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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

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UNITED STATES OF AMERICA

NUCLEAR REGULATORY COMMISSION

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

(ACRS)

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SUBCOMMITTEE ON ESBWR

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OPEN SESSION

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TUESDAY

JULY 13, 2010

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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 2:35 p.m., Michael L. Corradini, Chairman, presiding.

PRESENT:

MICHAEL L. CORRADINI, Chairman

J. SAM ARMIJO, Member

SAID ABDEL-KHALIK, Member

SANJOY BANERJEE, Member

DANA A. POWERS, Member

PRESENT: (continued)

MICHAEL T. RYAN, Member

JOHN D. SIEBER, Member

JOHN W. STETKAR, Member

CONSULTANTS TO THE SUBCOMMITTEE:

THOMAS S. KRESS, Consultant

GRAHAM B. WALLIS, Consultant

NRC STAFF:

CHRISTOPHER BROWN, Designated Federal Official

AMY CUBBAGE

JOHN McKIRGAN

LESLIE PERKINS

HANRY WAGAGE

JOSEPH SHEPHERD

TUAN LE

MANOMOHAN SUBUDHI

SAMIR CHAKRABARTI

MANUEL MIRANDA

ALSO PRESENT:

WAYNE MARQUINO

RICK WACHOWIAK

JERRY DEAVER

JOHN GELS

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P R O C E E D I N G S

Time: 2:35 p.m.

CHAIRMAN CORRADINI: We are back in session. Hanry, are you going to lead us? Oh, I am sorry, Leslie. I am sorry. Excuse me.

MS. PERKINS: Yes. My name is Leslie Perkins. I am the PM for Chapter 6, ESBWR, and this afternoon the staff is going to discuss the hydrogen accumulation in the PCCS, which is RAI 6.2-202. This presentation starts on Slide 11 in your packet.

Staff that are presenting are Hanry Wagage, Tuan Le and Samir Chakrabarti, and we have also Joe Shepherd from Caltech. So at this time, I will turn it over to Hanry.

MR. WAGAGE: Hi. My name is Hanry Wagage. Dr. Joe Shepherd and I will be presenting PCCS function, design and detonation pressure loading. Other two presenters will be discussing structure analyses for PCCS and containment.

ACRS raised concern on the possibility of hydrogen accumulation in PCCS at the November 2009 meeting. The staff expanded the issue to ICS. Staff has not received submittal on the response to the RAI in terms of for ICS. We heard from GE, but we have to receive the response and evaluate. We are not ready to discuss the evaluation on ICS, because we haven't received the response.

CHAIRMAN CORRADINI: So that will be taken up at a later time. She hasn't objected to my inference. So I guess we are okay.

MS. CUBBAGE: Yes. We can take that up at a later time.

MR. WAGAGE: MELCOR results showed the hydrogen and oxygen mole fractions, 48 percent, and then for 24 percent in PCCS lower drum at 8 hours after LOCA. At these high concentrations of hydrogen, they really maybe needed for PCCS --

CONSULTANT WALLIS: What does that mean? What does minimal energy mean? Does it mean the energy of a baseball or a cosmic ray or what? That is a lot. That is much more than you get from radioactive decay.

DR. SHEPHERD: A few millijoules. In the world if ignition, that is a pretty small number.

CONSULTANT WALLIS: Just got to excite a few molecules.

DR. SHEPHERD: More than that, yes.

CONSULTANT WALLIS: Can radioactive decay do that. You got to have something more significant than what is already there, and still there is a wet atmosphere. Everything is wet.

DR. SHEPHERD: So do you mean wet by having a liquid film or steam?

CONSULTANT WALLIS: Everything is covered with water in this thing.

DR. SHEPHERD: So it depends. Depends on where your ignition source is.

CONSULTANT WALLIS: Is there any?

DR. SHEPHERD: That is a good question.

MR. McKIRGAN: If I may, I believe from the staff's perspective and also from GE, this is one of the points that we are actually in agreement on in that we cannot preclude a detonation, and so we are proceeding under the assumption --

CONSULTANT WALLIS: That there could be one.

MR. McKIRGAN: -- that there would be an ignition.

CONSULTANT WALLIS: But minimal energy doesn't mean anything, does it, and you got to get more specific.

MR. McKIRGAN: I think the only point there is that we are going to assume --

CONSULTANT WALLIS: It's kind of small, but you might as well be zero. Right? Okay.

MEMBER POWERS: Actually, this is one case where there is a minimum. There is a minimum in the ignition energy at the stoichiometric composition.

DR. SHEPHERD: Yes, the minimum ignition energy is usually defined in terms of electrical discharge. You don't have to have an electrical source for the ignition, and as you vary the stoichiometry, as Dana indicated, your stoichiometric or slightly rich is usually a minimum. Then as you go to the rich and the lean size increases. So you use very typical, sort of U-shaped curve. Then if you do something like add steam, it goes up from there.

CONSULTANT WALLIS: It is energy per unit volume or something.

DR. SHEPHERD: Well, it is an interesting thing. The way that it has been characterized over the years in the explosions hazards business is, in fact, in terms of energy. We recently have been looking at this, and we believe it is a linear spark. It is more energy per length, but you are right. It is to say that it is energy per unit volume, because it is really the temperature you have, because also a characteristic size that you need. It is not just temperature --

CONSULTANT WALLIS: Because if it is

losing energy -- You know, it is like lighting a fire. It is big enough so that it produces more heat than is being lost. So it will grow.

DR. SHEPHERD; Yes, exactly. So there is some criteria connected with that.

MR. WAGAGE: ACRS raised a concern on -- Regulated criteria applicable to this issue are 10 CFR 5457(b)(5) and GDC 38 and 50.

Staff issued RAI to 6.2-202 on December 11, 2009. After that, we had several public meetings and issued a Supplemental RAI to address other issues that came up.

GEH submitted NEDE-33572P Revision 1 to provide technical details. As a result of this RAI, GEH changed their PCCS design basis to perform its safety function after multiple hydrogen detonations.

Before we go through the details of our presentation, we would like to bring to the Committee the status of this one, the status of this resolution is ongoing. However, we resolved certain issues. There are certain open issues. I would like to list those issues right at the beginning.

We have resolved issue on hydrogen concentrations. GEH, they are using the maximum possible hydrogen concentration and stoichiometric ratio of hydrogen and oxygen in the condenser. That is conservative.

CONSULTANT WALLIS: Actually, it is not a maximum. If you had 100 percent hydrogen, you wouldn't have a problem, would you? It's a stoichiometric thing.

MR. WAGAGE: That is right. That is right.

CONSULTANT WALLIS: You really should say that.

MR. WAGAGE: I had that later, stoichiometric issue.

Detonation pressure loading in PCCS. GEH calculated detonation pressure loading on tubes. Staff calculations confirmed those numbers.

Case by case evaluation using ASME Section III Class MC components is recalled. Loading combination to include detonation plus all other applicable loads for NUREG-800 SRP 3.8.2. Next one.

Open issues on this are: Detonation pressure loading in PCCS lower drum and then in vent lines. Dr. Shepherd is going to talk more about detonation pressure on lower drum, and drain and vent lines, you see the LTR. You see that pressure loading on drain and vent lines are 407 megapascals.

GEH concern at that time was that the vent line was prevented from detonation by having catalyst at the entrance of the vent line. Then staff raised a concern that, although this prevented formed detonation, however, in the business of closing in the lower drum, that how you close, the mixture would expand to the vent line, and the vent line pressure has to be higher than the 407 megapascals. So we chose the highest peak LOCA pressure.

MEMBER ABDEL-KHALIK: Can you repeat that number, please?

MR. WAGAGE: 407, and you see that --

MEMBER ABDEL-KHALIK: 407 what, though? That is where we didn't --

MR. WAGAGE: 407 megapascals.

MEMBER ABDEL-KHALIK: Megapascals or kilopascals.

MR. WAGAGE: No, kilopascals, kilopascals.

CHAIRMAN CORRADINI: Good. Good. I was guessing we were off by 1,000. I just wanted to make sure.

MR. WAGAGE: That is the highest pressure experienced by the -- That is in the LTR. We pointed to GEH that, when the explosion occurs in the drum, the explosion mixture expands through the vent line.

The vent line will go to pressures higher than that 407 kilopascals.

CONSULTANT WALLIS: The force of this is a delta P anyway. It is the same inside as outside.

MR. WAGAGE: I will tell you the outside is --

CONSULTANT WALLIS: Four hundred and seven, isn't it? It's the same thing, much the same. There is no delta P from 407.

MR. WAGAGE: That is right.

CONSULTANT WALLIS: It is the 38.7 that we are asking them to use?

MR. WAGAGE: The point was that it cannot be the LOCA pressure.

CONSULTANT WALLIS: Are you asking them to use the same pressure as in the drum? I thought that was the resolution of it.

MR. WAGAGE: If they would pick a pressure the same as the drum, that wouldn't be an issue. Resolution is that we haven't seen the response yet. I mean, we pointed to GEH that 407 kilopascals should not be the correct level.

Ignition effects on -- The second one was that drain lines -- Originally, GEH pointed to that, asked that drain lines would contain water. Because they contain water, they is less likelihood that hydrogen would be there, and there will be no distinction. That is why that in the staff response -- in the NTR GEH is proposing 407 kilopascals pressure for the drain line.

Staff pointed to GEH that it is possible that there may be some -- the drain is not flowing full. There will be hydrogen and oxygen that could detonate, and GEH has corrected that.

There is an open issue on modification for lower drum covers and drain nozzles to account for high stresses. Detonation effects on PCCS components not directly exposed to detonation, for example, in anchorage, support frame, and pool --

CONSULTANT WALLIS: Does that include the fans?

MR. WAGAGE: Fans? It should. Fans, that should be the higher pressure, because originally that drain lines, that GEH assumed drain lines do not see higher pressures, but right now, because of that high explosive mixture expanding to the drain lines, fans also have to be qualified for that.

Fatigue evaluation for multiple detonations have been resolved, and as we discussed before, design of ICS is an open issue.

Because of the changes in PCCS design, the thickness of the tubes were increased, and that releases the heat transfer, and new method, it has lower thermal conductivity than the previous material. That increases the heat resistance to heat transfer.

CONSULTANT WALLIS: May I ask you something? What are the effects of this bang on the operators? Do the operators hear a loud bang when this thing happens? Do they hear nothing? Do they have a sensor that tells them there has been an explosion in the PCCS? How do they know what is going on?

MR. WAGAGE: Does GEH have answers?

MR. WACHOWIAK: Yeah, this is Rick Wachowiak from GE.

In the ICS it is easier to tell, and I know we are not talking about that yet, because we have indication of pressure and temperature in that heat exchanger. In the PCCS we would have to infer it from other pressures in the other areas of containment.

There will be a fluctuation, slight fluctuation, in the drywell pressure and possibly you would be able to see a signature in the wetwell as gases are pushed through there, but maybe not quite so much there.

It won't be as easy to tell this, because that was one of the things that we wanted to make sure, is that the detonation in the PCCS did not affect the drywell pressure significantly so that we would have an issue with that part of the boundary.

So it is a good question that -- We did not need to answer that question to address the design basis of that. So --

CONSULTANT WALLIS: You don't think they will hear anything? Will they hear something, too?

MR. WACHOWIAK: It is under water.

CONSULTANT WALLIS: It will be too far away.

MR. WACHOWIAK: Too far away in a different part of the building. I just don't know. But you are probably not the last one that is going to ask that question. So I am guessing that something will happen over time to determine what is that signature or what is going to tell the operators that that has happened. But to do the safety evaluation, you don't need that piece of information.

MEMBER POWERS: What I know is that in the hydrogen combustion event at TMI, people heard a sound that they described as a bang, and people now conclude that, in fact, it was water hammer when the sprays were ignited, and they did not hear the deflagration at TMI. No sound would have transmitted out.

CONSULTANT WALLIS: That was a relatively mild burn, wasn't it?

MEMBER POWERS: Yes. About an eight percent burn. It actually was you would kind of expect for large dry containments to be kind of routine. It definitely did not have a shock wave associated with it.

CONSULTANT WALLIS: It is a good thing.

MR. WAGAGE: The next open item we have on this is accounting for thermal effect generated by detonation in the design. In the structural areas, GEH has used that temporary --

CONSULTANT WALLIS: What is the detonation on the design? A mistake in English somehow? Design blow up?

MR. WAGAGE: Thermal in the design.

MEMBER ABDEL-KHALIK: You mean energy added.

MR. WAGAGE: In designing the PCCS, GEH had to consider the higher temperature generated by the explosion. That is the point.

MEMBER ABDEL-KHALIK: If you go back one

slide, Slide 15, if they are predicting at most consecutive detonations, why do they have to do the fatigue evaluation?

MR. WAGAGE: Scott, do you want to answer that? Mano, you want to expand on that?

MEMBER ABDEL-KHALIK: If you are going to get to it later, we can wait until you present that.

MR. WAGAGE: Because the fatigue evaluation was to -- Ask Mano, and I think he can explain on that.

The question raised was that the GEH is considering -- a number of detonations. After considering that many number of detonations, why does the design have to consider fatigue evaluation. That is the question.

MR. SUBUDHI: My name is Manomohan Subudhi from Brookhaven National Lab. According to ASME criteria, we do want a fatigue analysis for class level A and B, but we do sometimes ask to use with SSE, which is not a subject level A and B, to be included.

This particular -- there is no precedence. That is, we don't know how to deal with it, but we wanted to see, because this PCCS is required to remain functional for this sort of severe accidents. So we want that it doesn't leak enough to violate the 10 CFR Part 100 requirements.

So from that point of view, we wanted to see how much damage, how much fatigue life it is taking away by calculating at least the alternating stress and material property to see that how many cycles we can survive. If it is going to fail due to fatigue only, due to detonation, then we have no life left for the severe accidents.

CHAIRMAN CORRADINI: But is your -- Okay, but I assume it is your expectation that it will -- You are not expecting to see a fatigue?

MR. SUBUDHI: No. We are not expecting any fatigue calculations or anything. We want to see that how much fatigue life it is eating away.

CHAIRMAN CORRADINI: Okay. Thank you.

MR. WAGAGE: As a result of this RAI, GEH made several design changes to PCCS. For the tubing, GEH changed the material to XM-19 and increased the tube thickness, increased number of tubes per module.

For the drum, GEH increased thickness of the drum and changed the material to XM-19, added catalyst, platinum or palladium coated plates, to the vent in the lower drum of the condenser.

On the next slide, this has more about our evaluation of the catalyst. Impact of potential performance inhibitors, example, aerosols and condensate, etcetera.

There is little potential for poisons and inhibitors other than steam is expected during design basis accident, because the core is not going to be uncovered. There is little possibility of most of the poisons other than steam and some droplets of water.

Design of the vent entrance limits water droplets getting into the catalyst, and --

CONSULTANT WALLIS: Is this a qualitative statement or do you know how much water is tolerable, and do you know how much water will actually be carried in?

MR. WAGAGE: This is a qualitative statement. Because of the design, and there is some little water can get in. Even if some water gets in, droplets get in that recombine when it is -- settle on the recombiner, it evaporates. CONSULTANT WALLIS: If the recombiner has initiated recombination, whatever. It can't ignite. It can't stop. Then there is a difference problem.

MR. WAGAGE: If it is completely soaked with water, that may be the possibility, but at the beginning there is a high steam flow and noncondensable flow through that.

CONSULTANT WALLIS: So what? There is no incentive to dry it if it got water on it, because it is still saturated.

MR. WAGAGE: But the --

CONSULTANT WALLIS: The drying effect of saturated steam.

MR. WAGAGE: I think, because of the flow, so water would be carried away from the plates. If it exposes in certain areas, needing to start the recombination and heat the plates.

CONSULTANT WALLIS: Now there is a transition from that state to the state where there is no nitrogen. There is still steam there, and then there is more of the oxygen and hydrogen. There is a transition period.

I think you can't get away with just qualitative statements. There has to be some convincing demonstration that it will start recombining. You can't just say publicly the water will be blown off or something. It has to be something better than that.

MEMBER ARMIJO: I think there is. I think the very fact that in operating BWRs today people put in noble metal chemical additions, and they effectively are recombiners right in the core and cooling system, and they work. They drop the electrochemical potential dramatically and protect the stainless steel.

So if it works under water at full power, I think a recombiner in the steam phase would fire up just fine. In fact, I would rather put the catalyst in the core --

CONSULTANT WALLIS: If it is in the core, then you've got dissolved oxygen and hydrogen.

MEMBER ARMIJO: You've got dissolved oxygen and hydrogen.

CONSULTANT WALLIS: Here, you've got the oxygen and hydrogen in the vapor phase.

MEMBER ARMIJO: And there may be a time delay in dissolving it and getting it to the catalyst, but I think it will get there.

CONSULTANT WALLIS: Well, at least --

MEMBER ARMIJO: They are going to do the test, that qualification. They are going to do the test. They have to do the qualification test. I am just guessing that that would work.

CHAIRMAN CORRADINI: But I guess the one thing, though, that I want to make sure you -- at least my interpretation of what you were saying, which is the evolution of the gases coming out will be nitrogen and steam, then steam and hotter and hotter steam passing through -- right? -- because everything is rising in pressure and, therefore, the -- and I am going to continually get out some small amounts going through the vent line.

So whatever I might have in initial water, I don't think I would have --

CONSULTANT WALLIS: It is not hotter steam, because the steam temperature is governed by the temperature at the bottom of the condenser, which is the temperature of the pool.

CHAIRMAN CORRADINI: Right, but everything is rising, though. Everything is rising in pressure. So everything is going to have to rise in its appropriate temperature.

CONSULTANT WALLIS: Then there is deposition of water going on all the time.

CHAIRMAN CORRADINI: But if I understand the design -- Again, it is just I think what I was interpreting their answer to you was that they expect it to dry up, be in a saturated environment but dry, not covered in water for this reason. Am I understanding your logic?

MR. WAGAGE: Yes, I think that, because of the flow, it is going to carry away some water. It is going to expose certain areas of the catalyst, and once it exposes the areas, some areas of the catalyst, it is going to start recombining. There is flow of hydrogen and oxygen, when that then recombiner moves heat up and evaporates the water.

CONSULTANT WALLIS: That is a supposition. Speculation.

MR. WAGAGE: Yes, speculation.

CHAIRMAN CORRADINI: Judgment

CONSULTANT WALLIS: A hope.

MR. WAGAGE: EPRI evaluations showed functionality under and beyond design basis conditions. Flow channels of PCCS catalyst are equal or larger than EPRI prototypical design.

Now for this application of catalyst warm-up, catalyst warm-up is unimportant because of other designs, and the catalyst is placed in the containment. It takes some time for the flow through the catalyst, but in this case hydrogen and oxygen flow through the catalyst. There is not significant timing or warm-up.

At peak recombination flux, GEH should confirm the recombiner temperature will be below the auto-ignition limit, the reasoning that the temperature goes significantly higher, about 560 degrees Centigrade, to ignite and start the ignition in the drum.

GEH should confirm ESBWR-specific calculations to assess impact of various catalyst design parameters on gas mixture entering the vent line under design basis conditions to demonstrate module effectiveness.

GEH should address impact of detonations on structural integrity of the catalyst module, because this catalyst module has to survive detonations occurring in the drum.

CHAIRMAN CORRADINI: Let me make sure I understand these last few bullets. "Should confirm," "should perform," "should address" -- does this mean this is going to be part of a qualification test? I am trying to understand -- Well, maybe I should ask the question this way.

Do you view that their design of the catalyst has closed this open item or are you still in discussion to close it, and these are things they are going to do shortly or in some qualification test?

That is what I don't understand.

MR. WAGAGE: Some qualification, some GEH has to address, because this is ongoing issue. We have -- Right now we don't have information to complete this.

CHAIRMAN CORRADINI: Okay. So it is still an ongoing open issue.

MR. WAGAGE: Ongoing open issue.

CHAIRMAN CORRADINI: Okay.

MEMBER ABDEL-KHALIK: So I am trying to understand the second bullet. If it is higher than this limit, are you concerned that the loads may actually be higher than what they used in their analyses?

MR. WAGAGE: No.

MEMBER ABDEL-KHALIK: So what is the concern here?

CONSULTANT WALLIS: Because you are assuming ignition anyway.

MEMBER ABDEL-KHALIK: Right. I am just trying to figure out what is the concern here vis a vis the analyses that they had already presented.

MEMBER ARMIJO: Is it about catalyst performance or is it about actually burning more?

MR. WAGAGE: It is because -- That is, it is not the calculated value should be bounding, that this is the initiation of ignition.

CHAIRMAN CORRADINI: But, Hanry, I guess

where we are confused is: Is this about the performance of the catalyst and it being damaged or is this about creating another burn out of the sequence of N burns?

MR. WAGAGE: Actually, GEH report this for two reasons. One is that it can start initiate ignition in the drum, and --

MEMBER ABDEL-KHALIK: They have already assumed that.

MR. WAGAGE: That is right. It should be covered by -- That is not an important issue. But, however, this temperature has to be considered, because the testing done for these catalysts were for hydrogen and air mixtures. Now we have hydrogen and oxygen mixture, which may rise to significantly higher temperature. That may affect the catalyst's effectiveness. That may affect the integrity of the catalyst. Because of that, that temperature issue has to be resolved. What temperature will it go?

It has to be resolved for the purpose of confirming that catalyst would stay intact, because the tests were done for hydrogen and air. This application is for hydrogen and oxygen.

MEMBER ABDEL-KHALIK: I am just still trying to figure out what the concern is with regard to 560 degrees C. Is it the auto-ignition and, therefore, the loading that would result from that and whether that loading is different than what they had assumed, or is it the survivability of the catalyst between successive detonations?

MR. WAGAGE: Five hundred sixty degree report because starting detonation in the drum. However, that would not apply. The question is that, when the temperature rises, it has to be -- the 560 degrees would not matter. What temperature would the catalyst go?

CHAIRMAN CORRADINI: So you are worried about -- Said, let me give you what -- Is it the operability of the catalyst or is it the temperature the catalyst will have in inducing additional burns or combustion events? Which one of those are you worried about? That is what I think we are still unclear about.

MR. WAGAGE: We are worried about the second one mostly.

MEMBER ABDEL-KHALIK: Auto-ignition, and the question then is: Isn't that bounded by whatever loading calculations they have assumed?

MR. WAGAGE: But the ignition would not be an issue. The loading combination would bound it.

MEMBER ABDEL-KHALIK: Okay. Thanks.

CHAIRMAN CORRADINI: We are just making sure. Okay.

MEMBER POWERS: One of the issues that I have always wondered about these catalysts, if they get very hot on the surface, do you lose surface area?

CHAIRMAN CORRADINI: You evaporate some of the stuff off. Oh, you burn it off?

MEMBER POWERS: If it is operating at these temperatures for a couple of hours -- The only reason it works is it is a very high surface, the volume ratio and material is at center, and you lose surface area.

MR. McKIRGAN: Hanry, is it fair to say that the staff hasn't evaluated that, and the review is ongoing, and we will take that feedback from the Committee?

CONSULTANT WALLIS: So if it is centered, what happens when it gets wet? Does the water go into the center and fill up the pools?

CHAIRMAN CORRADINI: You enjoy to talk about water, don't you?

MEMBER POWERS: At this temperature, you don't need to worry about water.

CONSULTANT WALLIS: If you get up to that temperature.

MEMBER POWERS: I will not worry about water at all.

CHAIRMAN CORRADINI: Keep on going.

MR. WAGAGE: These figures are the schematic of PCCS. Top drum and intake lines were not designed for ignition, because the reason is that, when steam -- steam comes from the top. That could have -- The top intake line and top drums would have less concentration of hydrogen --

Thee issues to be resolved in PCCS design are: PCCS heat transfer capacity should be sufficient for containment long-term cooling, because there are changes, because of the material change, the thermal conductivity reduced, and because of that, heat transfer could go lower. To compensate that, GEH increased the number of tubes. Overall effect has to be evaluated with calculations to how it would affect the heat transfer capability of the PCCS.

As I said, staff raised the issue with the vent and drain lines designs.

pressure loading on the lower drum should include deflagration to detonation transition, (DDT).

