for supporting reviews of application that the Agency expects to receive for new reactors. The industry was immediately notified that the NRC staff initiated this work, the development of the reg. guide. In addition, this is one of the high priority reg. guides to be completed by March 2007.

In February and August this year, NRC

staff and ANL, we had presented at the ASME Code Meetings the technical basis draft, NUREG CR6909. On July 24, 2006, both the draft reg. guide and the NUREG technical basis report were published for public comments and the public comment period ended September 25.

In addition, on July 25, ANL presented a paper on the technical basis again.

CHAIRMAN ARMIJO: Just to clarify something, new reactors, does that include -- do these rules apply to already certified design, such as the ABWR and the AP1000? Are they grandfathered by virtue of their certification?

MR. FERRER: This is John Ferrer from NRR staff. They're grandfathered by virtue of their certification that's already been addressed in the reviews there, so we're not backfitting this reg. guide to those certified designs.

DR. SIEBER: For 40 years though.

CHAIRMAN ARMIJO: Well, actually, if you read the safety evaluation, the way it was written said that they were evaluated for 60 years.

DR. SIEBER: Okay.

CHAIRMAN ARMIJO: That's kind of an inconsistency in a way because they haven't been built in the United States and if they were being certified after this reg. guide is issued, that would be the rule -- that would control the design, wouldn't it?

MR. FERRER: I wish I -- I agree with you. Unfortunately, the way certified design works is once we certify it, we'd have to go through a backfit evaluation if we were going to apply this. And what happened in the backfit evaluation, if you go back a couple of slides on the GSI-166 and the GSI-190, we did a backfit evaluation and showed the risk was not high enough to justify a backfit, but the reason we implemented it on license renewal was the fact that the probability of leakage increased significantly within 40 and 60 years.

But again, the risk which is the probability of getting a pipe rupture that would lead to core damage was still low..

CHAIRMAN ARMIJO: Thank you.

MR. GONZALEZ: Now I am going to go to an overview of the reg. guide.

Next slide.

How the reg. guide 1.207 relates to the regulatory requirements. GDC criterion, general design criterion 1, quality standards and waivers. And the part says that safety-related systems, structures and components must be designed, fabricated, erected and tested to the quality standard commensurate with the importance of the safety function performed.

GDC-30 states, in part, that components included in a reactor pressure boundary must be designed, fabricated, erected and tested to the highest practical quality standards.

In 10 CFR 50.55A endorses the ASME boiler pressure vessel code for design of safety-related systems and components. These are Class 1 components.

ASME Code Section 3 includes the design fatigue, includes the fatigue design curves. But these fatigue design curves do not address the impact of the reactor coolant system environment.

The objective of this regulatory guide is to provide guidance for determining the acceptable fatigue life of ASME pressure boundary components with the consideration of the light water reactor environment for major structural materials that will be carbon steel, low-alloy steels, austenitic stainless steel and nickel-based alloys. For example, alloy-600, 690.

So in this guide, describes an approach that the NRC staff considers acceptable to support reviews about the applications that the Agency expects to receive for new reactors.

Implementation, this will only apply to new plants. And no backfitting is intended. And this is due to the conservatism in the current fleet of reactors because of the design practices for fatigue work conservatisms all plants were designed.

Next slide, please.

Now I'm going to -- how the technical basis was developed. Omesh is going to give the presentation on the technical basis report.

MR. CHOPRA: Thanks, Hipo.

DR. BONACA: I have a question regarding your last statement. No backfitting is intended, conservatism on coolant reactors. If the approach was conservative on coolant reactors, I mean could it be used also for new reactors?

MR. FERRER: Let me try to answer that. In reviewing GSI-166 which was backfit to current operating plants, we evaluated the as-existing fatigue analyses and there were a number of conservatisms in the specification of transients and the methodology and the analysis.

We don't know whether or not that same conservatism will be applied in the new reactors. In addition, there have been some changes in the ASME code criteria since those original analyses were done that removed some of the conservatisms in the analysis. So if somebody were to do code analysis to the current code criteria may not have the same level of conservatisms.

DR. BONACA: I understand. Thank you.

MR. CHOPRA: The issue we are discussing here today is effect of light water reactor coolant environments on the fatigue life of structural steels. Over the last 20 to 30 years, there's been sufficient data accumulated, both in the U.S. and worldwide, especially in Japan, which shows that coolant environments can have a significant effect on the fatigue life of these steels.

And this data is very consistent. It doesn't matter where it has been rated, all show similar trends without any exception. And also, the fatigue data is consistent with a much larger database on fatigue crack growth rates affect on environment of fatigue crack growth rates. There's no inconsistency. The mechanisms are very similar and both show similar trends, effects of radius parameters, material loading and environmental parameters have similar inference on fatigue crack initiation and fatigue crack growth.

And this fatigue data has been evaluated to clearly define which are the important parameters. They're well defined and also the range of these parameters for which environmental effects are significant, it's clearly defined.

So we know the conditions under which environment would have an effect on fatigue life. The question is do these conditions exist in the fleet? If they exist, we will have an effect on the environment and it should be considered. We know from subsection 31.32.21 that the current fatigue design curves do not include the effect of aggressive environment which can accelerate fatigue failures and has to be considered.

So the burden is on the designer to better define these transients, to know what conditions occurred during these transients and whether environment would be involved.

Next, before getting into the environmental effects, I just want to cover a few background information. We are talking about the effect of environment on fatigue life. Let's understand what do we mean by fatigue life? The current code design curves were based on data which was where the specimens were tested to failure. Quite often, these design curves are termed as failure codes, but I think the intent was to define fatigue life as to prevent fatigue crack initiation, because the data which has been obtained in the last 20 to 30 years in these results fatigue life is defined as the number of sitings for the peak load to decrease by 25 percent.

And for the type of specimen, size of specimens used in these tests, mostly quarter inch or three-eighth round cylindrical specimens, this would correspond to creating a three millimeter crack. So we can say the fatigue life is the number of cycles for a given strain condition to initiate a three millimeter crack and from several studies we know that surface crack, about 10 micron deep form quite early during fatigue cycling.

So we can say that fatigue life is nothing but it's associated with growth of these cracks from a 10 micron size to 3 millimeter size and typically this is the behavior of the growth of these cracks is in this shape where crack length is a fraction of fatigue life varies like this and it's divided into two stages, initiation stage and a propagation stage. Initiation stage is characterized by decrease in crack growth rates. It's very sensitive to micro structure.

It involves sheer crack growth which is 45 degrees to the stress axis, whereas propagation stage is not very sensitive to microstructure. It was tensile crack growth which is perpendicular to the stress axis and this is the stage where you see on the fracture surface well defined striations.

Various studies have shown that this transition from an initiation stage to a propagation stage occurs around -- depending on the material, 150 micron or 300 micron, that range.

So initiation stage is growth of crack up to 300 microns. Propagation stage is beyond that to 3000 or 3 millimeter size.

Next slide.

CHAIRMAN ARMIJO: Before you leave that curve, just for the benefit of people who don't understand these curves, what is the time difference between or the fatigue life difference from the three millimeter crack initiated crack to through-wall failure in the case of let's say a one-inch pipe, one-inch wall thickness?

MR. CHOPRA: We would use the crack growth rate data.

CHAIRMAN ARMIJO: Would that typically increase the number of cycles by a factor of 2 or a factor of 10?

MR. CHOPRA: It depends on the conditions, loading conditions and environment and so on. So we know what the crack growth rates are for various conditions. So we have to use that. But maybe I can answer another way. In a test specimen, the difference between 25 percent load drop and complete failure of a specimen is very small. It's less than one or two percent.

So whether we call it failure of a specimen or defining it 25 percent drop, would be very small difference. The idea of using 25 percent load drop was to be consistent so that we define life as some consistent -- all the labs do the same thing. So that was the idea.

Otherwise, for a real component, if we deal with three millimeter steel in a tube, it would depend on crack growth rates.

