

**NUCLEAR REGULATORY COMMISSION**

ORIGINAL

Title: Advisory Committee on Reactor Safeguards  
Reactor Fuels Subcommittee - Open Session

Docket Number: (not applicable)

PROCESS USING ADAMS  
TEMPLATE: ACRS/ACNW-005

Location: Rockville, Maryland

Date: Tuesday, September 30, 2003

Work Order No.: NRC-1079

Pages 1-152/229-281

Closed session pages:

153-228

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

(ACRS)

REACTOR FUELS SUBCOMMITTEE

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TUESDAY, SEPTEMBER 30, 2003

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OPEN SESSION

+ + + + +

ROCKVILLE, MARYLAND

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The subcommittee met at 8:30 a.m. at the  
Nuclear Regulatory Commission, Two White Flint North,  
Room T2B3, 11545 Rockville Pike, Dr. Dana A. Powers,  
Chairman, presiding.

SUBCOMMITTEE MEMBERS:

DANA A. POWERS	Chairman
F. PETER FORD	Member
THOMAS S. KRESS	Member
GRAHAM M. LEITCH	Member
VICTOR H. RANSOM	Member
JOHN D. SIEBER	Member



1     ACRS STAFF PRESENT:

2     RALPH CARUSO

3

4     ALSO PRESENT:

5     BO CHENG                   EPRI

6     JEFF DESHON               EPRI

7     KURT EDSINGER           EPRI

8     ODELLI OZER              EPRI

9     ROSA YANG                EPRI

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

(8:30 a.m.)

CHAIRMAN POWERS: Back in session. This is the second day of the meeting of the Subcommittee on Reactor Fuels for the Advisory Committee on Reactor Safeguards. We have a much more robust subcommittee today to hear about the robust fuels program.

In attendance today are: Jack Sieber, Peter Ford, Tom Kress, Vic Ransom, and Graham Leitch. And I trust you gentlemen who are new today will stay with us for the duration and not go off to some silly license renewal or other sort of thing. It's clear that fuel is essential to the nuclear performance, and we want to see what the reaction is today.

Do any of the members have an opening comment that they would care to make?

(No response.)

CHAIRMAN POWERS: Well, for the new attendees, I will comment yesterday we had an examination of about two-thirds of the NRC's fuels research program. And I invite you to take an examination of the transcript and the viewgraphs. I think you will find it will be quite interesting, if somewhat reminiscent of what we heard last year in a similar subcommittee meeting.

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1 Today we are going to examine what is  
2 going on in the EPRI program in the form of the robust  
3 fuels program and a few other topics. And so without  
4 any more introduction, I will just turn it over to  
5 Rosa Yang, who will guide us through all of this.

6 10) ROBUST FUEL PROGRAM OVERVIEW

7 MS. YANG: I don't know about that.

8 Good morning. I am Rosa Yang, EPRI. I  
9 manage the robust fuel program. About a year ago,  
10 October 9th, the industry, EPRI, and the fuel  
11 suppliers and some utility folks were here at the  
12 invitation of NRR to discuss the topical report, the  
13 RIA topical report that we submitted a few months ago.  
14 And during that presentation, we were requested by  
15 this committee to come back and talk about the robust  
16 fuel program.

17 Specifically, I was asked to say, bring  
18 all your staff. So I did. And here they are. I am  
19 not going to take the time to introduce them because  
20 you will hear from every one of them.

21 The only comment I want to make, as you  
22 will see, what I will try to do is to give you an  
23 overview of the program, how it was formed, why it was  
24 formed, and how is it functioning now in the industry.  
25 I won't get into too much technical detail because

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1 most of them will be covered by EPRI staff later on.  
2 Feel free to interrupt any of us.

3 Because much of the work we do is  
4 proprietary, I'm very sorry. I hate to do this, but  
5 after my presentation and after the presentation which  
6 will be made by Odelli Ozer about the letter that we  
7 have sent to NRC -- he will make a brief presentation  
8 just by the content of the letter because it was  
9 discussed yesterday. After those two presentations,  
10 the rest of the presentation will be closed to the  
11 public. My apology for that.

12 If there is anything specific you would  
13 like to talk about and you are not able to participate  
14 in the rest of the presentation, we will be happy to  
15 talk to you about it. The reason we do it in this  
16 somewhat nonacademic fashion is because much of the  
17 work we do, we have special contracts with the fuel  
18 suppliers. And being fuel is a fairly competitive  
19 commercial environment, we need to honor those  
20 contracts.

21 One more thing I want to say is the  
22 handout you have, I'm going to follow in most of it  
23 until almost toward the end. Then I add a few slides  
24 about the RIA topical report that we submitted more  
25 than a year ago just to address some of the questions

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1 raised yesterday. So I intend to make a brief  
2 presentation of that subject. So you don't have that  
3 in the handout, but I will be happy to make those  
4 slides available later on because I just added them  
5 last night.

6 So let me start. The program was formed  
7 actually a couple of years before 1998 and officially  
8 kicked into work in 1998. There are two key reasons  
9 for the formation of this thing. One of them I will  
10 give you a little bit more detail, which is we are  
11 operating considerably differently today and maybe the  
12 last few years as comparing to, say, 10-15 years ago.

13 I think you heard a little bit from APS  
14 yesterday. The guy was talking about there is more  
15 boiling in his plant. So I will give you a few  
16 examples of how the environment has been more  
17 demanding.

18 The second reason is because the fuel is  
19 a fixed market and is very competitive. The price of  
20 the fuel has been going down steadily as a result of  
21 this competitive environment. So that doesn't leave  
22 enough money for the fuel suppliers to do R&D.

23 So you have a difficult situation. On one  
24 hand, you operate in a more demanding environment.  
25 And at the same time, we put on new products, which

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1 may not have been tested as it deserves. So  
2 sometimes, not all the time, sometimes, they don't  
3 perform as advertised.

4 So utility decided that they need to do  
5 something a bit proactive to form a program like this  
6 to make sure that they don't have operational  
7 surprises and they have regulatory stability and they  
8 have the flexibility in operating their plant because,  
9 like Dana said earlier, fuel is where the energy comes  
10 from.

11 Maybe after we solve all of those  
12 problems, we can look at burnup extension. So first  
13 I want to clarify that this is not just about high  
14 burnup. This program is about operational  
15 flexibility, about no surprises, about regulatory  
16 stability, and then the next step is burnup extension.

17 As I go through them, you will see most of  
18 the program content that we aimed at. Many of them  
19 are below 62,000, which is a current licensing limit.

20 MEMBER KRESS: That looks like the guy  
21 could probably high jump over that and --

22 MS. YANG: Oh, yes. I forgot to give due  
23 credit to one of our members, EdF, Nicolas Waeckel of  
24 EdF. He's looking at a PWR fuel assembly and this  
25 typical utility guy, trying to make a high jump. And,

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1 of course, he is armed with all of these robust fuel  
2 program reports, which you can't quite see the  
3 reading, but if you magnify enough, you can see.

4 And the first step is operational margins,  
5 which is what we keep talking about. We want no  
6 surprise. If you don't want surprise, you've got the  
7 margins. And after this first step, then the next  
8 step is burnup extension.

9 Of course, we are doing all of this with  
10 NRC's watchful eyes and all of the reg documents.

11 MEMBER KRESS: What's that thing up in the  
12 right-hand corner?

13 MS. YANG: This one?

14 MEMBER KRESS: Yes.

15 MS. YANG: Twenty-First Century, when we  
16 move into the future.

17 CHAIRMAN POWERS: Well, I'm surprised that  
18 you don't get fuel bowing when you use it that way.

19 MS. YANG: He's a science guy, electricity  
20 guy.

21 MEMBER KRESS: A good pole vaulting pole  
22 is very flexible.

23 MS. YANG: This is robust PWR stuff.

24 MEMBER SIEBER: Leave it to a utility guy  
25 to misuse the fuel.

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1 CHAIRMAN POWERS: Yes. He's probably an  
2 accountant.

3 MS. YANG: Okay. So a bit about the  
4 changes to make the environment more demanding. We  
5 have increased discharge burnup. We have extended the  
6 cycle length. I have slides of those to show you.  
7 And the peaking certainly has been increased, mostly  
8 because of the low leakage core. The enrichment has  
9 steadily increased. And I have a slide to show you.  
10 And the newest thing is plant uprate.

11 You know, they are the small one to 2  
12 percent ones, and then there are the 20 percent ones.  
13 And how that impacts fuel performance needs to be  
14 assessed.

15 Just overlay all of those to protect the  
16 plant. Many of the new water chemistry has been  
17 implemented. I listed the ones for PWR is elevated pH  
18 and lithium and zinc injection; for BWR, noble metal  
19 chemical addition, -- sorry for the acronym, noble  
20 metal chemical addition -- hydrogen water chemistry,  
21 and zinc injections. And, of course, there are design  
22 changes and new material introduced to satisfy the  
23 more demanding environment.

24 Not all of these things are adverse in  
25 terms of fuel performance. And, in fact, I would

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1 argue many of these are intended to improve the  
2 performance. It's just when you have new things and  
3 you make many changes at the same time, you could  
4 reduce a margin. And you certainly increase the  
5 unknown.

6 So let me show you --

7 CHAIRMAN POWERS: Rosa, how is the  
8 beginning-of-life boron changing in the plants  
9 nowadays?

10 MS. YANG: How many what?

11 CHAIRMAN POWERS: The beginning-of-life  
12 boron concentrations changing in the plants?

13 MS. YANG: It's higher. You know, as you  
14 go to higher, I think now the steady state boron is  
15 what, 1,800 or so, 18, 16. Yes. Eighteen hundred,  
16 yes. So it's increased considerably.

17 I think maybe ten years ago, you were  
18 looking at --

19 CHAIRMAN POWERS: Eight hundred.

20 MS. YANG: -- 900 or 1,000, yes.

21 CHAIRMAN POWERS: So we double the boron  
22 concentration.

23 MS. YANG: Yes.

24 MR. OZER: Longer cycle is required for  
25 boron.

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1 MS. YANG: Here's the list of cycle line,  
2 in effective full-power days. As you can see, from 10  
3 years ago or 12 years ago, we just steadily increased  
4 the cycle lines for both BWRs and PWRs. I think most  
5 of the BWRs are 24-month cycle now.

6 Look at the enrichment. Again, these are  
7 the average enrichment for the reload. It's steadily  
8 increased because of the mix of enrichment and all  
9 that. So we haven't quite hit the five percent limit,  
10 but it's pretty close there.

11 I told you about uprates. The different  
12 color shows different percent of uprate. As you can  
13 see, we have a considerable number of 20 percent  
14 uprate. So these are --

15 CHAIRMAN POWERS: No one is more familiar  
16 with the number of 20 percent uprates than this  
17 committee. You're killing us.

18 MS. YANG: Well, so far what we have  
19 looked into, we haven't really found a smoking gun in  
20 terms of uprate and how that impacts fuel performance.  
21 But it's just intuitive something you need to look at.

22 Okay. This is how our program functions.  
23 All the work or the majority, the engine is certainly  
24 with the working group. And there are four working  
25 groups. And you are going to hear from three of them

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1 today.

2 We left working group 2 out, which is  
3 dealing with RIA, LOCA, and burnup extension. The  
4 reason we left it out is because we know you were  
5 going to hear a lot about those issues yesterday from  
6 NRC research side, and we have a topical report that  
7 we submitted that we would discuss it separately with  
8 NRR and we made a presentation a year ago. So the  
9 original intent is not to spend too much time on that  
10 because we really have a lot of material to cover in  
11 other areas.

12 Given yesterday's presentation and  
13 discussion, I just thought we would have a brief one  
14 on RIA only to just refresh the committee members'  
15 memory.

16 Working group 1, working on the mostly PWR  
17 crud and water chemistry-related issues; and working  
18 group 3, working on hot cells and other high burnout  
19 properties; working group 4, working on the failure  
20 mechanisms. You will see the list of the utility  
21 chairmen and the EPRI project managers. As I said  
22 earlier, you will hear from each of the EPRI project  
23 managers.

24 So those are the work engine of the  
25 program. And the integration is really just the

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1 chairman and vice chairman of each of the working  
2 groups. And the executive committee and the senior  
3 reps, they are the management of the program. They  
4 are the ones deciding on program directions and  
5 budget. So it's a very important function.

6 And these are the executive committee  
7 members. You will see we also have nonvoting members  
8 from NEI and INPO. The current chairman is Joseph  
9 Sheppard of South Texas Project.

10 Here is our members. I just want to point  
11 out -- I guess I don't have a pointer, but I can use  
12 this. I just want to point out for the U.S., we have  
13 I think it's 20 utilities and about 80 units  
14 participating in the program.

15 I get criticized all the time when I talk  
16 about members because we have this interesting funding  
17 scheme. Part of our funding comes from membership.  
18 Part of it, the utility has to pay additional money.  
19 When I talk about members, I am talking about those  
20 who pay additional money. So these are the  
21 membership.

22 We have 103 units in this country. About  
23 80 units fund the program supplementally. We have a  
24 considerable number of international participation.

25 There are nine groups here listed, but if

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1 you look at number of units, they are actually more  
2 than the U.S. And, of course, we work very closely  
3 with INPO, NEI. Ralph talked about NRC research  
4 yesterday. We work with all of the fuel suppliers:  
5 Global Nuclear, Westinghouse, and Framatome.

6 So, for the rest of it, what I would like  
7 to do is to give you a very quick overview. First, I  
8 would like to start with what are some of the issues  
9 that face the industry. And then I want to go into  
10 what are some of the areas that we work on.

11 The issues facing the industry are there  
12 is a large number of BWR failures I think many of you  
13 have alluded to yesterday. And the root cause so far  
14 is unknown. You will hear a little bit more detail.  
15 And I would just give you a really quick 30,000 feet  
16 overview of the situation.

17 NMCA and zinc injunction, many of the BWRs  
18 are using it. And the impact of that on fuel  
19 currently is being assessed. We have channel bow  
20 issues, which interfere with the control blade  
21 insertion as some of the BWRs, which probably reminds  
22 them of the PWR incomplete control rod insertion many  
23 years ago.

24 On the PWR side, the major failure root  
25 cause continues to be grid-rod fretting. I just want

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1 to say we're not doing much here because this is  
2 purely a design, fuel design, issue.

3 We have looked at the issue. We have held  
4 workshops. So we have a good understanding of the  
5 issue. And then we, the committee, have decided that  
6 this is a vendor problem and a vendor-specific. And  
7 we highlight the issue. And I think there are  
8 measures in place to address them.

9 To most parts, they are somewhat  
10 effective. The problem is still here, but they are  
11 being addressed. So we, the robust fuel program, are  
12 not addressing it.

13 Axial offset anomaly still exists, but  
14 they are current. The frequency and the severity are  
15 down significantly from a few years ago. We have a  
16 very active program addressing this issue. And you  
17 are going to hear from Jeff later on about it more.

18 The PWR RCCAs or the PWR control  
19 assemblies have a cracking and deformation problem.  
20 And we have a program initiated to address that. So  
21 if you just look at the 30,000 feet view, what are  
22 some of the key performance issues facing the  
23 industry? And these are them.

24 Just a sort of a bit of background on the  
25 things I already said, here is the number of defect

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1 assemblies as a function of time. You know, some of  
2 the earlier days, you'll see I have a breakdown of the  
3 failure mechanism in a minute. For the past ten years  
4 or so, things are beginning to improve, especially for  
5 the boiling water reactor. And you see a big increase  
6 of the boiling water reactor in the last couple of  
7 years.

8 Here is a trend plot. Again --

9 MEMBER LEITCH: On that previous one, I'm  
10 trying to understand the scale here.

11 MS. YANG: I know.

12 MEMBER LEITCH: It's one and a half? What  
13 is that? One and a half what?

14 MS. YANG: It's fuel assemblies, number of  
15 defective assemblies per gigawatt, per thousand  
16 megawatts. So it's roughly one and a half assemblies  
17 per unit, per large unit.

18 MEMBER LEITCH: Yes. Okay. Got you.  
19 Okay.

20 MS. YANG: Which means every reactor has  
21 one.

22 MEMBER LEITCH: Yes.

23 MS. YANG: Of course, it's not like that.

24 MEMBER LEITCH: Yes. On average, yes.

25 MS. YANG: Okay. So here is a trend plot



1 of the type of failures for BWR. So, as you can see,  
2 the last couple of years, we have the two dominating  
3 failures are corrosion-related failures and PCI or  
4 PCI-like types of failures. Bo will review for you in  
5 great detail later on.

6 For the PWRs, I think I already talked  
7 about it. The major failures are grid-to-rod  
8 fretting.

9 CHAIRMAN POWERS: Why is there a large  
10 number of unknown, not inspected?

11 MS. YANG: Why?

12 CHAIRMAN POWERS: What does that mean?

13 MS. YANG: Oh. It means that they don't  
14 inspect it. In many cases, they have it either in the  
15 discharge batch that they know they have a small  
16 failure. They just didn't inspect it or sometimes  
17 when you say, "unknown," they know they have a  
18 failure. They probably even know where it is, but  
19 they just don't know what the root cause is.

20 You see, the others, we actually classify  
21 them in terms of the root cause. Sometimes a visual  
22 inspection at the pool does not yield to identifying  
23 the actual failure root cause.

24 I think it is fair to say those are maybe  
25 ones, two and they are very small. I think whenever

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1 we have a large number of defects or there is  
2 something like the BWR failures that we don't  
3 understand, I think the industry has been pretty good  
4 in going after the root cause.

5 CHAIRMAN POWERS: The scale on this  
6 particular plot, of course, is different from the  
7 other one. Is this the integral number of failed  
8 assemblies in the fleet or is it on a per-reactor  
9 basis?

10 MS. YANG: In the fleet.

11 CHAIRMAN POWERS: In the fleet?

12 MS. YANG: Yes.

13 MEMBER KRESS: What is this debris, the  
14 yellow?

15 MS. YANG: Yes. That's the foreign  
16 material intruded in the system, either from steam  
17 generator repairs, or whatever foreign materials.