With that, the Committee doesn't have more questions, I will transfer presentation to Dr.

Shepherd.

DR. SHEPHERD: Thank you, Hanry. So what I would like to do is to go through some discussion about what is being done here in the analysis and, hopefully, as part of that I can answer some of the questions that were raised earlier about the role of different codes, dynamic load factors and so forth.

So the GEH methodology is to use something that is often done in simplified engineering design for explosions, and that is to define an equivalent static pressure, and that equivalent static pressure is designed to accommodate in some conservative way the actual loading that would be experienced in the explosion and the dynamic response.

It does not include all of the details of the vibration, wave propagation in the structure, all of the possible range of things that can happen.

On the other hand, it is found to be a good tool for safety analysis and for design where you have a certain amount of conservatism involved, sufficient conservatism so you can accommodate other things.

You do need to go off and look at various issues; for example, more limitations in connection with vibrations and wave propagation, wave interference.

If you do a static analysis, you obviously don't have any dynamics whatsoever. So they are neglecting reaction forces that can be created. A wave propagates down to the end of the steam drum and reflects and produces a loading that causes them to be set into motion. That is something that would have to analyzed separately.

Finally, you are thinking of the loading itself as being averaged out in some way. There are some exceptional cases where you can have transition to detonation happening close to the closed end of the structure, and that can create responses that are higher than you would ordinarily experience.

So the ANSYS analysis is being done. That is using this approach of an equivalent static pressure based on some simple ideas about what kind of loading you would expect from an idealized loading, explosion detonation wave, and selecting a dynamic load factor based on some considerations of structural response.

This technique has also been validated by work that has been done, and I have cited my laboratory here, but there are many other laboratories around the world that have done this work. So on the next slide --

CONSULTANT WALLIS: Can I ask you about that? It says here detonations in tubes. If you have got a simple geometry, I can understand how you could do this, but when you have a more complicated one, there must be locations where it is a little iffy to do this.

DR. SHEPHERD: Well, it is. In fact, if you have a complex vessel that has a lot of flanges and nozzles and so forth on it, you have to think very carefully about that.

One of the things that the ASME has done is they have put together a working group on impulsively loaded vessels. That is being headed up by Bob Nichol. They are going to be meeting next month. They have been doing so for the last five or six years, and they have created, actually, a code case to deal with that.

In that case, it is necessary to do a fairly complete job of a dynamic analysis. That is, you want to do a calculation with ANSYS, not in the static mode, but you can run ANSYS in a dynamic mode. You don't necessarily have to model the wave propagation within the material, but you should model the structural motions in sufficient civility so that you get all of the stress risers and flexural motion that would be associated with those features.

So that is something that to think about here. And now what I would point out is that the effort that GEH is making with LS-DYNA is designed to look at some of those issues. I have not gone through that calculation in detail. I can't say how much of those issues they are going to be looking at.

LS-DYNA is certainly an appropriate tool for doing dynamic analysis. As always with any kind of computer simulation, it depends on what you feed into it is what you are going to get out. t. Okay? Anything else about that?

CONSULTANT WALLIS: Well, the question is, is this good enough?

DR. SHEPHERD: So good enough can be defined in various ways. It depends on what your metric is going to be. What I always like to see is some kind of comparison with experimental measurements or very high fidelity calculations for structures that have all the features you are interested in.

Obviously, we are not going to go off and build a PCCS system. We are not talking about that. If the time dependent finite elements simulations have enough fidelity, I believe that that can be used to provide a standard against which we can judge whether or not the static analysis is good enough.

The individual components we do have a lot of experience with and looking at the loading on individual pieces of tubing. That is something that I have a great deal of confidence in, and I believe this method is good enough.

MEMBER ABDEL-KHALIK: How would you get the boundary conditions for the transient analysis?

DR. SHEPHERD: I will talk about that in the upcoming slides.

MEMBER ABDEL-KHALIK: Okay.

DR. SHEPHERD: Let's just talk about detonations in straight pipes for a minute. So a detonation wave is a traveling load. So that is one of the things that makes this different than even other dynamic analyses.

Because the load is traveling, it can excite a number of different loads. On the little cartoon down here in the lower righthand side you can see a schematic that shows running out in front of the detonation wave, which might be moving at two to three thousand meters a second, are some waves in the pipe.

There is a longitudinal wave that is going to be moving at 5,000 meters a second, a sure wave at, say, 3,000. But the bulk of the disturbance we find in this case is a flexural wave. That is, it is a motion of the tube wall, and all the material in the tube wall is moving simultaneously and essentially axisymmetric, if the wave is plainer. That where almost all the energy is concentrated in.

So that is what you will pick up if you put strain gauges on this tube or, if you measure the deflections, you will see that when the detonation runs by, it sets the wave into motion -- sets the wall into motion, excuse me, of the pipe.

What the pipe will do, it will sit there and ring, and it rings at a frequency which is basically the frequency you would have if you just cut out a piece of material and calculated what the ringing frequency was as a single degree of system.

CONSULTANT WALLIS: What happens when the wave reflects off the end of the pipe?

DR. SHEPHERD: I am going to talk about that next.

So what is going to happen is you are going to create a shock wave, because you have got to bring all that flow to rest that is traveling behind the detonation wave, and then that shock wave will run back in the other direction. The pressure is going to go up to a higher value, and then decay. So that is what you are going to see.

That actually is -- If you are looking for a bounding case and you have a detonation in a closed-in tube, that is where you want to look. You will find out the loads are always the highest at the end of the tube.

CONSULTANT WALLIS: This doesn't account for a compression of the gas ahead of the wave.

DR. SHEPHERD: So this is a -- So that is what happens in DDT. What I am talking about here is a very idealized situation where you start the detonation wave right away, and there is not any significant period of compression. So we just have a supersonic disturbance.

So the case that you have mentioned is very important for accidents, and I will come onto that next.

CONSULTANT WALLIS: That is what happens in automobiles.

DR. SHEPHERD: Something like that happens in automobiles. It is sort of a knock phenomenon. So modern vehicles, you don't hear that very much, because they have got computers that keep that from happening, but you and I can remember when automobiles used to do that all the time. My old motorcycles do that. They get the timing wrong.

MEMBER BANERJEE: What happens if there is an area change? Is there an exception?

DR. SHEPHERD: Yes, anytime you have an area change, basically the detonation wave is really a shock wave followed by a thin zone of chemical reaction. So that shock wave is going to have to defract through that area change. If it gets bigger, you will make some expansion waves. It will slow down for a minute and then pick up again.

It is a self-propagating wave. It likes to travel at a speed, this Chapman-Jouguet velocity, which you can calculate by conserving maximal energy across the wave. It turns out that that is the slowest speed this thing can travel at, consistent with the conservation laws.

If you go through a constriction, what will happen is you will generate some compression waves, and it will momentarily speed up, and then it will slow back down to this speed.

So it wants to travel, if it has got a very thin reaction zone, at this idealized speed, but it will interact with any geometrical disturbances, produce expansions and compressions. You will have some gas dynamics that go along.

MEMBER BANERJEE: So turbulence does not have an effect on this, or does it?

DR. SHEPHERD: Turbulence has a very strong effect on the initiation of the explosion and the acceleration of a point in the detonation. It is absolutely crucial.

Once the detonation gets propagating, what is much more important is it is a balance between compressibility and chemical reaction. So this is a pretty high speed wave.

This wave is traveling at two to three thousand meters a second, as I said, which if you think about it in terms of mach number, could be -- For example, the sound speed in these hydrogen-oxygen mixtures is probably on the order of about 450 meters a second or something like that.

So this is about a mach-5 to mach-7 wave. So that is a -- Compressibility effects really dominate.

MEMBER BANERJEE: The ignition is going on in that cone behind it somehow.

DR. SHEPHERD: Well, what happens is the -- You can basically think of it as it is adiabatic compression. The shock waves comes along, adiabatically shock heats the stuff up to a temperature where now it starts to react, and then very quickly that reaction goes to completion behind it.

Now the wave is unstable, and there is little wavelets running back and forth on there, but in these kinds of mixtures, that instability doesn't play a big role. It is pretty close to an ideal wave, and that sort of classical one-dimensional analysis works pretty well.

So it is basically a chemical reaction that is created by this shock compression getting into high temperatures.

The coupling with the structural motion -- I just want to touch on that before I go to the next slide. When you have a wave that is a propagating load that is traveling through the tube like this, and it generates these flexural waves, it turns out that you can have a resonance when the group speed of these flexural waves, the flexural waves, of course, disperses.

When that is equal to the phase speed of the waves then and the energy builds up at the front and you get large amplitude, and that is what is shown as this peak here in this response of this dynamic load factor. That is the ratio of the response, say, in the strain to what we would have just with the equivalent static pressure.

That peak occurs because of this resonance. So one of the things that GEH has looked at is are we sitting at this resonance? The answer is, no, we are somewhere off to the right of that, and that means we have a dynamic load factor of about two.

Okay. So how do we calculate these Chapman-Jouguet properties, these detonation properties? Well, we can do that with thermochemistry. GE is using the CEA code.

We have a different set of tools that we use in our lab. They are all based on thermodynamics, and so they all give you the same answer if you use the right thermodynamics, and you are conserving stuff. You know, that always works for everyone all over the world, I have found.

So now what happens is, if you add steam, you are basically reducing the energy content per unit mass of the whole mixture. You think about now, if you took a kilogram of this stuff and made it 50 percent steam, it is not going to be -- This is 50 percent by volume, not by mass, but in any case, now the energy content is just through the hydrogen and oxygen.

So we have less energy. So the velocity goes down, and the pressure goes down, and we can calculate this. What you can see from the shape of these curves is that it is always bounding to assume that you don't have any steam, and it is also bounding if you assume that it is cold. It makes just a little bit of difference in this case to assume it is cold versus being at 100 degrees C.

So you go through all that, and you make your calculation.

CONSULTANT WALLIS: Your steam doesn't go down -- The steam fraction doesn't change CE to zero or whatever, Vc0.

DR. SHEPHERD: Oh, well, yes. You are starting to get down there, but I have looked at what some of --

CONSULTANT WALLIS: Far enough?

DR. SHEPHERD: You don't get far enough. You don't get far enough. So, for example, the Vc0 is for the PCCS tubes is 1540. For the drum, it would be about 2,700. So you are still a way from it.

So if I go through and calculate the numbers. I wound up with a bounding pressure of --

CONSULTANT WALLIS: This is or the

stiffened tubes, presumably, which have a --

DR. SHEPHERD: Yes. This is for the redesigned tube with a 4 millimeter wall.

I go through the calculations, and I used a factor of 2.5 times -- to account for reflection, which I will come onto next, and then a factor of 2 for the dynamic load factor. So that gives me an equivalent static pressure of 39 megapascals, which I think is comparable to what GE is assuming.

So I conclude that is the right static equivalent pressure to use.

What happens when the wave gets to the closed end? You can imagine this would be something like the drum. So the drum is about three meters long, I think, and three-quarters of a meter in diameter.

Now if we start a detonation and it runs down to the end of the drum, when it gets to the end of the drum, you've got all this fluid that is moving about halfway back behind the detonation wave.

That fluid has been set into motion, and then from halfway back to the closed end, it is not moving. So you have got a chunk of fluid that is moving. You have got to stop that. The way you stop that, with a shock wave that comes back out. When it does that out, the pressure jumps up by two and a half, and then the pressure decays, and that decay depends on the gas dynamics of the interaction of that shock wave that is running backwards with that non-steady flow field.

CONSULTANT WALLIS: Now the factor in this figure looks like more than two and a half.

DR. SHEPHERD: It is two and a half. It is 1.5 times two and a half, which would be almost four. Right?

CONSULTANT WALLIS: So it is 1.5. So I shouldn't start from the --

DR. SHEPHERD: No. No, start from the peak of the --

CONSULTANT WALLIS: Start from the red curve.

DR. SHEPHERD: -- red curve. Yes. That is right. So those are snapshots at different locations, and that is a little confusing about this picture, and I didn't give the snapshot right when it reaches the end.

So this is where the two and a half comes from. That can be calculated from thermodynamics, too. You just take the very instant in time when the wave arrives at the end, and you imagine you have a shock wave coming back. You have an infinitesimal little sliver of fluid that is at rest next to the end wall. You whip out your maximum and minimum energy conservation, and off you go.

So you can calculate that number. It turns out it is 2.4, but -- you know, 2.5 gives us plenty of margin there.

All right. So that is what happens with reflection. Any questions about that?

Now but what happens in explosions is really something very complicated. So you can't prescribe what is going to happen, because in almost all accidents you have some extremely small amount of energy.

As we were speaking before, you have to always say this in relative terms, but the energy you typically have with accidental ignitions is energy that is associated with millijoules.

So you don't make shock waves right away. All that you do is you make a little hot region. That little hot region then grows into a propagating flame. The flame itself is unstable. It produces flow that is turbulent. That turbulent flow then distorts the surface area of the flame, and then the flame accelerates.

If you watch the voluminosity on a high speed movie or video, you will see this flame accelerating. Accelerating gets up to around 1,000 meters a second, and bang, transitions with an explosion right inside the flame brush, and you get this shock wave that runs up, and the thing jumps up with 2000 to 3000 meters a second, and off it goes. So that is the transition to detonation, an extremely hard thing to calculate or predict.

So we do experiments, and examples are shown over there on the right. When that transition takes place, you get this high, spiky pressure, very -- something that is highly variable. You can get very peaks there, and I will quantify that in the next slide.

CHAIRMAN CORRADINI: Joe, the variability is simply because of where at the sides it wants to kick off and all that is compressed prior to that. Is that where the variability comes in?

DR. SHEPHERD: Yeah. It is a high Reynolds number flow, Mike, and these high Reynolds number flows and things that are happening because of natural instabilities is something that has a lot of variability in it, and it is like transition to turbulence in a boundary layer. Unless you are controlling everything to a super degree, you can't predict exactly when it is going to take place.

CHAIRMAN CORRADINI: Thank you.

DR. SHEPHERD: Okay. So on the next slide--

MEMBER BANERJEE: If it was very turbulent to start with, you predict it then?

DR. SHEPHERD: This process would be highly accelerated, but you know, trying to make predictions about the interactions of flames and turbulences is one of these challenging problems that folks are still spending a lot of time on in the academic community. And the answer is, no, we don't have good first principles predictive mechanisms.

You can do a lot with doing experiments and doing some careful correlations of your turbulence model results, but -- you know.

CONSULTANT WALLIS: Now this presented in a foggy atmosphere. That would make things less severe, wouldn't it?

DR. SHEPHERD: Well, that is an interesting thing. We thought about that. Back in the days after Three Mile Island, we did a lot of work on that at Sandia. I remember, one of the things that I did was I built a big box, and we got some of these showerheads and sprayed them into the box and tried to figure out what happens.

If you have big drops, it turns out that the flow over the drops generates a lot of turbulence, and it actually accelerates the flame. So you are a lot worse off if you have big drops.

Now if you have tiny drops, you can go off and make the drops tiny enough and, you know, maybe it will influence things. But they have to be really, really, really tiny, because they have to evaporate in basically 100 microns to one millimeter, which is the thickness of the flame that itself.

So it turns out, until you get those droplets to be very, very tiny, then it actually accelerates it.

CONSULTANT WALLIS: The droplets are worse -- make it worse?

DR. SHEPHERD: It can be, yes. Yes. So we had another bright idea where at Sandia we got all kinds of crazy things we came up with to try to prevent combustion.

One of them was going to fill up the whole containment with foam, one of these aqueous foams. Ah, that is great, you know. We just turn on the foam generator, and so we went out to the lab, and we had a pipe, and we filled it up with foam. But we foamed it, and we put a hydrogen air mixture inside. Man, that thing went like gangbusters, because the little skins in the surface tensions acted, and those little things erupted, generated all this turbulence, and then, boom, went right down the pipe. So don't do that.

So now what we have done to characterize this structural response when you have this complex unsteady motion is we have tried to do this in the old-fashioned way. We have done experiments.

CONSULTANT WALLIS: Done by law anyway. So you will be okay.

DR. SHEPHERD: I know. I know. I am just pretending that I have some influence over the science.

So what we have done, on the next slide you can see the kinds of experiments we do. You take a pipe, and you fill it up with gas. You instrument it with strain gauges. You put a lot of them down toward the end.

We have done this with all different sizes and lengths and shapes of pipes. I have done it with pipes with elbows and T's, and this is just an example of one of the simple experiments we have done.

We just start a flame at one end with a low energy ignition source, actually not even a spark but just a thermal ignition source, and then it runs down to the other end.

What we looked at is basically we did this a very large number of times and look at the ratio of the peak strains that we get to the strains that we would expect, and then we interpret that in terms of a very simplified model, which is this single degree of freedom model.

Then on the next page -- and basically we just think of this radial motion as a tube. There is a spring oscillator system. So it has a characteristic frequency. So there is a characteristic structural response time, which is associated just with the radius of the motion and the elastic modulus in the density.

Just for reference, some of the times that we have in our system are that the -- or not our system, but GE's system -- the PCCS tubes, that characteristic response time, the period of oscillation is about 30 microseconds for the radial motion of those PCCS tubes, the heat exchanger tubes.

For the drum, it is about 130 microseconds, and for the eight-inch pipe it is about

400 microseconds. So those times are actually all really short, and what does short mean? It means short in comparison to the time it takes for the waves to run the length of the tubes.

So the implication of that is really given on the next slide. It says that we are in a loading regime where basically it is a sudden loading regime. The load is applied very quickly, and then it decays slowly. So this gives us a dynamic load factor on the basis of this simplified model of about two. So that is where the two comes from. Now --

CHAIRMAN CORRADINI: Can I just make sure I get this right? So what you are really saying is the structure -- the characteristic time of the structure is much shorter than the characteristic time that I load, or vice versa?

DR. SHEPHERD: Unload.

CHAIRMAN CORRADINI: I'm sorry? Unload.

DR. SHEPHERD; Unload. Yes. So you load it. When you load it with a shock wave or a detonation wave, that loading happens in a fraction of a microsecond.

CHAIRMAN CORRADINI: So we are up like this?

DR. SHEPHERD: Yes. So we go jump up, and then it is a question about how fast do you unload. So if you unload really quickly, then that is an impulsive type of a situation. But you have to unload more quickly than about a quarter of the structural period for it to be considered to be impulsive.

CHAIRMAN CORRADINI: But in this case, you are not unloading that quickly.

DR. SHEPHERD: We are not unloading that quickly, and so it hangs up there --

CHAIRMAN CORRADINI: Okay. So it looks like a static load?

DR. SHEPHERD: Well, a static load is actually different yet. It looks like what I call a sudden load. It jumps up, and it hangs, and so you get a dynamic load factor of two. Now in a static load, the wave comes up very, very slowly, and so there is no chance for this thing to oscillate, and there you get a dynamic load factor of one for a static load.

CHAIRMAN CORRADINI: And if it was an impulsive load that unloaded quickly, you actually would have more strength in the structure.

DR. SHEPHERD: Because what happens is the dynamic load factor then decreases. So that omega tile -- If you look on the front on the lefthand side, that omega tile will go down over toward the zero, and then the load factor comes down.

CHAIRMAN CORRADINI: I see what you are doing. So the blue line is static. The sudden that you just said is green, and impulsive, if it unloaded fast enough, would be red.

DR. SHEPHERD: The green line is static. The blue line is the sudden, and if it is impulsive, it will be somewhere along here. If it is very, very short loading, very short, responding very short, you are going to be way down here. The longer that gets, the closer you get to the sudden approximation.

The quasi-static is actually a little different, because what you are changing is the time that you are taking to apply the load. So you are very, very, very slowly pushing on.

CONSULTANT WALLIS: It gets to four if there is a resonance of some sort.

DR. SHEPHERD: Yes. Now what happens to get to four -- what happens in the case where you have a traveling load, that is a special kind of resonance that has to do with the traveling load character.

CONSULTANT WALLIS: Which this is.

DR. SHEPHERD: This is a ring model, a ring model, and if I stay away from that resonance, I can use the ring model. So it is an approximation.

CHAIRMAN CORRADINI: And that is where in the RAI, if I remember correctly, GEH indicated that their speed was not close to the ringing speed.

DR. SHEPHERD: That is right. In fact, it is above it. So what happens is we go back now to Slide Number 24, and we can take a look at that. On Slide 24 you look now here.

So this is the resonance. So that is where you have this phenomenon, and all of these things are ringing. All these things. All these things are ringing, but this ringing is a resonant ringing.

If we are below this speed, it actually looks like it is a quasi-static load. You are actually going to have a dynamic load factor of one. So when you have a very slow wave, you wind up with a dynamic load factor of one. Your very fast wave, you have a dynamic load factor of two. Then you have this special situation. So they are operating up here.

Okay, back to page --

CHAIRMAN CORRADINI: Thirty-two.

DR. SHEPHERD: Thirty-two. Thank you. So back to the real situation. Here is where we made measurements in that tube, where we plastered the strain gauges all over it. These are the strain measurements. These are the peak pressures.

What you have is, over here at the left, I split the pressures up into two parts. The peak pressures are always highest at the end, and you can see that. Here we have -- this is not for -- This is for hydrogen and oxygen starting at one atmosphere, and here we can see we are up to 16 megapascals. In this particular case, it is not right at -- Stoichiometric would be actually over here, right? It is a little bit off of that.

This is what I would calculate. This is the calculated Chapman-Jouguet pressure. This is the calculated reflective pressure, and you see that, when I have this situation where I have transition to detonation, I can get these pressures that are up to, in this case, a factor of almost five greater than that, but the strains themselves are only about a factor of two larger than that, because these pressure spikes that you have in this transition process have more of an impulsive character.

So here is the strain I would calculate without any dynamic load factor. So this is without the factor of two. So this is the strain just calculated on the basis of taking radius over thickness times the delta P and dividing that by the modulus, and that is the strain that I get.

Now if I go to the next slide and I take the ratio of that equivalent static load for the reference values -- and I am using here as a reference value the Chapman-Jouguet reflective pressure, which is two and a half times roughly the CJ pressure -- and here I have drawn the line at two. You can see that I found all these points except for that one up there.

So this estimate also then gives me a reasonable estimate for the case --

CONSULTANT WALLIS: This is mole fraction of H2?

DR. SHEPHERD: This is mole fraction of H2.

CONSULTANT WALLIS: Hydrogen and oxygen mixture?

DR. SHEPHERD: Yes.

MEMBER BANERJEE: Does the length of the tube matter?

DR. SHEPHERD: The length of the tube matters. In this case, we are talking about lengths -- The length of the drum is about three meters, and the length of the heat exchanger tubes is -- help me out here, guys -- what is it, 1.25? And the way that matters is the following, that if you have a situation where you can get a prolonged period of acceleration and compression, and you shove a lot of gas up and compress it into the end, and then it explodes, then you can get to much higher pressures.

That is something that, I think, should be thought of in terms of, when you analyze this, what is the likelihood that you would get that situation as opposed to getting initiation right away. That is a much less likely thing --

CONSULTANT WALLIS: Like the automobile engine.

DR. SHEPHERD: Yes, That is right, because in the automobile engine the flame is burning, and you are still compressing at the same time. If you get this stuff compressed and then it all explodes at once, then you get this very strong explosion. So it is exactly that.

CONSULTANT WALLIS: Now on this graph, they are at .666, aren't they, where they are two-thirds hydrogen?

DR. SHEPHERD: This would be stoichiometric.

CONSULTANT WALLIS: Yes, they are over there.

DR. SHEPHERD: Yes. Why is the peak over here? Because what happens is that this mixture is very sensitive. So this mixture is pretty ideal. So this is a mixture that initiates very quickly, and you don't have much in the way of recompression.

You have to reduce the flame steam, and you do that by going off of stoichiometric, and these are very lean mixtures down here, and in fact, we can hardly get any combustion at all going on. This is just a flame. Just before you get to the point where you can no longer have a detonation, that is the worst situation.

So it is really these marginal cases. So that is why this stoichiometric mixture is really more favorable in terms of the loading.