CHAIRMAN ARMIJO: Okay.

MR. CHOPRA: Now the same curve I've plotted a slightly different way where I plotted still our cracked growth rates was the crack depths, decreasing growth rates in the initiation stage and increasing growth rates.

Now of course, crack growth would depend on applied stress ranges. The higher the stress range, the higher the crack growth. The delta sigma one at very low stresses, the cracks which form during cyclic loading may not growth to large enough size that they can -- the propagation stage takes over.

DR. WALLIS: Crack velocity is really growth rate and microns per cycle, not per unit of time.

MR. CHOPRA: Right, but depending on the time period one could convert it to --

DR. WALLIS: I know, but velocity is a strange word.

MR. CHOPRA: Yes, maybe this should be crack growth rate.

DR. WALLIS: If there's no cycling, there's no crack growth.

MR. CHOPRA: Yes, yes. Beta sigma one, when the stresses are very low, cracks may grow to large enough size for the propagation to take over and this is known as the fatigue limit of the material. This is true for constant loading.

MR. BANERJEE: What's the mechanism that changes the velocity so much?

MR. CHOPRA: Initial sheer crack growth. It will extent maximum couple of degrees. So it's a sheer crack growth, 45 degrees, whereas, once you go deep enough, large enough size, you get into a different process where actually fracture mechanics methodology can be used to express that. It's a tensile crack growth.

MR. BANERJEE: It's a multi-grain sort of size and then it starts -- a different mechanism.

MR. CHOPRA: Typically, a couple of grains. Fatigue limit is applicable only under constant stress conditions. If we have random loading, as in the case of a real component, then we can have situations where we have higher stresses, few cycles of higher stresses, where cracks can grow beyond this depth that you can grow even at stresses which are much lower than fatigue limit.

So the history of cycling is also important for evaluating fatigue damage.

DR. WALLIS: Delta sigma is the magnitude of this?

MR. CHOPRA: Of the stress range, applied extracted stress range. And environment also.

DR. WALLIS: Does it matter if it's 10 silo or compressible?

MR. CHOPRA: On the tests which are used for obtaining fatigue data, the strain range ratio is

-1, completely reversed. So we go from tensile to compressive.

Even in environment, corrosion processes can cause the cracks to grow beyond this and then propagation can take over. So environment also could accelerate. So the question is which part -- which of these stages is affected by environment? Initiation or propagation, or both?

DR. WALLIS: Your scales are linear, are they?

MR. CHOPRA: This is a schematic.

DR. WALLIS: Schematic.

MR. CHOPRA: This portion is plotted here where I have actual numbers. And I just wanted to show you that we know from crack growth studies that crack growth rates are affected by environment and it's very well documented.

DR. WALLIS: These data look unreasonably well behaved for materials data.

(Laughter.)

MR. CHOPRA: If we plotted a few tests, we will see this happen.

CHAIRMAN ARMIJO: Agreement is log, log.

DR. WALLIS: Even so, I mean.

MR. CHOPRA: Anyway, effect of environment is also, has been studied in fatigue crack initiation.

DR. WALLIS: These are real data?

MR. CHOPRA: These are real data. But we have calculated the crack growth rates in the fatigue samples by benchmarking the fatigue crack front at different stages during fatigue life. And so we can see the three environments here: high oxygen -- high dissolved oxygen water; low dissolved oxygen; PWR water and air. And we see if you take 100 micron crack length and air -- it took about 3,000 cycles to reach that. In water, it took only 40 cycles, which gives me an average growth rate of 2.5 micron per cycle and this is this region here, average of this.

In this case, it's .0033 microns per cycle. So we see two orders of magnitude effect of environment which suggests that even the initiation stage may be affected even more than what crack growth rate is affected.

I just wanted to show you that both stages are affected by the environment, even the growth of very small cracks.

Now next, the design curves, what do the design curves --

DR. WALLIS: Presumably, this is not just one batch of data like this.

MR. CHOPRA: There's lots of data. I'm just giving --

DR. WALLIS: There's a whole lot of data.

MR. CHOPRA: I'm just giving you one set, yes. There's a lot of data.

DR. WALLIS: Because if there were uncertainty in these, these curves might switch positions.

MR. CHOPRA: sure, but I'm just presenting that data to show that environment has a large effect. It's the relative difference between air and water which I was trying to show, not absolute crack growth rates, just to show that it took only 40 cycles in high oxygen water compared to 3,000 which suggests that environment has a large effect on fatigue crack initiation.

Now the design curves, we have -- the data which we have obtained is on small specimens. They are absolutely smooth and they were tested in room temperature air. This is what was used to generate the design curves in the current code. And all of them were tested under strain control, fully reversed, strain ratio of -1.

Now this gives me the best behavior of a specimen when a crack would be initiated in a specimen. To apply those results to actual reactor component we need to adjust these results to account for parameters or variables which we know affect fatigue life, but are not included in this data. And these variables are mean stress, surface finish, size, loading history.

DR. WALLIS: Does the humidity of the air make a difference?

MR. CHOPRA: Actually, if you look at the basis document of the current code, they use a subfactor which included surface roughness and environment and by that environment they meant a lab, well-controlled lab environment.

DR. WALLIS: Does the humidity of the air make a difference?

MR. CHOPRA: In some cases it would, but again, that is not studied as a -- it's not addressed as an explicit parameter in defining fatigue life. All data which was used was room temperature air to generate the design curves.

DR. WALLIS: Room temperature means 20 degrees Centigrade or something?

MR. CHOPRA: Yes, 25, yes. To account for these other variables like mean stress, surface roughness and so on, what the current code --

DR. WALLIS: I'm sorry, when you -- maybe you just said it. When you say PWR water, you mean at room temperature or --

MR. CHOPRA: No, no. The design curves do not address environment at all.

DR. WALLIS: But your data that you showed us, the well-behaved data.

MR. CHOPRA: Those are higher temperatures.

DR. WALLIS: Those are higher temperatures.

MR. CHOPRA: They would be at reactive temperatures.

DR. WALLIS: Okay. Could be a temperature effect as well as an environment effect?

MR. CHOPRA: There is and I'll come to that actually. In water, temperature is a very important parameter. And to convert this data on specimens to a real component, what the current code does now is take the best --

DR. WALLIS: Is the PWR water that is borated at initial strength or something?

MR. CHOPRA: PWR is. It both has boron and lithium.

DR. WALLIS: There's some sort of average condition throughout the cycle?

MR. CHOPRA: Right, right. Typically, people test around 1,000 ppm boron and 2ppm lithium.

To adjust these curves to an actual reactor component, what the code does is we take the best of the specimen data and adjust it for mean stress correction and then apply these adjustment factors of two on stress. We decrease the specimen curve by a factor of two on stress and 20 on life, whichever is the lower gets the design curve. But as I mentioned, it does not include the effect of an aggressive environment. In this case, what we are talking about is light-water reactor environments.

Now to summarize some of the effects of environment on carbon and low-alloy steels, there are several parameters which are important. Steel type, all of the data shows irrespective of steel type, it doesn't matter which grade of carbon steel or low-alloy steel, effect of environment is about the same. There is a strain threshold below which environments do not -- environmental effects do not occur. And this threshold is very close to slightly above the fatigue life of the steel. Strain rate is an important parameter. There is a threshold, 1 percent per second above that. Environmental effects are more great and lower the strain rate, higher the effect. And it diffuses the saturation at around .001 percent per second.

Similarly, temperature is very important. Once again, there is a threshold; 150 degree C. Higher temperatures, there's greater effect. Below 150 --

DR. WALLIS: Strain rate's lowest point is .001 percent a second makes a difference?

MR. CHOPRA: Yes. I'll show you some of the results.

DR. WALLIS: Really? That's awfully slow, isn't it?

MR. CHOPRA: Some of the transients are.

DR. WALLIS: Abnormally slow.