18 MEMBER LEITCH: You talked about PCI.  
19 About a dozen or more years ago, there were interim  
20 management recommendations for operating to avoid PCI.  
21 The plants are not operating under those bases any  
22 more, are they or are they? I don't know.

23 MS. YANG: No, no. In this particular  
24 case, these plants are using a type of barrier, which  
25 allow in principle should work to prevent the PCI

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1 failures.

2 MEMBER LEITCH: Okay. But what we're  
3 saying is, even with the barrier fuel, then,  
4 apparently there still are several PCI failures.

5 MS. YANG: We think it's PCI, but these we  
6 don't really know. I mean, I think we call it PCI  
7 suspect. We think it's PCI, but we haven't really  
8 confirmed it's PCI.

9 MEMBER LEITCH: Okay.

10 MS. YANG: Do you want to say anything,  
11 Matt? No? Sorry.

12 MR. EYRE: Sure.

13 MS. YANG: I don't want to put you on the  
14 spot. Sorry.

15 MR. EYRE: Matt Eyre, Exelon Nuclear.

16 A number of the I guess PCI suspect  
17 failures have been thought of as being due to, let's  
18 say, missing pellet surface, might have arisen out of  
19 a manufacturing process. And some of our operational  
20 guidelines don't account for that.

21 So when you operate the reactor, do a  
22 control rod maneuver, you may overpower that  
23 particular place and cause a PCI-like failure. And  
24 there you have it.

25 MEMBER LEITCH: Okay. Thanks, Matt.

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1 MS. YANG: Okay. So that is kind of  
2 laying the background. Now I really want to say, what  
3 are we focusing on in our program? Basically the way  
4 I see our program is I divide it into the four working  
5 groups. They address different technical issues. But  
6 I group them somewhat differently here in three areas.

7 The first area I call solving the current  
8 problem, solving existing problems. So I list a few.  
9 The second area is proactively trying to find out  
10 where our margins are. So this is totally reactive.  
11 So the second area is more proactive. The third area  
12 is just as proactive, but it deals with regulatory  
13 issues. So keep that in mind.

14 That's how I group the three different  
15 areas. And the reason I kind of want to highlight it  
16 is because I don't want to just read through these  
17 words. I am going to inject some slides in between  
18 them. So you might feel a little bit not so clear  
19 later on.

20 So existing problems, there are three.  
21 And I think in my earlier about what is the industry  
22 problem, they are the same issues: failures, fuel  
23 failures, impact of NMCA, and AOA.

24 The failure root cause, I think you have  
25 seen some of the charts. We have planned two hot cell

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1 examinations later this year. Both of them are to  
2 occur before the end of the year. So we are all very  
3 nervous to make sure that they do occur. You know,  
4 they have to fit in between the utilities' window that  
5 they give us and in between the orange alerts. So we  
6 are hoping that will occur.

7 We also are being very active in going to  
8 utility sites to assist them as specific failures  
9 occur, particularly Bo Cheng there being our expert in  
10 that area.

11 This is often a very challenging  
12 situation, as many of you familiar with these types of  
13 issues know, because you could spend millions shipping  
14 fuel to the hot cell and not being able to identify  
15 the failures because not all of them are that easy to  
16 identify.

17 What I have listed here is to show the  
18 four hot cells that we have conducted within this  
19 program. These are not the only hot cells, but these  
20 are the hot cells exams aimed at identifying failure  
21 root cause.

22 I think we have been pretty lucky. So far  
23 we have been very successful in identifying the  
24 failure root cause. The chart has a lot of  
25 information on it. There is a time line on it. There

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1 is the different type of failures being listed on when  
2 the shipments occur, when the exams occur. I think Bo  
3 is going to address, in particular, these things that  
4 we already have performed the hot cell that we have  
5 identified the root cause. And these two new ones are  
6 to occur. The shipment will occur later this year.  
7 And hopefully we'll have the results early next year.

8 CHAIRMAN POWERS: I guess maybe I'm just  
9 a little confused. Are you trying to tell me that  
10 fuel that you think has a PCI failure gets shipped to  
11 KKL or that KKL thinks that all failures are PCI-like?

12 MS. YANG: Oh, I'm sorry. I see the  
13 confusion. No. These two are independent. This we  
14 have conducted, actually already conducted a hot cell  
15 of PCI-like type of failure of GE barrier fuel. And  
16 that occurred in the past. And we have confirmed that  
17 is a PCI failure. And in that particular case, it was  
18 because of the missing pellets.

19 You know, if you think about it, you have  
20 these cylindrical pellets with the cladding. And if  
21 you miss a piece of the surface due to manufacturing  
22 chipping or something, then you create a local high  
23 stress. This is kind of the opposite of the classic  
24 chip situation, but it is the same effect. So that is  
25 what we have found here.

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1           Now, we have a new PCI-like failure of a  
2 different barrier design. And it's Framatome fuel.  
3 We don't know the failure root cause. It could be  
4 PCI. It could be any number of other things. We just  
5 suspect that it is PCI.

6           The Browns Ferry is corrosion failure and  
7 has been --

8           CHAIRMAN POWERS: And by "corrosion  
9 failure," you mean eaten through the cladding?

10          MS. YANG: Yes, lots of clad and, you know  
11 --

12          CHAIRMAN POWERS: Well, you seemed to  
13 distinguish between corrosion failure and crud-induced  
14 failures.

15          MS. YANG: They are some different  
16 nuances. And we're trying to understand what they  
17 are. They may be one of the same phenomena, just  
18 manifest somewhat differently, or may be different.  
19 But we are trying to identify those.

20          This thing is particularly puzzling  
21 because this particular case, as far as we know,  
22 pretty much follows all of the BWR water chemistry  
23 guidelines.

24          CHAIRMAN POWERS: We're very proud of that  
25 water chemistry there. I'll have to tell them that.

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1 MEMBER FORD: Rosa, you've got four hot  
2 cell examinations, presumably all in the United  
3 States.

4 MS. YANG: No. This one is KKL in Europe.

5 MEMBER FORD: Oh. I rather assumed that  
6 since it was a GE fuel that was being examined at  
7 Vallecitos.

8 MS. YANG: No. It's at Europe.

9 MEMBER FORD: Okay.

10 MR. OZER: The LaSalle fuel is going to --

11 MS. YANG: To Studsvik, too, yes.

12 MEMBER FORD: Because my follow-on  
13 question was, what other hot cells are you using? My  
14 assumption was wrong. These are not just United  
15 States hot cells.

16 MS. YANG: No, no, no.

17 MEMBER FORD: If there any work, for  
18 instance, in Japan? I noticed you have got a lot of  
19 stations in Japan. Are there hot cell facilities  
20 being used there?

21 MS. YANG: They are hot cells. There is  
22 a number of very good hot cells. We haven't used the  
23 hot cell in Japan, mainly because of the shipment and  
24 because of the U.S.-origin materials. But hot cell is  
25 an issue.



1           If you look at the long-term  
2 infrastructure for our industry, we don't have a lot  
3 of hot cells. And we don't have experienced hot cell  
4 staff.

5           MEMBER LEITCH: In all cases, this work is  
6 done with failed pins, not with pins that are similar  
7 to failed pins and have the --

8           MS. YANG: We usually take both. We  
9 usually take a sound rod as reference. And if it's  
10 PCI, we try to take symmetrical location --

11          MEMBER LEITCH: I see.

12          MS. YANG: All of them, we actually  
13 usually have done a considerable number of pool-side  
14 inspections, discussions trying to look at the  
15 manufacturing record, the operation record. And so we  
16 don't take things to the hot cell lightly because it  
17 is a big expense, on the order of several million.

18          MEMBER LEITCH: Okay. Thank you.

19          MS. YANG: And the shipment itself is  
20 becoming more and more expensive and takes time. I  
21 think you will hear from Kurt later on that it's  
22 because of this and in order to improve the fuel  
23 performance, we are trying to develop a considerable  
24 number of nondestructive inspection techniques to be  
25 able to perform at the pool side. So we can reduce

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1 our needs for the hot cell.

2 Noble metal, which is a technology  
3 implemented, is a GE-patented technology. It was  
4 first implemented in Duane Arnold in 1996. And you  
5 can see how quickly the majority of the U.S. fleet has  
6 implemented noble metal. The 27 BWRs are mostly in  
7 the U.S. I think there are a couple overseas, but the  
8 majority of them are in the U.S.

9 What I want to just highlight, one point,  
10 is the utilities facing demands from different sides.  
11 For example, the radiation field reduction is a big  
12 driver for the utilities, especially from utilities'  
13 operation perspective.

14 So zinc injection up her could be helpful  
15 to control the dose rate. So utilities want to inject  
16 zinc. And, of course, I think many of you probably  
17 know the fuel is the heated surface within the primary  
18 system and it has a lot of surface area.

19 So most of the stuff you inject, be it  
20 zinc, be it noble metal, be it whatever you inject,  
21 tends to end up on the fuel surfaces. So we need to  
22 look at the fuel performance.

23 Another driving force, other than the  
24 radiation field, is the material degradation. This is  
25 especially important as we go to plant life extension.

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1 In order to preserve the integrity of the components  
2 of the plant, noble metal is required. So quite often  
3 our work was needed to address the material  
4 degradation issue, to check how effective it is in  
5 addressing the plant material issues, the radiation  
6 field, and the fuel performance.

7 So quite often our program worked very  
8 closely with the chemistry department and with the  
9 material department. And we have this triangle trying  
10 to balance all of the issues and jointly develop  
11 guidelines to the utilities on the plant chemistry.

12 MEMBER LEITCH: Pushing in the opposite  
13 direction, I guess, is hydrogen water chemistry, is it  
14 not? In other words, it tends to elevate the  
15 radiation field significantly.

16 MS. YANG: Yes. But that's why you use  
17 noble metal. If you use noble metal, then the amount  
18 of hydrogen that's required would be considerably  
19 reduced. So that would reduce the radiation field.

20 MEMBER LEITCH: I see.

21 MS. YANG: So noble metal tends to have  
22 that benefit as well.

23 Okay. So those are the problem areas.  
24 And you will hear a lot about them later on. Now I'm  
25 moving into the next area, which as an area I said

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1 earlier is proactively trying to ensure margins and  
2 under high-duty conditions. I highlighted margin. I  
3 highlighted high-duty.

4 As you will remember earlier, we talk  
5 about we operate fuel considerably differently today  
6 as comparing to years ago. So we don't really have  
7 any hot cell data available of these modern high-duty  
8 fuels. And I will show you what they are in a minute.

9 In order to get a sense of the health, if  
10 you may, of these kinds of high-duty fuels, we need to  
11 conduct both pool-side and, more importantly, the hot  
12 cell examinations. And because of the expense and  
13 because of the time and resources required, I think we  
14 cannot afford to do a large number of them. So we're  
15 very, very careful in choosing what rods to take to  
16 the hot cell.

17 I would call our program probably as  
18 minimum in terms of number of hot cell examinations  
19 and scope. We try to be as comprehensive as possible,  
20 but they are certainly not overly broad. I think we  
21 try to be conscious about what we need and just get  
22 what we need. Those data are extremely essential.

23 I said earlier our main purpose is for  
24 margins. And the same type of data can also be used  
25 for burnup extension. I will show you why. This I

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1 think I already pretty much talked about that.

2 Another thing I may not have mentioned but  
3 you probably guessed it already, we want not only to  
4 choose the right type of fuel with the high-duty. We  
5 try to go to plants that have the type of chemistry,  
6 water chemistry conditions that we're interested in or  
7 concerned about. And for the PWRs, we try to go to  
8 the high-temperature plants. As you can see, what we  
9 are trying to do since we are doing the minimum  
10 number, we try to look at the bouncing case.

11 Another fairly busy chart, but we're  
12 intending to summarize the number of hot cell exams  
13 that we do, in this case, again, the time line in the  
14 middle; the BWR, the boiling water reactor, hot cell  
15 examinations listed on the bottom.

16 There are two major ones, both from  
17 Limerick. The first one is actually the one at 52  
18 assembly average. It's the same one that Mike Billone  
19 talked about yesterday at 56 or 57. He's talking  
20 about the rod burnup.

21 And we just made another shipment of the  
22 next higher level burnup. And the highest burnup  
23 there is 65. Again, it's the assembly average. We  
24 look at different processing material. And also it's  
25 the first time we really look at high-duty fuel with

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1 noble metal chemical addition. So those are the  
2 boiling water reactor ones for the pressurized water  
3 reactor.

4 Again, we already made the shipment of  
5 Zircaloy-4 from HB Robinson. And it's the same  
6 material that went to Argonne for the LOCA program  
7 that Mike talked about yesterday. We made another  
8 shipment last year of the ZIRLO cladding at 70,000.  
9 Here is why I talk about the same data.

10 It's the first time we look at ZIRLO under  
11 high-duty operating conditions, at least in this  
12 country. I think it's probably the highest burnup of  
13 ZIRLO ever looked at.

14 MEMBER LEITCH: So just so I understand,  
15 these are not failures? These are high --

16 MS. YANG: No, no. I want to  
17 differentiate. These are the hot cells --

18 MEMBER LEITCH: High burnup.

19 MS. YANG: -- to get to high burnup to get  
20 a margin. None of them failed.

21 MEMBER LEITCH: And then what do you do,  
22 examine the cladding or the fuel itself?

23 MS. YANG: We look at the fuel. We look  
24 at the cladding. I think I deleted the scope slide.  
25 Yes. I deleted it. Well, we mostly look at the

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1 fission gas release. We look at the cladding  
2 dimensional change as a result of irradiation. We  
3 look at the fuel morphology or microstructure change  
4 as a result of irradiation. Mainly we look at the  
5 cladding mechanical properties, ductilities,  
6 corrosions, hydrogen levels, mostly checking how the  
7 fuel would behave.

8 MEMBER LEITCH: Okay.

9 MS. YANG: And these data are quite  
10 useful, of course, to check the health of the  
11 material. It could be useful burnup extension  
12 licensing. It could be used for some of the RIA tests  
13 that we talked about yesterday, provided the  
14 mechanical property for the --

15 MEMBER LEITCH: These exposures are for  
16 that particular pin, not the average or --

17 MS. YANG: Seventy, I believe, is assembly  
18 burnup, is it not, Jeff? I mean, Kurt. I'm sorry.

19 MR. EDSINGER: Yes.

20 MS. YANG: Yes, assembly. So the pin may  
21 be ten percent higher.

22 MEMBER LEITCH: Yes. Okay. Thank you.

23 MS. YANG: So, as I said, it's the first  
24 time we look at it. We could do it at 62 first, then  
25 at 70, but we choose to look at 70. So there are some

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1       misunderstandings about this is entirely for burnup  
2       extension. It is not. It is the first time we look  
3       at ZIRLO.

4               Same thing here, same story here, a couple  
5       of years behind, North Anna. The burnup is about the  
6       equivalent. It's the first time we look at M5. For  
7       those of you who know, these are the two types of  
8       advanced alloys used in this country, ZIRLO and M5.  
9       And there are still some utilities using Zircaloy-4.

10              Here are the five hot cell exams, sound  
11       rod for margins. They could be used for burnup  
12       extension as well.

13              Very quickly, just one of the techniques  
14       that we developed within this program to sort of as an  
15       interim measure solve the AOA and the PWR crud issue  
16       is by using ultrasonically to clean the fuel.

17              The first application is at Callaway,  
18       which is the plant most plagued with AOA issues. It  
19       was a big success. And they are cleaning real low  
20       quantities of fuel right now. And it has since been  
21       used at South Texas units 1 and 2 and again fairly  
22       successfully.

23              It was intended to be used later on at  
24       Vogtle unit. So this is a technique developed by the  
25       program, and it probably will be fairly widely used.

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1           The interesting point here is not only the  
2           technique is useful, but the technique actually can be  
3           transferred to solve BWR issues. And Kurt will talk  
4           to you about how we are right now as we speak  
5           qualifying the same technique for the BWRs. And there  
6           their interest is for those rate reductions.

7           MEMBER KRESS:     You take these fuel  
8           assemblies out of the reactors and sit them on the --

9           MS. YANG:     In the pool.

10          MEMBER KRESS:    In the spent fuel pool?

11          MS. YANG:     In the spent fuel pool.

12          MEMBER KRESS:    And then you have an  
13          ultrasonic system?

14          MS. YANG:     To clean it.

15          MEMBER KRESS:    Clean it in the pool  
16          itself?

17          MS. YANG:     Yes.

18          MEMBER KRESS:    Where does the crud go?

19          MS. YANG:     It is a closed system. It has  
20          its own filtration. And it collects the crud. Do you  
21          have charts of those laid out, either of you?

22          MEMBER KRESS:    It's the tank that goes  
23          down in the pool and the tank is a closed system?

24          MS. YANG:     Right.

25          MEMBER KRESS:    So you collect the crud in

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1 --

2 MS. YANG: Yes.

3 MEMBER KRESS: Okay. That was my concern.

4 MR. EDSINGER: I do have some slides.

5 MS. YANG: Okay. The second area for  
6 margin, the third area --

7 MEMBER FORD: Excuse me. Rosa, before you  
8 go on to a new topic, just to come back to your slide  
9 on the hot cell projects to quantify margins, you made  
10 there that this is the first examination of ZIRLO and  
11 M5 in this country.

12 MS. YANG: Hot cell examinations for such  
13 high duty and high burnup.

14 MEMBER FORD: And you also pointed out  
15 that there won't be much of this data because of the  
16 expense of getting the data. And you also made the  
17 case that you want to move into a proactive phase. If  
18 you're going to go into a proactive phase, then you'd  
19 better have a good model of the various degradation  
20 mechanisms. And you use this sparse data presumably  
21 to benchmark that model.

22 Step back one further step. How solid do  
23 you feel about the models of material degradation,  
24 fuel degradation?

25 MS. YANG: Just during normal --

1 MEMBER FORD: Because that is going to be  
2 the skeleton upon which you are going to build your  
3 proactive management philosophy.