CONSULTANT WALLIS: But when you add steam --

DR. SHEPHERD: That is right. You are back into this situation, and you could make the same kind of plot with steam concentration, except that it would be as you increase the amount of steam, then you get into this situation.

CHAIRMAN CORRADINI: Say it again, Joe, that last part. I didn't understand.

DR. SHEPHERD: So what this -- Really, the variable here, instead of having fraction of hydrogen, this should be flame speed, and as you go from a high flame speed down to a low flame speed, this is when you get into trouble with this load.

CHAIRMAN CORRADINI: And so the presence of steam lowers the flame speed?

DR. SHEPHERD: Exactly. Exactly. So the group in Germany that -- the BWR's Owners Group fostered a good deal of research on this, has done a lot of measurements and calculations looking at situations in which one gets explosions, and this is in a given size of piping. That is something that I have a little bit of a hard time pulling out of this report. It is a really great report. It has got a lot of information in it, but it is a little bit of putting your light under bushel, because I don't think anybody else in this community has looked at it outside of myself, the combustion community anyway.

What they have shown is that this isn't quite the conditions we are interested in, but it is close. So we are interested in four-bar, not three, and temperature is 373 instead of 423, but the idea is very similar.

They have some other plots for different conditions in there. This is a plot -- Here we have hydrogen concentration on the y-axis, water on the x-axis, and inside of this blue region are all of the things that are flammable, so a very wide range of mixtures.

CONSULTANT WALLIS: How much oxygen is in there?

DR. SHEPHERD: What's that?

CONSULTANT WALLIS: How much oxygen is in there?

DR. SHEPHERD: Whatever is left over. Okay? So there is three components.

CONSULTANT WALLIS: Three plus three.

DR. SHEPHERD: If you pick a point in here -- right. So there is a line here that you can't -- There is impossible compositions on this side of the line. So you get the oxygen by subtraction.

MEMBER ABDEL-KHALIK: What is lambda in this plot?

DR. SHEPHERD: Okay. I am going to get onto lambda in a second, but that is basically called the detonation cell width, and so it is a measure of the sensitivity, and the smaller that number is, the more sensitive and the more easy it is to detonate.

What this actually does is set the upper size and the upper size typically is when that detonation cell width -- and that cell width is just a measure of instability wave facing in the front. When that is equal to the diameter of the pipe, that is considered to be the limit for getting transition.

So a small size of 100 millimeters -- you can't get transition and detonation in a 50 millimeter pipe, but you can get transition and detonation in a 100 millimeter pipe. So this plot is specific to a certain size of a pipe.

CHAIRMAN CORRADINI: And you have to wait a bit. In other words, the way I remember -- That is diameter.

DR. SHEPHERD: So there is some induction distance, and that is another variable you have to look at. But this gives an idea of the very wide range of conditions over which you can get flammability and transition and detonation.

So one of the questions, of course, is, well, what happens if we have steam in here, and we have looked at that a bit. You can have pretty large amounts of steam and still get deflagration and detonation and transition in this particular example. And I think that that is the case also for what we are talking about here.

What is the detonation cell width? Well, the detonation cell width depends on composition, and it depends on pressure. This is an example again from that same report.

This is without steam, and this shows a very strong dependence on pressure which is almost roughly inverse with pressure. So we are sitting about right here, and so you notice that, for hydrogen and oxygen mixtures without steam, this cell width is less than a millimeter.

That means that the structure of this front is extremely fine, and if you take a picture of it with an ordinary video camera, it just looks like a line. You can't even see the structure of it.

So I can use these measurements. GE used a different set of measurements that came from the group in Canada, but the results are pretty similar. What I can do is use a technique that we developed when we were working on this in Sandia, which is to use a calculation of the ideal reaction zone length.

This is using a set of reactions. We have described the hydrogen and oxygen reaction, and the idea is this detonation cell width scales with this reaction zone length.

Reaction zone length is just how long we have to wait after the shock wave until we get the energy coming out, and this gives us a prediction of how this detonation cell width is changing as a function of steam fraction.

What this shows is, if you take this diameter, which is equal to the PCCS tube diameter, that we are able to get up to something on the order of about 40 percent before we would expect not to have DDT inside of the PCCS tubes. Obviously, you go to higher steam fractions and get detonation inside the drum.

I think I have saturated you guys.

CONSULTANT WALLIS: So it is not conservative to assume no steam. They said to start with it -- they would assume no steam as conservative, but it isn't really conservative on this basis.

DR. SHEPHERD: Well, so conservative is one of those words that is very pejorative. I mean, depends on who is using it. So if you mean by conservative that it provides kind of the --

CONSULTANT WALLIS: Upper bound to the pressure.

DR. SHEPHERD: -- upper bound to the pressure, then that is the correct thing to say is, yes. It is conservative in another sense, which is that it also has the smallest cell size, which means that it is the most sensitive mixture. If you are going to ignite something with a little piece of high explosive, it turns out the energy you need goes like the cube of the cell width.

So these mixtures are much, much harder to detonate than these mixtures, if you are going to do it by that technique. Also, the distance that it requires for it propagate to transition the detonation from a flame generally scales with this cell width.

CONSULTANT WALLIS: Why don't they demonstrate that there is no ignition source which is capable of igniting it with this amount of steam in it, because it is sort of incredible that you get energy to fill a cell 43 millimeters in size.

DR. SHEPHERD: Well, I mean, that is a good question.

CHAIRMAN CORRADINI: What was the question, Graham? I'm sorry.

CONSULTANT WALLIS: Well, he said we know -- said that the energy goes as the cube of a cell size and so on. Looks as if it is very hard to set this thing off, if there is a steam fraction of 40 percent.

DR. SHEPHERD: That is the energy if you

are going to directly initiate the detonation and the explosion. What you need for a spark remains essentially down in the millijoule region.

CONSULTANT WALLIS: Just for the explosion.

DR. SHEPHERD: Yes. The hazard is always -- I was just trying to make an observation about how this cell width is tied in with a sort of loose concept of sensitivity of the material.

MEMBER BANERJEE: Do these detonation widths keep accelerating in a pipe or do they saturate?

DR. SHEPHERD: Well, they saturate, and so they -- Basically, they want to go and propagate at this Chapman-Jouguet velocity unless you have something in the pipe that keeps interfering with that, and so if the pipe is basically a piece of commercial pipe, it will run within a percent of that velocity after transient, in which all the gas dynamics size down.

So after-- We have a two-inch pipe. After five or six feet, we are basically within a few percent of the Chapman-Jouguet velocity.

Okay. So to summarize, we can have detonations up to about 40 percent of steam. There is another criteria that I didn't talk about that is in the FSedk Report, and that is that, when the stuff burns, that it has to generate a sufficient amount of volume. Turns out that we satisfy that criterion. It is a little bit more complicated than being larger than a certain number. It is discussed in detail in the report.

We satisfy the criteria that, at least for less than 40 percent steam fraction, and the cell size is sufficiently small. So I believe that transition and detonation will occur rapidly for these steam fractions between zero and .4 at peak conditions.

CONSULTANT WALLIS: So they will have detonation?

DR. SHEPHERD: Yes, if you get ignition. If you get ignition.

CHAIRMAN CORRADINI: Which is an assumed thing here.

DR. SHEPHERD: This is how all the safety analysis of this business goes. For 30 years, the number one problem has always been can you get ignition. Do you have any kind of ignition, and almost all the cases that I have been involved with, people throw up their hands at trying to determine ignition frequency or they shy away from getting involved in that, and they say, well, let's just go ahead and assume it ignites, and then we will look at the consequences.

So I think that the dynamic load factor of 2 bounds almost all the cases away from the tube end. So I think that, certainly, their assumptions are reasonable for the tubing.

As far as the drum goes, the original idea was to treat that differently. I believe that that is still an open issue, and that the mixture is just as sensitive there as it is in the tubes. The cell size is even smaller relative to the dimensions, and I don't believe you can rule out DDT.

CHAIRMAN CORRADINI: That is what, I guess, I didn't understand. Maybe I misread their RAI. Are they treating the drum differently? I thought they were using the 2 x 2.5 times Chapman-Jouguet.

DR. SHEPHERD: They are now treating it in the same way. Previously, they were not.

CHAIRMAN CORRADINI: Ah. So there is a time lapse from your comments and what I read?

DR. SHEPHERD: That is right.

CHAIRMAN CORRADINI: Okay.

DR. SHEPHERD: So that RAI came in at,

what?

CHAIRMAN CORRADINI: May-something.

DR. SHEPHERD: No, no. I am talking about the most recent one.

CHAIRMAN CORRADINI: Oh, we haven't seen the most recent one perhaps then.

DR. SHEPHERD: In the May one, though, they were going to do a constant line combustion.

CONSULTANT WALLIS: So the lower drum is now going to be treated differently from what we have seen?

DR. SHEPHERD: No. The lower drum, I believe -- I believe, and GE should respond to this, but I believe they are going to be treating it on the same basis.

CHAIRMAN CORRADINI: Could I have you guys say something at this point? Identify yourself.

MR. GELS: I am John Gels from GEH. Yes, we are applying the same load combination to the lower drum as we are for the tubes.

CHAIRMAN CORRADINI: And to understand that response, that means that they are not taking -- I am trying to understand. They are not taking credit for the venting through the tubes, or they are now; because I didn't understand. These two things kind of go together, and I didn't understand that.

MR. GELS: I think, in a previous iteration of our licensing topical report, we indicated that venting through the tubes would be a mitigating strategy for the pressure in the lower drum, but further research indicated that that might not be the case. So we are no longer going to be crediting that kind of phenomena.

CHAIRMAN CORRADINI: So the scale you quoted to us earlier -- we are in Open Session, so I -- (a) I don't remember them; (b) I can't say them if I happen to remember -- is a thickness that is consistent with this type of analysis?

MR. GELS: That is correct.

CHAIRMAN CORRADINI: Okay. Fine.

MEMBER ABDEL-KHALIK: Now how long are the tubes from one drum to the other?

CHAIRMAN CORRADINI: Careful.

MEMBER ABDEL-KHALIK: Can you say that in public? It is proprietary?

MR. GELS: It is roughly 1.8 meters.

MEMBER ABDEL-KHALIK: Is what?

MR. GELS: About 2 meters.

MEMBER ABDEL-KHALIK: Two meters?

CONSULTANT WALLIS: What about the drain

pipe -- well, go ahead with yours.

MEMBER ABDEL-KHALIK: The transit time of a shock wave from one end to the other within a tube would be in the order a millisecond.

DR. SHEPHERD: Well, so I will work those numbers up, because that is what is really relevant. Let me just find my scribbling here.

So if we take about -- take the number that was just mentioned, it turns out that the actual pressure transient is about half of the time. So t is about .6 milliseconds for the tube. So you are right. And for the drum it is going to be more like on the order of one.

So those are the times for the fluid dynamic unloading, and the important thing for the structure response is to look at those relative to this hoop oscillation period, which was much shorter.

So that ratio being very large, we are over on the side of the dynamic load factor where you are two.

CHAIRMAN CORRADINI: And just to make sure I understand, your blue highlighted conclusion, given that they are taking two and a half times the Chapman-Jouguet, they are being treated consistently?

DR. SHEPHERD: Yes.

CHAIRMAN CORRADINI: Okay. Thank you.

CONSULTANT WALLIS: Now you have in this drum -- You have this thing sticking up with the catalytic converter on it, and you have a pipe sticking down which takes out the gases or whatever, and also some liquid.

What happens when the explosion comes by and hits this structure and this side tube? What is the loading on the structure in the side tube? Can they work that out?

DR. SHEPHERD: I haven't seen any results for that, but I think that is a very good question to ask, and the staff has asked that question.

CONSULTANT WALLIS: We need to see a response to that.

DR. SHEPHERD: Yes, that is one of the open issues that was identified.

MEMBER BANERJEE: What are the other open issues?

DR. SHEPHERD: Go back to Slide 13. Not really.

CHAIRMAN CORRADINI: It is on here, Slide 14 and 15. Sanjoy, they went over them earlier.

MR. McKIRGAN: I think we will summarize those at the end as well.

MEMBER BANERJEE: Talk about them at the end again.

CHAIRMAN CORRADINI: I think you need to proceed.

CONSULTANT WALLIS: I am just wondering what is the response to the concept of these heat exchangers and condensers that are being designed for multiple hydrogen explosions. It is a little bit mindboggling, isn't it?

CHAIRMAN CORRADINI: This is just a comment back. If they went down the path that some of us might suggest, we would have them in here for five subcommittee meetings about where, how long, length scales, time scales, and we would drive them crazy about that.

So I think this is a cover -- an umbrella approach. At least, that was my impression of how they took it.

MEMBER ABDEL-KHALIK: If you go to your Slide 37, are you qualifying this conclusion by saying all cases away from the tube end or doesn't this apply for everything?

DR. SHEPHERD: I would apply it to everything. I think there is a role for a probabilistic risk assessment here to say that you need to look at things that are close to the tube end and decide whether or not --

MEMBER ABDEL-KHALIK: But the tube is open on both ends.

DR. SHEPHERD: The drum is not.

CHAIRMAN CORRADINI: The drum is not. That is what he is worried about.

DR. SHEPHERD: But if you think about -- I'm sorry. So I use the word tube here generically.

MEMBER ABDEL-KHALIK: Right.

DR. SHEPHERD: And so there is -- So in this case, it is the tube, and since the tube is open and doesn't have an end, it is good. But if we think about this generically as the drum, then there is an issue there.

MEMBER ABDEL-KHALIK: But you had a separate slide for this.

DR. SHEPHERD: Yes. I have a separate slide for the drum.

MEMBER ABDEL-KHALIK: As it applies for the tube.

DR. SHEPHERD: I apologize for this being not as crisp as it should be. I don't think -- I am not qualifying it for the PCCS.

MR. LE: My name is Tuan Le. The next

presentation, going to go to the structure review. In this review, there are two parts. One is the PCCS structure design, and also the containment structure design. I will present the PCCS structure design.

The Applicant had to make a change, significant change, in the PCCS condenser design. They desire it to withstand the loads resulting from the buildup and possible detonation of radiolytically generated combustible gases, particularly hydrogen, during a LOCA.

Secondly, the design of the PCCS, including the condensers, are modified to improve their ability to mitigate the hydrogen detonation loads.

Thirdly, the PCCS condenser tube-lower drum materials and thicknesses --

CONSULTANT WALLIS: I don't think you mean the word mitigate. You mean to withstand. Mitigate, to me, implies you are trying to reduce the load. You mean reducing the -- I guess you are reducing the loads -- the stresses. Right? But the applied loads is still the same. Right? You aren't mitigating the load from detonation. You are mitigating the stress by making it thicker.

MR. LE: Right. Well, it is to withstand

the loads.

CONSULTANT WALLIS: You are not trying to actually mitigate the load itself.

MR. LE: Yes, you are right. That word does not apply in this situation, because the Applicant had designed the PCCS, and it changed from the original design with the peak load on material and the thickness of tube and drum, and also number of tubes would take care of the detonations they calculate for this LOCA.

The next is for the condenser, it is required to perform heat transfer function after a LOCA. Even during a LOCA, they also perform function, but important that their function should be carried out after 72 hours and beyond that. So the condenser required to perform the heat transfer function after a LOCA.

The PCCS condenser is designed as a part of containment boundary.

The design criteria for PCCS condenser is: For containment pressure boundary, the entire PCCS condenser is classified as ASME Class MC component and is designed to ASME Subsection NE requirements. This also includes a small section of the drain pipe connected to the lower drum nozzle.

Also, the remaining portions of the drain and the vent pipe are classified as ASME Class 2 components, as the Applicant presented this detail, and this portion are designed to ASME Subsection NE requirements. This is part of the pressure boundary.

The third bullet, the third criteria for the PCCS condenser criteria is: All ASME MC components of the PCCS will be designed to withstand the hydrogen detonation pressure, and to remain essentially within the elastic stress range is an important criteria.

CONSULTANT WALLIS: What does essentially mean here?

MR. LE: Currently, there is some location where this meets the service level C, but other level -- for service level D, ASME D, some of the area would exceed the elastic range, but the Applicant committed to make a further modification of this local stress would exceed the elastic range, and to make it within the elastic range.

CONSULTANT WALLIS: So there might be some regions which are drastically deformed?

MR. LE: Yes.

CONSULTANT WALLIS: But not enough to change the geometry to change the performance --

MR. LE: Right.

MR. CHAKRABARTI: Service Level C is really differentially elastic behavior, but the primary -- that you can have local stresses exceed little bit beyond this.

CONSULTANT WALLIS: There is no significant geometrical distortion.

MR. CHAKRABARTI: Right.

MR. LE: This stress location is at the local member, and stress can exceed the elastic range. It is a localized area, and at the two locations that will be discussed later on.

CONSULTANT WALLIS: So the tube won't break?

MR. LE: Yes. Is there any other question for me?

CONSULTANT WALLIS: Are you satisfied that they can do this or this is essentially what they have to show now? Is it still an open item? They have to show that they will meet these requirements?

MR. LE: They will like -- Samir is going to discuss a different level that how they meet the service level D, level C and ASME code requirements. Essentially, the staff view that the level C gives more a conservative margin compared with level D service, which is -- They are going to meet all the elastic range, analyze all the part of the components which is withstand the detonation load.

So currently, there are two locations, and that will be discussed later on, and that was exceeding the elastic range, and they are going to modify it. One --

CHAIRMAN CORRADINI: Sir, you are speaking a big quietly there. So there is two locations. This is the ones that GEH identified that they have to go back and do what?

MR. LE: A little bit modification. One location is the -- the section, the tube and the lower drum, that component there where the high stress concentration occur. A resolution on that has been discussed, and they are going to proceed to modify that corner. It may be less susceptible to a high stress local membrane occur in that location.

The other location is the -- Okay. So the next presentation will discuss the location of that.

MR. CHAKRABARTI: I am Samir Chakrabarti. I am the technical reviewer for Section 3.8 which is section technical structure of the ESBWR design.

We have BNL consultant, Manuel Miranda, who provided technical assistance of this review.

We had reviewed structural design of the PCCS prior to detonation event. Since we all know it is part of the containment pressure boundary, and it has to meet ASME Class MC component requirement.

The design of the BWR PCCS is designed is in the SRP 3.8.2 guidelines that we have to make sure they pass the Class MC components are met.

The PCCS components that are within the containment pressure boundary are the steam supply pipes, the upper drum, lower drum, the tubes, and penetration area, and the lower drum penetration, the in-line that we talked over this morning. That is a little bit overlap, and depends on that we have not really seen the details and how it has been qualified. But that area is also in our containment pressure boundary.

The vent pipe and the other portions of the lower drum, the drain pipe -- they are not within containment pressure boundary, and we did not look at those.

Also, what we look at is structure that has been used to support the PCCS. That is also part of our review.

For the detonation loads, there are several issues.

CONSULTANT WALLIS: Are you looking at loads -- excuse me -- on the catalytic assembly as well?

MR. CHAKRABARTI: Not for pressure load.

CONSULTANT WALLIS: Small, but it is loaded.

MR. CHAKRABARTI: I know, but for Section 3.8 we are qualified with the PCCS components only which are part of the pressure boundary.

CONSULTANT WALLIS: Pressure boundary. Okay.

MR. CHAKRABARTI: That is containment areas, because that is where the components are.

CHAIRMAN CORRADINI: And that is something that will be handled by the components group and should be done or is a closed issue? That is what I didn't understand.

MR. CHAKRABARTI: I cannot say about that. It is not my part.

CHAIRMAN CORRADINI: I got that part. I understand that portion of what you said. So whose part is it? My question is, the way it was discussed is you are looking at it via the pressure boundary, and now you are looking at components. Is that still to be reviewed by the staff from a component standpoint?

MR. LE: Right.

CHAIRMAN CORRADINI: Okay. Thank you.

MR. CHAKRABARTI: Okay. Now so for the issue of PCCS containment pressure boundary, there are several issues: Assessment of the load; the loading combinations to be used; the acceptance criteria to be used.

We have some problems. One is the assessment of the load is fairly complex, as we all saw from Dr. Shepherd's presentation, and we got input from his review and Hanry's review to determine what load we should use for design of this PCCS component, and we are using the equivalence static approach using the detonation loads established.

That is above the detonation pressure, and also we need to determine what is the effect of the detonation on the overall PCCS, including several new structures. We have asked this question, and apparently some evaluation using LS-DYNA and all that has been done, but we have not seen the results yet. So that a portion of our ongoing review.

The evaluation of the effects: Like I discussed, we use the equivalent static pressure for design. The amplification factors for wave reflection and dynamic effects are considered; essentially linear elastic response of the components assumed. Detonation pressure used to design the condenser tubes, lower drum and portion of the drain pipe classified as MC component.

Now for determination of the load combination and acceptance criteria, we have to perform what we call case by case evaluation, because ASME SRP component does not specifically address how to design for detonation loading.

We chose that, if we use Class MC component Level C acceptance criteria, it is probably the most appropriate and will assure maintaining containment pressure boundary for this assembly.

The reviews for that -- I have listed reviews here, the basis: The structural integrity of containment pressure boundary is ensured; response of components remain essentially elastic, except some local yielding, assumptions in stress analysis; essentially elastic response, also the calculation of the dynamic load factors due to detonation; assure essentially elastic behavior of the tubes; maintaining Level C stress limits and ensure that; the ratcheting and other plastic instabilities will be limited, and other load combinations using the same acceptance criteria: The LOCA along with SSE, and hydrogen pressurization and burn resulting from fuel clad water reaction.

GE had alternately proposed using which would be not quite what -- with GM we jointly agreed to use service level C. In fact, ASME does allow the service level D estimates for very dynamic loading like get impingement and stuff, but there will be still some issues, how the --

CHAIRMAN CORRADINI: There are still issues about how what?

MR. CHAKRABARTI: Detonation effects, because that could be affected, the elastic limit -- the subsequent detonations may not be justified in the service level D, because that was much higher in the elastic limit.

CHAIRMAN CORRADINI: I guess I -- I'm sorry, Graham. Excuse me. Go ahead.

CONSULTANT WALLIS: What you mean is you keep stretching it a bit more, and --

MR. CHAKRABARTI: Right. Service level D, the test goes much higher into the plastic regime. That will have an lasting effect. You may not guaranty sensitivity of the multiple detonations.

CHAIRMAN CORRADINI: But let me make sure

I understand the logic. So that, if they go back and address these two areas that -- Well, I'm sorry. Maybe I am getting confused.

Are they in the elastic or in the plastic regime in their loading?

MR. CHAKRABARTI: They had figured, but we are going to accept only for those areas above.

MR. McKIRGAN: So, Samir, if I could, I could help.

CHAIRMAN CORRADINI: I don't understand.

MR. McKIRGAN: GE's commitment now is to get back to service level C.

CHAIRMAN CORRADINI: And by some means -- thicker walls, different material.

MR. McKIRGAN: Correct. And that will eliminate these issues that the staff had raised when we were talking about service level D. So the rationing and the plasticity issues are obviated by the commitment to service level C. They just need to get there, and the review is ongoing.

MEMBER ABDEL-KHALIK: Which means you only have to review one detonation.

MR. McKIRGAN: They are considering multiple detonations. It just so happens that, when they go to service level C, they will stay in the elastic regime.

MR. CHAKRABARTI: That is correct.

CHAIRMAN CORRADINI: But I guess I am -- I am going to ask the question that is going through at least a couple of minds here. If they agree to one thing, at least they are going to let them off the hook on doing things that are clearly a waste of time.

MR. CHAKRABARTI: I didn't get that.

CHAIRMAN CORRADINI: That is what I think we kind of thinking, in the sense that, if you are satisfying service level C as purely elastic behavior, going through multiple and additional ones makes no sense.

MR. CHAKRABARTI: That is correct.

CHAIRMAN CORRADINI: Okay. I wanted to make sure I understand that.

MR. CHAKRABARTI: That is right. It will take care of the ratcheting effect.

The stress analysis has been done using static, linear elastic, Finite Element analysis.

The global Finite Element model of the PCCS has been used for other loadings other than detonations, like dead, live and plastic loading, and refined Finite Element submodels that GE already presented were used for the detonation loading.