MR. CHOPRA: Temperature also, there is only a moderate effect below 150. Typically, when I mean moderate effect, up to a factor of 2. Any water touched surface may have up to a factor of --

DR. WALLIS: Linear decrease doesn't tell me how fast it is. Linear decrease in life after 150 doesn't tell me how rapidly it decreases.

MR. CHOPRA: There are some slides, I'll show you how much of a different it is.

MR. SANTOS: Do you have an equation?

MR. CHOPRA: Yes.

DR. WALLIS: Which goes right through the data?

MR. CHOPRA: Absolutely.

DR. WALLIS: Is this an Argonne equation or a universal equation?

CHAIRMAN ARMIJO: You'll see.

DR. WALLIS: We'll see, okay.

MR. CHOPRA: Dissolved oxygen is also similar. There's a threshold. In this case, low oxygen environmental effects on carbon low-allow steels are less. There's a threshold .04 ppm. Higher dissolved oxygen has an environmental effect, saturates around .05 ppm.

DR. WALLIS: How much sulfur is there in the reactor?

CHAIRMAN ARMIJO: That's in the steel.

DR. WALLIS: In the steel, I'm sorry. I thought you were talking about the environment. Now you're talking about the steel?

MR. CHOPRA: These are --

DR. WALLIS: Dissolved oxygen in the steel.

MR. CHOPRA: These are loading parameters. Some are environmental parameters. Some are material parameters.

DR. WALLIS: Okay.

MR. CHOPRA: Sulfur also has a large effect on fatigue crack initiation.

DR. WALLIS: There's no other effects, copper and stuff like that? There's no other effects?

MR. CHOPRA: In the steel? No. At least the ones which we have looked at. Sulfur is the one because it deals with the mechanism. Actually, the reason why these are higher for carbon and low-allow steels which these are very well documented. It's the sulfite iron density of the cracking. If we reach a critical sulfite iron density crack enhancement occurs. So these are very well documented in the data. This is a mechanism. That's why sulfur is important.

Roughness effects, we know if we have a rough specimen surface it provides sites for initiation. Life goes down. And in carbon low-alloy steel, in air, there is an effect of surface roughness, but some limited data suggests that in water, rough and smooth specimens have about the same life. So roughness effects may not be there for carbon low-alloy steel.

Flow rate also, most of the data has been obtained on very low flow rates or semi-stagnant conditions. If we do these tests in higher flow rates, effect of the environment does go down. Means fatigue life would increase in high flow rates by a factor of about 2.

Similarly, the effects on austenitic stainless steels, same parameters, steel type, again different grades of austenitic stainless steel, similar effects and even cast austenitic stainless steel have similar effects on the environment.

Once again we see a strain threshold below which there is no effect and it's very close to the fatigue limit. The dependence of strain rate and temperature are very similar to what we see in carbon and low-alloy steels.

The next three, dissolved oxygen, surface roughness and flow rate, the effects are very different from carbon and low-alloy steels. In this case, for austenitic stainless steel, it's the low oxygen which gives you a larger effect. And irrespective of what steel type we use or what heat treatment, heat treatment that means sensitization. Sensitized stainless steel or solution in the stainless steel both show similar life in low oxygen.

DR. WALLIS: That extends down to zero

oxygen?

MR. CHOPRA: Pardon me?

DR. WALLIS: That extends down --

MR. CHOPRA: If we can achieve that, you know, but typically in a PWR, we have around -- it's a low -- less than 50 ppm.

Yes, low oxygen, irrespective of the steel type or heat treatment, there's a large effect on environment, but in high oxygen, non-water chemistry, PWR conditions, some steels show less effect and these are solution annealed high-carbon steels which are not sensitized. All low carbon grades such as 316 nuclear grade or 304 L may have less effect in high oxygen.

Surface roughness and this is both in air and water environments, there's a reduction in life. Even in water. In carbonate steel we did not see a reduction in life for rough samples. In this case, both in air and water there is an effect of roughness. And flow rate, there is no effect of flow rate on fatigue life for austenitic stainless steels in water.

The differences between these three suggests that the mechanism may be different for austenitic stainless steels compared to carbon and low-alloy steel. I mention the mechanism for carbon and low-allow steels, the sulfite iron density of the crack depth. In this case, it's not well known -- there's no agreement on what is the mechanism. One possible mechanism would be that as we expose stress surface, hydrogen is created which changes the definition of behavior and of the crack depth. But this is one possible mechanism.

The next slides are details of what I summarized. Unless there are specific questions, I'm going to skip these next eight slides which basically give the data which I summarized in the previous.

CHAIRMAN ARMIJO: I think it would be better if you just highlight these things, just to make the key points from these charts because I think they're important.

MR. CHOPRA: This is the strain rate effect. You were asking about the strain rate. I plotted fatigue life for low-alloy steel, carbon steel under certain conditions, strain amplitudes. In air, PWR water and BWR.

DR. WALLIS: Are you claiming there's a significant difference between air and PWR?

MR. CHOPRA: It's up to about a factor of 2 and this could be a factor of 15 or 20 lower

DR. WALLIS: We're not going to put in that much oxygen, are we?

MR. CHOPRA: BWR has 200 to 300 ppb oxygen and in this case, there are correlations which will tell you how much -- depending on the oxygen, what would be the effect.

This is the maximum effect because this is I think .7. Saturation is at .5. So this is the maximum effect under these conditions.

This is strain threshold which I mentioned, the threshold about which effect of environment is there. This gives you dissolved oxygen at .04, this is carbon steel, higher oxygen levels, things go down. And again, in PWR there's only a modern effect.

I mentioned that for stainless steel, the effect of dissolved oxygen is different. Here, this is now three or four stainless at two different strainless amplitude. There are two different tests at different conditions, .25 and .33 and high oxygen, no effect upstream rate and low oxygen, it goes down. Whereas, a 316 NG or low carbon grade shows some reduction in life in high oxygen, but not at the same extent as you see in low oxygen.

So these are just a few examples I'm showing. There's a lot of data in Japan and Europe which shows similar trends. This shows the effect of sensitization. Sensitization is defined as a number, EPI number. Degree of sensitization is increasing and same conditions. In air, low oxygen, high oxygen and we see in high oxygen it decreases with degree of sensitization.

Effect of -- this is temperature again at 150 and lower, depending on what are the strain rates and what are the dissolved oxygen conditions. If it's very low, no effect. These are low oxygen conditions, no effect. High oxygen, depending on the strain rate and dissolved oxygen levels to the extent of the effect in pieces.

DR. WALLIS: You're just talking about a hundred cycles there, failure.

MR. CHOPRA: No, a thousand. In some cases in the environment, it is.

DR. WALLIS: Right.

MR. CHOPRA: There is up to a factor of 20 reduction in life.

Surface roughness again, stainless steel, open circles, smooth specimens; closed circles are symbols are rough samples. A factor of 3 in air, factor about the same in water.

CHAIRMAN ARMIJO: I don't want to belabor this, but I looked at these data and the one that shows -- the curve on the left for the air data, the right triangles. They don't go through the best fed curve at all.

MR. CHOPRA: Actually, this is 316 NG. 316 NG has a steeper slope, but for convenience we are using a curve for all steels.

CHAIRMAN ARMIJO: So that's the best fit curve there is for all --

MR. CHOPRA: All stainless steels, all grades, including high or low-carbon grades.

DR. WALLIS: The purpose of the ASME curve is to be below all the data, is that the idea?

MR. CHOPRA: Once we take into account, you know I mentioned those adjustment factors of 20 on fatigue and 2 on stress. Once we take that into account, once we do that adjustment, then we want to make sure that we are above that.

But these are best fit curves. So they give you the average behavior for all --

DR. WALLIS: The ASME code has a factor of 2 in it or something? I don't see that.

MR. CHOPRA: I'll come to that. Give me a --

DR. WALLIS: Okay. But the factor of 2 is in this curve here?