4 MS. YANG: Peter, you always ask tough  
5 questions. I think if I could answer your question a  
6 little bit differently, we have a fuel performance  
7 code, which is FALCON, which is a steady state and a  
8 transient code.

9 So we use the same code for normal  
10 operation to predict the fission gas release, the  
11 deformation, and those kinds of things. And we also  
12 use the same code for RIA and LOCA. That's a  
13 different subject. I think you are talking about the  
14 steady state here.

15 MEMBER FORD: I'm talking about them all,  
16 but, yes, take a steady state or transient. It  
17 doesn't really matter. You're going to have to have  
18 a model, a predictive model, on which you are going to  
19 base your proactive management philosophy.

20 MS. YANG: Yes.

21 MEMBER FORD: And you are going to use  
22 that data to benchmark the model.

23 MS. YANG: Yes.

24 MEMBER FORD: My essential question is,  
25 how solid do you feel?

1 MS. YANG: About our model?

2 MEMBER FORD: About your model because you  
3 are not going to have too much data to benchmark it.

4 MS. YANG: No. In fact, you're quite  
5 right. These data, we do look at them and feed back  
6 into the model. But I guess I am not quite sure how  
7 to address your question properly because the way I  
8 see it is for steady state operation, for normal  
9 operation, we are looking at margins.

10 We never look at failures. You never  
11 design the fuel for failures. So the code would never  
12 predict the rod would have failed. And, of course,  
13 the rods do fail.

14 I am thinking back at some of the failures  
15 that we encountered that usually is somewhat of a  
16 local phenomenon that the typical fuel performance  
17 model cannot last by itself. You always need to run  
18 some detailed either neutronics model or thermal  
19 hydraulics model or whatever model.

20 MEMBER FORD: Graham asked a question  
21 about PCI, --

22 MS. YANG: Right.

23 MEMBER FORD: -- which is an old problem.  
24 I suspect that the current PCI problems you talk about  
25 are not quite the same mechanism.

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1 MS. YANG: No, no.

2 MEMBER FORD: The actual splitting is not  
3 necessarily what we used to call PCI-before-barrier  
4 fuel.

5 MS. YANG: Right.

6 MEMBER FORD: So how good do you feel  
7 about being able to predict this new PCI problem or  
8 being able to predict the potentiality of zinc or NMCA  
9 to give you excessive corrosion on BWR fuel or these  
10 --

11 MS. YANG: Our model does address some of  
12 the chemistry additive. And I think they are in  
13 general good, but the reason, what I am trying to get  
14 to is that the reason, you have failure usually is  
15 because there is a local perturbation.

16 So if you input that, you probably will  
17 get the answer that you are looking for, but in most  
18 cases, I think failure occurs because we haven't  
19 tested the condition properly.

20 MEMBER FORD: Okay.

21 MS. YANG: So I would like to answer your  
22 question slightly differently. We have a document  
23 that Kurt will address later on. It's called  
24 "technical requirement document," --

25 MEMBER FORD: Right.

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1 MS. YANG: -- which is almost like a  
2 specification that utilities say, "I need the fuel to  
3 perform this way" so that it won't fail. So that  
4 document was more focused on the type of performance  
5 we need and the type of testing that we would require  
6 if there is any change in the material. So you can  
7 see that document itself would require knowledge and  
8 the feedback.

9 So what we are actually hoping is after we  
10 finish these things, in each of the cases, we don't  
11 just have a data report, we actually have a report  
12 that assesses the margin that's there.

13 MEMBER FORD: Okay.

14 MS. YANG: And we are going to take that  
15 and feed back into the technical requirement document  
16 to say, "Do we have the right criteria? Do we have  
17 the right knowledge to say how can we do things  
18 differently in the future so we don't get into the  
19 same problem that we have today?"

20 MEMBER FORD: Okay.

21 MS. YANG: So let me just finish. So my  
22 thought is for transient condition, you look at  
23 failures because you have to go there in order to see  
24 that, but for the steady state, you usually don't  
25 design to failure.

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1           So you predict, for example, fission gas  
2 release. So we do check if the code will predict  
3 fission gas release. In some cases, we're right on;  
4 others, we may be not predicting it well. So we have  
5 work to do there. We look at corrosion, and we look  
6 at the cladding dimensional change.

7           So maybe I am answering your question. We  
8 do look at these. And we check our code to see if we  
9 are predicting that. So this is kind of important to  
10 benchmark it.

11           One thing I want to point out is that  
12 these data are quite different from the Halden data.  
13 They are almost like two different populations. And  
14 any code in order to predict the light water reactor  
15 has to look at both.

16           MEMBER FORD: Okay.

17           MS. YANG: Matt wanted to say something.

18           MR. EYRE: Matt Eyre, Exelon Nuclear,  
19 again.

20           As Rosa pointed out, these are just  
21 basically a noting of the hot cell projects. One of  
22 the things that not only does Exelon Nuclear but a  
23 number of the other utilities have done or plan to do  
24 is also look at their fuel pool-side as well. So it  
25 will be a number of benchmarks to the hot cell and

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1 also the pool side and a number of different operating  
2 environments.

3 For example, we are going to be looking at  
4 our Three Mile Island unit 1 fuel next spring, which  
5 is M5. And it has gone to about 70 gigawatt days per  
6 metric ton, different operating environment than the  
7 North Anna fuel, similar burnup. And so we will be  
8 able to compare that with the North Anna fuel. So I  
9 will see somewhat sparse data up there.

10 There is a considerable body of pool-side,  
11 nondestructive examination that we will be able to  
12 compare with the North Anna work.

13 MS. YANG: Yes. Thanks, Matt. I think  
14 that is a really good point. Maybe in our trying to  
15 cover the hot cell, I didn't quite mention the  
16 pool-side. In fact, that is the majority of our data.  
17 These are just trying to confirm or get additional  
18 data that we can't get at the hot cell. But pool side  
19 is really important.

20 MEMBER RANSOM: Has any thought been given  
21 to including probabilistic effects into your model so  
22 that you would predict failure rates? Is that  
23 feasible, I guess, or --

24 MS. YANG: It's feasible. And I remember  
25 years ago there was a code, actually, like that. I

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1 forgot the name, Entropy, something. I forgot. Thus,  
2 I think it's feasible. I'm not quite sure we want to  
3 go there because fuel performance, fuel behavior is  
4 fairly complex in the --

5 MEMBER RANSOM: There is a move towards  
6 probablistic methods in risk analysis and safety --

7 MS. YANG: You could. You could. We  
8 haven't done that.

9 MEMBER RANSOM: It would seem like a good  
10 way to go.

11 MS. YANG: We haven't done that.

12 MEMBER KRESS: It's not particularly a  
13 risk issue, I wouldn't think.

14 MS. YANG: Not particularly.

15 MEMBER KRESS: I don't know why you would  
16 want a probablistic model to predict fuel failure.

17 MS. YANG: Yes. It's usually pretty low  
18 in a  $10^{-6}$ .

19 MEMBER KRESS: Low in risk base. It's an  
20 operational issue, I think.

21 MS. YANG: Yes. Thank you. I want to  
22 emphasize this is not a safety issue. This is a  
23 simple economic issue.

24 MEMBER LEITCH: You talked about  
25 ultrasonic cleaning in a couple of the future slides

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1 that you already covered. I guess you went back to  
2 it.

3 MS. YANG: Yes.

4 MEMBER LEITCH: I guess I am wondering.  
5 Apparently at Paks in Hungary, they were chemically  
6 cleaning, I guess. I don't know all of the details of  
7 that, but I guess they had a chemical cleaning process  
8 that went amiss.

9 MS. YANG: Yes.

10 MEMBER LEITCH: I am just wondering. Is  
11 anyone in the United States thinking about chemically  
12 cleaning?

13 MS. YANG: Not that I am aware of. Of  
14 course, this technique is totally different.

15 MEMBER LEITCH: Yes.

16 MS. YANG: And we won't leave it alone.

17 DR. MEYER: This is Ralph Meyer at NRC.

18 I gave a short presentation on this  
19 yesterday. I just wanted to make one point. The  
20 chemical process was completed and successful. This  
21 was just an overnight cooling of a clean fuel problem.

22 MEMBER KRESS: It was a loss of cooling.  
23 And I presume you can have a loss of cooling with  
24 these things, too.

25 MS. YANG: You could except that this is

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1 --

2 DR. MEYER: I was unaware of that. Thank  
3 you.

4 MS. YANG: This is not just this system.  
5 You have to be there. And it takes about one minute  
6 or so to clean each assembly. So it is a continuous  
7 process. You don't just leave it there.

8 Okay. I want to talk about a part of our  
9 program which deals with regulatory issues very  
10 briefly. The uniqueness of our role in this is we are  
11 the industry interface with NRC on fuel-related  
12 regulatory issues. And they are kind of a two-pronged  
13 interaction.

14 With NRR, we interact through NEI any  
15 regulatory and licensing issues. And many of these,  
16 it's really industry interaction. It's not just EPRI.  
17 It's EPRI representing the utilities and the fuel  
18 suppliers. So it's really industry through NEI,  
19 interact with NRR.

20 I think this approach has worked  
21 reasonably well on research issues. There is a  
22 memorandum of understanding between EPRI and NRC  
23 research. And there are many collaborations areas.  
24 Fuel is just one of them and I want to say has worked  
25 very well. Thank you.

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1 And we have these twice-a-year management  
2 types of discussions between EPRI and research, NRC  
3 research. And usually we get reasonably positive  
4 feedback to and from our management.

5 And specifically we have this LOCA program  
6 that you heard a lot about yesterday. And, of course,  
7 there is the Cabri water loop project that we  
8 collaborate together.

9 MEMBER KRESS: Is the iodine spiking  
10 phenomena part of this program? Are you looking ahead  
11 or has it gone away with the new fuels?

12 MS. YANG: Iodine spiking?

13 MEMBER KRESS: Yes, during transients or  
14 shutdown.

15 MS. YANG: During shutdown.

16 MEMBER KRESS: Yes.

17 MS. YANG: Yes. It's still there. I  
18 don't think we look at it. Maybe I'm not --

19 MEMBER KRESS: It's not part of your  
20 program?

21 MS. YANG: It's not part of our program,  
22 although we do know that if you have failed fuel when  
23 you shut down --

24 MEMBER KRESS: Yes. It seems to be  
25 related to failed fuel.

1 MS. YANG: It is, yes. And we have a  
2 handbook that kind of tells a utility what to do in  
3 case of fuel failures. And they talk about the iodine  
4 spike in there.

5 CHAIRMAN POWERS: Let me ask one question.  
6 Presumably, the tests being done at Argonne are being  
7 done to confirm regulatory decisions on the ability of  
8 fuels of the current types of satisfy the requirements  
9 of 10 CFR 50. And presumably once somebody concludes  
10 that question has been answered, NRC's funding for  
11 that work will come to an end.

12 MS. YANG: We hope so.

13 CHAIRMAN POWERS: What happens then? If  
14 the industry is moving to M5 clads, fuels of different  
15 types, and things like that, you still have the  
16 problem of showing that you comply with the  
17 requirements of Appendix K. So, I mean, what happens?

18 MS. YANG: I think I am going to answer  
19 your question. The way we work, for example, through  
20 the robust fuel program working group 2 to address  
21 your question is we would lay the groundwork, the road  
22 map, if you may, how to resolve any regulatory issues,  
23 be it RIA or LOCA, by submitting a topical.

24 Now, if, for example, the topical for RIA  
25 that has been submitted is for Zircaloy-4 but if NRC

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1 approves that topical, it basically says, "Here is a  
2 criteria. Here is what you need to do to show  
3 compliance." And although the criteria is Zircaloy-4,  
4 it is fairly straightforward for the vendors to take  
5 that approach and add to their data for M5 and to  
6 produce their criteria. That's one approach. And  
7 that's probably a more suitable approach for LOCA than  
8 RIA.

9 For RIA, because the advance alloys  
10 perform so much better than the Zircaloy-4 that we  
11 have used to develop the data, they could either  
12 develop a new criteria or they could say, "Well, this  
13 is a conservative criteria for M5. I'm happy with it  
14 the way it is. So they can take either approach.

15 Does that answer your question? We don't  
16 take it from the beginning to the end, but I think we  
17 do the work that is more efficiently done by the  
18 industry.

19 MEMBER KRESS: It sounds to me like you're  
20 presuming the phenomenology remains the same from one  
21 fuel type to the next.

22 MS. YANG: For RIA, I think it is. And I  
23 am going to get into a little bit technical discussion  
24 because RIA, the cladding force comes from the fuel.  
25 And then you just look at the cladding response.

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1                   And there are differences between one  
2 alloy to the other, but you can address that  
3 separately. Some may not be the same. But that's why  
4 I said for LOCA, it might be more different. In that  
5 case, the cladding may play a different role.

6                   Do, Jerry or Ryan, you want to say  
7 anything?

8                   MEMBER FORD: My question was somewhat  
9 along the same thought process. Just to clarify that  
10 when you are talking about the memorandum of  
11 understanding between EPRI and RES on the LOCA tests  
12 in ANL, there are no other tests being sponsored  
13 primarily by EPRI which address these issues. So  
14 those tests we heard about yesterday are the only  
15 tests going on in this country.

16                  MS. YANG: I want to --

17                  MEMBER FORD: Let me follow on for a bit.

18                  MS. YANG: Sorry.

19                  MEMBER FORD: We heard yesterday and you  
20 heard all the questions we brought up about those  
21 tests and the concerns about how would the results  
22 change if you had changes in composition of the  
23 materials.

24                  The answer I heard you give Dana just now  
25 is those specific questions, which relate to different

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1 allows, will be the responsibility of the vendor.

2 MS. YANG: Of the fuel suppliers, yes.

3 MEMBER FORD: And EPRI would not be  
4 funding any outstanding questions associated with that  
5 alloy-specific item.

6 MS. YANG: That's correct. That's  
7 correct. Thank you for the clarification. I also --

8 DR. MEYER: Excuse me. Could I --

9 MS. YANG: You are probably talking about  
10 what you are going to talk about anyway. Let me also  
11 differentiate one thing. I guess when I was answering  
12 Dana's question, I was more thinking about regulatory  
13 approaches. Okay? That was specifically more for the  
14 regulatory approaches.

15 But when, Peter, you are talking about  
16 these memorandums of understanding between EPRI and  
17 research, we are talking about research programs. We  
18 collaborate to do the test, just because the test  
19 itself is so hard to do. But we are totally  
20 independent in terms of analysis of the test results.

21 Is that what you wanted to add?

22 DR. MEYER: This is Ralph Meyer from NRC  
23 research.

24 No. What I wanted to comment on was  
25 Dana's original question about the programs for the

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1 new alloys. In our recently issued program plan, we  
2 have, in fact, planned and budgeted for continuation  
3 of the program at Argonne on M5 and ZIRLO alloys.

4 And, in addition to the LOCA tests, the  
5 mechanical property tests, which are applicable to the  
6 RIA accident, we also have testing specifically for  
7 dry cask storage and transportation of spent fuel.

8 Now, the big uncertainty is the form and  
9 extent of the cooperation between the NRC and industry  
10 in the future testing of irradiated M5 and ZIRLO  
11 because we do not have that material on hand at the  
12 present time.

13 CHAIRMAN POWERS: Let me ask another  
14 question. You have indicated down below at the bottom  
15 of that slide that you are a participant in the Cabri  
16 program. What do you anticipate getting out of the  
17 Cabri program?

18 MS. YANG: Well, I was one of the persons  
19 on record saying we don't need the Cabri water loop  
20 project. So personally I don't think we really need  
21 more of the failure/no failure type of tests. I am  
22 just about to get into the presentation that you will  
23 see that come across probably even more clearly.

24 I think we have a good understanding of  
25 the situation. We know how fuels behave under RIA

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1 condition. We have a good model. And the model  
2 predicts the results. So I don't think we need more  
3 of the water loop type of project.

4 However, if fuel can fail in the water  
5 loop, which is kind of a challenge right now, you  
6 know, they can't fail the rod in the water loop, if it  
7 does fail, then we can look at fuel-coolant  
8 interaction. That's the only thing that we may get.

9 CHAIRMAN POWERS: Yesterday there seemed  
10 to be some controversy over the width of the  
11 appropriate pulse to use in testing. Were you  
12 planning to elaborate on that?

13 MS. YANG: I'll try. Okay. We have three  
14 major regulatory focus areas. RIA, we submitted a  
15 topical; -- we talked about that -- a LOCA; and  
16 industry guide is for burnup extension. So let me go  
17 to RIA, which is most of these are not in your package  
18 because I added them last night, be happy to make them  
19 available to you, but I believe all of them really  
20 came from or most of them -- I'm sorry, not all of  
21 them -- most of them came from the presentation when  
22 we were here a year ago.

23 This is what we proposed, two separate  
24 curves: one for coolability, one for fuel failure.  
25 I want to make a few comments related to yesterday.

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1 And I will try to use some slides to illustrate the  
2 comment that I have here.

3 I think one of the key comments is the  
4 fuel behavior under RIA transient; well, fuel behavior  
5 in general anyway. And fuel behavior under RIA  
6 transient, in particular, is nonlinear, is very  
7 nonlinear, and is nonlinear with temperature for the  
8 fuel and for the cladding.

9 We know temperature is an important  
10 parameter. And the response is nonlinear with  
11 temperature and is nonlinear with another important  
12 parameter, which is the hydrogen.

13 The effect of hydrogen on the cladding  
14 ductility, it would strongly depend on hydrogen  
15 concentration but not just concentration by itself.  
16 The distribution of the hydrogen is extremely  
17 important in cladding ductility. I think there are  
18 ample data to support that.

19 What is very, very clear -- I don't think  
20 there is too much ambiguity here -- is spallation. If  
21 you do get into spall the situation, the spallation  
22 severely degrades cladding ductility. And I will show  
23 those in a minute.