Detonation loads applied as internal pressures on Finite Element submodels, and they have presented the results of the analysis.

The stress analysis reported in Licensing Topical Report. The condenser tubes and the lower drum are significantly strengthened compared to the original design. It has already been discussed.

Also the stress hot spots, the tube bends, lower drum covers, and the lower drum drain nozzles. These are the two areas right now that have higher stresses than service level C.

That concludes my presentation, and now we have again status of results and open issues. Before we go into that one, are there any questions on staff's evaluation of these?

CHAIRMAN CORRADINI: Okay. Does the committee have any questions for Mr. Le and Mr. Chakrabarti about structural issues that we have just heard about? Okay. Hearing none, let's broaden it into all the -- whether they be resolved or open issues.

We have the last two slides essentially discuss all the -- what they consider to be resolved issues and open issues. So we will open up the general discussion.

MS. CUBBAGE: Excuse me. I also wanted to point out that GE Hitachi did have a couple of slides on how they are evaluating the PRA impacts that we deferred from earlier. So if you would like to hear that, Ge can do that as well.

CHAIRMAN CORRADINI: That would be fine. Before we do that, I just want to make sure we get all the questions to the staff. All right.

MEMBER ABDEL-KHALIK: I have a question about one of your open issues. On Slide 54, accounting for thermal effects generated by detonations in the design.

If I have a tube that is 10 centimeters thick, and the transit of this detonation is a millisecond, do you think there is any thermal participation or thermal interaction during that one millisecond time period between --

MR. CHAKRABARTI: Yes, let me address that one. That question is really not the thermal impact of the thermal stresses on top of the detonation stresses. That question is primarily raised because of the detonation, the temperature inside the tube apparently may get higher, and how long this high temperature is going to stay there.

If that high temperature stays for certain period of time, then we need to look at it, because the detonation is not operating in multiple tubes. Probably in a single tube, we may have the detonation.

MEMBER ABDEL-KHALIK: It is sort of an artifact of the way they are doing the stress analysis for the detonation, that they are assuming it to be a steady load, but in reality this thing is going to die out very quickly before any thermal participation takes place.

MR. CHAKRABARTI: What we really wanted to know, if the temperature in a single tube when all the other tubes are holding the two drums, sustaining the two drums, whether it is going to cause stress on a single tube.

CHAIRMAN CORRADINI: It would cause what?

MR. CHAKRABARTI: Thermal -- excessive thermal stresses on a single tube.

MR. LE: Could I inject in this. In case of the single detonation, you have the one instant detonation, and you want to know the temperature, what the delta T, significant different from the initial temperature. But after multiple detonations, one detonation and carry on to the next detonation, the temperature add in to the whole entire tube design could be significant.

We look at thermal stress on that. Also back to the number of cycles due to fatigue, if you have a high loading of thermal stress, even if you have a few cycles, it will be significant impact.

CHAIRMAN CORRADINI: I guess I don't want to quote, because I don't have the numbers in front of me, but the energy released -- Make sure I understand this. You are worried about the thermal stresses because of some sort of thermal stress in the structural part.

MR. LE: Yes.

CHAIRMAN CORRADINI: And you have done the calculation? I mean, my guess is there is not a lot of energy there to heat up the steel. Am I missing something? That is what I want to ask. Have you guys done that comparison point?

DR. SHEPHERD: So we haven't gone into this in detail for the PCCS tubes, but I have gone into this in other problems I have worked on in the last five years.

Surprisingly, what happens is there is a skin effect, and there is a very small amount, and this thermal stress causes tension to be created in all o the members of this thing, because you have got this region that is trying to expand right at the interior surface.

Now when you compare that to the strains that are generated by the questions from the explosion itself, it is something that is relatively modest, but it turns out it is much larger than the strain that you would get just from constant volume combustion. Very surprising.

We have actually measured this, and we did it with that experimental facility that I showed, that tube. I had a graduate students, who are very creative, and after he did it, I said, what the hell did you do this for.

He rolled up a roll of rubber material inside of half of the tube and compared the strains in the half that had the thermal insulation with the half that didn't have it, and sure enough, you could get strains that are two to three times what you would get with constant volume explosion just due to the thermal stress.

It takes a little while for that stuff to soak in, and in comparison with a detonation, it is negligible, but if you have something that can distort, those thermal stresses can play a role.

CHAIRMAN CORRADINI: So it is because they are fixed at the end?

DR. SHEPHERD: No.

CHAIRMAN CORRADINI: No?

DR. SHEPHERD: It is because you've got this thin shell of material, and you've got this confinement of this cold stuff, and so it is like doing a shrink fit. Then that stress gets felt all the way through the material.

MEMBER ARMIJO: But if each side of that tube is under compression, isn't it?

DR. SHEPHERD: Yes. So -- and it pushes on the other part of the tube, which is restraining.

MEMBER ARMIJO: Restraining is colder, and it is moving pretty strong. So how does that lead to structural damage?

DR. SHEPHERD: It doesn't necessarily lead to structural damage. It is an effect that exists, if you think about such things.

If you were, for example, to just think about deflagrations. Let's suppose we don't have any shock waves or anything like that. We just burn the stuff. It turns out the stresses you really want to consider are the thermal stresses.

CHAIRMAN CORRADINI: Okay. That makes sense.

DR. SHEPHERD: That result is actually

very surprising to most people. They don't believe it until I show them the data. Thermal stresses will be larger than the mechanical stresses.

MEMBER ABDEL-KHALIK: But if this skin heating produces compressive stresses because of this very thin layer that has the time to participate in heating --

DR. SHEPHERD: It puts the whole system into --

CONSULTANT WALLIS: Like a thermal shock.

DR. SHEPHERD: -- into tension.

CONSULTANT WALLIS: A thermal shock.

DR. SHEPHERD: The thing is being held together from the outside. I misspoke. Then on the inside it is trying to expand. Right? So the outside is trying to hold it together, and the inside is trying to expand. The net result of that is that you will get tensions on the entire thing.

MEMBER ABDEL-KHALIK: So it is additive.

MEMBER ARMIJO: The magnitude is what really counts.

DR. SHEPHERD: The magnitude is what really counts. It is a residual stress. Right?

CHAIRMAN CORRADINI: So it remains past the pressure.

DR. SHEPHERD: That is right. it shows up at the end.

CHAIRMAN CORRADINI: All right. Thank you. Other questions? Okay. I will thank the staff, and we will come back to what we had delayed in terms of the PRA discussion, brief, because this, if I understand, is also like the isolation condenser in that this is still an ongoing discussion with the staff.

CONSULTANT WALLIS: So what we heard about was the PCCS. The ICS is another day or something?

CHAIRMAN CORRADINI: The ICS is still in process. One of the open items from the in-process part, as these guys are getting themselves set up, is we wanted to see some details in terms of timing.

Do we have to go back Closed on this? That is a question.

MR. WACHOWIAK: I will let you know what I can't answer in Open.

CHAIRMAN CORRADINI: Okay, but there is nothing in your slides?

MR. WACHOWIAK: The PRA is not proprietary, and we are not intending on putting anything proprietary in the PRA.

CHAIRMAN CORRADINI: Okay. Good. Thank

you.

MR. WACHOWIAK: All right. So the reason we want to talk about this today is because we are in -- We are a little bit strapped for time on this. We are doing this in parallel. Once again, you can't quite do a real good job on the PRA until you know what it is you are modeling.

It took us up through about now to know what it was we were going to have to model. We've had considerations for what we were going to do, but we have now gotten to the point where we know what we are going to look at, and we want to let you know, in parallel with the staff, what it is we are doing so, if it looks like we are missing something, we don't want to find out about it three months from now or whenever we come back to Chapter 19. We would like to know about it now so we can have it resolved in the same time frame.

So we take a look at what it was that we did. In general, for containment analysis for the severe accidents, we look at what kind of capability the containment has beyond what is considered in the design basis.

For the rest of the containment, that was going from a service level A-B sort of analysis for the design and taking it to a service level C analysis for the severe accident.

Well, as you just heard over the last few hours, we used service level C for the PCCS heat exchanger. So that is not where the margin is. it is not in the capability to withstand the loads. The margin are the things that we talked about earlier in what is the actual load.

So talk about what the differences are. In the severe accident we are starting from a higher pressure. If you look in Chapter 8 of the PRA, it will show you that in the defined, more likely severe accidents -- your term, not mine -- the initial pressures are at about six bars rather than four.

Okay. Where we end up saying that we are going to vent are up more at 10 bars rather than six. So we've got some margin there, but when we start the initial pressure higher, as we said, along with everything else, the detonation -- the ultimate load scales up with initial pressure.

So what do we have to deal with here? We have got the gas composition. We neglected any steam or residual nitrogen left in the heat exchanger when we calculated these pressures. We also assumed a very low temperature. Both of those effects tend to push it toward the bounding region of the pressure curves.

So what we looked at was what kind of steam do we expect to be in the drum mixed in with the drum and tubes, mixed in with that? What is in the drain lines, that sort of thing? What do we predict for it, and what kind of temperatures are we expecting to see?

When we did that straight analysis and then accounted for the possibility that the temperature inside the drum could be as low as the temperature of the water in the PCCS pool, we found that we exceeded the pressure by -- that we calculated for the design basis event, by about 10 percent. So it wasn't a factor of 10, like if you just looked at the initial pressure, but it was still bounding or still beyond what we had.

So what we needed to do is look for an additional way to mitigate the pressures. We could have gone through another redesign cycle of the PCCS heat exchanger to increase the capability. That would probably work, but then it would bring into question more, okay, so exactly how certain of you of the steam concentration at the exit of the tube on the PCCS, and other questions that I may have heard earlier today.

So rather than go through that exercise

and stick with the same set of uncertainties that we had before, what we looked at was adding -- for the severe accident cases where the pressures are elevated is a set of igniters in the lower drums that we would operate off of the BiMAC system. Essentially, now the BiMAC detects the core outside -- the core outside the vessel scenario. It turns on the deluge line. It would also turn on a sequence for these igniters.

the purpose of the igniters is not to eliminate the potential for detonation. It is to burn out the oxygen so that the oxygen concentration isn't at the stoichiometric mixture that allows for the super-high detonation pressures.

Using the CEA code that we have talked about here earlier, what we see that, if we knocked the oxygen down by about a factor of 50 percent, we can get a reduction in pressure, ultimate pressures in the system, and including the steam -- we can get a pressure load reduced by more than 50 percent.

MEMBER ABDEL-KHALIK: In reality, though, wouldn't you want these igniters to work a lot earlier than that? I mean, this might help you in the PRA space, but in real life --

MR. WACHOWIAK: In real life, there is nothing that says during detail design that we would prohibit the use of this earlier. Okay? But for right now, the automatic actuation and the things that we are crediting will be in the PRA and credited only when the BiMAC is in operation. Okay?

Remember, in our PRA -- If we remember at all these different meetings we had, we tried not to rely too much on what the operators were going to do, because we don't have the control systems done yet. We don't have the control room. We don't have the HRA analysis, and that would add additional uncertainty that -- You never know how that could go.

So our base case for the design PRA was minimize the reliance on the operators. Let that go into the final PRA that is done just before fuel load, when you have all that, and we would expect that to be an improvement by adding in the operators. We don't expect that to be an improvement, but -- and so we wouldn't put anything in that precludes the operators from using this.

MEMBER STETKAR: Would it make much difference if, instead of triggering them off high temperature down in the lower drywell, triggered them in something like upper drywell pressure or temperature, that type of thing?

That would fire the igniters, you know,

long before you got core damage and still keep the operators out of the picture, and still pick up signals that you have already.

MR. WACHOWIAK: Yes, but once again, that was additional things that we didn't have -- We tried to minimize what it was we were changing here, and there might be a better signal to do it, but the only time when we found a problem with this is when we were relying on the BiMAC and the PCCS working in concert with each other to keep the containment intact.

So if we are only relying on it when the BiMAC is in operation, the signal that we put in here is that one.

CONSULTANT KRESS: Well, here you've got a lot more hydrogen. It is no longer stoichiometric.

MR. WACHOWIAK: No, it is no longer stoichiometric. It is out of balance.

CONSULTANT KRESS: Way out of balance. So you can get rid of this 02 without --

MR. WACHOWIAK: Exactly.

CHAIRMAN CORRADINI: So I wanted to ask a question to make sure I am clear. I'm sorry. So just to be clear, because you are using it in this mode, it is not -- it is not going to -- you are not going to need the DC power to use these. You will use --

MR. WACHOWIAK: We will use the same DC power source that the BiMAC squibs use.

MEMBER STETKAR: They have got a separate --

MR. WACHOWIAK: A separate system.

MEMBER STETKAR: -- separate system for the BiMAC squibs.

MR. WACHOWIAK: And the other thing that is nice about that, not necessarily for this evaluation, but in other places where we are trying to market this reactor, there are requirements for totally independent severe accident systems, in other markets, and this would qualify for that. So it also helps us in that sort of a regime.

CONSULTANT KRESS: Is there a problem of where to put the igniters for the maximum effect?

MR. WACHOWIAK: For maximum effect, yes, there is a problem. However, we are not relying on maximum effect. We have done some sensitivity studies on this, and we have shown that, if we knock the oxygen down a few percent, halfway, a quarter of the way, it takes us off the bounds, and we are showing a reduced pressure from the flame, so from the detonation, which then we still apply the two and a half and the two -- other factors to get the load in the heat exchanger.

CONSULTANT KRESS: You are back within this 10 percent?

MR. WACHOWIAK: And we are back below the same loads that were analyzed for the design basis case.

CONSULTANT KRESS: I see.

CONSULTANT WALLIS: Well, this -- Is this lowering oxygen and hydrogen?

MR. WACHOWIAK: It will lower hydrogen some, but remember, there is a lot more hydrogen in the problem now, because we have generated 800 kilograms of hydrogen or whatever it was from the ZrP water reaction. I think that was the bounding case, but we have generated a lot more hydrogen.

So now as these burn off, we are cycling vacuum breakers a little bit more, and so we bring back more nitrogen and hydrogen back. So it stays out of balance.

So we have done that modeling. We have run those cases for the Level II, and we have also identified where in the containment event tree we would need to model this, and I will get back to that probably right around this slide somewhere.

MEMBER STETKAR: Rick, have you recycled

back through the -- I am not a structural guy. So forgive me -- through the stress analyses -- I mean, you have to insert these igniters into the lower drum somewhere through penetrations.

MR. WACHOWIAK: We have not gone and done that piece yet. It is likely -- The likely location would be through the end covers. The maximum stress on the end covers is at the bolting around the edges, and we don't really have a problem with the center. That is what we are thinking right now. Have not located them yet, though.

CONSULTANT KRESS: It is a pretty small thing.

MEMBER STETKAR: They are small things.

MR. WACHOWIAK: They are small. Yes. All right. So that is the phenomenology change that we have to make.

We also have to put in a description of the hydrogen mitigation features. Right now it just says we don't have to worry about it, because we are inerted. We are not going to say that anymore. We will say something else, but we will provide a description of that.

CHAIRMAN CORRADINI: Let me just say, prior to this you knew there was hydrogen and oxygen from radiolytic decomposition. You just didn't consider it?

MR. WACHOWIAK: There is a section in the DCD that discusses radiolytic decomposition of water to produce hydrogen and oxygen. When we did that, we mixed the hydrogen and oxygen with the drywell air space, the wetwell air space. It takes much, much longer than 72 hours before we get to any sort of a flammable concentration. So we discounted it, because it wasn't -- that wasn't an issue at that point.

CHAIRMAN CORRADINI: Okay.

MR. WACHOWIAK: Now inside these specific components, we need to address it, and we will describe how we address it.

CHAIRMAN CORRADINI: Thank you.

MR. WACHOWIAK: Okay. So we discussed the ICS earlier. It is -- We probably could have described that other piece without updating the PRA qualitatively, and because the way that the igniters would interact in the containment of entry, it acts exactly like the squib components i the BiMAC.

So where we would have it in the containment of entry -- I don't think I brought the containment event tree, but where we have it in there, if the BiMAC is operating, which means the control system works, then the igniters have to operate. So the only delta between the two are the igniters for the deluge valves and the reliability of the igniters.

The reliability of those two types of components are similar. So we would expect that we would get a very small increase of large release frequency associated with that, in the 10^{-12} order. When I look at those specific cut sets, not going to be an issue.

So the big part is on the ICS. Now in the ICS, we are saying that, when the ICS is active, it has to vent. In the PRA before, we had uncertainty there.

So we always said that it had to vent, even though in the design basis case it didn't -- we didn't always show that it would vent. But in the PRA, we said that there really are more cases, and it wasn't hurting us.

So we always said that, if the ICS doesn't vent, we are going to fail that ICS. Okay, but the configuration for how it is vented now is different. It is de-energized to actuate where it used to be energized to actuate. It is actuated now on the initiation of the ICS rather than separate pressure signals.

So we put that into the model. What we have now is actually a more reliable vent than what we had before, and we weren't trying to do this, but it is just an artifact of putting in the real model. Cordite damage frequency dropped a smidge. Okay? Not enough to change anything, but it is a different number.

Then we went through and we added in the ICS isolation, because now we are saying during the LOCA scenario, if you don't isolate ICS, we are going to put a hole in the containment boundary.

That is just an assumption we are going to make. So we are not trying to quantify the probability of getting a hole. We will just say, if it doesn't vent, we have one.

So we were able to add to the containment event tree, and -- let's see; I put it here somewhere. Well, I don't see it right now. So we added to our trees here. It is a little bit difficult to see on this scale, but you can see that we are putting it into the model.

Here in the cases where we have a LOCA -- this is a large LOCA -- once we get past vapor suppression, we add ICS isolation. So ICS isolation is required to go through the rest of the system of entry.

Likewise, in the transient scenarios, this is the inadvertent open relief valve. if we have a failure of the ICS -- there are, obviously, cases where ICS is not working -- and the DPVs have opened. So here is one branch. DPVs have opened, and here -- somewhere else is another branch, and the DPVs have opened.

We add in the requirement to isolate the ICS. It must isolate to get to success. Otherwise, it goes to failure. Our initial case that -- It goes to transfer right now. Our initial case we did, we wanted to say, oh, let's just say these go to failure and, if it doesn't affect anything, we are done. We don't have to update the PRA. It is irrelevant. Didn't work out.

MEMBER STETKAR: When you say failure, you mean --

MR. WACHOWIAK: Any ICS fails to isolate.

MEMBER STETKAR: Goes to melting and containment failure?

MR. WACHOWIAK: Well, originally we were going to say goes to melt and containment failure. If that had gone to melt and containment failure and it didn't affect the cut sets appreciably, we would have just called it good, you get a sensitivity, and moved on. Didn't work out that way. It goes to a transfer.

So what we have modeled here is, once we have a failure to isolate, we assume that there is now some sort of a hole in the containment pressure boundary, and in our thermal hydraulic analysis that we are performing right now, we are looking at a spectrum up through what we think could be the -- you know, from one tube to the maximum amount that could get through the velocity limiters on the component. All right?

If we have failure then of our GDCS system, then we are just taking it right -- failure of GDCS, failure of active injection, it goes to a containment bypass. Okay?

We get about -- In the whole base model, we get about 15 cut sets that come down to this range, but if we change it from the Level 1 quantification to the Level 2 quantification, none of them make it through. It is right on the edge of the truncation limit for each of those cut sets. So it is there. Not important.

CONSULTANT WALLIS: Could you go back to this ICS vent failures to operate?

MR. WACHOWIAK: Okay.

CONSULTANT WALLIS: Then you blow a hole in the ICS?

MR. WACHOWIAK: No. If the ICS vent fails to operate, we consider that an ICS failure in the model, and --

CONSULTANT WALLIS: How is that treated then?

MR. WACHOWIAK: That is -- The way that that is treated is eventually it will get down to this branch where we ask does it need to isolate.

CONSULTANT WALLIS: Fails to do its job of heat transfer.

MR. WACHOWIAK: Fails to do its job. Yes.

CONSULTANT WALLIS: It doesn't mechanically fail by explosion?

MR. WACHOWIAK: It can. Okay? So it can mechanically fail by explosion, depending on how -- But remember, we still have two other ways that, in a scenario, that are already modeled that a rupture of that isolation condenser -- that is detectable by another control system, and it can be isolated.

CONSULTANT WALLIS: Then you isolate it. Then you shut it off?

MR. WACHOWIAK: Yes. There is a system there. That is not explicitly in here yet. We will consider doing that, but I am pretty sure, after we went through all this, that that particular scenario is not going to be significant, because none of the control systems that provide that isolation in this case are combined with any of the things that are causing this failure from the vent line.

So I don't see that as a big impact. It is something to consider, and we are looking at that.

If we have a success of the GDCS pools and we have the hole, the calculation that we have now shows that it is more than 72 hours before we get to core uncovery from loss of inventory.

So the way the rest of entry goes is, you know, if we fail the equalizing line in, fail the other active injection systems, we are just going to call that a Class 2 sequence, add it to the Class 2s and Level 2, go on. No cut sets survive this branch.

We look at, if the GDCS is successful and the equalizer line is successful, then we have more than 100 hours before we get to core uncovery. I'm sorry, I said core damage. I meant core uncovery. Then core damage happens some number of hours after that. So we have 100 hours on this branch.

What we have looked at is that we can probably -- AS long as we get any kind of active system going, including FAPCS and suppression pool cooling, given the long time frame on this, these are going to be okay. We have got active systems that are working. Suppression pool cooling will delay it out another some number of tens of hours out there, but these PRA analyses, once you get out beyond 72 hours -- some would say once you get out beyond 24 hours -- become a little suspect in terms of their accuracy.

So we have got an active system, active system, active system, active system. If we can have active systems, we are going to say we are okay. Otherwise, we will look at how these progress into Class 2 sequences, because there is a hole and we are going to lose the water.

The only thing that actually ends up surviving the quantification of the base case are the ones that come from success of the passive injection systems and the success of the containment with no further injection. We get about a 10^{-11} increase in CDF from these sequences. So it is not a significant change to the CDF. It is not a significant change to the risk profile. When you propagate this through Level 2, it is not a significant change to the Level 2, even though this is a form of a bypass case in the class. We just call those hard releases in Class 2.

So we know enough now to say that this -- and I can leave this up here. We know enough now to know that this isn't going to affect our base case.

The other place where we were worried about this has a potential impact to the PRA was in the fire scenario, because the fires have the potential to degrade the reliability of some of these things.

When we were designing these systems, we did a couple of things that we had done for designing the previous systems in the plant. When we have an active control system that is providing one of these barriers, like this isolation, we have a control system. We need to have a back-up control system.

In this particular case, because it would cause the isolation of the ICS, it had to be a safety-related control system. So we have a secondary safety-related independent control platform, a control system that provides a back-up isolation. No new valves, but just a new control signal for the isolation valves.

The other thing is we are using the same spurious actuation mitigation scheme for these valves that we use for other things that we didn't want to have spuriously actuate for fires. Took credit for that.

We ran at least the first unverified run through the PRA. It has yet to be validated by an independent modeling and run, but in the initial run no additional cut sets were added to the PRA fire analysis because of this.

MEMBER STETKAR: Go back to the transient, the front end model that you had there. I need to get re-oriented a little bit. There it is.

MR. WACHOWIAK: I don't have a hard copy of this.

MEMBER STETKAR: Point to where the isolation is.

MR. WACHOWIAK: Isolation is in this row right here. This row here, and so this branch and this branch.

MEMBER STETKAR: So it is after you have -- I am assuming it is after you have degraded ICS, so you have to blow down.

MR. WACHOWIAK: Yes. ICS degraded --

MEMBER STETKAR: Is up in there somewhere.

MR. WACHOWIAK: -- is here. So we are on the -- I'm sorry. This is an IORV. We don't take credit for ICS in IORV. So on all the other transients it is after ICS degrade.

MEMBER STETKAR: That is what I was going to -- This is IORV.

MR. WACHOWIAK; Inadvertent open relief valve.

MEMBER STETKAR: Right. Do you have a small LOCA? I mean, this is kind of like a small LOCA model.

MR. WACHOWIAK: Kinda sorta.