MR. CHOPRA: No, these are --

CHAIRMAN ARMIJO: ASME codes.

MR. CHOPRA: The code curve has the factor of 2.

DR. WALLIS: No safety factor.

MR. CHOPRA: This is the best fit. These are showing that even --

DR. WALLIS: Oh, I see. So you've give up your margin of 2?

MR. CHOPRA: Right.

DR. WALLIS: Okay.

MR. CHOPRA: What we are saying is only the margin or adjustment factors are gone for the --

CHAIRMAN ARMIJO: That's it.

MR. CHOPRA: Environment has taken care of all that and still be within bound for a lot of other factors like surface roughness and so on.

DR. WALLIS: You're going to tell us what you're going to do about that?

MR. CHOPRA: Sure.

DR. WALLIS: Okay.

(Laughter.)

CHAIRMAN ARMIJO: Absolutely.

MR. CHOPRA: This gives you the effect of flow rate. I mentioned that for carbon and low-alloy steels, effect of environment is less.

Now a few slides for nickel alloy. There's much less data on nickel alloys. Here, I've plotted the data which is available --

DR. WALLIS: Much less data. So you're showing us more than you showed us for steel?

MR. CHOPRA: What we do is rather than coming with a new curve for nickel alloys, unless we have enough data, what I'm trying to show is that we can use the austenitic stainless steel to represent the nickel alloys and even the few data we have for alloy 690 suggests that we can use the austenitic stainless steel code to determine usage factors, fatigue usage factors for nickel alloys in air.

MR. BANERJEE: So temperature has almost no effect here.

MR. CHOPRA: For carbon and low-alloy steels there is some effect. Going from room temperature to 300 may reduce life by about 50 percent, but stainless up to 400. There's not much effect.

MR. BANERJEE: Including nickel alloys?

MR. CHOPRA: Nickel alloys, no. At 400, in fact, they show longer life. But again, the data is very limited. There's few data sets at 400 which actually show longer life for alloy 600. But again, at present, since all curves are based on room temperature data, we are not taking any temperature dependence for air. But for water effects, temperature is important and explicitly defined in the expressions to calculate fatigue life in water.

DR. WALLIS: That means it is through the median of the data in some way?

MR. CHOPRA: I'll show you how we got the best fit curves.

DR. WALLIS: It's supposed to be an average right through the middle of the data.

MR. CHOPRA: Right.

DR. WALLIS: It's not best fit to a 95 percentile or something like that? You'll get to that too, but what you're showing here is --

MR. CHOPRA: Average, right. These results show nickel alloy data for alloy 600 and some of the welds. In BWR, normal water chemistry, BWR environment and PWR environment and again, what we see is the effects are similar to what we get for austenitic stainless steels. There's larger effect in low oxygen than in high oxygen. PWR environment has larger effect than BWR, but the focal effect is much less than what you would see for austenitic stainless steel.

Typically, under certain conditions in austenitic stainless steel we see a reduction of a factor of 14 or 15. In this, the maximum is a factor of 3. So the effect is much less, but we can use this limited data to define the important parameters and how to estimate environmental effects.

Now we have all this data. How do we generate the expressions? All -- in air, all data, fatigue data I expressed by this modified Langer equation where fatigue life is expressed in terms of strain amplitude and these constants A, B, C --

DR. WALLIS: Is this an equation because you plotted the data on log paper, is that why it is?

MR. CHOPRA: This is the expression used and it presents the data best.

DR. WALLIS: It's because you plotted it on log paper. It looks good on log paper and it's linear.

MR. CHOPRA: Well, the trend is also -- it does represent the trend.

DR. WALLIS: Okay.

MR. CHOPRA: And C is the fatigue limit or related with the fatigue limit of the material. B is the slope of that curve. A is a constant which would vary with heat to heat. Depending on a more resistant material would give a higher A or lower means it's less resistant to fatigue damage.

We can do a best fit of the data and also use this A to represent heat to heat variability and come up with a median value, how median material would behave. Best fit gives me the average behavior, whereas a distribution would give me how various materials behave and I get a median curve and then come up with a number which would bound 95 percent of the materials. And that's what I'm going to show.

One more thing, another term, D can be added to impute in 1, which would include parameters like temperature, strain rate and so on.

DR. WALLIS: Does the ASME curve have a similar equation?

MR. CHOPRA: Yes. The Langer equation is very -- yes.

This shows for low-alloy steels in air and water various heats. Now each did define even if I have 10 data points, it's 1 point. Another may have 500 data points. But if it's the same material, it's just one point on this plot. This way, I can give you, we can determine the median value for the materials and if I select a fifth percentile number, in this case, 5.56, if I select the A or 5.56, that curve would bound 95 percent of the --

DR. WALLIS: It's the coefficient.

MR. CHOPRA: So this is how we obtain the design curve by defining what subfactors I need to adjust the best fit curve for average curve to come up with a design curve which would bound 95 percent of the materials.

I'll give the loca probability of track initiation.

MR. BANERJEE: There's B and C as well, right?

MR. CHOPRA: B and C, what I do is use it for normalizing to get A for each heat which is the average heat and I get a standard deviation. That's what I've plotted here. For the particular heat, I've given the average value and the standard deviation for the data set.

MR. BANERJEE: You lost me.

CHAIRMAN ARMIJO: B and C are relatively constant.

MR. CHOPRA: A is the one that changes.

MR. BANERJEE: So you fix B and C to some value?

MR. CHOPRA: Right, right. And we know even environment does not change. The strain threshold was close to fatigue limit so I don't have to change the fatigue limit. And there is no data which suggests that C changes, means that the fatigue limit changes for material.

DR. WALLIS: The range of that is not very big, but if N is E to the A, so it's a factor of about 10 on the whole range.

MR. CHOPRA: Right.

MR. BANERJEE: Do B and C govern the shape of the curve?

MR. CHOPRA: Yes. Right. The slope is B. C is where at 10^6 or 10^7.

DR. WALLIS: I see where it's flat.

CHAIRMAN ARMIJO: So all the environmental effects are just put into the A constant?

MR. CHOPRA: Right.

CHAIRMAN ARMIJO: Okay.

MR. CHOPRA: Now we come up with these expressions which can be used for predicting fatigue life under various conditions. Again, Langer equation A, constant A; slope B and C. And this is the environmental term B which would have these -- which would depend on these three parameters for carbon low-alloy steel, same for content, given by these expressions, temperature, dissolved oxygen and strain rate.

CHAIRMAN ARMIJO: Now the A is the five percent number?

MR. CHOPRA: No. These are still the average numbers.

CHAIRMAN ARMIJO: These are average numbers.

MR. CHOPRA: Next, I'll get to where we apply those adjustment factors to get the design growth.

DR. WALLIS: What does N mean here?

MR. CHOPRA: Cycles --

DR. WALLIS: Environment. N for environment, is that PWR?

MR. CHOPRA: No, this is in error what the expression is. This is in the light water reactor.

DR. WALLIS: Okay.

MR. CHOPRA: It doesn't matter whether it's BWR or PWR because these are the parameters which will change in various environments, reactor environments.

MR. BANERJEE: Is there no effective hydrogen on it at all?

MR. CHOPRA: In BWR environment, there's about 2 ppm dissolved hydrogen, but I think it's the hydrogen which is created by the austenitic reaction which is more important than what is -- it does control ECP, the electrical potential of the environment. So hydrogen would change the ECP, but below -250 electrical potential, effects are not that much different. But you know, in crack growth rates there is some effect, depending on -- well, in this case all -- we use only 2 PPM hydrogen.

MR. BANERJEE: These are all done in autoclaves or whatever?

MR. CHOPRA: And we do simulate these conditions. BWR, it's high oxygen, high purity, very high purity. And pressurized water reactor, again high purity. Then we had boron or boric acid to get boron, 1,000 PPM and 2 PPM lithium, by adding lithium hydroxide. And measure the pH. We measure the conductivity and maintain all these water chemistry parameters constant during the test.