24 The next point, given it is such a  
25 nonlinear behavior or phenomenon, you need to model

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1 it. And you need a good transient fuel, thermal  
2 mechanical model to model the phenomenon. And FALCON  
3 is just one of the possible codes. That is our code.

4 And in our code, we have incorporated the  
5 high burnup properties up to the burnup level that we  
6 are looking at these phenomena in terms of thermal  
7 conductivity as a result of high burnup, the rim  
8 effect, and the power depression for high burnup. All  
9 of these are extremely important in terms of  
10 temperature distribution.

11 And also, as all of you know, the fuel  
12 performance code, I think John showed a very complex  
13 chart. It is complex. And you can write some  
14 fundamental equations for most of the phenomena.

15 But at the end of the day, there are these  
16 fudge factors that there is no way around it. You  
17 have to tune them. And you have to tune them with  
18 good, representative data from Halden because that is  
19 the only place that you actually measure temperature,  
20 you measure the gas release. So you need those. And  
21 at the end of the day, we are dealing with light water  
22 reactors. So you have to have the light water reactor  
23 data.

24 So you need a good code that has the good  
25 model in it, good property in it, and should be

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1 benchmarked properly. And another thing is you need  
2 a good understanding of the mechanism. And that can  
3 only be provided by these RIA simulation tests that  
4 Cabri and NSRR and the SPIRT CDC tested earlier.

5 And there are more than 100 of such  
6 elaborate and highly sophisticated tests. Some are  
7 more sophisticated than others. There are more than  
8 100 of those available.

9 I am going to get into you also need a  
10 cladding mechanical property because that is the one  
11 really responding to the drive. And there are some  
12 separate effects tests if you want to answer when the  
13 fission gas release occurred and things like that.

14 What we have done, the industry has  
15 submitted last May in a topical report is separate  
16 cladding failure and core coolability limit. I think  
17 in those cases, we have incorporated the key  
18 controlling parameters.

19 For the failure, we think high corrosion  
20 and hydriding are the dominating factors. And I will  
21 try to define that. For the coolability, we will look  
22 at UO2, the incipient melting of UO2, as a function of  
23 burnup. And we look at the burnup effect as well. We  
24 believe those are the controlling parameters.

25 Both limits are supported by either

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1 integral data or separate effects data, I mean  
2 separate effects. And this separation of coolability  
3 and failures is consistent with the current regulatory  
4 criteria to separate the two.

5 We don't see any justification for  
6 combining the two limit because they are totally  
7 different phenomena and by combining them is  
8 unnecessarily conservative, is way conservative.

9 The coolability limit proposed by the  
10 industry is conservative by itself because I am going  
11 to show you it's a belt-and-suspenders type of  
12 approach. And it is supported by data. So those are  
13 just outlines of what I would like to show.

14 The first thing, just to illustrate the  
15 nonlinear feature of this phenomena, as you all know,  
16 in an RIA transient, the energies are mostly deposited  
17 at the rim.

18 This is the temperature versus the radial  
19 position. This is the center of the fuel. This is  
20 the pellet rim right here. And the cladding is here.

21 So let's look at early in the pulse.  
22 Let's look at the 87 milliseconds. You see the  
23 temperature is very high at the pellet rim. And that  
24 is where all the actions occur.

25 And for this solid line, the cladding

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1 temperature is the solid line. I'm sorry. I should  
2 have said in the beginning, this is the cladding  
3 temperature, is black. And if the pulse goes into the  
4 black, the cladding temperature goes like that. And  
5 at the end --

6 CHAIRMAN POWERS: That was too remarkable  
7 for me. You put a pulse in. And so the temperature  
8 and the clad go down?

9 MR. OZER: No, no. The temperature and  
10 the cladding are way at the bottom, way down, way  
11 down.

12 MS. YANG: Yes. Sorry. Here, this one.  
13 This is the beginning-of-life temperature. This is  
14 the end-of-life temperature. Sorry. This is  
15 beginning. This is the end.

16 This is 87 milliseconds. As you go to the  
17 end of the pulse, the temperature, the heat is  
18 beginning to conduct through the center of the pellet.

19 So the pulse, the temperature shape kind  
20 of smoothes out, becoming this curve. And the  
21 cladding temperature increased from this solid line to  
22 that line. And, of course, after a long time, the  
23 temperature goes to two seconds later, goes through  
24 your typical parabolic distribution.

25 So the nonlinearity is the temperature

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1 keeps changing as you go through the pulse. And it  
2 progressively moves to the center of the pellets. At  
3 the same time, the cladding temperature increased.

4 CHAIRMAN POWERS: I guess you just totally  
5 confused me.

6 MS. YANG: Okay.

7 CHAIRMAN POWERS: The slide says we have  
8 a 9.5-millisecond pulse.

9 MS. YANG: Right.

10 CHAIRMAN POWERS: Okay. So now you are  
11 looking at 87 milliseconds. That must surely be a  
12 long time after the pulse. So we're not going through  
13 the pulse. We're just enjoying the response of the  
14 system to the pulse.

15 MS. YANG: Say that again.

16 CHAIRMAN POWERS: We're not going through  
17 the pulse. We're sitting here looking at the  
18 aftermath of the pulse.

19 MS. YANG: The temperature response in the  
20 fuel has a delay from the pulse. We have a  
21 temperature chart of the energy, of the pulse and the  
22 energy. I will find it for you later at the break.

23 MR. OZER: Rosa, the origin of the pulse  
24 is not at zero. The pulse starts later on. Early in  
25 the pulse, 74.5 milliseconds is only the beginning of

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1 the pulse. At the peak of the pulse, you are at 87  
2 milliseconds.

3 MS. YANG: This one?

4 MR. OZER: Yes. So the counter starts  
5 before the pulse. And then the pulse is introduced  
6 around 70 or so. And 87 is the peak of the pulse.  
7 And then it starts to decrease after that.

8 CHAIRMAN POWERS: That is certainly not --

9 MS. YANG: No, no. There is the energy  
10 input. There is a delay in the pulse. You don't heat  
11 up the fuel, by the way. I'll show you. I think, in  
12 fact, we have a nice energy input versus when you  
13 cross --

14 CHAIRMAN POWERS: I can safely say I am  
15 totally confused, but --

16 MS. YANG: All right. The timing, we can  
17 clarify that, but the key point in trying to make  
18 assuming if you will just follow the zero time here,  
19 this is at 87 milliseconds, then the pulse keeps going  
20 inside.

21 MEMBER SIEBER: It would be interesting to  
22 show a plot --

23 MS. YANG: I will show you. It's on the  
24 computer.

25 MEMBER SIEBER: -- of the energy creation

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1 especially --

2 MS. YANG: Yes, exactly.

3 MEMBER SIEBER: -- and then look at that  
4 versus what the temperature results.

5 MS. YANG: Versus temperature, yes.

6 MEMBER SIEBER: Then I think it becomes  
7 clear.

8 MS. YANG: I can see why you are confused,  
9 but let's forget about the time zero. We will define  
10 that later. In an RIA pulse, you deposit energy at  
11 the rim.

12 MEMBER SIEBER: Right.

13 MS. YANG: So this is the temperature  
14 distribution at some point. And as time goes along,  
15 this temperature shape widens and eventually goes to  
16 the parabolic.

17 CHAIRMAN POWERS: I assume that all you're  
18 telling me is that there is conduction.

19 MEMBER SIEBER: Yes.

20 MS. YANG: There is conduction, right.

21 CHAIRMAN POWERS: Now, conduction is  
22 something I believe in.

23 MS. YANG: And that conduction --

24 CHAIRMAN POWERS: What that has to do with  
25 9.5-millisecond pulses versus 30-millisecond pulses,

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1 I'm not entirely certain about.

2 MS. YANG: Okay.

3 CHAIRMAN POWERS: I have no idea what this  
4 slide is trying to tell me other than that there  
5 assuredly must be conduction.

6 MS. YANG: Okay. There are two points on  
7 the slides I want to make, and maybe I'm not making it  
8 clearly. The first one is the most of the energy is  
9 at the edge. And the narrower the pulse, the narrower  
10 --

11 MEMBER SIEBER: The sharper the peaks.

12 MS. YANG: The sharper. This is the peak.  
13 And that affects the temperature in the cladding,  
14 which changes with time. So that's one of the first  
15 nonlinear situations.

16 Now I want to go into the cladding failure  
17 because that's one of the criteria we propose. Then  
18 I will go to core coolability. Most of the  
19 simulation, RIA simulation, tests deal with cladding  
20 failure.

21 There are over 100 of them. And, just by  
22 studying them, I think this is kind of the conclusion.  
23 There are two different phenomena for high burnup and  
24 for low burnup.

25 For the lower burnup ones, it's mostly a

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1 high-temperature failure. It's called post-DNB  
2 operation. And we won't discuss too much of that here  
3 because most of what we are concerned about is high  
4 burnup. And for beyond 30 or 40 thousand, the failure  
5 is by pellet-cladding mechanical interaction. And  
6 that can be modeled very successfully.

7 So far the experiment has not produced any  
8 data that suggests otherwise. So pellet cladding  
9 mechanical interaction is the failure mechanism. And  
10 the driving force for that is from the fuel thermal  
11 expansion and the fuel extension as a result of  
12 fission gas swelling.

13 For those of you who I think are less  
14 familiar with pellet-cladding mechanical interaction,  
15 the cladding ductility is the key parameter in  
16 determining if the test failed or not.

17 This is also the conclusion of the PWR RIA  
18 PIRT that Ralph chaired, which says cladding ductility  
19 is a key parameter. Now, as you remember, now we're  
20 looking at the current regulatory criteria at high  
21 burnup.

22 So this point is trying to say burnup per  
23 se is not an important parameter, but the result of  
24 the burnup, the cladding corrosion and hydriding as a  
25 result of irradiation and burnup is really the key.

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1           You could have very low burnup, a very  
2           high corrosion, and you could fail. The cladding  
3           could become very brittle or, conversely, you can have  
4           very, very high burnup but very good cladding, has  
5           very low corrosion. The cladding would have survived.  
6           And many of the Cabri tests have demonstrated that.

7           MEMBER SIEBER: But the fact is that it  
8           does become less ductile as burnup increases absent  
9           the corrosion effect, right?

10          MS. YANG: You mean the irradiation  
11          damage?

12          MEMBER SIEBER: Yes.

13          MS. YANG: Yes. And that doesn't seem to  
14          be as important as the hydrogen in the cladding. In  
15          the Cabri test, they have conducted two very high  
16          burnup rods with advance alloy and with very low  
17          corrosion levels, like 20 microns or so. And they  
18          have survived the highest energy input at 70,000  
19          burnup.

20                 So that is a good demonstration, if you  
21          may, that the hydrogen, when you have low hydrogen,  
22          even with the irradiation damage, it could survive  
23          this type of transient.

24          MEMBER SIEBER: And zinc makes the  
25          hydrogen low?

1 MS. YANG: Zinc?

2 MEMBER SIEBER: Yes. What chemical  
3 addition can you reduce the hydrogen from? Any?

4 MS. YANG: I don't know.

5 MR. BILLONE: I'm sorry. What was the  
6 question?

7 MS. YANG: What chemical in the coolant,  
8 addition in the coolant, would make hydrogen low --

9 MEMBER SIEBER: Lower.

10 MS. YANG: -- lower in the cladding?

11 MR. BILLONE: I don't think you can do it  
12 that way because basically you have water. And water  
13 is going to break up. And some of that hydrogen is  
14 going to go through the oxide, which is not  
15 protective, and will get to the cladding bare metal.  
16 It happens locally.

17 MS. YANG: In this particular advanced  
18 cladding, just corrosion is very low. And this  
19 hydrogen was also very low. If the rod is spalled, as  
20 I said, once a spalled, it severely degrades its  
21 ductility.

22 In the Cabri database, there are no  
23 failures up to 64 and now up to 70 thousand for both  
24 Zircaloy-4 and advanced alloy. As long as it doesn't  
25 spall, you can have fairly high corrosion, up to 80,

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1 90, 100 microns. But there are no failures if the rod  
2 did not spall. So spallation does create a special  
3 challenge to the ductility.

4 In my slides, you are going to see I sort  
5 of favor the Cabri data in the sodium loop. We only  
6 have two new data points in the water loop. And one  
7 is not even quite confirmed.

8 So all the data I'm talking about here are  
9 in the old program in the sodium loop. And the reason  
10 I favor that I think is the same reason that Ralph  
11 Meyer talked about yesterday. These are the most  
12 representative simulation tests. They have the right  
13 temperature and the right pulse.

14 CHAIRMAN POWERS: I thought one of Ralph's  
15 major points was that the temperature was a bit high.

16 MS. YANG: For this?

17 CHAIRMAN POWERS: For the Cabri data. I  
18 mean, he went through the whole exercise with us on  
19 REP-Na10. And he made an adjustment for the higher  
20 temperature.

21 DR. MEYER: Yes. This is Ralph Meyer.  
22 The temperature was high as a consequence of the pulse  
23 width. The initial test temperature is the right --  
24 it's the same as the hot standby temperature.

25 MS. YANG: So you are adjusting the --

1 DR. MEYER: The high temperature that I  
2 was talking about, Dana, was a consequence of the  
3 artificially broadened pulses that they're using. And  
4 these are the temperatures of the cladding at  
5 approximately the time that the failure took place.

6 MS. YANG: So you are really adjusting the  
7 pulse widths?

8 DR. MEYER: Yes. For Cabri, the  
9 adjustment was just for pulse width.

10 MS. YANG: For the pulse width.

11 DR. MEYER: For the NSRR data, the  
12 adjustment was for both pulse width and test  
13 temperature; the initial temperature of the test in --

14 MS. YANG: In that case, the temperature  
15 is very low. The pulse width is very narrow. So you  
16 adjust upwards both cases?

17 DR. MEYER: Yes.

18 MS. YANG: Mr. Chairman, you talked  
19 yesterday about something new in the topical. I  
20 assume you are referring to the failure model talked  
21 about here. This strain energy density approach has  
22 been used elsewhere. This is not something really  
23 invented by Anatech. What it does is it really just  
24 integrates under the stress and strain curve that you  
25 get from the mechanical property measurement.

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1           What is unique, I would say, is the CSED,  
2           which defines the failure. You know, you look at the  
3           stress-strain curve. And you look at the total strain  
4           here. And then you integrate between the  
5           stress-strain curve. And that is the failure CSED.

6           The reason we take this approach is  
7           because it takes into consideration the strain rate,  
8           the temperature, and the stress biaxiality effect.  
9           I'm not the expert on this.

10           So I can't really defend this too much.  
11          But I think we need this because if you want to take  
12          a mechanistic approach of the RIA, instead of just  
13          looking at the data empirically, you need something as  
14          a gauge to say what is the measure of the adverse  
15          effect on the rod so that it fails or not fails. And  
16          this is our gauge.

17           You can look a number of cases. You can  
18          use strain. You can use stress. But we decided to  
19          integrate under the stress-strain curve as our gauge  
20          for failure.

21           So when I look at the response of any RIA  
22          simulation tests, I can calculate the SED for that  
23          particular test and then depending upon if it's M5, if  
24          it's ZIRLO, if it's Zircaloy-4 and how much hydrogen  
25          in the cladding, then I create a CSED curve, which is

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1 clearly mechanical property. There's nothing more  
2 than mechanical property. And if the mechanical  
3 property is good enough, then the rod will not fail.  
4 And if the mechanical property is not good enough,  
5 then the rod will fail.

6 So it is a concept of taking advantages of  
7 the mechanical property data. And I think because of  
8 this, you can actually -- I think Tom yesterday talked  
9 about extrapolating into advanced alloys. Because of  
10 this way of making use of the basic mechanical  
11 property data, you can extrapolate it or extend it to  
12 advanced alloys.

13 Now, one of the concerns or the criticisms  
14 is how good are the data. And here is our database.  
15 There are hundreds of data. They are not all created  
16 equal. They are burst tests, axial tension tests,  
17 ring tension tests. And there are different ways of  
18 doing ring tension tests. I would argue that axial  
19 tension test is probably not that relevant because we  
20 are looking at the hoop direction here.

21 I would also argue some of these very  
22 early or very old data are probably not as good as  
23 some of those on the lower end curve. But you can see  
24 the database is pretty extensive. They cover  
25 different fuel type, different burnup level, fluence,

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1 oxide, temperature, strain rate. The fact it is very  
2 comprehensive probably resulted in the scatter of the  
3 data. And here is the data. There is considerable  
4 scatter. I would agree.

5 I just want to use this curve to make a  
6 few points. A) do we want better data? Yes. You can  
7 always get better data. And we have many programs in  
8 place. The one at Argonne is one and some of our own  
9 programs.

10 We can always refine it, but the one thing  
11 I want to point out here is different shapes. Well,  
12 some of the scatter is due to temperature. As you  
13 know, temperature is an important parameter. And what  
14 I want to point out is these solid symbols. They are  
15 from the material that has spalled. The open symbols  
16 are, at least from the metallography, that they are  
17 not spalled. And this blue line is the best estimate  
18 fit of all the data. And this is the best estimate of  
19 all the spalled.

20 So I think it is clear that they are two  
21 different populations.

22 CHAIRMAN POWERS: I'm tempted to quibble  
23 --

24 MS. YANG: With that?

25 CHAIRMAN POWERS: With a lot of stuff

1 about this plot. For instance, let us take your  
2 spalled solid data point out of the plot. And let's  
3 look at the residual open spot. Why wouldn't I fit  
4 that with a constant?

5 MS. YANG: Well, one of the reasons we  
6 don't want to fit it with the constant, Dana, is  
7 because we do know there is a relationship here. What  
8 you are plotting is the strain energy density as a  
9 function of oxide to cladding thickness ratio. It's  
10 a flange parameter, but we use it. You can just look  
11 at it as oxide. The reason we divided by the cladding  
12 thickness is because, if you remember, our data had 14  
13 by 14, 15 by 15, 16 by 16, 17 by 17. So this is just  
14 a way to normalize the data point.