MEMBER STETKAR: This is like a medium sort of LOCA. Right?

MR. WACHOWIAK: The small LOCA tree looks very similar to that. So the key is here, it is added in after successful operation of the DPVs.

MEMBER STETKAR: Well, that is what triggers it. Don't they have to isolate on any LOCA?

MR. WACHOWIAK: They do.

MEMBER STETKAR: Regardless of whether the DPVs are successful or not?

MR. WACHOWIAK: If you look at the branch that goes down below here --

MEMBER STETKAR: You showed it to us earlier.

MR. WACHOWIAK: But the way that the small LOCA in this works is, if the DPVs fail, then it goes to core damage.

MEMBER STETKAR: Right.

MR. WACHOWIAK: You don't ask again, does it go to worst core damage. It still goes to core damage.

MEMBER STETKAR: But I am thinking, on the top part of the tree you get into where things work. Don't even get into the DPV demands, though. On the top part of the branch you get into --

MR. WACHOWIAK: Were we okay.

MEMBER STETKAR: -- were you okay.

MR. WACHOWIAK: So on the OK branch, the first OK branch we have an active cooling system. Doesn't matter if we have a hole in the ICS. We have an active cooling system. The second OK branch, we have an active cooling system. So if there is active cooling, we don't need to worry about this.

MEMBER STETKAR: Right, right. Yes.

MR. WACHOWIAK: It is only when we are going to be relying on the passive cooling. In the large LOCAs, we don't ask DPV. So you have to go directly and ask ICS isolation. In the smaller LOCAs, if there is no DPV, you already go to core damage. So e don't have to go to double core damage. We just go to core damage, and then we pick up in the containment event tree whether or not we are going to have additional failure in containment. So we will have to look at that.

MEMBER STETKAR: I was going to say, you could still have -- If you are looking at damage to the IC tubes --

MR. WACHOWIAK: So that would be up in the Level 2, and that is another consideration in the Level 2s. We haven't built that event tree yet. We think we know what it looks like, but we haven't built that yet, and you are right. If there are any sequences going into the Level 2 --

MEMBER STETKAR: They would be out there.

MR. WACHOWIAK: -- that end up as OK under CD1 or CD3 in the Level 2, we would have to have asked did the ICS isolate.

MEMBER STETKAR: Yes. Okay.

MR. WACHOWIAK: Haven't gotten that far yet.

MEMBER STETKAR: As long as he has got a tick mark, then he needs to look at it.

MR. WACHOWIAK: So if there is anything else -- good points there that we need to look at. We just want to make sure that we are covering all of our bases, and if you think of something else that we need to look at, great. We will factor it in. We are not quite there yet.

My conclusion from before, after looking at the fire scenarios, I am expecting the flood and high wind scenarios to come out to be the same, that initiators on those are low enough that we don't degrade the mitigating systems enough, that these are going to just fall out in the truncation, and we won't see them.

I think I covered all those. The one thing that I am not sure that I did cover was one other area that we had to look at in this particular case.

If you remember, back in 2006 -- I think most of you were herein 2006 -- we made a presentation on the thermal hydraulic uncertainty for a success criteria. You remember from earlier in the day, we changed some of the parameters of the PCCS heat exchanger, which changed its heat transfer characteristics.

We have re-performed the PCCS portion of the thermal hydraulic uncertainty calculation, and while the numbers are somewhat different, the conclusions are exactly the same as what we had before.

CHAIRMAN CORRADINI: In terms of success criteria?

MR. WACHOWIAK: In terms of success criteria. There is margin down to including only two PCCS heat exchangers as working without having any appreciable effect on the containment pressure in the severe accident case.

So we think we have got that. That is the one main uncertainty that we -- uncertainty analysis that we knew we needed to re-perform because of the changes we made here, and again it doesn't --- There is an interesting phenomenon that goes with this, though.

As you -- If -- and I am not sure how we can fail a PCCS heat exchanger, but if you do fail PCCS heat exchangers and get down to fewer and fewer available, then the hydrogen and oxygen concentrations go way down, and the steam fractions are up at 100 percent because it bypassing enough steam.

So it is just an interesting phenomenon. Not sure what we can do, if we can do anything with that, but it is an interesting phenomenon.

CHAIRMAN CORRADINI: That answers, actually, a question you asked privately about this.

MEMBER STETKAR: Well, no, he is talking

PCCS. I was talking ICS.

CHAIRMAN CORRADINI: Oh, it is probably a similar sort of argument.

MR. WACHOWIAK: That is essentially what that purge or what that new vent line is doing, is it is providing a bypass of steam.

CHAIRMAN CORRADINI: Okay. I think we are going to go around the table and get --

CONSULTANT KRESS: One quick question. Could you, just out of curiosity, refresh my memory on what your definition of LRF is? Is that becomes a bypass sequence or --

MR. WACHOWIAK: Our definition for ESBWR design PRA, LRF is defined as any release that is greater than tech spec allowed.

CONSULTANT KRESS: Does it matter when?

MR. WACHOWIAK: Doesn't matter when, doesn't matter where.

CONSULTANT KRESS: Doesn't matter when or where.

MR. WACHOWIAK: Right. if the core is damaged and there is something getting outside of the containment, then we just call it a release. Ours is really more ARF than LRF, any release frequency. Certainly bounds large release frequency, and someday somebody will come up with a definition for a large release frequency and figure out how to deal with it.

CHAIRMAN CORRADINI: Graham.

CONSULTANT WALLIS: This last item, the PCCS severe accident igniters -- now that is there in the drums at the bottom?

MR. WACHOWIAK: Lower drum.

CONSULTANT WALLIS: And that is something else you are adding to the PCCS?

MR. WACHOWIAK: Yes. Let me say this. If we get management approval to add them to the lower drums on Thursday, they will be added.

CONSULTANT WALLIS: Well, will you use them then to mitigate the -- with the build-up of combustible material we were talking about earlier today?

MR. WACHOWIAK: The way we are doing this is we are adding it to the BiMAC control system.

CONSULTANT WALLIS: So it wouldn't come on.

MR. WACHOWIAK: So it wouldn't come on automatically.

CONSULTANT WALLIS: But it is there.

MR. WACHOWIAK: It would not come on automatically in that time frame, and what I said is we would not put in a requirement that it must not come on. So I think we will be leaving the opportunity for our HFE guys to go in and look to see if that is something worth crediting as an operator action performed from the control room when we do the DAC for the HFE.

MEMBER STETKAR: They are not wiring it into any safety-related instrumentation and control system design.

MR. WACHOWIAK: The only safety-related aspect of these igniters would be their pressure retention capability.

CONSULTANT WALLIS: But they could be used.

MR. WACHOWIAK: They could be used, but we are not crediting it at this point in time.

CONSULTANT WALLIS: Not taking credit. Okay.

MR. WACHOWIAK: So we left the opportunity for the HFE to decide that they should be.

MEMBER STETKAR: In the event you don't management approval to put these igniters in, what would you do?

MR. WACHOWIAK: We will do something else. We have gone through the steps necessary. We have done the briefings. We just haven't executed the last step. We would have liked to have done that before coming here, but it was not possible.

CHAIRMAN CORRADINI: So I will thank Rick, and I would like to go around to all the members, starting with Jack, about comments that I can take down.

Let me encourage you all to keep your comments in two bins. Bin one is long term cooling, which was the very first thing we heard from them and from staff this morning, and Bin Two is everything else; because the everything else is going to be a letter that is still on track for October-ish, whereas long term cooling, we have to respond back to the Commission on a per advance planned basis, and that is September.

So I would like to make sure I get your comments separated like that, so in case there is a problem with long term cooling, I can capture it. Jack?

MEMBER SIEBER: I have no comments or concerns.

CHAIRMAN CORRADINI: Graham?

CONSULTANT WALLIS: Well, first of all, we heard about this containment pressure. It is long term cooling, and there was a response to an RAI, SO-6. There were a lot of things in that response that weren't discussed today, like the oscillation flow and the discharge from the PCCS.

I was wondering if the staff is going to pick up on some of those. They said everything was resolved. So I will mention that.

In the vacuum breakers -- is it okay to talk about the vacuum breaker? This facility, which I think is clear, needs to be designed with more care and more attention to detail, and a thought given to what really happens physically in there. We spent a lot of time on that.

On the hydrogen issue, I would like to hear more about the ICS. We were told that it built up over a certain period of time, but there was no detail about that. What is the concentration versus time? What are the volumes involved? I would like to satisfy myself that TRAC is doing the right job of those predictions. It takes 10 hours before you have to do anything. Seems an awful long time.

On the last one, the PCCS redesign, it is sort of a surprising thing to have to redesign it so much, but I think, from what I have heard, that you are on a reasonable track. You seem to be considering the right things. I am not an expert on these factors of 2.5 and 2 and 19 and all that, but if they are valid, then you seem to be on a reasonable track. We still have to hear more about the ICS.

CHAIRMAN CORRADINI: And maybe I should have said at the beginning. My impression is that when we get to Chapter 6 in the Subcommittee meeting in September, we will come back and hear about that topic.

CONSULTANT WALLIS: And, of course, I will write you my usual report which will elaborate on all things, too.

CHAIRMAN CORRADINI: With details and line drawings.

MEMBER RYAN: I didn't have any concerns, but I wanted to especially mention Dr. Shepherd's presentation. I thought it was very lucid and informative and appreciate the detail he provided.

MEMBER ABDEL-KHALIK: I am still concerned about this vacuum breaker leak detection. I think you ought to be thinking about Plan B, because intuitively, despite the detail and the experiments,

I am not sure that this approach will ultimately allow you to detect leaks down to the .6 square centimeter level, but I am willing to wait until you run the experiments, and we will see what the results look like. But I just think there is a great deal of uncertainty on the relationship between the leak and the quantity that you will detect.

The parameter that you will measure, that to be able to use that relationship to take such an action as isolating the vacuum breaker will be a bit tenuous.

As far as the PCCS redesign, I am just amazed at how robust these components have become, and intuitively I think that this should be able to handle any of these explosions that will fall its way.

CHAIRMAN CORRADINI: Sam?

MEMBER ARMIJO: As far as the long term cooling, I think that issue is resolved. The new -- The updated MELCOR-TRAC analyses match the peak pressure, and then on the longer term the pressure is not going up, and the deltas between these two analyses aren't really important for the long term.

I am a little more optimistic about the ability to detect the temperature increase, even at these tiny, tiny leak rates, but again the only way to really nail it is by experiment.

CHAIRMAN CORRADINI: Right.

MEMBER ARMIJO: The PCCS has gotten to be a tank. It is really a robust system. I just wonder why GEH hasn't taken a look at another approach, but this is the approach you have taken, and I think you can make it work.

That is all I have.

MEMBER STETKAR: I have nothing more.

CONSULTANT KRESS: I have to agree with Sam, and I think the long term cooling issue has been properly addressed by the staff and by GEH, and that's pretty good.

I share Said's problem with the vacuum detection system. I think it can be made to work, but I think we need to see a little more about how many thermocouples, where they are going to be, and that sort of thing. I am skeptic, but I think it can be made to work.

I think we did bring up a question about what happens if all three vacuum breakers had been isolated, and we ought to hear something about that they have got a way to get around that, but we have yet to hear that.

MR. WACHOWIAK: We identified that as a follow-up item. The person I need to get to answer that is not available today.

CONSULTANT KRESS: I guess I agree with

Graham that we need to see more of the details on the ICS calculations and concentrations.

There was one issue that got passed over a little bit, and that was the PCS system's parallel path with saying delta T pressures on each end. I do think there is a potential there for one path to starve the other, and I think that needs to be thought about at least and looked at to see if there is such a potential.

The way it can work is if you get a little bit of non-parallel -- But what can happen is you can back up liquid in one and starve it from flow through the other one, and it can end up with the same delta P, but most of the play going down one path. It is not your standard parallel path in instability, but it can happen.

I think that needs to be thought about a little bit.

i think they designed he PCCS to where it can stand any detonations you get from radiolytic decomposition, and I think Level C is the right level to think about all those, too. So I think that is all right, a substantial design. That's it.

CHAIRMAN CORRADINI: That's it?

MR. WACHOWIAK: I do want to bring up one amendment to an earlier comment. When Wayne was talking about the flow rate through the vacuum breaker, he had mentioned a value, one pounds per second. The question is does that seem reasonable, and it doesn't seem reasonable.

So we are in the process of checking that to see if that was a unit conversion issue or a decimal point placement issue, but we are not warranting the .1 feet or pounds per second number.

CONSULTANT WALLIS: there were some problems when you presented this source before, and I think I calculated that you have mach three going through the holes.

MR. WACHOWIAK: There is something with that. I would expect to -- It is too high. The velocities come out to be around 700 feet per second, and they should be more like 180 feet per second.

MEMBER ARMIJO: I kind of withdraw my comment about the detectability thing, because I was using that number to do my own back-of-the-envelope.

MR. WACHOWIAK: So it seems too high, and I am not -- We will find out what the right value is.

MEMBER STETKAR: Rick, this is a side comment, but it is a question I have been trying to think about. There is a tech spec requirement that, once every two years or once a refueling outage, you have to verify that the leakage through those vacuum breakers is less than whatever the equivalent of two square centimeters is.

MR. WACHOWIAK: It is less than that, but yes.

MEMBER STETKAR: Yes. Actually, it is less than -- It is half that. By pumping up the drywell, I guess --

CHAIRMAN CORRADINI: No, no, no. They had answered that early on.

MEMBER STETKAR: Oh, did they really? Okay.

CHAIRMAN CORRADINI: Put essentially a hut over each one of the vacuum breakers and essentially --

MEMBER STETKAR: Oh, yes.

MR. WACHOWIAK: And we talked to a company that does that type of leak break testing, and I think when we presented that the first time, we said that.

MEMBER STETKAR: I see. Sorry. Thanks.

CHAIRMAN CORRADINI: So the only thing I guess I have to add -- and I think I captured all my colleagues' comments. I think the one thing, and I know you were pressed for this -- I asked you a bit aside -- is that I guess I am looking for, when we see

Chapter 6 again and the isolation condenser, is an evolution of how you get to where you want to isolate or get to how you want to vent.

That just whizzed by way too quickly for me in terms of a calculation. Now Graham was asking very specific things about concentrations here, but I think we were expecting to see some evolution of this to the point of venting, to the point of essentially isolating and venting, depending the two approaches.

I think that might give us a bit more confidence, because at this point we are, I would say, a tad in the ark about that.

MEMBER STETKAR: I think it is mostly the venting, the timing on the venting.

CHAIRMAN CORRADINI: I'm sorry, the timing on the venting.

MEMBER STETKAR: The timing of the venting.

CHAIRMAN CORRADINI: But everything up to that venting point, to make sure there is time, because you were choosing a time, and it was related to the time in which build-up occurs. I think that is the one thing that would give us some confidence. Other than that, I think all the other points were captured.

MR. WACHOWIAK: We had that information.

CHAIRMAN CORRADINI: I understand.

I want to ask, though, because -- I'm sorry. I wanted to ask: Was a member of the public going to make a comment or just wanted to listen in?

MR. KEEGAN: Hello. Yes, I have been listening in. Some very interesting information.

CHAIRMAN CORRADINI: Yes, go ahead.

MR. KEEGAN: This is Michael Keegan with Don't Waste Michigan.

CHAIRMAN CORRADINI: Okay.

MR. KEEGAN; Yes. Very appreciative to be able to sit in. I am looking forward to reading and reviewing the transcript, and I have no further comments at this time.

CHAIRMAN CORRADINI: Okay. Thank you. I just wanted to make sure, because I wasn't sure if you were listening in or you had a comment for us. Thank you very much.

MR. KEEGAN: Thank you very much.

CHAIRMAN CORRADINI: So with that, I will thank members of the staff and of GEH for today, and we will adjourn the meeting.

I will talk with Amy separately as we prepare for the full Committee meeting relative to long term cooling, and to remind everybody, we have a Subcommittee on the week of the 16th. I don't dare give you the dates, because they will probably change, the week of the 16th of August and the week of the 22nd or 21st of September.

Meeting adjourned.

(Whereupon, the Subcommittee adjourned at 5:14 p.m.)

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United States Nuclear Regulatory Commission
Protecting People and the Environment

Presentation to the ACRS ESBWR Subcommittee

ESBWR Open Items

July 13, 2010

ACRS Subcommittee Presentation ESBWR Open Items

Staff Review Team

- Project Manager
  - Leslie Perkins

- Technical Staff
  - NRO/DSRA/SBCV Reviewer – Hanry Wagage
  - NRO/DSRA/SRSB Reviewer – George Thomas
  - NRO/DE/EMB1 Reviewer – Tuan Le
  - NRO/DE/SEB2 Reviewer – Samir Chakrabarti
  - NRO/DE/CIB2 Reviewer – Robert Davis
  - RES/DSA/FSTB Reviewers – Allen Notafrancesco and Hossein Esmaili

Outline

Containment long-term cooling (RAI 6.2-140)

– Hanry Wagage

Hydrogen Accumulation in PCCS (RAI 6.2-202):

PCCS Functional Design and Detonation Pressure Loading

– Hanry Wagage and Joe Shepherd (Caltech)

PCCS Structural Design

– Tuan Le and Mano Subudhi (BNL)

Containment Structural Design

– Samir Chakrabarti and Manuel Miranda (BNL)

Vacuum Breaker Leakage Detection (RAI 6.2-148)

– Hanry Wagage

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Presentation to the ACRS ESBWR Subcommittee

ESBWR Open Items: Containment Long-term Cooling (RAI 6.2-140)

Hanry Wagage

July 13, 2010

Containment Long-term Cooling (RAI 6.2-140)

- Regulatory Criteria: 10 CFR 50.46(b)(5) and GDC 50 of 10 CFR 50 Appendix A
- December 3, 2009, ACRS meeting
- TRACG and MELCOR differences
- PCCS pool level control
- PCCS vent fan submergence

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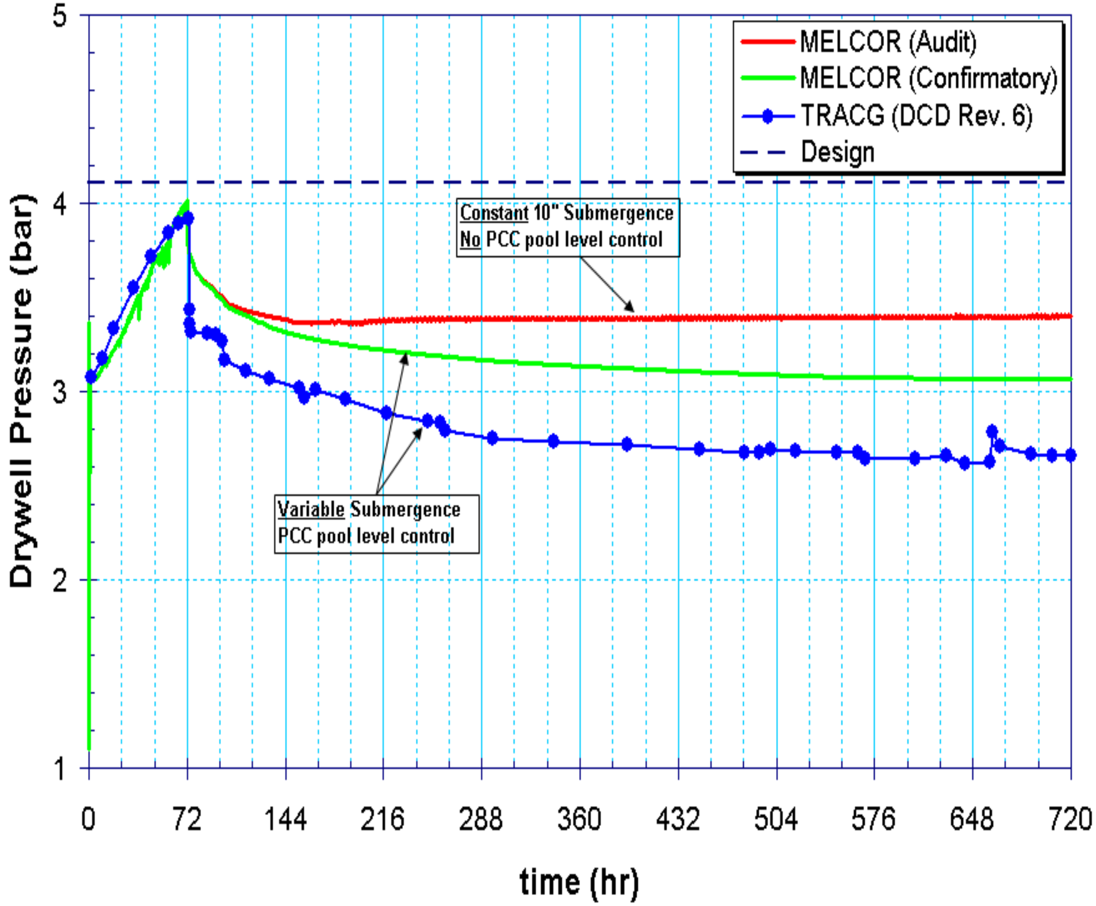

DCD Rev 6 (TRACG)

Pool level control (variant procedure)
Fan vent with varying submergence (variant design)

Confirmatory Calculation

MELCOR ESBWR plant
with level control
without GDCS pool tray

Figure 1. Drywell pressure predicted by MELCOR and TRACG (DCD Rev. 6) for MSLB (bounding case) (presented at December 3, 2009, ACRS Meeting)

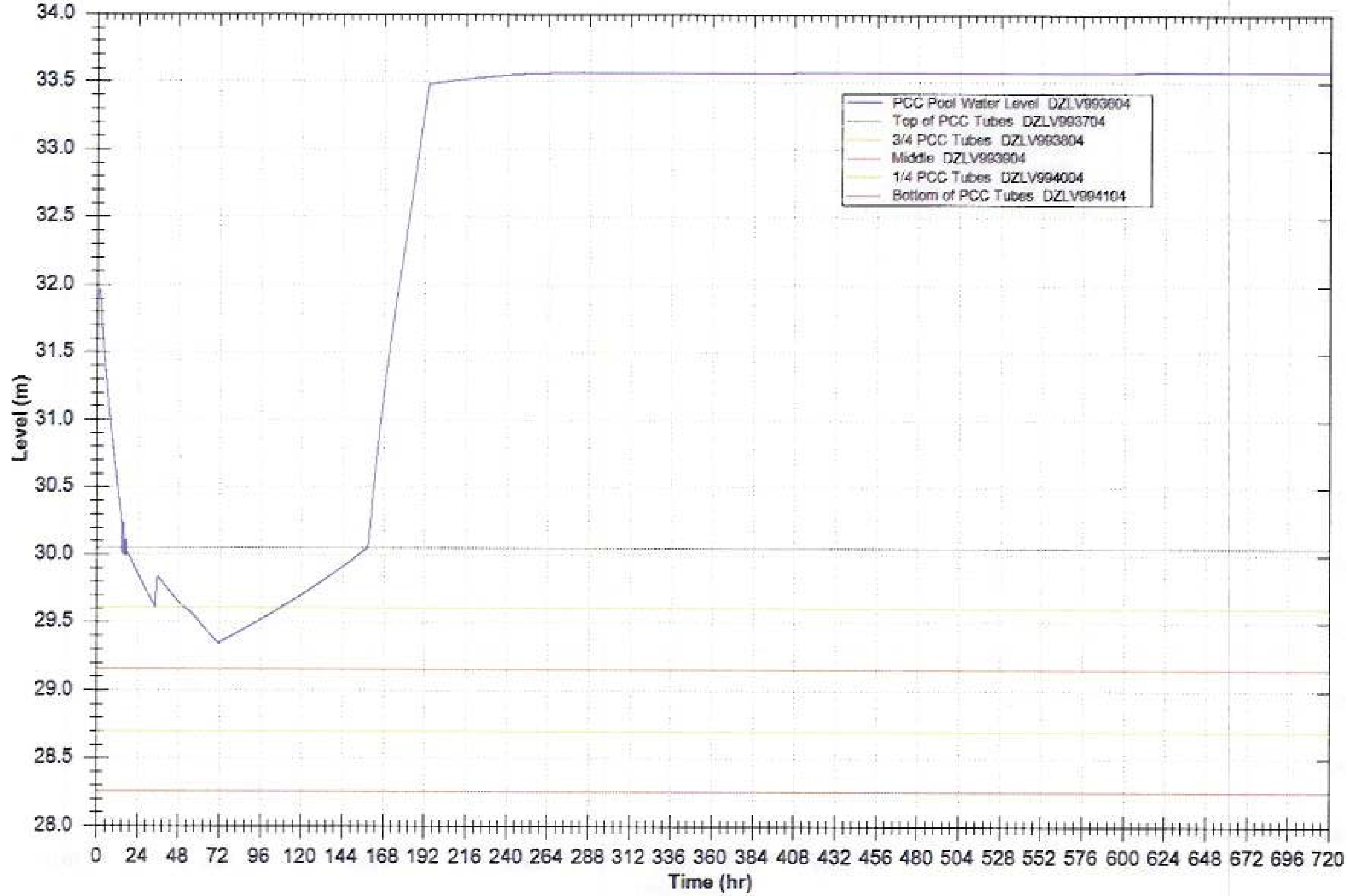

Figure 2. PCCS pool level predicted by TRACG (DCD Rev. 7) for MSLB (bounding case)