CHAIRMAN ARMIJO: These are flowing a loop type --

MR. CHOPRA: Very small flow rates. I think if you look at the -- my plot, they would amount to 10^{-5} meter per second. Very low.

CHAIRMAN ARMIJO: They're not static autoclaves?

MR. CHOPRA: They're not static and they are continuously reconditioned. So if they are, it's once through. They're not repeated.

DR. WALLIS: How long are the tests done typically?

MR. CHOPRA: Depends on the conditions. At low strain amplitudes and low strain rates, it may take up to 5 to 8 months and those results are very limited. In the range which people have -- we have tested .25 to .4 strain amplifies, it can take anywhere from a few days to a month or two, depending on the environmental effects. In air, they're much longer. So one has to consider all of these. We can't just dedicate and that's why you see very low, less data under conditions which have very long durations.

Now I just want to mention that these expressions are average behavior after median material. Same thing for rod and gas stainless steel. Now as you mentioned that the slope of the 360 NG was different, what we have done is we have used a single expression to represent all grades of steel and this number, the fatigue limit we chose what studies in

Japan have established. And Jaske and O'Donnell in 1978 pointed this out that the current design curve for stainless steel was not consistent with the experimental data.

DR. WALLIS: I want to check this about oxygen. You say it's worse to have less oxygen?

MR. CHOPRA: Pardon me?

DR. WALLIS: N goes down when you have less oxygen?

MR. CHOPRA: In stainless steel, life goes down dissolved oxygen is low.

DR. WALLIS: But these it goes the other way?

MR. CHOPRA: No. The oxygen, there's a constant factor --

DR. WALLIS: In the one before, the carbon and low-alloy steels?

MR. CHOPRA: Yes. Now in carbon and low-alloy steel it's the high oxygen which is more damaging.

DR. WALLIS: Then it doesn't make -- okay, okay. That's right. Okay. Because I thought it was the other way around. That's a negative --

MR. CHOPRA: The strain rate term is a negative.

DR. WALLIS: That's right. I was crawling through that and then I was trying to go back to before.

MR. CHOPRA: Actually, this whole term is --

DR. WALLIS: I understand that. Just before, but the other with the stainless steel, the low oxygen is bad.

MR. CHOPRA: Right.

DR. WALLIS: Okay, that's what I'm trying to --

MR. CHOPRA: I just mentioned that we established a single curve and this we selected from what was proposed by these studies.

Now we have the specimen data. We know how to predict what will happen with specimens.

DR. WALLIS: What effect does this have on welds of dissimilar metals?

MR. CHOPRA: Welds have different --

DR. WALLIS: All together different?

MR. CHOPRA: Yes.

DR. WALLIS: Is there some basis for that?

MR. CHOPRA: It depends on the data.

DR. WALLIS: You're not addressing that?

MR. CHOPRA: No. This is the current code design curves for these grades or types of structural steel.

CHAIRMAN ARMIJO: For example, a welded stainless steel is like a cast stainless steel, a weld --

MR. CHOPRA: I think the behavior is very similar. But --

CHAIRMAN ARMIJO: If it's similar, there's a difference.

MR. CHOPRA: Because in some cases there may be difference. We are just looking at here the rod products.

CHAIRMAN ARMIJO: Stainless.

DR. WALLIS: Is there any effect of fluence on this?

MR. CHOPRA: Irradiation? I'm sorry, I didn't get that?

DR. WALLIS: Is there any effect of fluence?

MR. CHOPRA: We're not studying that. There is an effect, but that's not -- in the design curve --

DR. WALLIS: It's all synergistic.

MR. CHOPRA: No environment is considered and the designer has to account for other environments which are not considered in their design.

We have the data for specimens. Now to use it to come up with a design curve for components, I mention that they apply this adjustment factor of 20 on life and this factor is made up of effects of material availability, data scatter, size, surface finish, loading history.

In the current code, these are the subfactors which are defined in the basis document. Loading history was not considered, a total of 20 adjustment factors. In our study, based on the distribution I showed for individual materials, this subfactor can vary anywhere from a minimum of 2.1 to 2.8. These numbers are taken from studies in the literature. Size can have an effect, minimum 1.2, 1.4 and so on. So we see a minimum of 6, maximum of 27. When we take a large number, for example, 20, what we are basically saying is I have a very bad material which is very poor in fatigue resistance. I have rough surfaces and I have the worse loading history.

So we used a Monte Carlo simulation and using these as a log normal distribution to simulate what would be the best adjustment needed to define the behavior of components.

CHAIRMAN ARMIJO: So the present study,

you've agglomerated the date for carbon steels and austenitic stainless steels and all these factors are all pushed together.

MR. CHOPRA: Right.

CHAIRMAN ARMIJO: But you've separated them. Are they different?

MR. CHOPRA: No, these are not the effects of materialability is here and that depends on the material. But effects of surface finish of the component, size of the component or loading history means random loading, high stress cycle followed by low stress cycles. These -- in the current data, these effects are not included. So somehow I need to include these effects to come up with a design curve which would be applicable to a real actual reactor component.

Now the question is 20 was selected with some basis. Is this reasonable because quite often, this is what is being questioned. There may be conservatism in this which we need to eliminate. So we are trying to see what possible conservatism might be there in this margin or the adjustment factor of 20.

DR. BONACA: Twenty was arbitrarily taken as a bounding number, right?

Where did you get the 27?

MR. CHOPRA: I just took from the literature what people have observed, effect of surface -- surface finish is very well documented. Depending on the average surface finish, an autonomous value of surface finish, they have a harmless reduction in light. So I can use typical finish for grinding or milling operation and so on. It's well documented. We can come up with what would be a typical fabrication process, minimum and maximum. So that's how we came up with this number.

DR. WALLIS: What is the basis of the numbers? Is it trying to bound the data or bound the 95th percentile?

MR. CHOPRA: To come up with a design curve which will be applicable to components.

DR. WALLIS: What's the basis of this? Is there a rationale?

MR. CHOPRA: Right, 95 percent.

DR. WALLIS: Ninety-five, 99, 95?

MR. CHOPRA: Ninety-five?

DR. WALLIS: Why is 95 good enough?

MR. CHOPRA: Well --

DR. WALLIS: Why not 99?

MR. CHOPRA: We can do a statistical

analysis to see what are the probabilities.

CHAIRMAN ARMIJO: I think 95/5 basis is sort of a typical basis we've used in a lot of other studies on failure data. But the reason that 95/5 is okay is we've already done risk studies with fatigue cracks initiating and growing to failure and growing to leakage and the fact of a 95/5 probability of fatigue crack initiation still keeps you in acceptably low probability of getting a failure.

DR. WALLIS: Okay, so it's related to the overall --

CHAIRMAN ARMIJO: Overall margin, yes. If it were just a 95/5 to failure it would be an unacceptable criteria.

DR. WALLIS: If the consequence were much worse, you'd need to have a --

CHAIRMAN ARMIJO: Yes.

MR. BANERJEE: Can you expand a bit more by what you mean by this log normal distribution?

MR. CHOPRA: We assumed that the effects of all of these parameters have a log normal.

MR. BANERJEE: Of some mean?

MR. CHOPRA: Right. And I took these two ranges as the 5th and 95th percentile of that distribution.

MR. BANERJEE: So what happens if you chose a different distribution? Does it make any difference to the results?

MR. CHOPRA: We have tried three different, I think Bill tried and this gets the best --

MR. BANERJEE: Best in what sense?

MR. CHOPRA: Very consistent result. There's not much difference between normal and log normal was not much difference. And log normal -- you want to --

DR. SHACK: It's basically sort of an arbitrary engineering judgment question. Experience has indicated that when we have enough data, these things do seem to be distributed log normally.

We generally don't have enough data, actually, to determine the distribution. So we have sort of just made the engineering judgment that the log normal is close enough.