15 Basically, you are saying that the  
16 critical strain energy density is reducing as you  
17 increase the hydrogen content. I think it does have  
18 a slope to it, especially if you look at individual  
19 data sets.

20 CHAIRMAN POWERS: You can have a religious  
21 belief there is a slope there, but I fail to see it in  
22 the data.

23 MS. YANG: One of the scatters, the reason  
24 is because we plot all the data that may not belong to  
25 the same curve. But if you look at individual sets,

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1 like this ring tension test, it does have a slope to  
2 it.

3 And if you look at burst tests, which is  
4 typically believed to be more demanding than an RIA or  
5 PCMI type of test. It has a very sharp slope to it,  
6 which is consistent with the mechanistic understanding  
7 of the mechanical properties.

8 I do agree as we improve, I think for many  
9 of the people here, they know that there are  
10 challenges for these either burst tests or the ring  
11 tension tests. You basically get different results if  
12 you do ring tension tests or burst tests. And  
13 depending on the gauge lines, depending upon how much  
14 friction you have and all of that, you get scatter in  
15 the data. And they can be improved, and they are  
16 being improved.

17 What we have done here -- and I will show  
18 you what we have done -- is we look at different ways  
19 of using the best estimate. We think for RIA types of  
20 transient, it is not a good idea to just take the  
21 lower bound given the type. Being risk-informed  
22 approach, you should look at the best estimate but  
23 trying to quantify the uncertainties or the scatter in  
24 the data. And we have done that in the report.

25 CHAIRMAN POWERS: It's a very peculiar

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1 characterization of the uncertainty in that report.  
2 If you were to put the confidence bounds around that  
3 line, about where would they show up? You can take  
4 any percentage confidence you want, 50 percent, 80  
5 percent, 90 percent.

6 MS. YANG: Yes.

7 CHAIRMAN POWERS: Where would they show up  
8 on that curve?

9 MS. YANG: On the curve?

10 CHAIRMAN POWERS: Yes.

11 MS. YANG: I'll show you. What we did,  
12 this is the best estimate curve. Then we said we will  
13 only look at the burst data. We will look at a  
14 different set. We said we will only look at the burst  
15 data, which is the green curve. Then we said we will  
16 look at the lower bound of all the data, which is a  
17 red curve. So you do get different curves.

18 The bottom line, these are the three  
19 curves. I'm sorry. The red become black here. These  
20 are the three curves. If we take the lower bound of  
21 all the mechanical property data we have, we will have  
22 predicted those tests failed and they didn't. And so  
23 we decided consistent with the risk involved, we  
24 should take a best estimate approach.

25 But if you really want to, if you take a

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1 list of the burst tests, which we know is more  
2 conservative than the PCMI type of scores, if you take  
3 this, you still would show this rod fail.

4 So we kind of lack data. We don't have a  
5 good justification. The right curve to be totally  
6 probably should be something like that, but we don't  
7 really have a good basis to draw a line here.

8 And then in the report, we did estimates  
9 of taking any of the curves. How does that affect the  
10 criteria that we have proposed? And we quantify that  
11 in the report. The bottom line is very, very small,  
12 basically because these curves are so flat and we use  
13 a very conservative corrosion correlation, just to  
14 refresh your memory, because these curves are  
15 basically flat here.

16 So if we take the lowest, lowest bound, we  
17 probably end up with a curve like that. So it is  
18 going to be lower than what we proposed but not by  
19 very much.

20 So basically when everything is sort of  
21 put together in terms of the failure curve, it is not  
22 that different from what we proposed. And these are  
23 discussed in great detail in the topical report.

24 So yes, I agree there is considerable  
25 scatter in the data. And we have looked at ways to

1 quantify the scatter and the uncertainty. And we have  
2 quantified that. And the bottom line is that doesn't  
3 really change the final criteria.

4 CHAIRMAN POWERS: If you model that  
5 database as a constant, which it certainly looks like,  
6 then it says there's no dependence on strain energy  
7 density and it's a failed concept. That's the  
8 problem.

9 You have said, "Look, this thing depends  
10 on strain energy density." You draw a curve through  
11 it to get yourself a slope. You show how it depends,  
12 but you may be fooling yourself because the data is so  
13 scattered there may be no dependence on strain energy  
14 density. It may have nothing to do with it.

15 MS. YANG: If that's the case, then this  
16 curve you could plot. I don't think strain energy  
17 density is very unique here. You can plot the total  
18 elongation here, for example.

19 CHAIRMAN POWERS: I can plot the tides of  
20 the moon on this plot and do a calculation and get a  
21 curve through it. It doesn't mean there is one. You  
22 see, the data is so scattered that it is very, very  
23 difficult to convince yourself that the slope you have  
24 there is distinguishable from zero.

25 MR. CARUSO: Why is it a curve? Why isn't

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1 it a straight line?

2 MS. YANG: It's a best fit curve.

3 MR. CARUSO: But when you do a fit, you  
4 have to fit to an equation and decide what the shape  
5 of the data is. Is it linear or it a quadratic or is  
6 it a cubic? How did you decide that it was that  
7 shape?

8 MS. YANG: It's a statistical fit of the  
9 data. I mean, that's the shape that comes out of the  
10 fit.

11 MR. CARUSO: To what? I mean, you have to  
12 decide that it varies as the square or as the log or  
13 as the? Where does that come from? If you do a fit  
14 to a particular type of curve --

15 MS. YANG: The fitting routine gives you  
16 what is the best fit form.

17 MEMBER SIEBER: If you do a multiple  
18 regression, it will come out either a straight line or  
19 some kind of a curve.

20 CHAIRMAN POWERS: If you do a multiple  
21 regression in any real program, it will also tell you  
22 whether the coefficients are distinguishable from zero  
23 or not.

24 MEMBER SIEBER: Right.

25 CHAIRMAN POWERS: And here I just can't

1        imagine it would come back with any of the terms  
2        having a coefficient that was distinguishable from  
3        zero.

4                MS. YANG: Oh, I think it does.

5                MEMBER SIEBER: You may be right.

6                MS. YANG: Dana, one other thing I want to  
7        point out is probably our fault. We plot all of the  
8        data we have just because they're in that not damaged  
9        mechanical property data. But what I would argue is  
10       some of these axial tension tests are not that  
11       relevant for the PCMI type of driving force that we  
12       are talking about here.

13               So if you take the blue square and the  
14       green or the upside-down triangle, which is a lot of  
15       the scatter right here, I think that the slope you are  
16       looking for may be more clear.

17               MEMBER SIEBER: I think you are making  
18       your argument based on what you are observing there,  
19       but it would be interesting just to take the sets of  
20       data and plot the curves and see what they actually do  
21       look like, rather than have a single curve --

22               MS. YANG: Yes.

23               MEMBER SIEBER: -- trying to represent all  
24       of the data.

25               MS. YANG: And I believe they are in the

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1 report, the different sets. Like I said --

2 MEMBER SIEBER: Well, I don't know that.

3 MS. YANG: If you look at different sets,  
4 I think the dependence is more clear. It's just when  
5 you overlay the different sets of data, they appear to  
6 be more scattered.

7 CHAIRMAN POWERS: Now, when I look at the  
8 individual sets, what I see is a high degree of  
9 sensitivity to individual data points, that, in fact,  
10 if I take one data point out of each set away and say  
11 there was something wrong with that data, I end up  
12 with curves having zero slope.

13 MS. YANG: I'm not sure I understand. Say  
14 it again.

15 CHAIRMAN POWERS: Well, what I understand  
16 is we are going to run out of time on this session.  
17 So let us wrap up as quickly as you can.

18 MS. YANG: Okay. This is what was  
19 proposed. And these are the REP-Na tests, which have  
20 the right temperature condition and with different  
21 pulse widths. You can see the curve bounded the data  
22 quite well, even maybe somewhat more conservative for  
23 that one.

24 Coolability. We have shown here is all of  
25 the data, the RIA simulation data, which had fuel

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1 dispersal, some dispersal. And what we have plotted  
2 here is the amount of energy deposition after the  
3 failure as a function of the pulse width.

4 All of those on this side of the curve  
5 have fuel dispersal. All of those on the other side  
6 of the curve have failed. And some of them have  
7 considerable energy deposition after they fail, but  
8 they are no fuel dispersals.

9 So this is an empirical approach. And we  
10 have drawn a line here, and the line actually should  
11 be drawn between these two sets. Basically we observe  
12 you only have fuel dispersal when the pulse width is  
13 less than 10 milliseconds.

14 There is a chart which in the interest of  
15 time I don't want to get into that explains why the  
16 narrow pulse would have resulted in dispersal because  
17 the temperature distributions are considerably  
18 different for the narrow pulse and the wider pulse.  
19 So because we think the typical PWRs or BWRs that the  
20 pulse width is greater than 30 milliseconds.

21 So it is not possible to expect fuel  
22 dispersal with the prototypical pulse width. However,  
23 if you want to assume dispersal in case you have a  
24 very high energy input, then we look at the data in  
25 the industry that shows how that affects the rod

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1 geometry and how the fuel and coolant would interact.  
2 And there are these references.

3 But the bottom line is really only molten  
4 fuel would result in high energy fuel-coolant  
5 interaction, as illustrated in this experiment here.  
6 Is the measured energy conversion ratio as a function  
7 of the mean diameter of the particle?

8 The molten for the molten fuel dispersed  
9 that the energy conversion is high. But for the same  
10 diameter that if you don't have molten fuel, the  
11 conversion ratio is significantly reduced because of  
12 it.

13 So what we had proposed here is to limit  
14 fuel melting. We want to limit any amount of fuel  
15 melting, even if it's incipient melting, just local  
16 melting.

17 If you recall, the temperature  
18 distribution for the RIA pulse is peaked at the rim,  
19 which happened to be the highest burnup area, which  
20 they are fuel particles there due to the so-called rim  
21 effect.

22 So what we have done is to propose the  
23 criteria that limit any amount of fuel melting right  
24 here. We have used very conservative thermal  
25 conductivity data.

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1           We have used fuel melting as a function of  
2 burnup. So we didn't just use the fuel melting  
3 temperature for fresh fuel. We have used a  
4 correlation from experimental data that reduced the  
5 fuel melting temperature as a function of burnup. So  
6 we used that to develop the fuel coolability curve.  
7 That's why you see this going down as you go to higher  
8 burnup. And they are these data, these Japanese data,  
9 that we have found that sort of support the curve that  
10 we propose.

11           So, to summarize, we have proposed a fuel  
12 failure limit, which is based on PCMI and the  
13 mechanical property. And we have proposed a  
14 coolability limit, which is based on preventing fuel  
15 melting. And both are supported, which we're using an  
16 analytical approach, mechanistic approach, trying to  
17 represent the phenomena and take the lower bound of  
18 many of the values that we have used, especially  
19 corrosion, which we use the bounding case of  
20 corrosion. So this is a curve that was produced and  
21 supported by the Cabri experimental data for the  
22 coolability.

23           We don't think there will be fuel  
24 dispersal if you have representative pulse width.  
25 However, if you do want to calculate dispersal, we

1 have limited the fuel temperature to melting because  
2 of this more mechanistic type of approach that can be  
3 extended to advanced alloys.

4 So that I think, Dana, you asked the  
5 question yesterday. When you extend the methodology  
6 to advanced alloys, do you still need it to run any  
7 RIA tests? And I think the answer is yes, but you  
8 don't need as many so that you can get a good  
9 statistical distribution.

10 What you need are one or two of these RIA  
11 types of tests to confirm what you know, but what you  
12 need once you develop a new criteria for advanced  
13 alloys, you need good mechanical property data for the  
14 advanced alloy because we have found from the RIA  
15 simulation tests up to 73,000 burnup, which is the  
16 licensing burnup extension limit that we are looking  
17 for that PCMI is still the driving force. There are  
18 some mechanisms being hypothesized earlier, but we  
19 haven't observed that at this burnup level.

20 So we think what we proposed is  
21 conservative and considering the risk of the rod  
22 ejection accident, we think there is no basis to merge  
23 the two curves because in one case, you have cladding  
24 failure. And in many cases, they are the PCMI types  
25 of cracking. They certainly were not the same as

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1 causing a core coolability concern. So that's the  
2 added slides for the RIA.

3 For the LOCA program, coming back, closing  
4 to the end of my presentation on the LOCA, I am not  
5 going to talk about the Argonne program, which was  
6 being talked a lot yesterday. In addition to that  
7 program, we have a collaborative program with EdF,  
8 which looked at the separate effects of the LOCA face,  
9 which is quite different from some of the other  
10 experiments.

11 Basically you look at the ballooning and  
12 the burst phase. And then you look at the oxidation  
13 and the quenching phase. Just look at the cladding.  
14 You use fresh cladding, and you use hydrided cladding  
15 to simulate the hydrogen.

16 The intent here is assuming that the  
17 irradiation effect will be annealed out for the LOCA  
18 type of condition. Of course, that needs to be  
19 demonstrated to be the case. And I think the Argonne  
20 program will provide us some insight to that. And  
21 some of these French tests will provide that.

22 We are also monitoring the Japanese ALPS  
23 program and the Halden program, which is using real  
24 fuel rods to run LOCA tests in a test reactor. The  
25 purpose of this slide is just to let you know that we

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1 are actually approaching LOCA very similar to what we  
2 are approaching RIA.

3 We are actually going to model all the  
4 experimental results so that we have a better  
5 understanding of how much margins we have. I think  
6 the stylized LOCA phrase was used. And we need to  
7 know how much margin we have between the real LOCA,  
8 real hypothetical LOCA, and the stylized LOCA.

9 Very quickly, we have an effort for  
10 industry guide for burnup extension. This is to sort  
11 of lay out the framework or the road map for getting  
12 to burnup extension. This is being mandated by NRC  
13 to, instead of different fuel suppliers coming in for  
14 different topicals that the NRC mandate to save the  
15 resources to be more efficient use of the resources,  
16 we should do it on an industry-wide basis. And the  
17 target of this effort is 75,000 for PWRs and 70,000  
18 for BWRs.

19 What we have done is we have looked at the  
20 current regulatory criteria described in SRP 4.2 and  
21 trying to look at each criteria to see how the burnup  
22 impacts that particular requirement and then decide on  
23 if new criteria should be proposed.

24 We have a fairly rigorous approach in this  
25 and have been discussing with NRR in the past. We're

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1 continuing with this. We are pretty much done on this  
2 except the LOCA section. I think you can understand  
3 why, but we'll complete it and submit it to NRC for  
4 review sometime next year.

5 So, to summarize the program, as I said  
6 earlier, we have many international participants. And  
7 they play a very active role. They don't just come to  
8 get data in many cases. They provide the data and the  
9 operating experience to the program. And we have  
10 addressed many of the key issues, like AOA and noble  
11 metal. And we have completed the RIA topical report.  
12 We are in the midst of hot cell examinations, trying  
13 to obtain data to ensure margins to avoid big  
14 surprises.

15 So a little bit of the PR here. We are  
16 aimed at reliable and efficient fuel operations. And  
17 we have industry-wide collaboration, trying to resolve  
18 safety and regulatory issues in an integrated and  
19 effective manner. Although I said it's PR, that is  
20 certainly what we are striving at and just to show  
21 some of the interactions and interfaces that I have  
22 talked about before.

23 So that's the end.

24 CHAIRMAN POWERS: Any questions of the  
25 speaker?

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1 (No response.)

2 CHAIRMAN POWERS: Seeing none, thank you  
3 very much.

4 MS. YANG: Okay.

5 CHAIRMAN POWERS: We will recess until 10  
6 of the hour.

7 (Whereupon, the foregoing matter went off  
8 the record at 10:38 a.m. and went back on  
9 the record at 11:00 a.m.)

10 CHAIRMAN POWERS: Let's get back to work  
11 here before people try to chase us out of the room.  
12 They won't succeed. We're comfortable here. We're  
13 enjoying this. This is a salubrious environment.

14 Let's get back to talking about -- what  
15 were we talking about now? Oh, LOCA tests. Odelli,  
16 it's yours.

17 MR. OZER: Thank you. Thank you, Mr.  
18 Chairman.

19 As Rosa mentioned, our robust fuel program  
20 is a collaborative program. We work very closely with  
21 our sponsoring utilities and the fuel vendors. This  
22 collaboration is probably the strongest in working  
23 group 2. We work very closely with our vendors.

24 And at the last working group 2 meeting,  
25 we had a considerable amount of discussion of the ANL

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1 LOCA program. There was a considerable amount of  
2 concerns that were expressed. And the decision was  
3 made to express those concerns, to transmit them to  
4 NRC in the form of a letter. So it's the basis of  
5 this letter, the contents of this letter, that I was  
6 asked to talk about.

7 I think they concerned the tests that are  
8 being done to confirm the LOCA criteria. I think  
9 yesterday we got a very good presentation from Ralph,  
10 Ralph Meyer, on the basis of the LOCA criteria. They  
11 were established for the 1973 ECCS rulemaking  
12 hearings. At that time, there was very little data  
13 that was available on the types of forces that fuel  
14 would experience during a LOCA event.

15 So ductility was considered to be sort of  
16 a proxy, if you wish, a surrogate, to ensure adequacy  
17 of the fuel. And two limits were established. There  
18 was generally good agreement among the industrial  
19 participants that 17 percent was a good oxidation  
20 limit. And the 2,200 temperature limit was  
21 established to a certain extent to stay away from the  
22 region where reactions become autocatalytic.

23 Also, there was some evidence that  
24 oxidation at higher temperatures was more harmful than  
25 oxidation at the lower temperatures. So those were

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1 really the bases of the criteria as far as we're  
2 concerned.

3 Now, as I said, the 73 criteria were based  
4 on very limited information. In the ten years that  
5 followed, there was a considerable amount of  
6 information, experiments that were conducted by the  
7 commission's own assessment.

8 \$1.5 billion were expended on trying to  
9 understand the behavior of reactors during a LOCA  
10 event. Seven hundred million dollars -- this is 1980  
11 dollars -- were NRC's own LOCA programs. The  
12 remaining half was DOE and international participants  
13 in the industry in general.