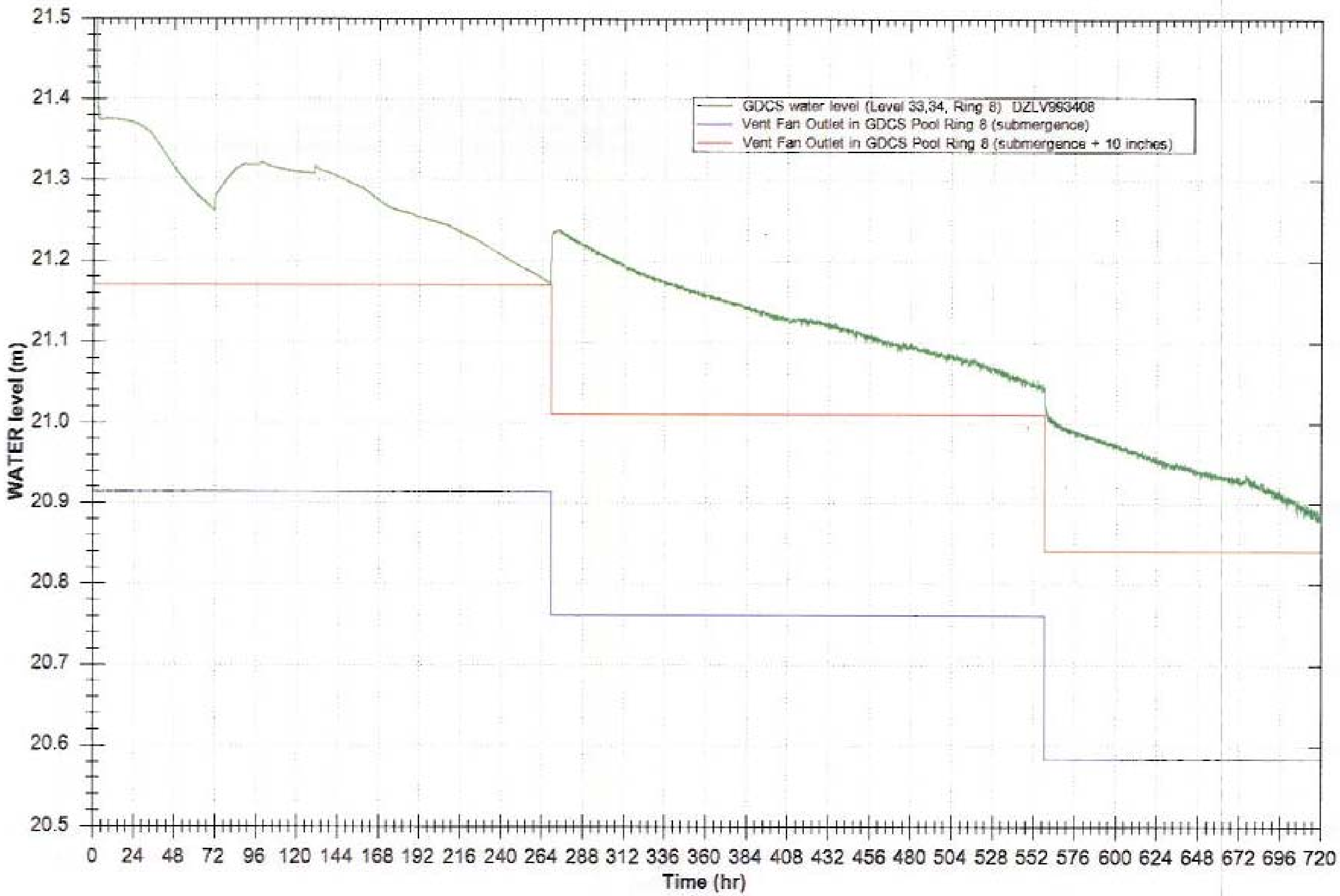

Figure 3. PCCS vent line exit elevation used and GDCS pool water level predicted by TRACG (DCD Rev. 7) for MSLB (bounding case)

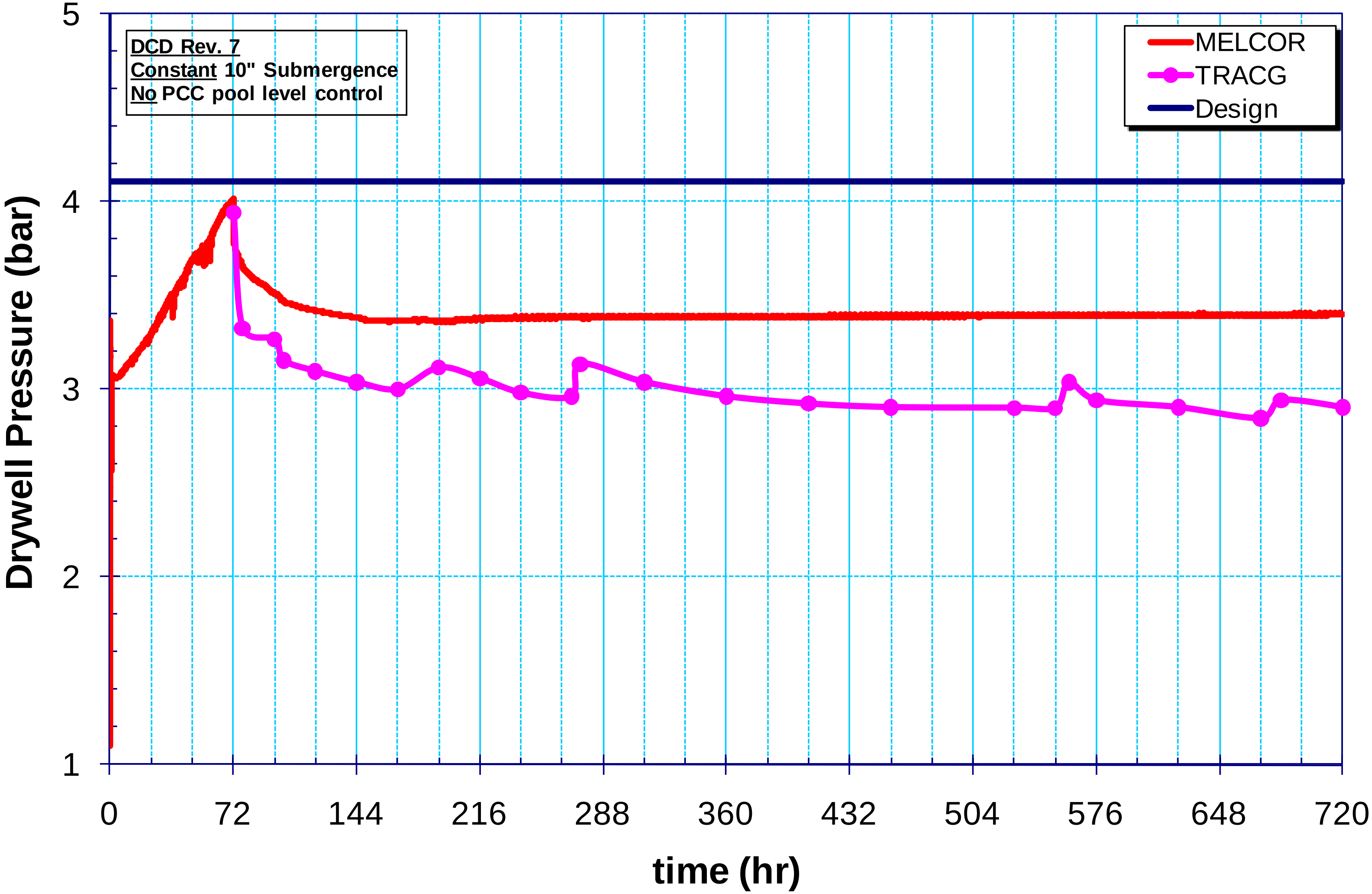

Figure 4. Drywell pressure predicted by MELCOR and TRACG (DCD Rev. 7) for MSLB (bounding case)

Containment Long-term Cooling: Conclusion

- ESBWR design-basis LOCA containment long-term pressure response calculated by TRACG, which is confirmed by staff's MELCOR analysis, is below the containment design pressure and is acceptable
- RAI 6.2-140 is closed

United States Nuclear Regulatory Commission

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Presentation to the ACRS ESBWR Subcommittee

ESBWR Open Items:
Hydrogen Accumulation in PCCS (RAI 6.2-202):
PCCS Functional Design and Detonation Pressure Loading

Hanry Wagage and Joe Shepherd (Caltech)

July 13, 2010

Hydrogen Accumulation in PCCS (RAI 6.2-202): PCCS Functional Design and Detonation Pressure Loading

- **ACRS raised a concern on the possibility of hydrogen accumulation in PCCS at a November 2009 meeting**
- **The staff expanded the issue to ICS**
- **MELCOR results show hydrogen and oxygen mole fractions of 48%, and 24%, respectively, in the PCCS lower drum, at 8 hours after a LOCA**
- **At high concentrations of hydrogen and oxygen, a minimal energy is needed to initiate ignition**

PCCS Functional Design and Detonation Pressure Loading

- Regulatory Criteria: 10 CFR 50.46(b)(5), and GDC 38 and 50 of 10 CFR 50 Appendix A
- Staff issued RAI 6.2-202 on December 11, 2009
- Additional issues discussed in public meetings and issued as supplemental RAIs
- GEH submitted NEDE-33572P Rev. 1 to provide technical details
- PCCS design basis is to perform its safety function after multiple hydrogen detonations

Hydrogen Accumulation in PCCS (RAI 6.2-202): Summary of PCCS Design

Status:

- **Issue resolution is ongoing**

Resolved issues:

- Hydrogen concentrations
- Detonation pressure loading in PCCS tubes
- Case by case evaluations using ASME Section III Class MC components
- Loading combination to include detonation pressure plus all other applicable loads per NUREG-800 SRP 3.8.2

Hydrogen Accumulation in PCCS (RAI 6.2-202): Summary of PCCS Design

Open issues:

- Detonation pressure loading in PCCS lower drum and drain and vent lines
- Modifications of lower-drum covers and drain nozzles to account for high stresses
- Detonation effects on PCCS components not directly exposed to detonations (e.g., anchorage, support frame, and pool slab penetrations)
- Fatigue evaluations for multiple detonations
- Design of ICS

Hydrogen Accumulation in PCCS (RAI 6.2-202): Summary of PCCS Design

Open issues (con.):

- PCCS Heat transfer capacity
- Accounting for thermal effects generated by detonations in the design

PCCS Functional Design and Detonation Pressure Loading: PCCS Design Changes

- **PCCS condenser tubing**
  - **Changed material from SA-213 Gr TP304L to SA-312 Gr XM-19**
  - **Increased thickness**
  - **Increased number of tubes per module (2 modules in each PCCS condenser)**
- **Increased thickness of lower drum and changed** material to SA-182 Gr XM-19
- Added catalyst (platinum or palladium coated plates) to the vent in the lower drum of the condenser

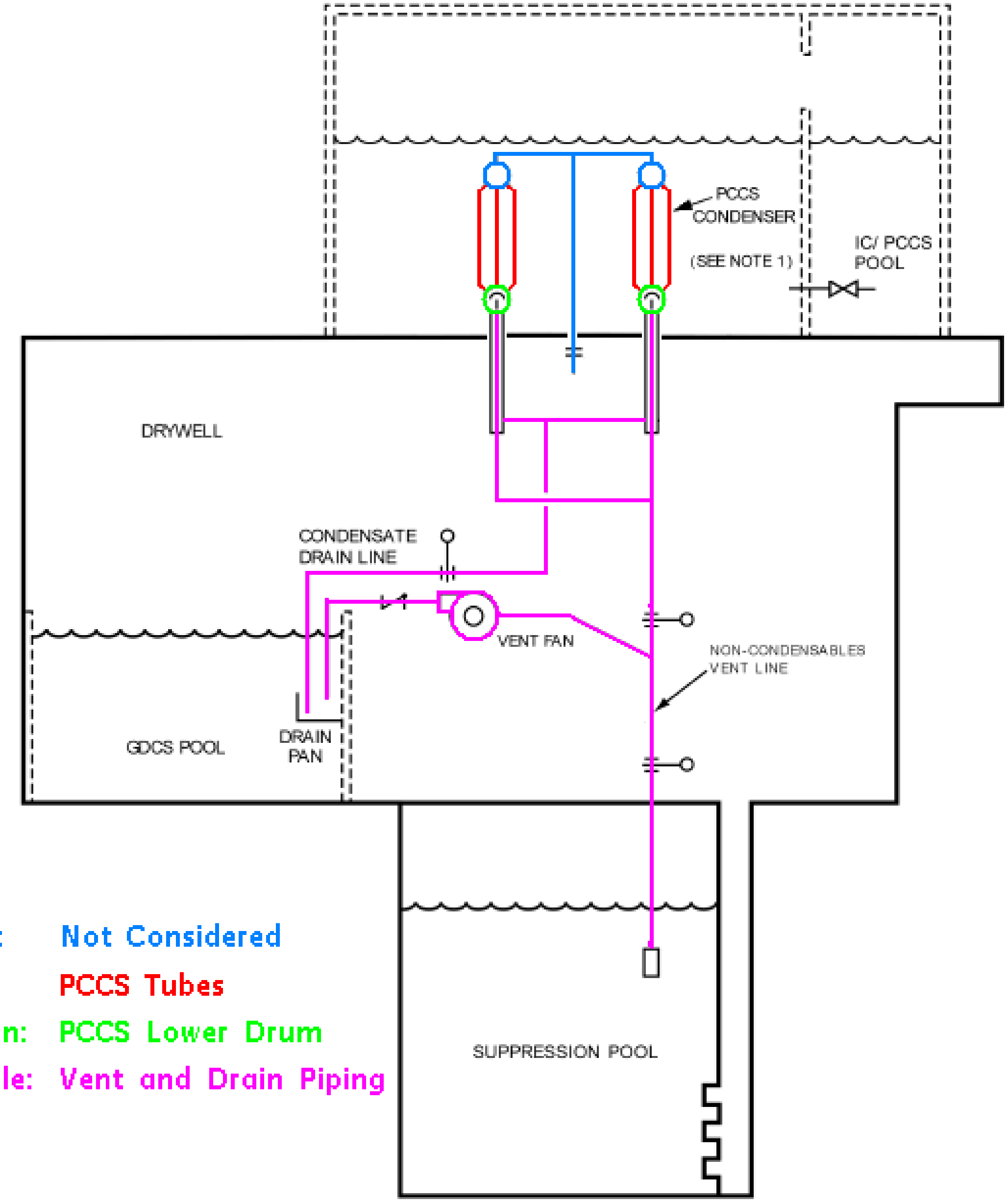
PCCS Functional Design and Detonation Pressure Loading: Evaluation of the Catalyst Module

- **Impact of potential performance inhibitors (e.g., aerosols, condensate, etc.):**
  - **Little potential for poisons and inhibitors other than steam is expected under ESBWR DBA conditions**
  - **Design of the vent entrance limits water droplets carryover; high temperature during recombination causes any water carried into the recombiner to evaporate**
  - **EPRI evaluations showed functionality under beyond DBA conditions; flow channels of PCCS catalyst are equal or larger than EPRI prototypical design**

PCCS Functional Design and Detonation Pressure Loading: Evaluation of the Catalyst Module (con.)

- **Catalyst warm-up is unimportant since flow through the catalyst module does not depend on convection currents (i.e., flow is driven by differential pressure between drywell and wetwell).**
- **At peak recombination flux, GEH should confirm that recombiner temperature will be below the auto-ignition limit (i.e., ~560 ºC). GEH should establish final design values (e.g., recombination rate, temperature, etc.)**
- **GEH should perform ESBWR-specific calculations to assess impact of various catalyst design parameters on gas mixture entering the vent line under DBA conditions to demonstrate module effectiveness.**
- **GEH should address the impact of detonations on structural integrity of the catalyst module**

Figure 1: Portions of PCCS Considered for Detonation



Blue: Not Considered
Red: PCCS Tubes
Green: PCCS Lower Drum
Purple: Vent and Drain Piping

PCCS Functional Design and Detonation Pressure Loading: Issues to be Resolved

- PCCS heat transfer capacity should be sufficient for containment long-term cooling
- The staff raised issue with vent and drain lines designs
- Pressure loading on the lower drum should include deflagration to detonation transition (DDT)

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Presentation to the ACRS ESBWR Subcommittee

ESBWR Open Items:
Hydrogen Accumulation in PCCS (RAI 6.2-202):
Evaluation of Detonation and DDT response of PCCS

Joe Shepherd (Caltech)

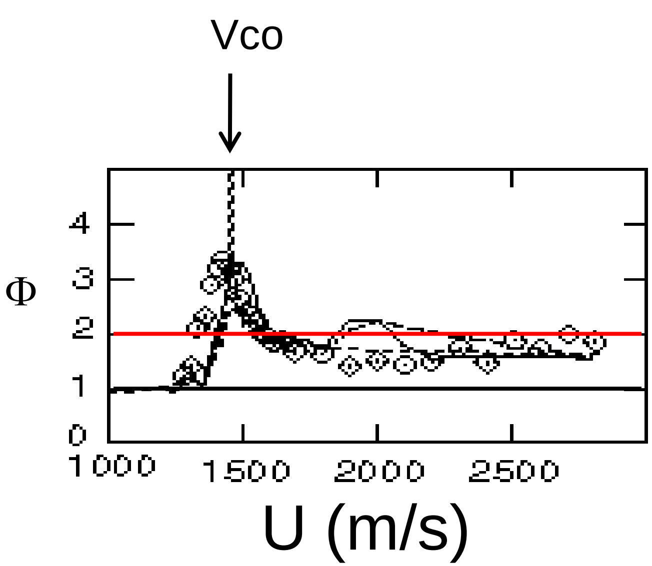
July 13, 2010

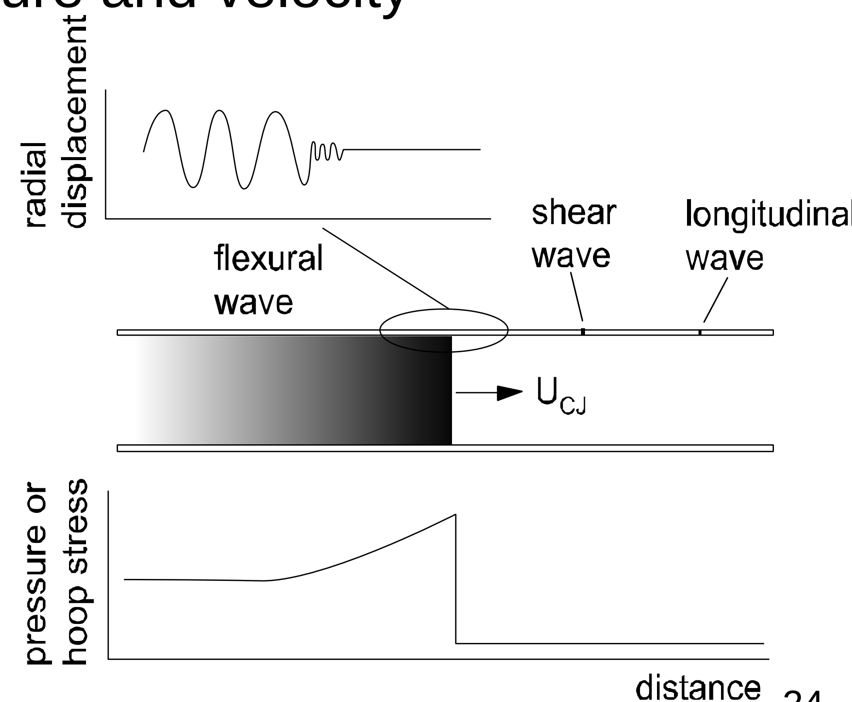
GEH Methodology for PCCS Tubes

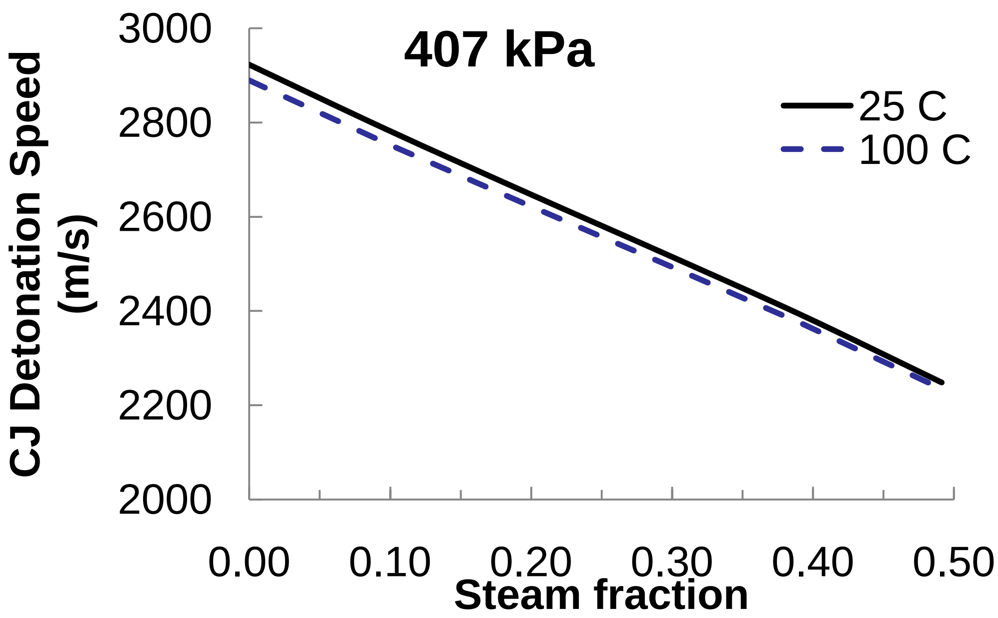
- Static analysis based on dynamic load factor and equivalent static pressure
- Approach is based on experimental data and analysis of detonations in tubes (Shepherd and Beltman, 2002)
- Select multiplier based on
  - Single-degree-of –freedom models of structural response
  - Experimental measurements of strains
- Limitations
  - Neglects vibrations and wave interference effects
  - Neglects reaction forces due to propagating waves changing directions
  - Deflagration-to-detonation transition can result in higher loads – requires estimating response based on experimental data.