As John was explaining --

MR. BANERJEE: It doesn't affect the results.

DR. SHACK: It doesn't affect the results very much. What we're trying to do is to bound the data in some reasonable fashion because the consequence is not core damage when we're done. The fact that we're not highly precise on this is not something that concerns us, but we think we've built in sufficient conservatism to account for these variables in a sensible way without going overboard.

And the fact that these affects can be considered as independent is also something we don't have data on. We have to sort of work on an engineering judgment basis. So the Monte Carlo simulation that we do assumes the log normal distribution, assumes the independence.

MR. CHOPRA: I want to add one more, quite often, actually in the welding research that WRC Bulletin by industry, they are suggesting that in this margin of 20, we can use a factor of 3 to offset environment. This kind of analysis can suggest or show that 3 number is very high. We do not have that, at least what is the possible --

DR. KRESS: Is it a theoretical basis for assuming the log normal? There may be, you know. You can look at the physical phenomena and --

DR. SHACK: Well, the loading, probably --

DR. KRESS: Loading you would think would be log normal. I'm not sure about the effects of the other things.

DR. SHACK: The log normal turns out to be slightly more conservative than the normal and so those were my -- if I don't have enough data to define a distribution --

DR. KRESS: You might as well use --

DR. SHACK: I pick one or the other, sort of on some sort of engineering judgment. The differences are not very large between the two and we just pick the log normal.

DR. WALLIS: If you know the distribution, why do you need -- if you know the equation for the distribution, why do you have to do a Monte Carlo analysis?

DR. SHACK: Because I'm taking a bunch of random variables.

DR. KRESS: That's the way you find the mean, right?

MR. CHOPRA: There are four or five of these things.

DR. SHACK: There are four or five distributed variables.

DR. WALLIS: Easier to do it than to try to go through the mathematics of predicting.

DR. SHACK: Yes, it's easier. Yes, I could do it the other way, right.

DR. KRESS: Is the 95 value four times the mean?

DR. SHACK: No.

DR. KRESS: It has to be if it's log normal.

DR. WALLIS: Four times the mean on a constant A would be horrendous.

DR. KRESS: You've got to find the mean value.

DR. WALLIS: Mean value is about five.

CHAIRMAN ARMIJO: Let's move on.

MR. CHOPRA: Doing this simulation, we get these curves where this dash curve is now for the specimen, the distribution of A for the specimen and solid would be the distribution for the real component. And we see that the median value has shifted by about 5.3.

And 95 of 5th percentile is a factor of 12. So we can say that in this factor of 20, there is some conservatism and we can use adjustment factor of 12 on life instead of 20.

DR. WALLIS: Where did 20 come from?

MR. CHOPRA: It's in the design basis document of the current code.

DR. WALLIS: It's the judgment of a few

wise men?

CHAIRMAN ARMIJO: Many years ago.

MR. CHOPRA: Basically, that's what it was.

MR. BANERJEE: Not so bad.

MR. CHOPRA: The design has several -- yes.

I've covered -- there is some conservatism in the fatigue evaluations and often this conservatism is used to offset environmental effects and there are two sources of conservatism, in the procedures themselves, the way we define design stresses and design cycles or this adjustment factors of 2 and 20.

I showed there's not much margin, only 1.7 in this factor of 20, but the current code procedures --

DR. WALLIS: Is there enough to account for environmental effects?

MR. CHOPRA: No, environmental effects can be as high as a factor of 15.

DR. WALLIS: Yes.

MR. CHOPRA: Or carbon C would be even higher.

DR. WALLIS: These are all reactor data you've got, right?

MR. CHOPRA: Those are -- unless you define the operating transient conditions. In certain conditions those may be possible, but again, it's up to the designer to define what are the conditions during a transient, mean strain rates, temperatures and so forth.

MR. BANERJEE: But I'm wondering whether in your database you have anything which you've evaluated from N reactor data or reactor data. Do you have any information at all?

MR. CHOPRA: There are some components and so on and I list a few examples where there have been some studies. And I'll show you near the end of this.

DR. SHACK: The trouble with doing this with field data is it's hard to control variables like knowing that the strain range and because that has such a strong effect on it. Unless you know that accurate, it's hard to back out the result.

MR. CULLEN: Bill Cullen, Office of Research. I'd like to explore Dr. Banerjee's question a little more to find out what's behind it.

Are you concerned about irradiation effects which really do not come into play for pressure boundary? Or are you concerned about the actual aqueous environment and its characteristics?

I'm not sure -- what is the basis?

MR. BANERJEE: Well, the basis is more -- it would be nice to see some validation under field conditions. There are always sort of surprises between the lab and what happens in the field and even if this sort of validation is not all that thorough, a couple of data points would set your mind at rest that it's not some unexpected factor that comes in.

It's more like -- I have a concern always of going from the lab to a real field situation. It's not for any specific issue, not like radiation or combination of factors or boron plus temperature in fatigue cycles which are slow. All these things may or may not be there but just a general question, more a general question.

MR. CULLEN: I understand the general question. I'm a little concerned about your word about there always are surprises when you go from the laboratory to the actuality.

MR. CHOPRA: Maybe that's too strong.

MR. CULLEN: A little bit.

(Laughter.)

DR. WALLIS: Oftentimes, surprises may be small.

MR. CULLEN: Thank you.

MR. BANERJEE: I don't mean to say that this stuff should not be used or anything. Right.

MR. CHOPRA: I mentioned that in fatigue evaluations the procedures are quite conservative, but the code allows us to use improved approaches, for example, finite element analysis, fatigue monitoring to define the design stresses and cycles more accurately. So most of this conservatism can be removed with better methods for defining these design conditions.

So in that case, there is a need to address the effect of environment explicitly in these procedures.

Now the two approaches which we can use either come up with new set of design curves or use some kind of correction factor, F_{en}. Now since environmental effects depend on a whole lot of parameters, temperature, strain rate and so on, either we come up with several sets of design curves to cover the possible conditions which occur in the reactor or field conditions or if you use a bounding curve, it would be very conservative for most of the conditions.

Whereas this correction factor, F_{en} approach is relatively simple. You can -- it's very flexible. You can calculate the environmental effects for a specific condition. And this is what is being proposed in this reg. guide.

The correction factor is nothing, and this was proposed in 1991 by the Japanese. A correction factor is nothing but a ratio of fatigue life and air versus life and water. So we have these expressions I showed you in the previous slides and we can then calculate F_{en} for different steels, carbon steel, low-alloy steel, and below a strain threshold there's no environmental effects, so the correction factor would be one.

Other than that, we use these expressions, actual conditions, temperature, strain rates and so on to calculate the correction factor. To incorporate environmental effects, we take the usage, partial usage factors obtain for specific transients in air, U1, U2 and so on, multiplied by the corresponding correction factor and we get usage factor in the environment.

Now to calculate usage factors in air, we should use design curves which are consistent with or conservative with respect to the existing data. And as has been pointed out quite a few years back, the current code curve for stainless steel is not consistent with the current existing data and should not be used for obtaining usage. And I just want to show before I get to that, these are the expressions for nickel allows. Correction factor, again, as a function of these three variables. And usage and air would be obtained from the curve for austenitic stainless steels.

Now I mentioned that the current design curve for austenitic stainless steel is not consistent with the data. I plotted the fatigue data for 316, 304 stainless in air, different temperatures and this dashed curve is the curve, current code mean curve. This is the mean curve which was used to obtain the design curve.

DR. WALLIS: Where is your design curve?

MR. CHOPRA: Design curve would be what you adjust this curve for mean curve correction.

DR. WALLIS: Your recommended curve would actually bound the data, wouldn't it?

MR. CHOPRA: This is the best -- actually, this data, the curve is based on austenitic stainless steel.

DR. WALLIS: I thought you were recommending a bounding curve with this factor.

MR. CHOPRA: I'm just trying to show that the current --

DR. WALLIS: What's your design curve? You should show that, shouldn't you?