14 As far as the two licensing criteria that  
15 we are most concerned about, the most relevant ones we  
16 feel are the experiments conducted at Argonne by Chung  
17 and Kassner consisting primarily of subjecting rods to  
18 a LOCA-like scenario, quenching them. And rods that  
19 survived the quench were subjected to impact tests  
20 with 0.3 joule hammers. And then it was determined  
21 whether they survived that or not.

22 Now, following these tests, in the mid  
23 1980s, the NRC staff reviewed the large amount of data  
24 that was generated. They concluded, first of all,  
25 that now there was a sufficient amount of data to

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1 estimate the extent of conservatism in the criteria  
2 that were established in 1973. This is summarized in  
3 NUREG-1230.

4 Following the review, the 10 CFR 46 was  
5 revised, 10 CFR 50.46 was revised, based on  
6 NUREG-1230. The criteria were left the same at 2,200  
7 and 17 percent. However, the commission allowed the  
8 use of best estimate models as long as the  
9 uncertainties involved in the overall modeling process  
10 were accounted for appropriately. This allowed the  
11 use of corrosion correlations that are more relevant,  
12 such as Cathcart-Pawel, as opposed to Baker-Just.

13 At the same time, the commission felt that  
14 there was sufficient conservatism in these criteria.  
15 And they de-emphasized at that point the use of ring  
16 compression tests or ductility in general in favor of  
17 the impact tests. The impact tests provide sufficient  
18 margin.

19 Here we are plotting all of the impact  
20 tests that failed, but we are plotting on the  
21 ordinance. The x-axis is the inverse of the  
22 temperature. So this is low temperature. As the  
23 temperature goes higher and higher, we progress in  
24 this direction. And we come to the limit, 2,200  
25 Fahrenheit or 1,200 degrees Centigrade.

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1 I am only plotting here the rods that  
2 failed and the level at which they failed. The y-axis  
3 represents the time that each rod spent in the  
4 oxidizing environment, the amount of oxidation, if you  
5 wish, different temperatures. So at this temperature,  
6 it would take this much time to oxidize the rods to a  
7 certain level.

8 Now, where does the 17 percent stand with  
9 regards to these failure levels? If you use the  
10 original Baker-Just correlation, you get this line.  
11 This is the 17 percent line. And there was a  
12 considerable amount of discussion about Baker-Just  
13 versus Cathcart-Pawel.

14 This is the Cathcart-Pawel oxidation  
15 limit. Yes, it decreases somewhat the margin, but  
16 still there is a considerable amount of margin.

17 Now, what I should stress is that some of  
18 these rods would have failed the ring compression  
19 tests. Depending on where you take your sample for  
20 ring compression, if you take it from the hydrided  
21 rim, they probably could have failed. Nevertheless,  
22 the NRC felt that this was sufficient evidence of  
23 conservatism and went on.

24 Now, we feel that the current regulations  
25 are based on the 1988 assessment, which relied on

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1 quench and impact tests. We feel that impact tests on  
2 the irradiated fuel are necessary to provide this  
3 linkage to the 1988 reference.

4 What we are trying to establish is, first  
5 of all, this reference between irradiated versus  
6 unirradiated impact tests. Eventually what we would  
7 like, of course -- I think this is consistent with  
8 what ANL and Ralph would like to do -- is to determine  
9 whether we can establish a correlation between the  
10 irradiated material response and the response of  
11 unirradiated but pre-hydrated material so that we can  
12 estimate the response of materials sooner without  
13 having to go through the post-irradiation process.

14 We feel that impact tests are more  
15 representative of expected post-LOCA loads. We feel  
16 that reliance on ring compression tests is  
17 problematic.

18 Mainly the results are subject to  
19 interpretation. They're qualitative. There is no  
20 clear way to relate the ring compression tests to the  
21 type of data that was used in 1988; in other words,  
22 the impact tests.

23 We acknowledge that yes, they have some  
24 limited use and they were used recently to  
25 inter-compare different materials to the response, to

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1 compare the response of the advanced cladding, for  
2 example, to that of Zircaloy-4 and to compare, for  
3 example, E110, confirm that the E110 behavior is  
4 there. But that's a rather limited use.

5 We are very concerned about the  
6 uncertainties that will be introduced by defueling of  
7 high-burnup fuel rings for doing these tests. The  
8 response of fuel in a post-LOCA seismic event will be  
9 to a great extent controlled by the rigidity of the  
10 rods. And the rigidity will be affected by the fuel  
11 that is inside those rods.

12 Yesterday Mike Billone showed dramatically  
13 different responses when you leave rather rigid  
14 pellets inside a four-point bend test. Now, if we are  
15 doing these tests on defueled samples, the impact of  
16 this effect will be lost. We will not know how to use  
17 it, really.

18 And we think that it has questionable  
19 relevance to post-LOCA load. For that reason, we are  
20 proposing to hold a stakeholders' meeting to ensure  
21 that appropriate input is considered. This would be  
22 a meeting of experts in mechanical properties and  
23 testing and so on, which I'm not.

24 So this is really a very brief summary of  
25 why we submitted that letter and what we are concerned

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1 with.

2 MR. BILLONE: Mike Billone from Argonne.  
3 Just for clarification, in Hee Chung's work, they did  
4 a lot of impact tests. They did a lot axial tensile  
5 tests. And they did a lot of ring compression tests.  
6 The research included all the three testing types. It  
7 wasn't just impact tests.

8 MR. OZER: That's correct. Nevertheless,  
9 I mean, some of those ring compression tests, as I  
10 said, would have shown not enough ductility or would  
11 have shown that material would be failing around 17  
12 percent of the ring was taken from the hydrided rim  
13 region.

14 MR. BILLONE: Right. Just for  
15 clarification, because I have to translate this into  
16 a testing program in a way, there are different ways  
17 of running impact tests. And I'm wondering if you are  
18 asking for a screening test, a .3 joules screening  
19 test, or whether you do the traditional impact where  
20 you impact the failure and you look at energy absorbed  
21 in the failure.

22 MR. OZER: I think this would be best left  
23 for the stakeholders' meeting. But as a minimum, I  
24 think we would like to see the 0.3 joules test to  
25 provide the reference to what was done in the 1980s.

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1 Again, that is a subject for debating.

2 MEMBER FORD: Would you mind putting up  
3 your graph, please? Just for my information, the data  
4 points which were done under thermal shock conditions  
5 or high strain rate conditions, what was the burnup,  
6 the highest burnup?

7 MR. OZER: They were zero burnup.

8 MEMBER FORD: Zero burnup?

9 MR. OZER: Zero or very low burnup.

10 MEMBER FORD: So you would expect those  
11 lines to move down towards the current mix with  
12 burnup?

13 MR. OZER: Yes.

14 MEMBER FORD: The question is how far the

15 --

16 MR. OZER: The question is how much.

17 MEMBER FORD: How much?

18 MR. OZER: Yes, exactly.

19 MEMBER FORD: Okay.

20 DR. MEYER: Mr. Chairman, may I make a  
21 comment?

22 CHAIRMAN POWERS: Sure.

23 DR. MEYER: This is Ralph Meyer from  
24 research. We, in fact, have responded to the letter.  
25 We are happy to arrange the stakeholders' meeting and

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1 to discuss this possibility.

2 I do want to comment on the impact test in  
3 the light that I see them. Up until the time of the  
4 impact tests, which were done around 1980, both at  
5 Argonne and at the JAERI Laboratory at Tokai -- well,  
6 they didn't do impact tests, but both of them were  
7 exploring the mechanical behavior of a balloon  
8 specimen.

9 At the time the rule was made, the data,  
10 the mechanical data, ring compression testing, was all  
11 done on under-formed specimens. And an algorithm was  
12 cooked up so that you would apply that information to  
13 the ballooned region.

14 So the impact testing that was done at  
15 Argonne was some of the first testing that actually  
16 showed that the recipe worked because the intention  
17 was to have some ductility left after you survived  
18 quench.

19 And so the impact testing then showed that  
20 you had at least some strength left after you survived  
21 the quench. So I don't see any conflict between the  
22 impact testing and the ring testing.

23 In the current program, we have plans for  
24 four-point bend tests, rather than impact tests. We  
25 considered impact tests a couple of years ago, and we

1 will reconsider impact tests in discussing this with  
2 stakeholders. But the current plans were based on  
3 doing four-point bend tests to explore the integral  
4 effect with fuel inside on the ballooned region.

5 So I think the current test plan is that  
6 it does cover the difficult areas, all of the  
7 difficult areas that Odelli mentioned, using the  
8 four-point bend tests. And we can explore the  
9 possibility of adding impact tests in the  
10 stakeholders' meeting.

11 CHAIRMAN POWERS: Maybe for my own  
12 edification, suppose one comes back and says, "Gee,  
13 this particular device survived one magnitude of tests  
14 and didn't survive the next one." What do I do with  
15 that data?

16 DR. MEYER: Could you repeat the question?

17 CHAIRMAN POWERS: Okay. Well, let's just  
18 take one from the plot up here. It says here is one  
19 that survived the .15 joules impact but failed under  
20 a .3 joules impact. Now, what do I conclude from  
21 that? As long as I have guys with real tiny hammers  
22 inside the core, it's okay?

23 MR. BILLONE: To get out of that, you  
24 would run the impact test of all of the failure, which  
25 is traditional. And then you would get an absorbed

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1 energy associated with that failure. And then you  
2 generated a database that is not arbitrary.

3 You have a screening test. You are always  
4 going to be criticized by what you pick, .03, .15.  
5 And the point is that with those, your material could  
6 be really brittle. And it can survive a low-impact  
7 test.

8 This is out of my league. A lot depends  
9 on how much confidence you have in the loads you are  
10 calculating in reactor by picking a screening test.

11 CHAIRMAN POWERS: And I guess I agreed  
12 with Ralph when he said yesterday that they lacked  
13 confidence in their ability to predict the loads under  
14 LOCA conditions, but maybe I'm wrong about that.

15 MR. BILLONE: That one is out of my  
16 league.

17 MR. OZER: The loads during the LOCA or  
18 after the seismic loads that would occur?

19 CHAIRMAN POWERS: I guess the answer is  
20 yes to that question.

21 MR. OZER: Both? Okay. The loads during  
22 a LOCA, the ability to survive the loads during a  
23 LOCA, is demonstrated by surviving the quench thermal  
24 shock. If a rod survives a quench thermal shock, then  
25 it survives it. That's proof.

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1 MR. BILLONE: No. But I think the point  
2 was there might be additional loads beyond that. That  
3 was the issue, are there additional loads beyond just  
4 simple thermal stress in the cladding? I thought that  
5 was the issue of the unknown or the gray area.

6 DR. MEYER: Well, in addition to that is  
7 the uncertainty as to whether the test where you are  
8 doing the thermal quench is adequately representing  
9 the constraints that would exist in the fuel assembly  
10 undergoing a LOCA.

11 This is where JAERI has come in with lots  
12 of constrain tests of varying constraints and where  
13 one ultimately has to come down to some assessment of  
14 what the loads are. Either they think it usually  
15 comes down to some tensile load, axial tensile load,  
16 on the cladding, arriving either from an axial force  
17 related to thermal contraction or a lateral loading  
18 that causes damage in swinging of fuel assemblies.

19 MR. OZER: I think that yes, the  
20 constraint due to quenching is a consideration. I  
21 think the Japanese did probably the most extreme thing  
22 imaginable.

23 In a PWR assembly, 17 by 17, you have some  
24 260 some rods, fuel rods. The constraints will be  
25 controlled by the fuel rods, not the 24 guide tubes.

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1 There are 24 or 25, including the instrumentation  
2 tube. I mean, any forces that will be coming from the  
3 contraction of the fuel rods will overwhelm any forces  
4 that may be coming from the guide tubes.

5 As far as swinging of the rods and  
6 disbursing fuel pellets, there is no clearance between  
7 adjacent fuel rods sufficient to allow pellets to fall  
8 out. I mean, you would have to have a whole  
9 guillotine-type break, and there just isn't room for  
10 that. It's just not realistic.

11 But I really think that these kinds of  
12 issues should be discussed at the stakeholders'  
13 meeting. I don't think this is the place for it.

14 MEMBER KRESS: Why are we worried about  
15 aftershocks? Are we presuming that the LOCA was  
16 caused by an earthquake?

17 MR. BILLONE: At one time, we did.

18 MEMBER KRESS: This seems a little like  
19 going a little too far in regulatory space.

20 DR. MEYER: I don't think this is the crux  
21 of the discussion. The heart of the matter seems to  
22 be that the ductility criterion was invoked so that  
23 you didn't have to consider the loads. And if you now  
24 have changed to a strength criterion, then you have to  
25 ask what loads might be imposed.

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1 MEMBER KRESS: I think that's a reasonable

2 --

3 DR. MEYER: I don't think it's an  
4 essential part of the discussion.

5 MEMBER KRESS: Yes. That's a reasonable  
6 question to ask, but I certainly wouldn't add  
7 aftershock earthquake loads into that equation.

8 MR. CARUSO: I think that is part of the  
9 stylized nature of this accident. It's just a  
10 postulated sequence of events.

11 MEMBER KRESS: I think I would rule that  
12 out on --

13 CHAIRMAN POWERS: I don't think it matters  
14 because I don't think that you can make a persuasive  
15 case to me that you could calculate the loads in a  
16 real LOCA. It would be exceptionally hard to do that.

17 Now, that doesn't obviate the question  
18 here of what is the easy way to get things. I mean,  
19 one solution clearly is to say there is some  
20 ductility. The problem comes in as soon as you say  
21 there has to be sufficient ductility. Then you get  
22 into the same problem you've got here.

23 So maybe you have come to the right  
24 answer, to have the group of experts get together and  
25 kick it around, then come back and talk some more

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1 because I don't think we are going to solve it here.

2 MR. BILLONE: You're not going to solve it  
3 here, but the group of experts had better define the  
4 tests and tell you what you've learned from these  
5 tests.

6 The fundamental thing which has to be  
7 resolved is, are you going to move away from a  
8 ductility criteria to a strength criteria? That group  
9 of testing experts and material scientists probably  
10 can't answer that question.

11 CHAIRMAN POWERS: Yes. The only comment  
12 I think I can intelligently make now is that I am very  
13 suspect of coming in and saying, "Let's run .15 or .3  
14 joules hammer tests" and walk away from it at that  
15 point because I just don't think that tells me  
16 anything useful except make sure any of the little  
17 guys that climb through the core during cooling have  
18 real small hammers. That's the only thing it tells  
19 me.

20 Any other questions?

21 (No response.)

22 CHAIRMAN POWERS: Thank you, sir.

23 Rosa, where are we now?

24 MS. YANG: We will present -- go ahead,  
25 Jeff. We are going to talk about AOA and rods, PWR

1 rods.

2 MR. CARUSO: But this will be closed,  
3 Rosa?

4 MS. YANG: I think it's okay.

5 MR. DESHON: Yes.

6 MR. CARUSO: So this will be open.

7 11) PWR CRUD

8 AXIAL OFFSET ANOMALIES

9 MR. DESHON: Well, good morning. My name  
10 is Jeff Deshon. I am kind of a lone wolf at our fuel  
11 group at EPRI. I am not a physicist or nuclear  
12 engineer or material science guy.

13 I actually worked at one of these power  
14 plants for 16 years as either a chemist or a chemistry  
15 manager. And I came to EPRI in 2000 to work for Rosa.  
16 So that's not necessarily a bad thing, but I'm not one  
17 of those people because --

18 CHAIRMAN POWERS: Working for Rosa isn't  
19 a bad thing.

20 MR. DESHON: Because the issue that I came  
21 to EPRI for was to work on this phenomenon that's  
22 referred to as the axial offset anomaly. And in  
23 attacking this problem for the industry, it's really  
24 as much of a chemistry issue as it is a fuel issue.

25 So this presentation is broken down. I

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1 thought I would kind of get everyone on this equal  
2 footing from the very beginning and go through, number  
3 one, what our objectives are from our particular  
4 working group in the robust fuel program, give you  
5 some background information, what is AOA, the history  
6 and implications of the phenomenon to our operating  
7 plants, and then here discuss with you some  
8 information that you probably haven't seen before in  
9 the area of crud -- and this is work that we have been  
10 conducting for the last several years -- and then  
11 finally review with you some strategies that we are  
12 pursuing in trying to resolve AOA.

13 Okay. Our objective for working group 1  
14 of the RFP is indeed to minimize the threat of PWR  
15 axial offset anomaly. And the focus here is on doing  
16 that through managing core crud deposits.

17 Axial offset is normally defined as the  
18 integrated power in the top half of your core minus  
19 the bottom half over the sum of the two. Axial offset  
20 anomaly is a significant deviation from those, the  
21 numerator and denominator. It's typically observed as  
22 a negative offset.

23 Now, if you are of combustion engineering  
24 vintage, they express it essentially in the reverse  
25 order. And they refer to it as the axial shape index,

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1 or ASI. And it's merely the negative axial offset if  
2 you were to use the other definition.

3 Well, every core design has with it an  
4 associated predicted axial offset or AFD it's commonly  
5 referred to, axial flux difference, curve. And these  
6 are done using the design codes, either ANC from  
7 Westinghouse or SIMULATE. And they predict the axial  
8 offset during the cycle at various burnups during that  
9 period.

10 On a monthly and more frequent basis, our  
11 power plants will go ahead and conduct flux maps. And  
12 what they will do is compare the power data from those  
13 flux maps to the predicted code.

14 A few utilities have fixed in-core  
15 detectors. These are kind of nice features to have at  
16 a power plant because it gives you real-time data.  
17 It's constant data generation. The only problem with  
18 them, their resolution isn't quite as great as the  
19 movable in core detectors.

20 So getting back to the anomaly, as I  
21 mentioned, it's a significant deviation between the  
22 measured power data and the predicted. Now, the  
23 deviation results from a phenomenon where boron  
24 concentrates within crud and as crud is occurring in  
25 the upper strands of your core, where you have

1 significant subcooled nucleate boiling taking place.