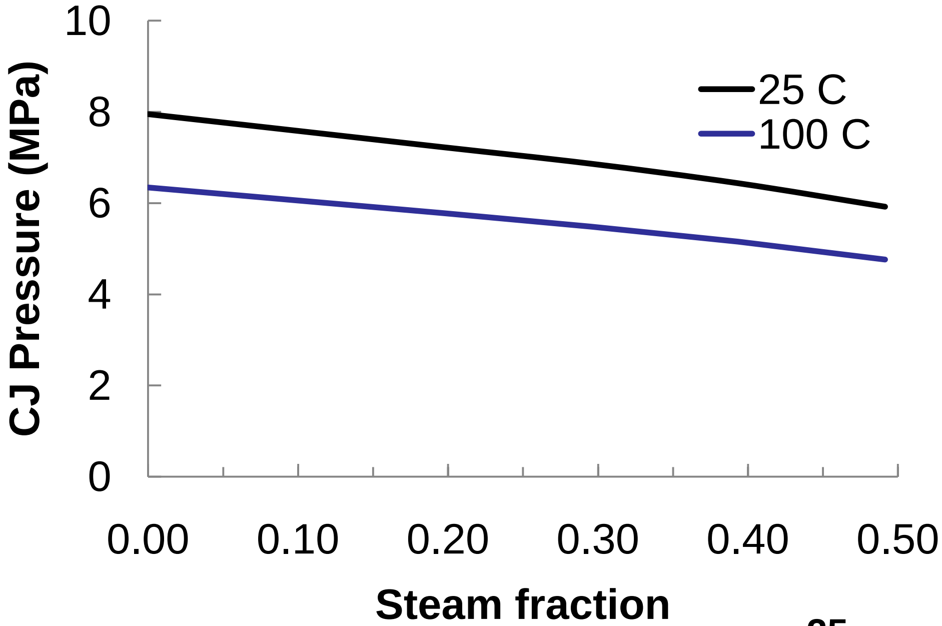
Detonations in Straight Pipes

- Traveling load – step increase in pressure $\sigma_h = \Phi \frac{R}{h} \Delta P_{CJ}$
- Hoop strain in straight pipes
  - Dynamic effect 2 x equivalent static response $\Phi = 2$
  - Exceptional situation of resonance up to 4 x static $\Phi \leq 4$
- Bounding estimates from
  - Thermochemical computations (**CJ = Chapman-Jouguet model**) of detonation pressure and velocity
  - Simple structural models







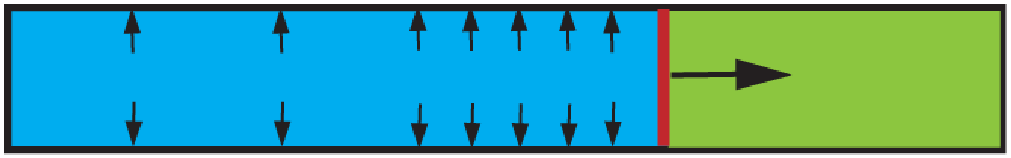


- Thermochemical computations of CJ detonation properties
- Bounding case, 25 °C and 407 kPa, 0 % steam
- CJ Pressure 7.95 MPa (P_{cj}/P_o = 19. 5)
- Wave speed substantially higher than V_{co} => Φ ~ 2
- Equivalent static pressure 7.95 x 2.5 x 2 = 39.8 Mpa

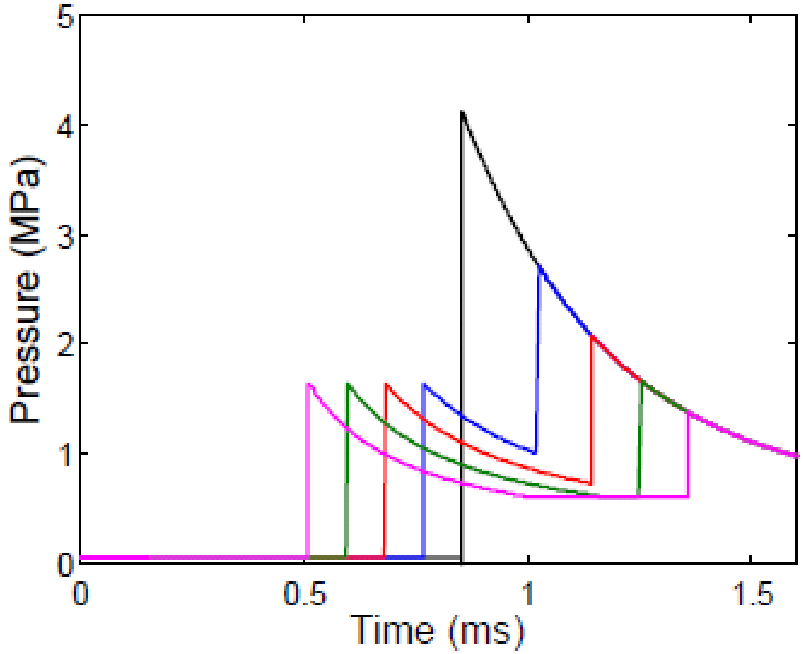
Assumes reflection of detonation

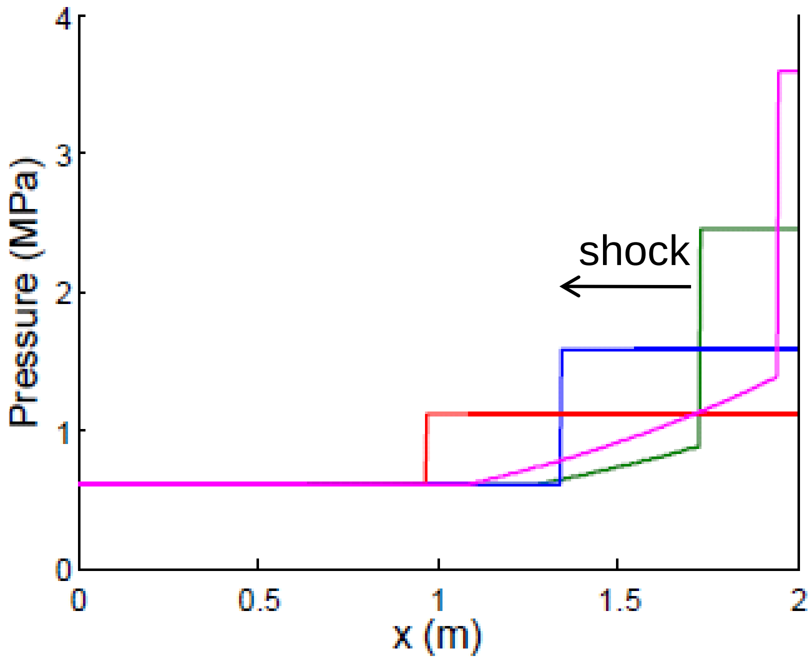
- GEH assumes 38.7 Mpa

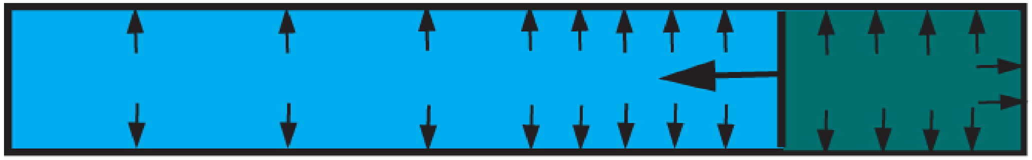
Computation using Shock and Detonation Toolbox FM



Incident detonation



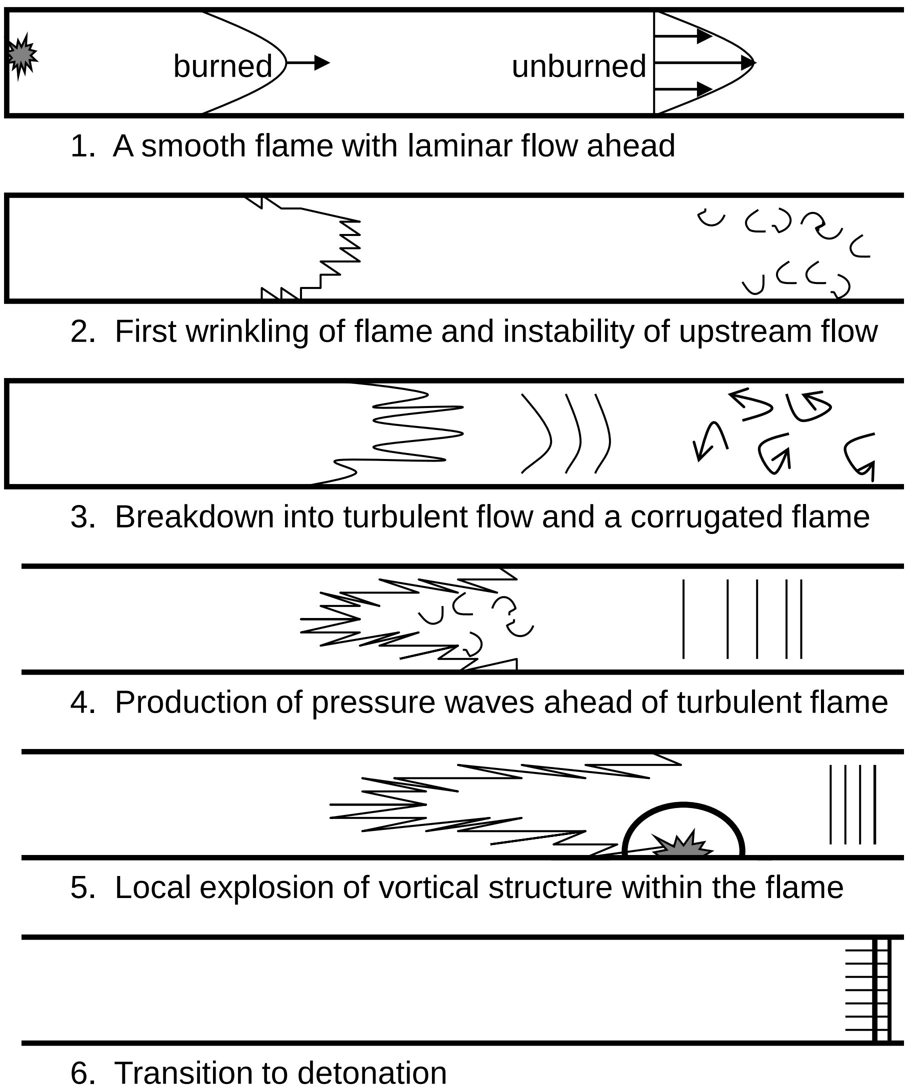




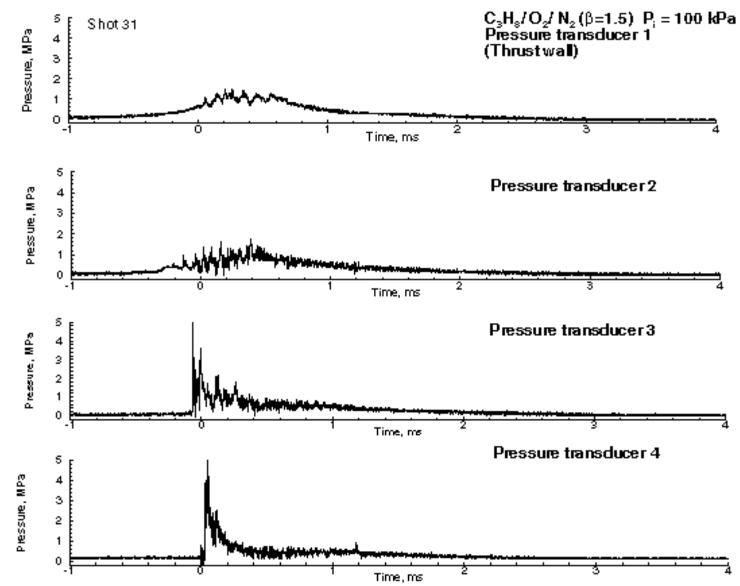
Reflected shock wave

Detonation Induced Strain in Tubes, Ph D Thesis, J. A. Karnesky
California Institute of Technology Pasadena, California 2010

Deflagration to Detonation Transition



- Flame creates flow
  - Pressure build-up
- Detonation onset
  - Localized



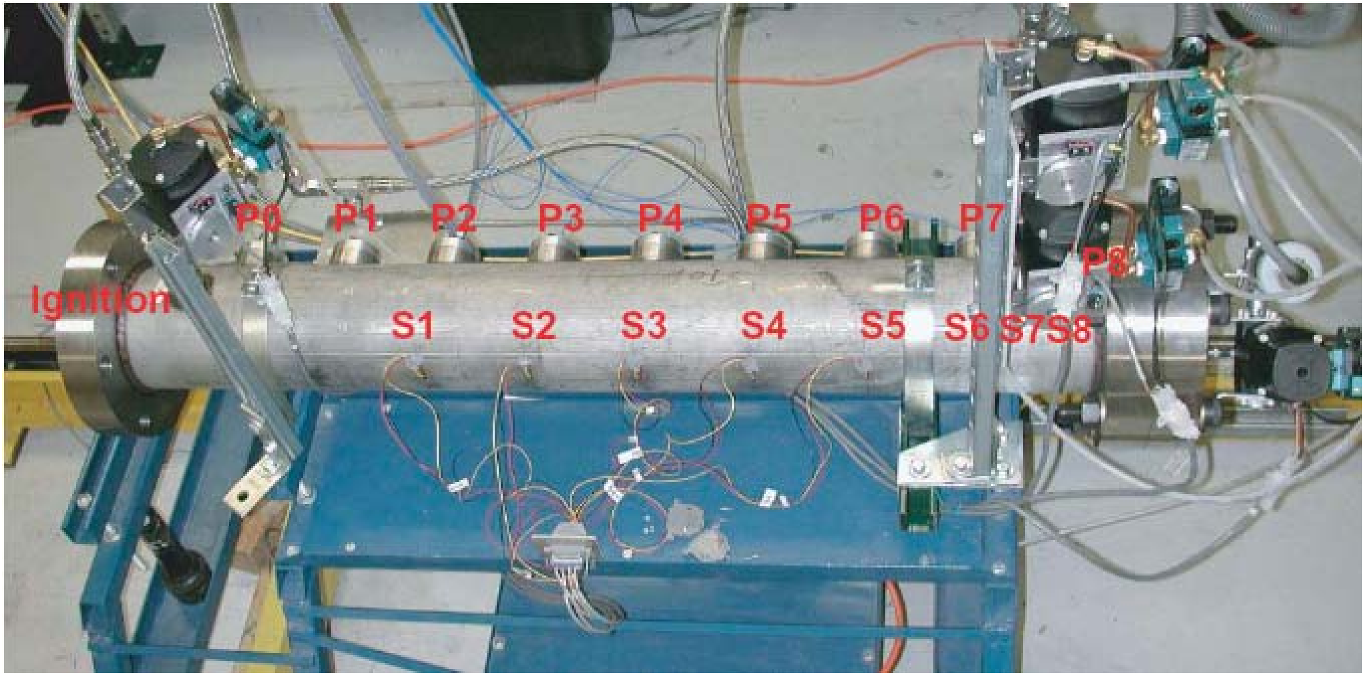
Characterizing DDT Structural Response

- DDT more hazardous than detonation
  - Structural loading higher
- Requires testing of mixtures and geometries of interest
  - Complex, unsteady motion in gas
  - Computational methods in research stage
  - Loading is
    - Localized
    - Unsteady
- Use direct measurements of strain to define dynamic load factor

$$\Phi = \frac{\text{Peak dynamic strain}}{\text{Reference Static strain}}$$

Measuring Structural Response to DDT

Thick walled vessels for elastic response
Thin-walled vessels for plastic response and failure



Use bars or tabs as “obstacles” to cause flame acceleration

FM2010.005

Single Degree of Freedom (SDOF) Model

Maximum dynamic hoop stress

$$\sigma_H = \frac{\Phi \Delta P R}{t}$$

Φ = dynamic loading factor

$\Delta P = P_{max} - P_{atm}$

R = tube radius

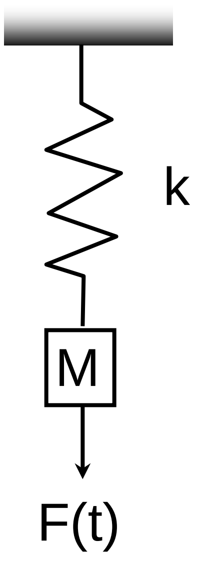
t = tube thickness

τ = characteristic structural response time

$$\omega = \frac{2\pi}{\tau} = \sqrt{\frac{k}{M}}$$

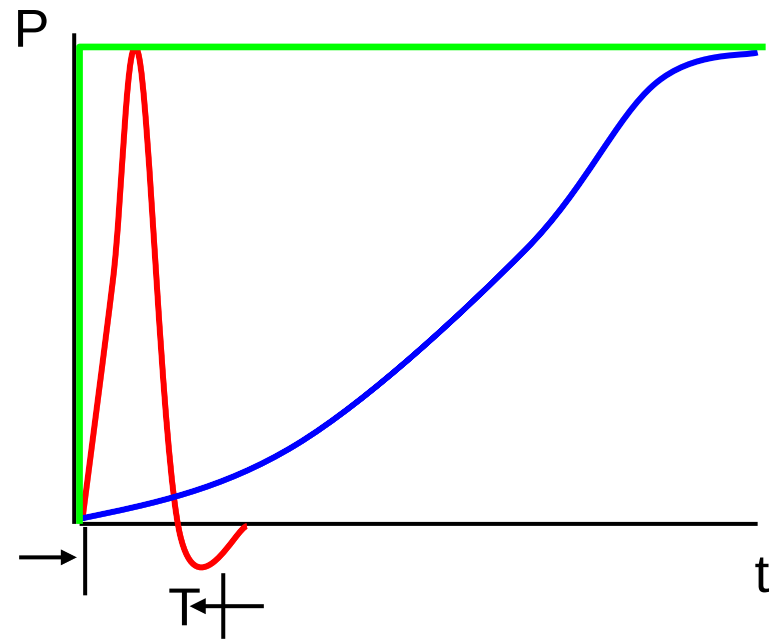
$$\tau = \frac{2\pi R}{\sqrt{E/\rho}}$$

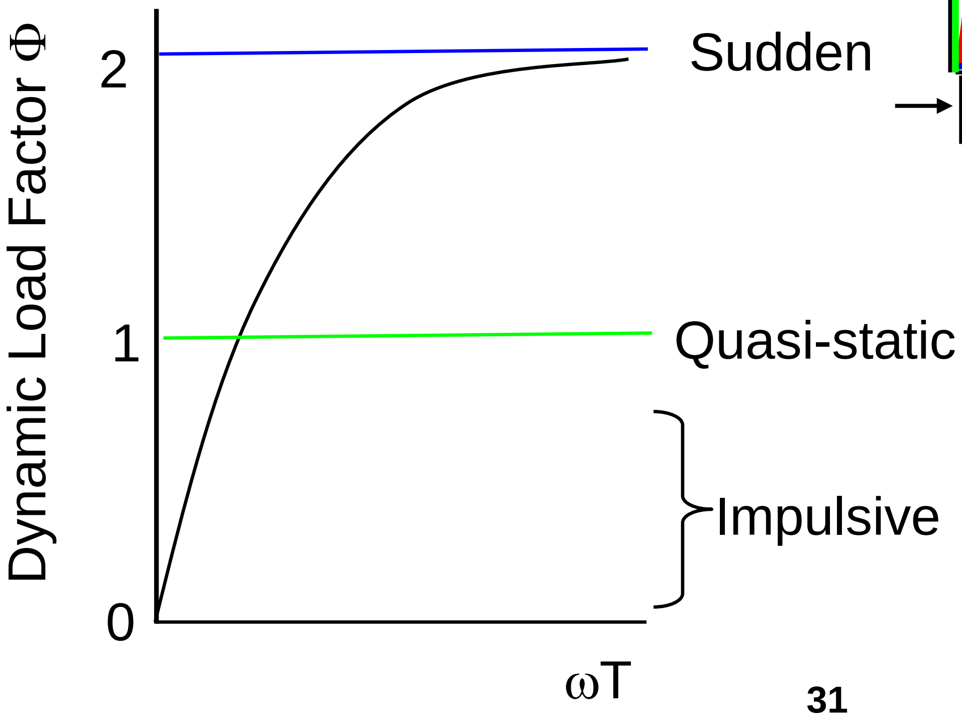
SDOF Model for Φ



Loading Regimes

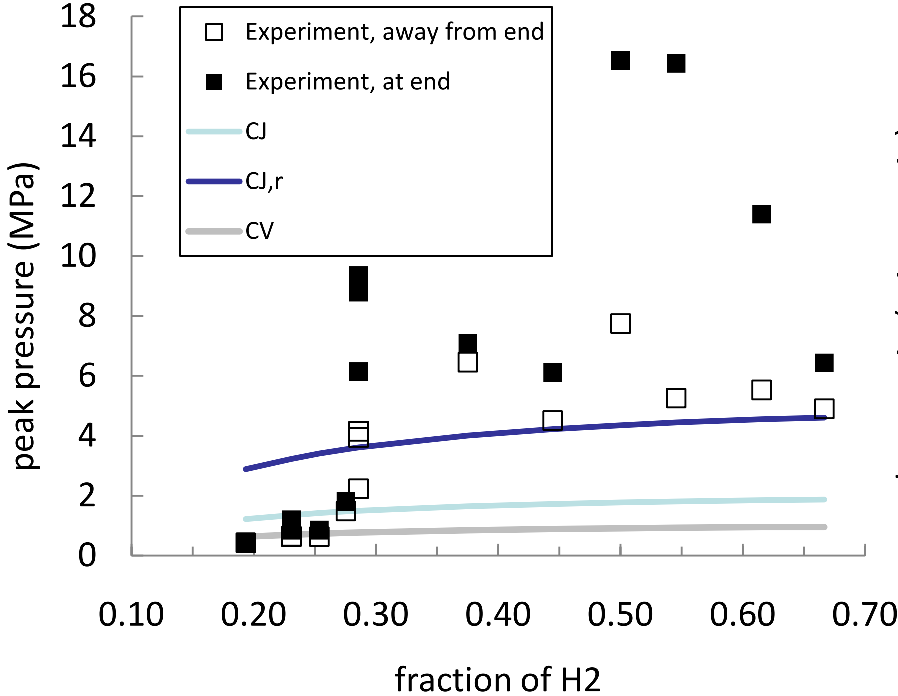
- Sudden
  $\Phi = 2$
- Impulsive $T/\tau < 1/4$
  $\Phi = \omega T$
- Quasi-static $\omega T >> 1$ $\Phi = 1$