MR. CHOPRA: These are mean curves.

DR. SHACK: This is air data, mean curve. If we put a design curve on here, we could have a design curve in air and a design curve in --

DR. WALLIS: There's all this air data. Are you going to get to your -- it's so far down the road, I can't -- okay.

CHAIRMAN ARMIJO: I think he's just trying to show the difference between the two sets of means.

MR. CHOPRA: That the current means --

DR. WALLIS: You do show the effect of the F factors yet.

MR. CHOPRA: No. I'm just trying to show --.

DR. WALLIS: We've just been talking about --

DR. SHACK: What he's trying to demonstrate here is that the F factor requires him to take the ratio in air. He's got to have the right air curve.

MR. CHOPRA: And the current mean curve for air, for austenitic stainless steel, is not consistent with the data.

Now I'd like to mention one thing, it's been suggested that this curve, the data may be different from the mean curve because of the way fatigue life has been defined or the way we conduct experiments. I can assure you that this difference in the mean curve and the data is not due to any artifact of test procedures or the way the fatigue life is defined in terms of failure or 25 percent load drop.

DR. WALLIS: What occurs to me is the ASME code mean curve was a mean curve to something.

MR. CHOPRA: Right.

DR. WALLIS: And it was presumably through other data.

MR. CHOPRA: This curve, the current code curve was based on very limited data. Now we have much more. So I'm just showing that the data which has been obtained since then is not consistent with what we have.

DR. WALLIS: You have a much broader data base.

MR. CHOPRA: Right.

DR. WALLIS: Okay, that's why yours is better?

(Laughter.)

MR. CHOPRA: We are saying we should

change the current code curve. The current code curve is not consistent with --

DR. WALLIS: It must have been based on something.

MR. CHOPRA: And that data is somewhere in here, up here. But since then we have much more data.

DR. WALLIS: Either that or steels have been getting weaker.

MR. CHOPRA: Actually, that is the reason. Mostly like because of the strength of the steel, probably these curves were obtained on steel which was stronger.

DR. WALLIS: Wait a minute --

MR. CHOPRA: Possible difference.

MR. CULLEN: Bill Cullen, Office of Research again. Omesh, if you could go back to that, I'd like to also point out that the curves on which the original ASME code were based I think the data only went out to a factor of about, fatigue life of 10^6 or something.

MR. CHOPRA: Not even 6.

MR. CULLEN: So you've got two orders of magnitude extrapolation there that we're doing now to illustrate. But the other thing again is those tests were all done at room temperature and you're showing data from a wide variety of temperatures up to and including operational.

MR. CHOPRA: Stainless does not --

MR. CULLEN: Doesn't show much difference, right. To me, that's kind of the point. It all hangs together on the lower curve.

MR. CHOPRA: This difference is genuine. We need to use a different curve. And we have now proposed a design curve for air for austenitic stainless steels, the solid line. The current dashed line is the current code of 10^6 and the high cycle extension in the code. And the solid line curve is based on the Argonne model plus adjustment factors of 12 on life and 2 on stress. It's not 20 and 2. It's 12 and 2.

DR. WALLIS: Now the kink that you have here at 10^6 doesn't appear in the previous curve you showed.

MR. CHOPRA: The design curve extends only up to 10^6.

DR. WALLIS: So you've just extrapolated it here in your figure?

MR. CHOPRA: Yes, because now there is a need to go all the way to 10^{11}.

DR. WALLIS: But you're saying mean curve, so where do you stop at 10^6?

CHAIRMAN ARMIJO: Two different things here, hold on.

MR. FERRER: This is John Ferrer. I think originally the stainless steel curve went out to 10^6. Later, they got more data at high cycles and the data was clearly showing that there was a drop off and so they -- this is an artifact of fairing the two curves together and the new correction we're doing really is straightening out what they should have straightened out to begin with.

DR. WALLIS: Well, it's a curve, it can't be straightened out.

(Laughter.)

MR. FERRER: Fur the earlier slide was the man curve through the data. Now we are talking about the code curve which would include these factors.

DR. WALLIS: Okay.

MR. GURDAL: There is still a curve A, B and C.

My name is Robert Gurdal. I'm AREVA, Lynchburg, Virginia. Those curves is because before just now there are three curves, there is A, B and C and they are not indicated there. I just wanted to be sure everybody knows.

The reason you have the lower one which is called a curve C --

MR. CHOPRA: But the region which we are talking about is this 10^6 to 10 --

MR. GURDAL: You go above 10^6, you have a curve A, curve B and curve C.

MR. CHOPRA: I have plotted that.

MR. GURDAL: The correct curve is curve A which is the top one.

DR. WALLIS: So it's C on this figure and it's A on the previous figure.

MR. GURDAL: Maybe, it could be.

DR. WALLIS: Maybe. It probably doesn't matter that much.

MR. GURDAL: And the C is for the heat affected zone compared to the A.

DR. WALLIS: This is the A in this one.

MR. GURDAL: That one could be the A, because it does not have the kink.

MR. CHOPRA: This is the mean curve.

MR. GURDAL: Oh, that's the mean curve. Sorry about that. But the design curve, if you go to the design, there is a curve continuing without any disconnection.

DR. WALLIS: Without any king, yes. Okay.

MR. GURDAL: And that's the A. This one is a C.

MR. CHOPRA: But the region we are talking about is this.

MR. GURDAL: Okay, but the question was about 10^6.

MR. CHOPRA: Which needs to be corrected.

DR. WALLIS: Okay, we've resolved that, I think. Thank you. That's very good.

CHAIRMAN ARMIJO: Which gets to the point, your design curve treats the weld heat affected zones or the base material, everything as the same as opposed to the code.

MR. CHOPRA: Yes, I think so.

MR. FERRER: I think so. In the code, I think the previous gentleman was talking about their -- in the high cycle regime, there are three separate curves proposed by ASME that extend past the 10^6 cycles.

In our proposal we've just bounded that with one curve.

MR. CHOPRA: We also have generated design curves for carbon and low-alloy steels based on the same approach using the Argonne models and adjustment factors of 12 and 2. This is for carbon steel and next is for low alloy.

Now current code curve for these is only 10^6 and now this is the current code curve and an extension has been proposed by a subgroup, fatigue strength. This was proposed a few years back and it's still not approved by the ASME code committees. We are -- we have another approach to define extension of this curve beyond 10^6 cycle. I just wanted to give a couple of slides to show that.

What the subgroup fatigue strength proposed was extension of the curve which is based on load control data and the data extends only up to 10^6 and they use maximum effect of mean stress and they propose extension which is expressed by applied stress amplitude given in terms of life with an exponent of -.05 which means 5 percent decrease in life, in stress every decade. And since the data only extends up to 5 times 10^6, extrapolation to 10^{11} may give conservative estimates.

Another way of extending this curve would be to use the approach with Manjoine had proposed a few years back where the high-cycle fatigue is represented by elastic strain with life blots and if we use existing data which we have extending up to 10^8 cycles for these various speeds, we get a slope of -

007. Manjoine proposed -.01 and we can use this expression where the exponent is smaller and which is consistent with the data and this would be for the mean curve.

Now we take this adjusted for mean stress correction using Goodman relation which is a conservative approach and actually if we do that this exponent would be .017. So it's slightly lower than what is being proposed by the subgroup fatigue strength, but we can use this expression and that's what we have used to define that extension to the curve.

DR. WALLIS: When you make these proposals, did you negotiate something with ASME or did you just say this is what we use --

MR. CHOPRA: This has been presented to them.

DR. WALLIS: There wasn't any give and take. It was just -- you deduced this from your data?

MR. CHOPRA: I attended the subgroup fatigue strength and all our work has been presented there.

DR. WALLIS: But the proposal is essentially yours. It isn't some compromise proposal. It's your proposal.

MR. CHOPRA: This was proposed by Manjoine a few years back, so this is nothing new.