2           Once there is a critical or a sufficient  
3 boron that has accumulated within that crud deposit,  
4 then you will start observing flux depressions in the  
5 top of the core. For the core to maintain power, it  
6 will physically shift the neutron flux downward,  
7 actually, towards the bottom half of the core. And it  
8 results in this more negative axial offset than the  
9 prediction.

10           Now, historically a plant that has  
11 encountered AOA has been defined as a deviation of  
12 greater than, say, -3 percent. And that is to  
13 incorporate all of the uncertainties that might be  
14 present in the nuclear code design.

15           Here is a curve of what the power plants  
16 are trending during the operating cycle. This y-axis  
17 here is percent AO or it could be AFD, axial flux  
18 difference.

19           The x-axis is in burnup. And the  
20 characteristic features of this is typically axial  
21 offsets anomaly will start rearing its ugly head at a  
22 burnup of between maybe four and eight gigawatt-days  
23 per metric ton. And you will typically start seeing  
24 a dramatic shift in the slope of that line.

25           In this case here, this is a fairly

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1 dramatic case of axial offset anomaly, where the  
2 deviation is quite far from the predicted line, here  
3 on the order of maybe -8 percent.

4 Now you will see it gets at its worst at  
5 about maybe 10 to 14 gigawatt-days per metric ton but  
6 starts taking a very positive, steep change towards  
7 the end of the cycle.

8 What is happening there is basically you  
9 are later in cycle, you have less boron in your active  
10 coolant system, you're burning up the low portion of  
11 your core, and the flux is starting to shift upward  
12 towards the end of the cycle. And, hence, you get  
13 this very steep slope coming out on the back end.

14 Here is a flux map of an individual  
15 assembly. And it's actually taking over the course of  
16 the operating cycle. What I wanted you to observe  
17 from this, from an individual assembly, is what we  
18 have here is this is a normalized power distribution  
19 for this assembly. And on the x-axis is the axial  
20 position in feet.

21 So this is your pretty typical 12-foot  
22 length assembly. And this aqua color here was the  
23 first flux map that was taken of this assembly. You  
24 can see it's very symmetrical. It was taken at a  
25 burnup of only 208 megawatt-days per metric ton. So

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1 it was taken up very shortly after the plant achieved  
2 full power during the cycle.

3 But if you take a look at the dark blue  
4 line here, taking close to 10,000 burnup or 10  
5 gigawatt-day burnup, you can see that you've got a  
6 significant neutron flux taking place in the bottom  
7 half of the core.

8 Anything from this side to from six feet  
9 down below is the bottom portion of your core. And to  
10 the right of that is your top portion. You can see  
11 you've got more power being generated in the bottom  
12 half than you do on this, the top half. And this has  
13 persisted, even through a burnup of about -- what is  
14 that? -- 16,500 with this green line, but towards the  
15 end of the cycle, at a burnup of around 21,000, you  
16 can see this red line. You've got a more symmetrical  
17 shape distribution for this particular assembly.

18 So this is the kind of information that  
19 the operators or reactor engineers are looking at at  
20 the plant. The first documented case of AOA took  
21 place actually back in the early '70s at the Obrigheim  
22 unit in Germany. Their reactor coolant chemistry  
23 control wasn't particularly strong. PH wasn't  
24 controlled very well. And, most importantly, they had  
25 very little hydrogen over-pressure on the reactor

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1 coolant system. So they actually had oxygen and  
2 oxidizing conditions in the reactor coolant system.

3 What this led to was excessive corrosion  
4 of their ex-core materials and the corrosion products  
5 deposited in the crud. And what that did was it  
6 provided that foundation or that substrate for boron  
7 to concentrate and deposit.

8 The first domestic case occurred in the  
9 late '70s. And what was speculated in that case was  
10 that they had during a specific period during the  
11 cycle a significant amount of oxygen intrusion into  
12 the coolant. That in itself created additional  
13 corrosion products to circulate and deposit in the  
14 core. Again, it was enough corrosion product that  
15 deposited such that the boron could concentrate in  
16 deposits there to cause the flux depressions.

17 So AOA wasn't fashionable until the '90s,  
18 if you will. And why did that happen? Well, we've  
19 got good chemistry control. We've got good hydrogen  
20 control. You know, we learned from those earlier  
21 experiences in the '70s.

22 So what really transpired or initiated  
23 this problem was that the utilities were going to  
24 longer operating cycles. That was based pretty much  
25 on an economics position.

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1           So to improve their fuel cycle economy  
2 with these longer operating cycles, they had to go to  
3 higher assembly powers, higher enrichment in the rods,  
4 higher thermal duty. And in some cases, to further  
5 improve their economics position, they were loading  
6 fewer assemblies. Therefore, they needed more energy  
7 out of the assemblies that they were actually loading,  
8 so higher thermal duty.

9           So if we connect the y to the root cause  
10 of AOA, accompanying these transitions to a  
11 higher-duty fuel, it created higher subcooled nucleate  
12 boiling taking place in these new assemblies that were  
13 being loaded.

14           And the subcooled boiling was taking place  
15 in those upper spans, typically in a Westinghouse  
16 assembly, spans 5 and 6; in a combustion engineering  
17 assembly, maybe in spans 7 and 8.

18           Well, having higher subcooled nucleate  
19 boiling does result in an enhanced deposition rate of  
20 corrosion products. Now, corrosion products are going  
21 to and always have deposited on fuel assemblies,  
22 regardless of fuel duty. That's just the relative  
23 thermal dynamics and chemistry behind frozen product  
24 release and deposition. Where you have significant  
25 subcooled nucleate boiling, it does act maybe as a

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1 magnet to these corrosion products.

2           Once a sufficient crud thickness has been  
3 established, the local conditions within that crud, be  
4 it the temperature, morphology, -- there are a number  
5 of them -- they create the environment that boron will  
6 concentrate and will either deposit through a  
7 precipitation process or, what we have also learned  
8 through our studies, through an absorption process as  
9 well.

10           To place it all in Venn diagram form, we  
11 believe you need three components, constituents for  
12 AOA to manifest. The first thing, you need the  
13 subcooled nucleate boiling component because before we  
14 started really pushing these assemblies with their  
15 fuel duty, the subcooled nucleate boiling taking place  
16 was present but not at such a high rate.

17           You need corrosion products that are  
18 circulating in your core because it's the crud that  
19 deposits in these areas of subcooled nucleate boiling  
20 that creates the environment for boron to deposit.  
21 And, of course, the boron rate here is in the green,  
22 designated in the green circle. So root cause is the  
23 boron deposit in crud in these high steaming  
24 assemblies.

25           So what? What if a PWR encounters AOA?

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1 Now, I told you I was a chemist at the beginning. I'm  
2 not an expert in the physics business, but that's why  
3 I have actually put more description in here to help  
4 me out.

5 Steady state power operation for the most  
6 part, you know, AOA is not going to have that much of  
7 an impact on you. And that certainly might depend on  
8 the severity of AOA that you're encountering.

9 An example of where it could create a  
10 problem for particularly one with severe AOA is  
11 towards end of cycle because with each one of these  
12 axial offset or AOD prediction curves, there are also  
13 limits associated with those as well.

14 So towards the end of the cycle, I showed  
15 you on slide number 8 there. Towards the end of the  
16 cycle, there was a very rapid escalating AO shift for  
17 that particular plant. And that condition can  
18 approach your tech spec limit for AFB.

19 Now, additionally we've got a lot of  
20 utilities out there that undergo coastdowns at end of  
21 cycle. And, as you see here in this last sentence,  
22 the coastdown end of cycle may make the AOA situation  
23 worse because as the temperature is dropping, you are  
24 adding more reactivity into the top of that core. So  
25 the AO becomes more positive.

1           So that was during steady state  
2 conditions. During power transient conditions, again,  
3 it depends on the severity of the AOA. But during a  
4 downpower maneuver, what you will find is just try to  
5 visualize the boron and the crud are on those upper  
6 spans of those fuel assemblies because of the  
7 subcooled nucleate boiling.

8           When you downpower, your boiling actually  
9 ceased to exist for the most part. So what happens is  
10 that boron that has precipitated or absorbed there  
11 actually goes back into solution.

12           So the result of that, you have a little  
13 bit more boron in your reactor coolant, maybe a ppm or  
14 two, but you also have a more reactive upper portion  
15 of the core.

16           So then you're talking about rod worth.  
17 You actually reduce the rod worth of those control  
18 rods that you're inserting because you have a more  
19 reactive upper portion of your core.

20           So in severe cases, the control rod  
21 insertion limits may be insufficient to perform or to  
22 permit operation within the AFD control vents.

23           Another thing that takes place is just the  
24 reverse. When the power escalates back up to 100  
25 percent and you start getting into your subcooled

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1 boiling taking place in those upper spans, then the  
2 boron goes back into the crud.

3 What happens is you have got actually  
4 pressure boron being deposited because prior to that  
5 downpower, you had boron there, but it was actually  
6 being depleted over the course of the operating cycle.  
7 So when you actually downpower and then ascend back  
8 up, that infusion of fresh boron or less depleted  
9 boron actually makes your axial offset or your flux  
10 depression more severe.

11 Here is an example of it here. Your  
12 y-axis is percent AO. Your burnup here is in  
13 megawatt-days per metric ton. And if this is a  
14 controlled shutdown here. And you can see there was  
15 a slight change in axial offset resulting from that.

16 But if we concentrate on this power  
17 transient here, where they went down to 30 percent  
18 reactor power, you can see a very dramatic change in  
19 the AO of that particular core from about maybe -4  
20 down to close to -8 right here. The cause of that is  
21 largely because of this infusion of fresh, undepleted  
22 boron going back into the crud.

23 This graphic here, these are actually  
24 computer simulations. It's an example of a power  
25 maneuver for a plant without AOA. And, just to give

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1 you some reference here, this y-axis here is percent  
2 power. And it's also the control rod insertion  
3 percentage.

4 So you've got to kind of look at it in  
5 reverse order. The power starting out is 100 percent.  
6 And the control rod insertion is 100 percent full out.

7 This dream curve represents boron. And  
8 this dotted line is your rod insertion limit here.  
9 And down below, this is your axial flux difference or  
10 AO y-axis. And your x-axis on both is time.

11 So in this case, they're middle-of-cycle  
12 conditions. And the power plant is reduced to 28  
13 percent at 8 percent per hour. They hold at ten  
14 hours. And then they increase at eight percent on the  
15 way back up.

16 The control rod insertion limits and AFD  
17 operating bands are shown. And you can see that they  
18 don't encroach on the RIL limits, and they certainly  
19 don't encroach on the AFD limits here.

20 In the next example, we do have a plant  
21 with AOA. You can see starting from the get-go, they  
22 already have rods partially inserted into the core at  
23 mid cycle to keep power normalized while at full  
24 power.

25 The blue line again is the power rampdown,

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1 hold at 28 percent and go back up. But in this case,  
2 you can see they're having to insert rods earlier,  
3 from the very beginning but earlier, in the downpower.  
4 And they come very close to the limits.

5 At the same time, you can see there they  
6 really have to borate at a much steeper rate and at a  
7 higher concentration as well in order to achieve the  
8 power levels they're seeking.

9 Down here you can see the AFD curve  
10 likewise is having some dramatic effect in that  
11 they're starting off at a lower AFE, -10, and as the  
12 downpower starts taking place, you've got all of this  
13 new reactivity taking place in the top of the core.  
14 So it's causing your AFD curve to go vertical. So  
15 they come close to the AFD limits as well.

16 So this is the sort of thing that  
17 challenges operators that have a case of AOA.  
18 Granted, this is more of a severe case of AOA, but  
19 it's something the operators have to be very mindful.

20 Then you also hear about AOA having an  
21 effect on your shutdown margins. I am really not an  
22 expert here on this. So I provided as much  
23 information as I can here, but the bottom line is  
24 you're burning out a great deal of your reactivity  
25 over the course of the cycle in the bottom half. And

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1 when you shut down your reactor; you have got all of  
2 this excess reactivity in the top half. It causes  
3 your rod work to be minimized quite a bit.

4 So the net effect is some degree of  
5 shutdown margin is lost following reactor trip as  
6 compared to operation without AOA.

7 MEMBER SIEBER: Does that affect the  
8 temperature coefficient?

9 MR. DESHON: MTC? I can't answer that.  
10 MTC is certainly a factor in your AO for sure.

11 MEMBER SIEBER: I would think so.

12 MR. DESHON: So there must be some  
13 interrelationship there. Jeff, would you happen to --  
14 does the AOA affect MTC?

15 MR. SCHMIDT: It could slightly because  
16 you're getting your power distribution. So you're  
17 getting a slightly different weighting of your  
18 moderator temperature coefficient, but I don't think  
19 it would be a big effect.

20 MR. DESHON: Well, a couple of other  
21 implications that have been observed at our power  
22 plants. Yovan Lukic mentioned a couple of fuel  
23 failures that have occurred during the 1990s. There  
24 have been three that crud has played a role in those  
25 failures. And in the three cases, AOA was also

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1 present.

2 I did want to make mention, though, that  
3 AOA in itself does not necessarily lead to fuel  
4 failures. And we have had about 40 operating cycles  
5 in the United States that have encountered AOA, some  
6 of them very severe.

7 Some of you might be aware of the Callaway  
8 Cycle 9 case. It's the worst recorded AOA case that  
9 we have had in the United States. And it actually  
10 forced them to de-rate down to 70 percent power. And  
11 they gradually recaptured some of that during the  
12 cycle. But even in that severe case, they didn't  
13 encounter any excessive corrosion on their fuel  
14 assemblies.

15 Another issue that is very important to  
16 the plant, the fact that with these mounting crud  
17 levels that can occur in these plants, when they shut  
18 down for their refueling outages, this crud can be  
19 released, sometimes in an uncontrolled manner. And it  
20 leads to very high dose rates in the reactor coolant  
21 system.

22 So not only do we have this AOA  
23 operational issue, but we have got a couple of other  
24 issues that are quite important to the utilities.

25 MEMBER SIEBER: I thought all the PWR

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1 operators had practice of borating the plant to a very  
2 high level while it was still hot to sort of cause a  
3 crud burst so that they would reduce the outage. Is  
4 that the case?

5 MR. DESHON: That is true. The whole  
6 purpose of shutdown chemistry is to induce a crud  
7 burst in a controlled manner. And part of that is  
8 indeed to borate early, to create an acid environment  
9 very early that will help you as you cool down  
10 dissolve that material so it can be removed  
11 efficiently by your demineralizers.

12 However, we have encountered when during  
13 either the rampdown for refueling outage or after all  
14 the rods have been dropped in, we see this release of  
15 corrosion products. And they're particulates. And  
16 they go out there, and they stick on the system  
17 surfaces. They're just very difficult to remove under  
18 our standard control parameters.

19 MEMBER SIEBER: Okay.

20 MR. DESHON: So our business here or focus  
21 has been on trying to address this component of the  
22 Venn diagram. Let's see if we can control deposits.  
23 We're not going to do anything in the near term about  
24 taking boron out of our systems unless we go to a Navy  
25 reactor design.

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1           The subcooled boiling, it's the subcooled  
2 boiling portion of this Venn diagram that utilities  
3 have had to back off on or have addressed AOA by. And  
4 what they have done is instead of loading, say, 80  
5 assemblies per reload, they have loaded, say, 86 or 90  
6 or more assemblies to actually reduce the overall  
7 boiling duty of these courses. So our focus here is,  
8 what can we do about these corrosion products to  
9 mitigate AOA?

10           So I wanted to discuss this aspect of our  
11 program. We have got a number of aspects, research  
12 activities, that we have got going. But this might be  
13 of interest to you.

14           We devoted quite a bit of resources and  
15 time into understanding corrosion products, what is  
16 circulating in the reactor coolant as well as what is  
17 depositing on these fuel assemblies.

18           With this learned knowledge, we hope to be  
19 able to improve our modeling capability of the  
20 phenomenon as well as help us in our pursuit of  
21 mitigation strategies.

22           To this end, we have installed  
23 high-temperature samplers. That's two PWRs. Those  
24 are at Catawba and Diablo Canyon. Why did we do that?  
25 The sample systems for our PWRs are really quite poor

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1 in terms of being able to use them to characterize  
2 corrosion products.

3 You're taking reactor coolant that's 500,  
4 600 degrees and cooling it down to ambient temperature  
5 at the sample sink. And during that cooldown process  
6 and then after you actually sample it, it's exposed to  
7 air, you bring it back to the laboratory, it's just  
8 not very conducive for corrosion products because they  
9 undergo certain kinetics and thermodynamics that don't  
10 afford you to collect the actual specimen that is in  
11 the reactor coolant.

12 So we have installed high-temperature  
13 samplers at these two units. And the next slide will  
14 describe those a little bit. Additionally, we have  
15 performed a number of crud scrapes at these units and  
16 cycles over the last several years.

17 I've actually put two of the Vogtle cycles  
18 in green here because they actually paid for those,  
19 but they are providing that information to our  
20 program.

21 Okay. We have installed the  
22 high-temperature samplers. I told you pretty much the  
23 purpose behind those samplers. One of the aspects  
24 that we are trying to look at is, is there any  
25 difference between circulating corrosion products at

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1 the beginning of cycle versus the way they are at mid  
2 cycle or end of cycle?

3 MEMBER SIEBER: How many zinc injection  
4 PWRs are there?

5 MR. DESHON: Let's see. We have got the  
6 two Farley, two Diablo, Palisades, two Sequoyah units,  
7 and Beaver Valley, and Callaway right now. Those are  
8 the ones I am aware of.

9 MEMBER SIEBER: And why are they doing it?

10 MR. DESHON: Well, the first units that  
11 did it, Farley and Diablo Canyon did it largely for  
12 PWSCC mitigation. The other units that I mentioned  
13 have done it for dose rate reduction, which it has  
14 been very effective at doing that, reducing radiation  
15 fuels.