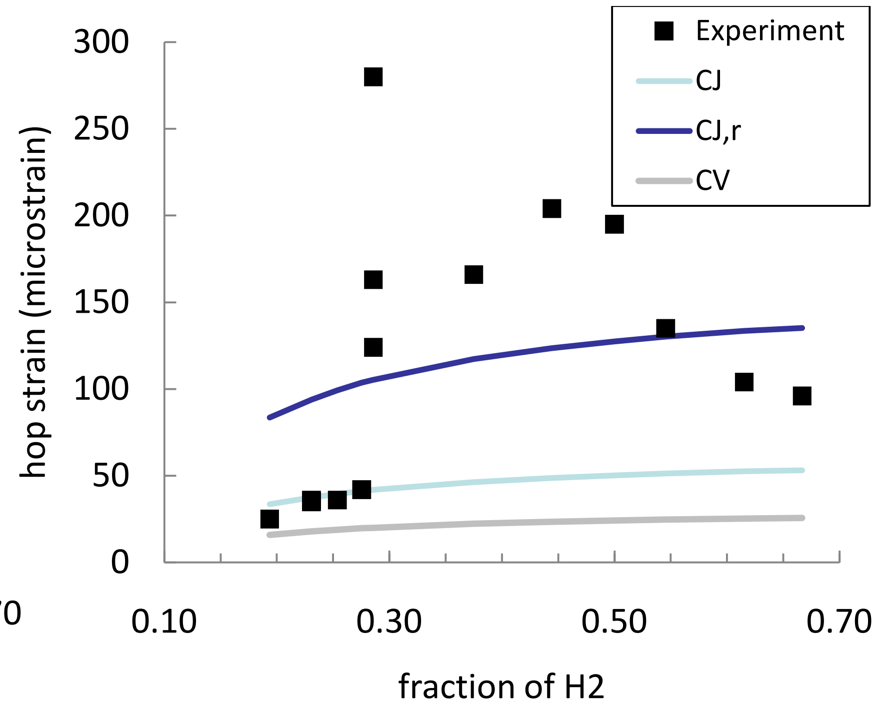




$$\Phi = \frac{\text{Peak dynamic strain}}{\text{Reference Static strain}}$$

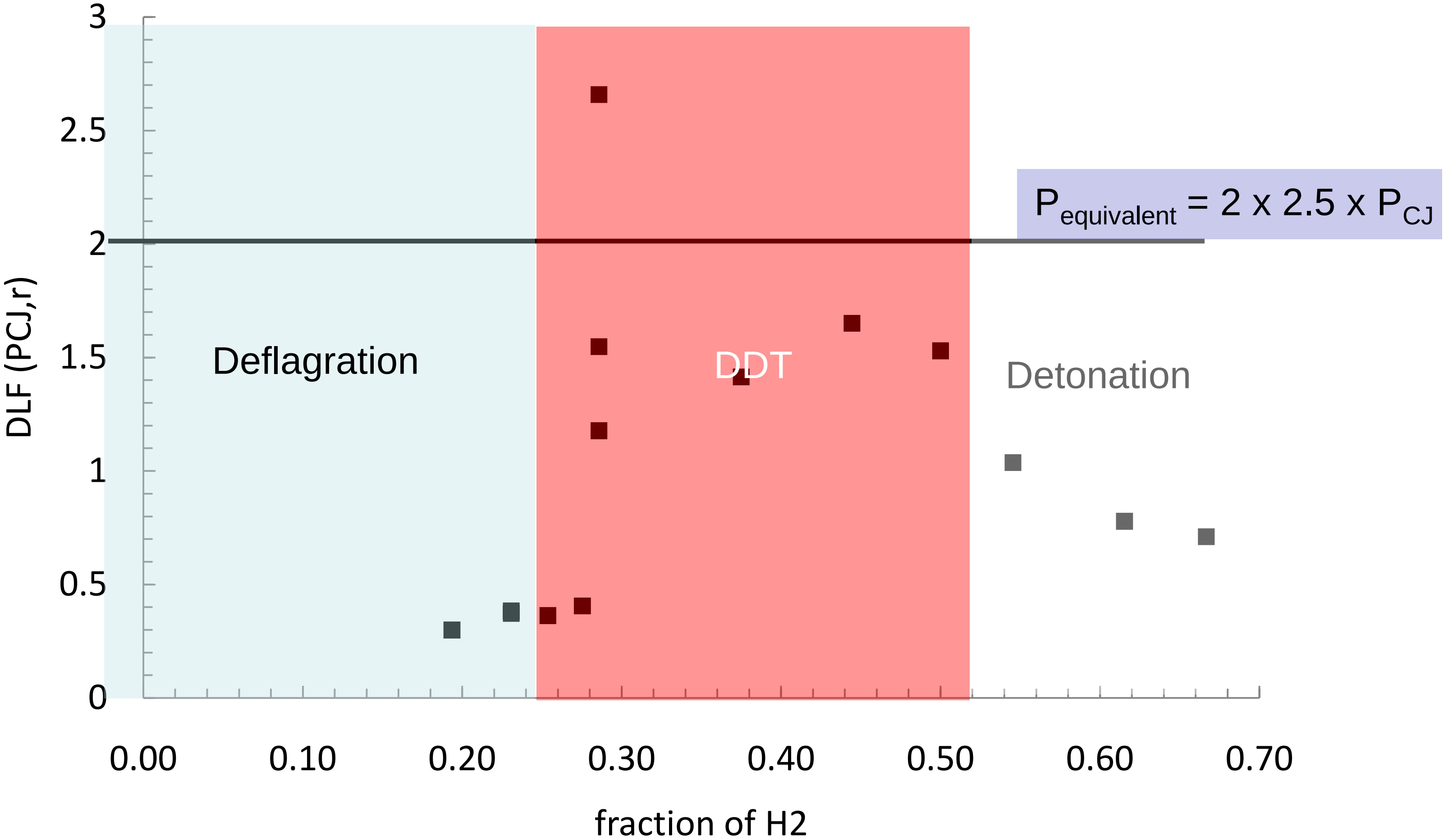
H_2-O_2





Structural Response of Tubes to Deflagration-to-Detonation Transition
Z. Liang and J. E. Shepherd Graduate Aeronautical Laboratories
California Institute of Technology Pasadena, CA 91125
Explosion Dynamics Laboratory Report FM2010.005

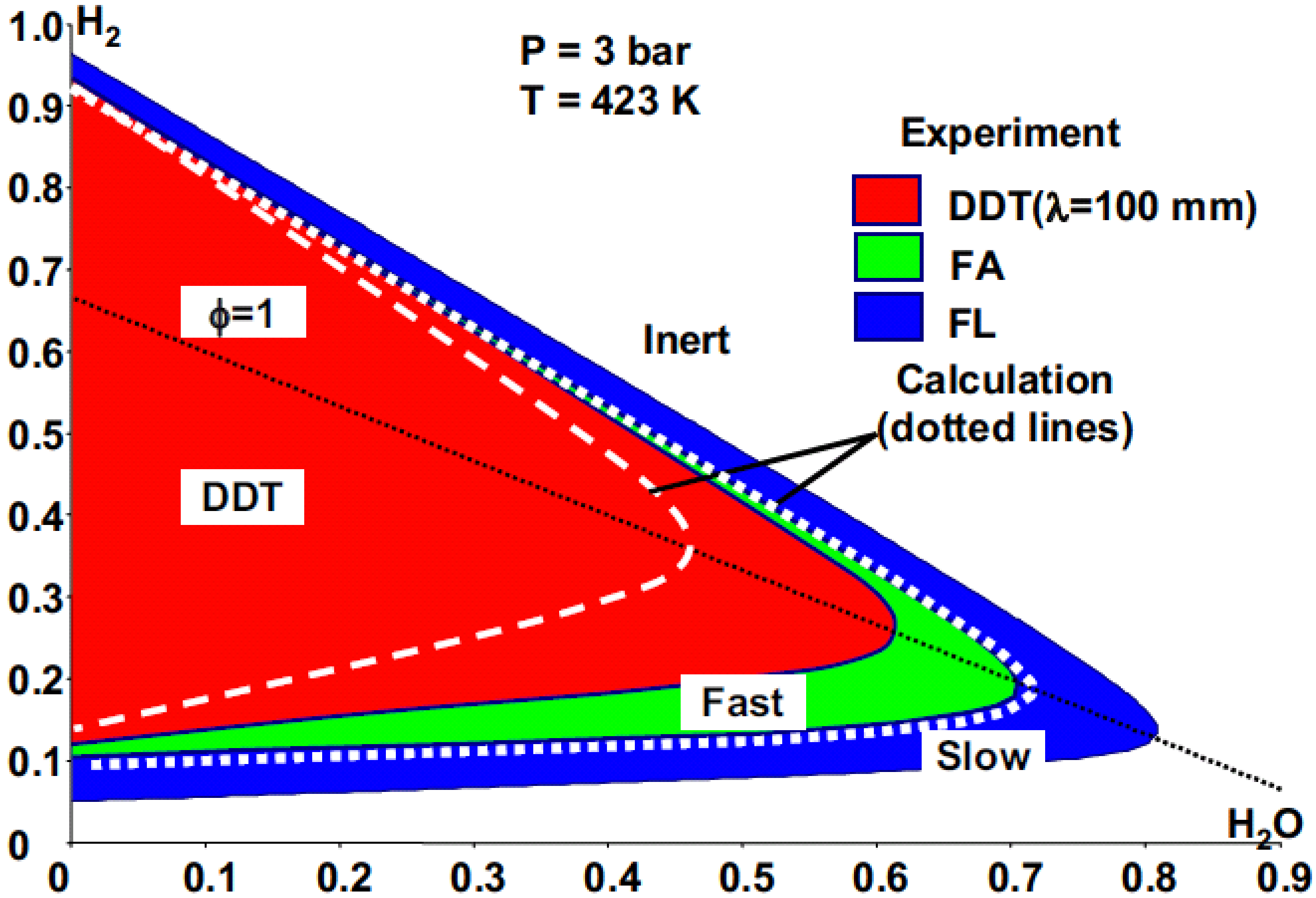
H_2-O_2, 100 kPa, 25 °C



Explosion loads within 5-in diameter pipe, 1.25 m long

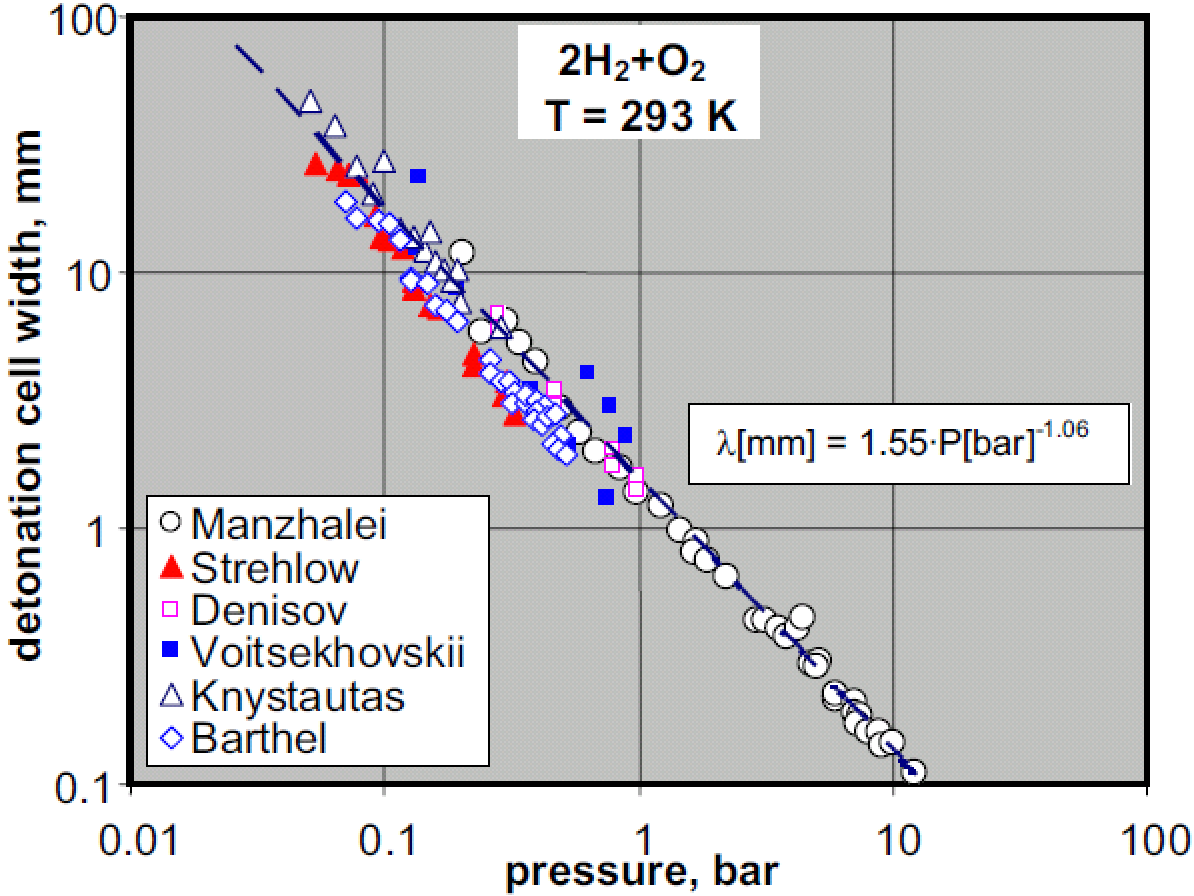
FM2010.005

Combustion Regimes



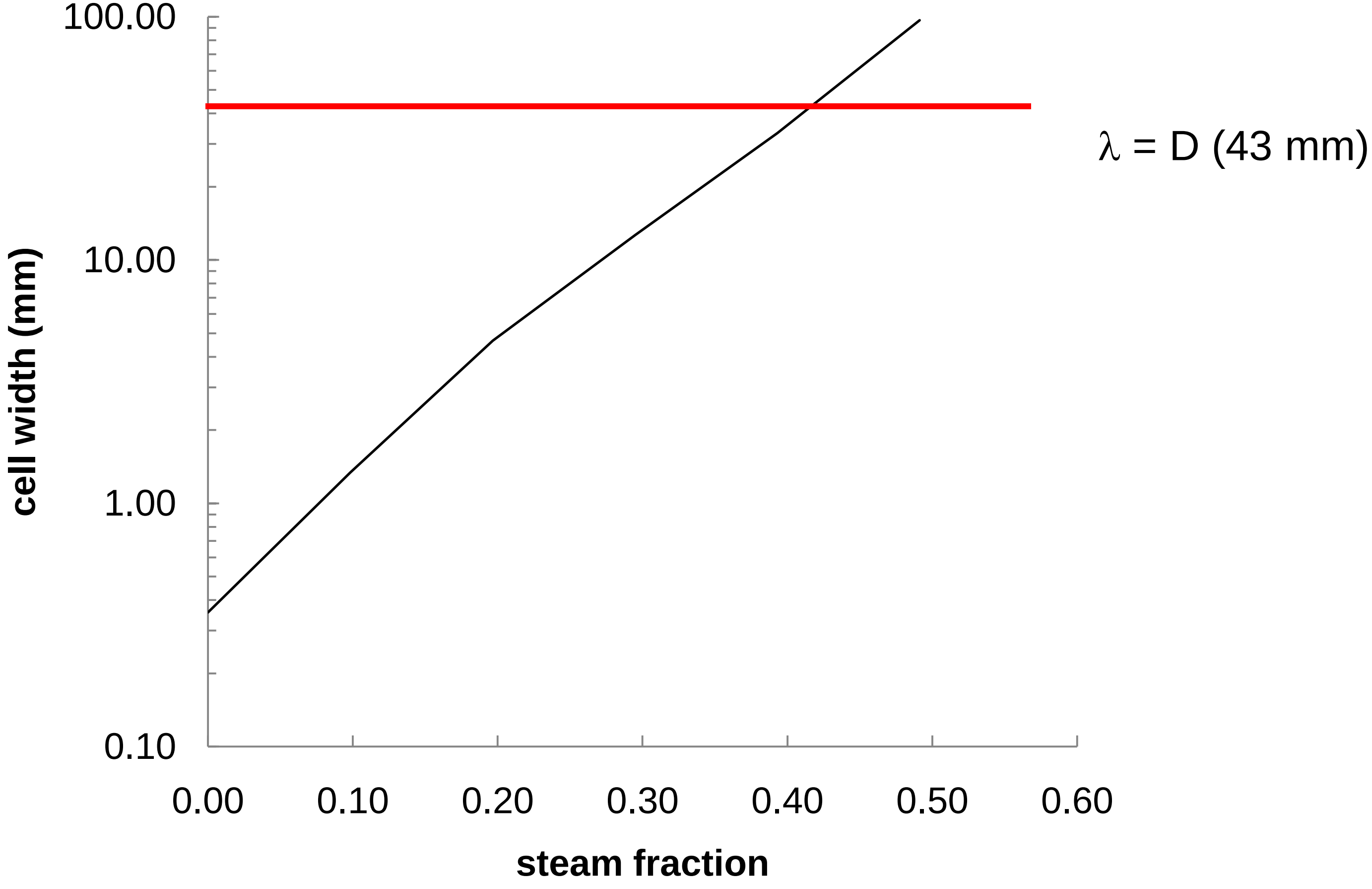
p. 5.1.21, COMBUSTION OF BWR-TYPICAL RADIOLYTIC GAS MIXTURES, W. Breitung et al, FZK Report 2007

Detonation Cell Width



p. 5.2.4, COMBUSTION OF BWR-TYPICAL RADIOLYTIC GAS MIXTURES, W. Breitung et al, FZK Report 2007

Estimated effect of steam 407 kPa, 100 °C



Scale cell width with reaction zone length, $\lambda_2 = \lambda_2 \, \Delta_1/\Delta_2$

DDT Summary

- DDT possible with up to 0.4 steam fraction
  - Expansion ratio sufficiently high $\sigma > 3.5$
  - Cell size sufficiently small $\lambda < D$
- Transition to detonation will occur rapidly for steam fractions between 0 and 0.4 at 407 kPa
- Conclusion:

Dynamic load factor of 2 applied to $P_{CJ,r}$ bounds almost all cases away from tube end. => GEH assumptions are reasonable for PCCS tubing.

PCCS Lower Drum

- GEH proposed to treat combustion as constant volume and take credit for venting through tubes.
- Mixture is very sensitive, cell size is very small relative to dimensions of drum and DDT cannot be ruled out.
- No analysis was done on efficacy of venting in preventing DDT – likely to be difficult to show
- Conclusion:

Analysis of lower drum is an open issue.

Presentation to the ACRS ESBWR Subcommittee

ESBWR Open Items:
Hydrogen Accumulation in PCCS (RAI 6.2-202):
PCCS Structural Design

Tuan Le and Mano Subudhi (BNL)

July 13, 2010

Design of PCCS Condensers

- To withstand loads resulting from buildup and possible detonation of radiolytically-generated combustible gases, particularly hydrogen, during a LOCA

- The designs of PCCS including the condensers are modified to improve their ability to mitigate the hydrogen detonation loads

- The PCCS condenser tube/lower drum materials and thicknesses, and the number of tubes are modified to provide adequate heat transfer function during a LOCA

Design of PCCS Condensers

- PCCS condenser is required to perform its heat transfer function after a LOCA
- PCCS condenser is designed as part of the containment pressure boundary

Design Criteria for PCCS Condensers

- For containment pressure boundary, the entire PCCS condenser is classified as ASME Class MC component and is designed to ASME Subsection NE requirements. This also includes a small section of the drain pipe connected to the lower drum nozzle

- The remaining portions of the drain and the vent pipe are classified as ASME Class 2 components and are designed to ASME Subsection NC requirements

- All ASME MC components of the PCCS will be designed to withstand the hydrogen detonation pressure and to remain essentially within the elastic stress range under the bounding pressure load

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Presentation to the ACRS ESBWR Subcommittee

ESBWR Open Items: Hydrogen Accumulation in PCCS (RAI 6.2-202): Containment Structural Design

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Design of the ESBWR PCCS

- Maintain structural integrity of the containment pressure boundary (ASME Code, Class MC component) during 72 hour LOCA
- Staff review under NUREG-0800, SRP 3.8.2, “areas relating to steel containments or to other Class MC steel portions of steel/concrete containments”
- PCCS components within containment pressure boundary:
    - steam supply pipe including pool slab penetration
    - upper and lower drums
    - condenser tubes
    - portion of drain pipe including pool slab penetration
- Structural support for the PCCS assembly

Considerations for Design of PCCS to Address Effects Due to Detonation of Non-Condensable Gases (hydrogen and oxygen) inside PCCS

- Additional loads due to detonation not considered in original design
- Detonations possible in condenser tubes, lower drum and drain pipe
- Other PCCS components not directly exposed to internal detonations, but affected by energy release from detonation
- Multiple detonation events considered during 72 hour LOCA
- Appropriate loading combinations and acceptance criteria

Evaluation of Effects Due to Detonation

- Equivalent static design pressure: 38.7 MPa absolute (approx. 5600 psia) to account for detonation
- Amplification factors to account for wave reflection and other dynamic effects were included
- Essentially linear elastic response of components assumed
- Simplified equivalent-static methodology to compute structural response to detonation pressures
- Detonation pressure used to design condenser tubes, lower drum and portion of drain pipe classified as MC component

Structural Acceptance Criteria

- Case-by-case evaluation by the staff
- Guidance in NUREG-0800 SRP 3.8.2 and ASME Code interpreted for unique loading conditions
- Acceptance criterion:
  - Level C Service Limit per ASME Code, Section III, Division I, Subsection NE
- Design load combination:
  - Detonation pressure plus all other applicable loads per NUREG-0800 SRP 3.8.2 (e.g., dead, accident temperature, and SSE loads)

Basis for Structural Acceptance Criteria

- Level C Service Limit chosen because:
  - Structural integrity of containment pressure boundary is ensured
  - Response of components remain essentially elastic (localized yielding is possible) per assumptions in stress analysis and estimation of detonation pressures
  - Essentially elastic response prevents geometric distortions of components, thereby maintaining the heat removal function of the PCCS
  - Ratcheting and other plastic instabilities are limited
  - Other load combinations using same acceptance criteria include:
    - Design-basis LOCA in combination with SSE
    - Hydrogen pressurization and burn resulting from 100% fuel clad metal-water reaction

Basis for Structural Acceptance Criteria (con.)

- Detonations are dynamic loads of very short duration
- ASME Code NE-3113.4 Level D Service Limits:
  - "This service limit applies to those loads subject to other service limits in combination with loadings of a local dynamic nature, such as jet impingement, pipe whip, and pipe reaction loads resulting from a postulated pipe rupture, for which the containment function is required."
- Conservative approach adopted, Level C chosen over Level D because:
  - Uncertainties in estimation of detonation pressures
  - Level D implies allowable stresses (general primary membrane stresses) significantly greater than yield limit
  - Stress analysis and estimation of detonation pressures assume essentially elastic response of components

Stress Analysis

- Static, linear elastic, Finite Element (FE) analysis
- Global FE model of PCCS (including support frame) used in analysis for loads other than detonations
- Refined FE submodels used in analysis for detonation loads of:
  - condenser tubes
  - lower drum
- Detonation loads applied as internal pressures on FE submodels
- FE results combined and compared to ASME Code limits

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Stress Analysis (Cont.)

- Stress analysis reported in Licensing Topical Report NEDE-33572P "ESBWR ICS and PCCS Condenser Combustible Gas Mitigation and Structural Evaluation"
- Condenser tubes and lower drum significantly strengthened compared to original design:
  - Tube thickness and lower drum thickness increased. Tube material changed to SA-312 Gr. XM-19; drum material changed to SA-182 Gr. XM-19
- Stress hotspots:
  - condenser tube bends
  - lower drum covers
  - lower drum drain nozzle

Hydrogen Accumulation in PCCS (RAI 6.2-202): Summary of PCCS Design

Status:

- **Issue resolution is ongoing**

Resolved issues:

- Hydrogen concentrations
- Detonation pressure loading in PCCS tubes
- Case by case evaluations using ASME Section III Class MC components
- Loading combination to include detonation pressure plus all other applicable loads per NUREG-800 SRP 3.8.2

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Hydrogen Accumulation in PCCS (RAI 6.2-202): Summary of PCCS Design

Open issues:

- Detonation pressure loading in PCCS lower drum and drain and vent lines
- Modifications of lower-drum covers and drain nozzles to account for high stresses
- Detonation effects on PCCS components not directly exposed to detonations (e.g., anchorage, support frame, and pool slab penetrations)
- Fatigue evaluations for multiple detonations
- Design of ICS

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Hydrogen Accumulation in PCCS (RAI 6.2-202): Summary of PCCS Design

Open issues (con.):

- PCCS Heat transfer capacity
- Accounting for thermal effects generated by detonations in the design

PCCS Evaluation for Severe Accidents

PCCS overpressure analysis

- Initial pressure – containment pressure is higher in severe accident scenarios
- Gas composition – steam reduces DET pressure
- Temperature – higher temperature reduces DET pressure

Bounding severe accident case exceeds PCCS pressures analyzed by 10%

- Addition of igniters in lower header reduces O2 concentration
- Pressure load reduced by more than 50%
- BiMAC control system used to operate igniters

ESBWR Design PRA Changes

ICS vent – Needs to operate when ICS is active

- More reliable
  - De-energize to actuate
  - Does not rely on pressure signals
- CDF reduction of about 3%

ICS isolation to prevent rupture in LOCA-like scenarios

- Implemented in SSLC-ESF & ICP
- Designed to address external event scenarios

T-H Uncert conclusions remain valid

PCCS severe accident igniters needed

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PRA Results - Preliminary

CDF does not change

- ~10^{-11} increase in calculated mean
- All are late core damage / release sequences
- Core damage after 100 hrs

LRF due to igniter failure is negligible

- ~10^{-12}

No change to fire CDF or LRF

- No change expected for other external event scenarios

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