DR. WALLIS: All these green curves are Argonne curves, proposed by Argonne?

MR. CHOPRA: No, the best fit curves are what we have defined.

DR. WALLIS: Right, so they're not something which has been negotiated and agreed on or anything like that?

CHAIRMAN ARMIJO: It's certainly been discussed.

DR. WALLIS: It's been discussed. IT's been presented. ASME hasn't come around and said yes, you guys are right.

DR. SHACK: One thing to think about for the carbon and low-alloy steels, there's really in air there's no disagreement over the mean curve. The shape may shift just a smidgen, but the only real difference between this design curve and the current is they use a factor of 12 instead of 20. Then you do have the discussion over how to extend it.

The environmental effect is a --

DR. WALLIS: It's the big one.

DR. SHACK: That's the big one.

CHAIRMAN ARMIJO: In the reg. guide, does this curve really extend out to 10^{11} or does it -- is it truncated at 10^{7}, since there seem to be a big difference.

MR. CHOPRA: The proposal is up to 10^{11}.

CHAIRMAN ARMIJO: Up to 10^{11}, but compared to the ASME code for this particular steel, your curve is nonconservative.

MR. CHOPRA: Well, this is --

CHAIRMAN ARMIJO: You predict a much longer life.

MR. CHOPRA: This is based on the data we have.

CHAIRMAN ARMIJO: Right, but nobody has data out to 10^{11}.

MR. CHOPRA: No.

CHAIRMAN ARMIJO: It's a less conservative --

DR. WALLIS: You have a C. You have a constant C or --

CHAIRMAN ARMIJO: Right.

DR. WALLIS: I'm surprised it isn't completely flat to a green curve.

MR. CHOPRA: Made up of two. I mentioned that extension is a different slope.

DR. WALLIS: Do they ever have 10^{11} cycles in a nuclear environment?

MR. FERRER: Vibration --

DR. WALLIS: Shaking things that shake.

MR. CHOPRA: So the method to apply the correction would be to use for carbon low-alloy steel you can use either the current code design curves or the curves I've mentioned to reduce some conservatism.

As you see, it's -- they're based on adjustment factors of 12, rather than 20.

For austenitic stainless steels and nickel alloys, we use a new design curve for austenitic stainless steels. And in the appendix to NUREG, there are certain examples given to determine some of the parameters.

For example, lab data shows quite often people don't know how to calculate, how to define the strain rates. Lab data shows average strain rate always is a conservative approach.

And similarly, if we have a well-defined linear transient temperature change, that can be represented by average temperature and it could be okay.

Now this one shows two more slides and I'll be done. There was a question that lab data does not represent the feed. There are certain reports where some operating reports where some operating experience and component test results have been published.

This is EPRI report, 1997, and gives a complete chapter, a couple of them, giving examples of corrosion fatigue effects on nuclear power plant components.

Similarly, studies in Germany, MPA and other places have shown the conditions which lead to what they call strain-induced corrosion cracking. This was demonstrated for BWR environments. And there are examples, even these examples are component test results. We support the lab data.

I want to just show the results of one particular test, component test, recent tests, again, sponsored by EPRI where they used tube u-bend tests tested in PWR water at 240. And I'm just plotting the results for a given strain amplitude what was the fatigue life they measured.

In earth environment, these are the triangles. So that serves as a baseline you would expect in air. Then they tested in PWR water in two conditions: a strain rate of .01 percent per second and diamonds are .005 percent per second. And this would give me for this strain amplitude a life in air of 12,500. This is about 36,000. This is 1700. And you can determine for a component test what is the environmental factor.

In this test, inert environment cracks were on the OD. And they were biaxial conditions. And the water, they were on the ID. And nearly uniaxial. So since there was a conversion, there's a question whether this number is accurate.

There's another way we can determine the baseline life. They have a very well-defined strain rate effect between these two. I applauded the component test results with the lab data, exactly the same slope and we know somewhere there's a threshold. That would be the life in air. So I've got a number 8,000; 12,000. I use an average of 10. Gives me a reduction of 5.8 for one strain rate; 2.8.

And the F_{en} we have presented, give you 5.5 and 3.6. Ii think these are very reasonable comparisons from a real component test.

MR. BANERJEE: So the test was done outside the reactor, right?

MR. CHOPRA: This is a component test, where they took an actual u-bend tube and strained it. So it's not a small specimen. They are testing a real component -- it demonstrates that lab data is applicable to actual component test conditions.

CHAIRMAN ARMIJO: Did you compare any of the other component tests that you referenced in the previous slide with your data to see how your data predicts?

MR. CHOPRA: Some of the earlier, no, we have not.

MR. BANERJEE: Do you have any idea of the -- is there anything which happened in a reactor where you have the strain history or something for a period of time?

MR. FERRER: I think the answer to that is it's very difficult to have the exact data on the strain history in an actual operating event. We've tried to estimate it and the best you can do is estimate it. I think Omesh presented some references. I think the EPRI one which attributed some of the cracking to environment, but you couldn't prove it absolutely because you just don't have the exact temperature measurements and the strain measurements at the location of your cracks.

MR. BANERJEE: But you can estimate them, right? Based on those estimates, what does it look like?

MR. FERRER: If you go back to the

reference EPRI report, you know, I think based on their estimates they attribute some of it to environmental, but I say those estimates are very crude. They're not nearly as controlled as the lab data and if you look at fatigue, the -- at the low cycle end, the small change in stress gives you a fairly large change in the number of cycles if you look at the shape of the curve.

And so it's not that easy. There are some estimates, but they're more judgmental than accurate calculations.

MR. BANERJEE: But the evidence or supports -- what you're saying --

MR. FERRER: Well, there's some evidence. What you'll hear from -- probably from ASME is the overall operating experience doesn't show that there's a big problem there.

MR. BANERJEE: Okay.

CHAIRMAN ARMIJO: Okay. That's it?

MR. CHOPRA: Yes.

CHAIRMAN ARMIJO: Any other questions from the Committee?

MR. GONZALEZ: I would like to go back to the reg. guide to present a summary of the three regulatory positions.

Regulation position 1, we are endorsing that we will calculate fatigue using air with ASME code analysis procedures plus use the ASME code air curves for new ANL modern air curves. This is for carbon and alloy steels only.

Then we will calculate the F_{en} using the appendix A of the NUREG for carbon and alloy steels and this will be applied to calculate the environmental uses factor.

But we're given the option of using the ASME curve or the new air curve from the ANL model. Or austenitic stainless steel, we will calculate the fatigue use factoring there with the ASME code analysis procedure, plus the new ANL model air stainless steel curve.

We'll use the -- also the F_{en} equation for stainless steel and then calculate the environmental usage factor.

For nickel chrome alloys, will be Alloy 600, 690. You will use again the ASME code analysis procedure plus the new ANL model air stainless steel curve. As the reason was it was explained before was because of the new data.

And if the F_{en} specifically for nickel alloys and calculate the usage factor -- the environmental fatigue usage factor.

In summary, Reg. Guide 1.207 will endorse the use of a new air curve for austenitic stainless steels and also will endorse the F_{en} methodology. It will give guidance on incorporating the environmental correction factor, the fatigue design analysis and this is described in Appendix A of the NUREG report and also the NUREG report will describe in detail the technical basis.

That's it. Any more questions?

CHAIRMAN ARMIJO: Okay, any questions? We're scheduled for a break about now, but we're a little bit ahead of schedule. I don't know if we can reconvene in 15 minutes or do we have to wait until 3:35?

We'll just take a 15-minute break. Be back at 3:25. Is that right? 3:25, thank you.

(Off the record.)

CHAIRMAN ARMIJO: Okay, we've got -- incredibly we're about five minutes ahead of schedule, so that's good.

So Mr. Gonzalez, would you like to continue?

MR. GONZALEZ: This is our second part, second presentation. It's in the resolution to public