16 MEMBER SIEBER: Well, the amount of  
17 corrosion products, is the amount that is circulating  
18 around in the coolant system less or is it just in  
19 different places?

20 MR. DESHON: In the zinc plants?

21 MEMBER SIEBER: Yes.

22 MR. DESHON: I think I touch on that in a  
23 later slide.

24 MEMBER SIEBER: All right. I'll wait.

25 MR. DESHON: If I don't, hit me up on it

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1 again.

2 MEMBER SIEBER: I will.

3 MR. DESHON: Okay. Here are the  
4 attributes of the high-temperature samplers that we've  
5 got. We have probably all had an opportunity to read  
6 this. So I won't go into it any further.

7 I guess the key point here is we are  
8 collecting these samples at between 430 and 445  
9 degrees versus 25 degrees. The sample lines installed  
10 at these stations are on continuous flow. So there is  
11 never any interruption.

12 So in corrosion product sampling, you  
13 can't just go out there, open a valve, and expect to  
14 get a good sample five minutes later.

15 MEMBER SIEBER: Right.

16 MR. DESHON: You need to have continuous  
17 flow through these things for days, if not weeks,  
18 before you can feel fairly certain you're collecting  
19 a representative sample. Well, that didn't come out  
20 very well, did it?

21 Here is a particulate sample that we have  
22 collected. It was actually the Catawba station. And  
23 the sample is collected at the beginning of the cycle.  
24 Basically, it looks like garbage, circulating garbage  
25 in the reactor coolant system. You have few

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1 well-formed crystals. And these crystal sizes vary  
2 rather dramatically.

3 Here is an elemental mapping of the same  
4 sample. This didn't come out very well either. What  
5 you have here is you have got various elements down  
6 here. You've got manganese, chromium, nickel. The  
7 ones to concentrate on are iron, nickel, chrome, and  
8 zirconium.

9 So what we have found in these  
10 high-temperature samplers was that: number one,  
11 you've got metallic nickel. Now, this is a single  
12 nickel atom that is not in the +1 or +2 state. So  
13 it's actually a particulate.

14 You've got chromium, when present, as part  
15 of the iron oxide phase. And something kind of  
16 interesting that we found was that we've got quite a  
17 bit of zirconium, zirc oxide particles, circulating in  
18 these cores, particularly at the beginning of cycle.

19 What you will see a little bit later in  
20 the actual crud samples is you have got a fairly high  
21 fraction of zirc oxide in those.

22 MEMBER SIEBER: Is that due to the  
23 manufacturing or is that some corrosion product?

24 MR. DESHON: Well, it's from the fuel.  
25 We're not certain how or why it's coming from the



1 fuel, but most --

2 MEMBER SIEBER: It sounds like it's some  
3 kind of residue left over from the manufacturing.

4 MR. DESHON: Perhaps that or maybe on a  
5 reload or reinsert fuel that has had maybe some  
6 spallation take place, corrosion taking place. It's  
7 being released into the coolant just due to the  
8 start-up effects. So thermal and hydraulic --

9 MEMBER SIEBER: Got it.

10 CHAIRMAN POWERS: But don't claim there's  
11 any spallation. Rosa says that's a terrible field,  
12 right?

13 MR. DESHON: Okay.

14 CHAIRMAN POWERS: Let me ask you. You  
15 showed some EDX maps. The problem with EDX is you  
16 can't detect boron. When you try to assess the  
17 chemical form of these species from EDX, do you know  
18 they're not borates?

19 MR. DESHON: Well, we don't anticipate  
20 boron to be part of any of the circulating corrosion  
21 products because boron is very soluble. And it will  
22 only be part of a corrosion product if it's on an  
23 assembly where there is subcooled nucleate boiling  
24 taking place and that mechanism has forced it to  
25 deposit within that crud structure.

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1 CHAIRMAN POWERS: Boron in the form of  
2 boric acid or an alkaline metal borate is soluble, but  
3 some of these borates, like iron chromium and things  
4 like that, they can precipitate at fairly low  
5 concentrations.

6 MR. DESHON: With boron?

7 CHAIRMAN POWERS: Yes.

8 MR. DESHON: Well, we haven't seen it.

9 CHAIRMAN POWERS: You never will with EDX.

10 MR. DESHON: Okay. What you will see here  
11 is that we don't rely on a single analysis for these  
12 data. Here is an example of that. This is an XRD  
13 graphic here. And this isn't as good as one down a  
14 few more pages.

15 This blue here is a silver peak. The  
16 silver is there purely because these samples are  
17 collected on a silver-impregnated membrane. So that's  
18 why there's silver. It's not that we have circulating  
19 silver in our reactor coolant system.

20 MEMBER SIEBER: It's not clear to me that  
21 you don't, though, because the control rods are  
22 filtered. And so if you have a bunch of cracked  
23 control rods, you are likely to have silver in some  
24 small quantity in the coolant.

25 MR. DESHON: Yes. I'll grant you that

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1 possibility exists, yes. These silver peaks are very  
2 high, though. The red line iron oxide are magnetites.  
3 The aqua blue is trevorite or nickel ferrite. And the  
4 black lines are zirc oxide.

5 This doesn't show up here very well, but  
6 the point here is that what has been extracted from  
7 the data is that we have got a highly substituted  
8 nickel ferrite as a major phase. And by "highly  
9 substituted nickel ferrite," I mean that  $\text{NiFe}_2\text{O}_4$   
10 component has more nickel present than a traditional  
11 corrosion product you might see, say, on a fix to a  
12 steam generator surface. And, again, zirc oxide is a  
13 major phase in circulating crud.

14 Now, again, this was from Catawba station,  
15 which is a non-zinc plant. Here is an end-of-cycle  
16 sample that you can see and is a pretty dramatic  
17 difference between the beginning of cycle.

18 You know, the beginning-of-cycle sample  
19 looked like, again, garbage. Here you've got very  
20 well-defined crystalline structures, octahedral in  
21 shape. It's still a nickel ferrite, but the nickel  
22 fraction of that ferrite is very low.

23 The XRD scan that you'll see I think next  
24 detected nickel ferrite almost exclusively. And the  
25 SEM suggested minor zirconia and metallic nickel in

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1 chromium-rich oxide.

2 Look at these very nicely shaped crystal  
3 structures. Here is the elemental map showing the  
4 same sample with -- you can see this pretty much  
5 confirms that it's a near magnetite sort of corrosion  
6 product. The nickel fraction is very low here. And  
7 here is a sole zirconia particle right there.

8 This arrow is pointing to what was  
9 believed to be nickel metal right here.

10 MEMBER SIEBER: Did you say that was one  
11 atom?

12 MR. DESHON: No, not one atom. What I  
13 mean, it's --

14 MEMBER SIEBER: I was going to say that  
15 was a pretty good picture.

16 MR. DESHON: Yes, high magnification.  
17 It's essentially a nickel particle comprised solely of  
18 nickel. So from the Catawba sampling, trying to just  
19 generalize here, you have high nickel in ferrites and  
20 more zirconia at beginning of cycle. You've got the  
21 nickel ferrites again at end of cycle but low in  
22 nickel concentration. And you don't have nearly as  
23 much zirconia circulating in your coolant.

24 Here is a zinc sample from Diablo Canyon.  
25 This one was taken at middle of cycle. You can see

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1 here -- and this was something of a common theme, not  
2 only with the corrosion product samplers but also the  
3 crud that we have sampled from Diablo Canyon, as that  
4 the crystalline structures aren't nearly as  
5 well-defined and -- I hate using this term -- almost  
6 amorphous in its visual appearance.

7 Here is an XRD map of that particular  
8 sample. You can see we have got nickel ferrite or  
9 trevorite circulating in there. We have got zirconia,  
10 nickel metal. You see a very significant peak of  
11 carbon, which kind of intrigued us, but the zinc  
12 addition taking place at the applicant is in the form  
13 of zinc acetate. So chances are it's from a reduced  
14 form of the acetate.

15 Once again, looking at this scan, carbon  
16 is a constituent of circulating material. You can see  
17 these corrosion products really don't have defined  
18 edges to them like they do in the other plant.

19 MEMBER FORD: Where did the zinc go?

20 MR. DESHON: That's an excellent question.  
21 We don't expect to see a whole lot of zinc in these  
22 particulate samples because zinc is very soluble in  
23 the reactor coolant.

24 So, in fact, its solubility is somewhere  
25 between 100 and 200 parts per billion. These plants

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1 are only adding. Diablo, in this case, I think we're  
2 adding somewhere between 15 and 20 PBB. So chances  
3 are you are not going to see a whole lot of zinc in  
4 these particle samples.

5 MEMBER FORD: In the BWR, zinc is  
6 incorporated, I remember, into the magnetite.

7 MR. DESHON: I'm not a BWR guy, but we  
8 have got plenty of BWR experts back there that  
9 certainly could confirm that.

10 CHAIRMAN POWERS: You're a much higher  
11 class than BWR people.

12 MR. DESHON: The boilers couldn't give you  
13 information on these circulating corrosion particles  
14 like we have. All right. Excuse me. I digress.

15 So here are some general observations of  
16 our high-temperature corrosion product sampling thus  
17 far. And I don't want to read all of these to you,  
18 but something of interest to us here is the fact that  
19 we haven't seen any nickel oxide in these samples.  
20 And you will see in a few later slides nickel oxide is  
21 a component of crud from these high-duty plants that  
22 have experienced AOA.

23 Another interesting part here is that  
24 metallic nickel particles are an important part of  
25 reactor coolant system circulating corrosion products.

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1 And we don't analyze a whole lot of nickel  
2 in crud samples. The reason for that is that nickel  
3 is very soluble under the shutdown chemistry process  
4 that we employ at these PWRs.

5 So we have been able to confirm that it is  
6 quite important during the operating cycle, and we  
7 know, therefore, it's present in the actual crud that  
8 we measure after the plants have shut down.

9 And the other aspect here is what we just  
10 didn't appreciate is that zirc oxide is a common  
11 circulating corrosion product.

12 CHAIRMAN POWERS: I'm surprised you don't  
13 see more manganese.

14 MR. DESHON: Yes. It's not a large  
15 component in the structural materials. And it perhaps  
16 could be due to how well manganese will diffuse  
17 through that corrosion film and reside in the soluble  
18 form or particulate form in the coolant.

19 MEMBER SIEBER: This is probably a stupid  
20 question, and maybe you didn't do it, but have you  
21 compared the high-temperature samples that you would  
22 draw as a liquid versus the fuel scrapings?

23 I would expect a lot of different  
24 constituents because you could have something that is  
25 soluble in the coolant and not be on the fuel and vice

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1       versa.

2                   MR. DESHON:   Yes.

3                   MEMBER SIEBER:   Could you say a word or  
4       two about that if you did it?

5                   MR. DESHON:   We are in the process of  
6       doing that right now.   One of our major deliverables  
7       for next year is we are going to publish a report that  
8       collects all of this data that we have obtained  
9       through crud scraping.

10                   Westinghouse, we have been working on this  
11       with Westinghouse a great deal.   They are going to  
12       introduce crud scrape data that they have done  
13       previously.

14                   And we are going to look at not only the  
15       crud scrapes.   We are going to look at the primary  
16       water chemistry during those cycles, how much nickel  
17       and iron was removed during the shutdown chemistry  
18       process at end of cycle.   And we are also going to be  
19       looking at these high-temperature corrosion product  
20       data.

21                   The goal here is to try to piece  
22       everything together.   And so, to answer your question,  
23       we don't have any definitive response to that right  
24       now, but we are in the process of analyzing it.

25                   MEMBER SIEBER:   I think that would be

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1 interesting when you arrive at conclusions from that  
2 work.

3 MR. DESHON: That's right. That's right.  
4 Exactly.

5 MEMBER SIEBER: I'd love to read it.

6 MR. DESHON: Okay. We're going to move  
7 into the crud samples.

8 What time are we going to stop for lunch,  
9 12:30?

10 CHAIRMAN POWERS: We're going to stop when  
11 you're done, but we have targeted 1:00 o'clock.

12 MR. DESHON: 1:00 o'clock, wow. I'll be  
13 done before then, I think.

14 CHAIRMAN POWERS: I just have a time  
15 listed down for your presentation.

16 MEMBER SIEBER: There will be another  
17 meeting going on in here.

18 CHAIRMAN POWERS: Not a chance.

19 MR. DESHON: We're going to move into the  
20 crud scrape data now. Just to kick this off, I showed  
21 you on a previous slide we have collected crud scrapes  
22 at a number of plants. What we have tried to target  
23 are higher-duty units that have experienced AOA and  
24 some that have not experienced AOA and tried to  
25 compare the cruds from those two camps of PWRs.

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1 Now, here is an example here. This y-axis  
2 here, the unit is it's mass evaporation rate, pounds  
3 mass generation per hour foot squared. It's a unit of  
4 measure that we use to measure the duty of a  
5 particular assembly.

6 And this particular assembly here did  
7 experience severe AOA during the operating cycle. You  
8 can see that. And what these different colors  
9 represent is the calculated mass evaporation rate at  
10 different burnups during the operating cycle.

11 So the way that these designed these  
12 cores, these assemblies is that they will have higher  
13 duty at different points during the operating cycle.  
14 So that's what these different colors reflect.

15 Here is an assembly, a high-duty unit as  
16 well, but this particular assembly did not experience  
17 AOA. Now, you can see the duty of this particular  
18 assembly here was certainly less than this, but I  
19 happen to also know that this assembly came from a  
20 central core location. And it was surrounded by  
21 already burned assembly.

22 So those also influence crud deposition as  
23 well. Yovan Lukic mentioned that yesterday during his  
24 speech with his ring-of-fire discussion or Saturn  
25 pattern-type loading patterns versus checkerboard.

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1           So here is a kind of a topical look at  
2 crud from the assembly that did not experience AOA.  
3 And it looks kind of like a moon structure here. Each  
4 one of these holes represents a boiling chimney taking  
5 place.

6           You hear about crud. Crud is bad. Well,  
7 not all crud is bad because having a little bit of  
8 crud on your fuel surface actually enhances heat  
9 transfer. It gets your subcooled boiling taking place  
10 a little bit better. Subcooled nucleate boiling is a  
11 much more effective heat transfer mechanism than  
12 forced convection.

13          So having fairly thin crud with these  
14 boiling chimneys isn't necessarily bad. This crud is  
15 comprised of particles. It has boiling chimneys, the  
16 thickness generally less than 20 microns. There were  
17 a few samples here that were upwards to 20 microns.  
18 But on average, the crud thickness from this  
19 particular sample was less than ten.

20          Now, something that we can point out here  
21 is that I want to point out that the nickel-to-iron  
22 ratio in this sample here was on the order of .57.  
23 Now, that's a fairly traditional nickel-to-iron ratio  
24 that we have found in the historic crud database,  
25 anywhere from, say, .4 to .6.

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1 Here is crud from the other assembly that  
2 encountered severe AOA. Again, this did not show up  
3 very well. However, this was crud that we were able  
4 to measure flake thicknesses from on the order of 125  
5 microns. And this is the clad interface right here.  
6 And this is the coolant interface up here. And you  
7 can see these very large voids in the crud,  
8 representing these boiling chimneys.

9 An additional feature to this crud -- and  
10 it doesn't show up real well here. I do have another  
11 slide that I should have brought along as well.

12 There is a region around here where this  
13 is almost exclusively zirconium in this particular  
14 crud flake. Just going down here -- well, I mentioned  
15 this here already. Zirconia layer approximately 25  
16 microns from the clad interface.

17 And another observation is that it's a  
18 very high nickel-to-iron ratio, on the order of 1.5 to  
19 2.5, certainly well beyond the stoichiometric nickel  
20 ferrite that you see in traditional crud samples.

21 It looks a lot better on my laptop. Wow,  
22 look at that. Have you ever seen crud look like that?  
23 You contrast the previous sample of the non-AOA crud.  
24 It was comprised of particles. Well, this stuff here,  
25 this rod-like or needle structure, was something that

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1 we had never seen before.

2 Now, this was, again, I wanted to point  
3 out, from a very severe case of AOA. But what you are  
4 looking at here from this vantage point down to here  
5 is just a side view of that flake.

6 So what did we find in that crud flake?  
7 Well, we found a new material called bonaccordite.  
8 Now, getting back to Dana's comment earlier,  
9 bonaccordite, just advance here one, does indeed have  
10 a boron constituent to it. But the only other place  
11 bonaccordite has ever been seen is at a meteor site in  
12 South Africa. So that's kind of a strange occurrence  
13 that it is taking place inside our reactors here.

14 So this particulate crud flake was made up  
15 of four primary components: bonaccordite, trevorite.  
16 That's this particle here that's attached by a number  
17 of these needle-like structures. We had nickel oxide,  
18 and that's this kind of matte-looking material here.  
19 And this brain-looking structure here is monoclinic  
20 zirconia here.

21 So what is unique about this is: number  
22 one, we see this bonaccordite structure. We actually  
23 believe we have seen this now in two reactors. Both  
24 units were experiencing severe AOA on the assemblies  
25 that were scraped. And the crud flake profile looked

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1 very, very similar between the two.

2 The other unit, we had some -- actually,  
3 it wasn't us. It was Westinghouse had done some less  
4 sophisticated analyses on that particular crud scrape  
5 campaign. So we weren't able to specifically identify  
6 this bonaccordite structure, but it sure looks like it  
7 because it, too, had needles in its composition.

8 So what's unique, again, is the  
9 bonaccordite and the presence of this nickel oxide  
10 because the nickel oxide isn't typically seen in  
11 thinner or from rods from lower duty. So if we take  
12 a look at that observation, bonaccordite comprised a  
13 significant fraction of the weight, 50 weight percent.  
14 And this material was found insoluble. You just can't  
15 beat it up.

16 Now, the only thing that they applied that  
17 would make any impact on it was hydrochloric acid.  
18 It's just not going anywhere through your normal  
19 shutdown chemistry program.

20 Zirconia found mostly at the -- let's see  
21 here -- at a depth -- let's see. How did I word this?  
22 At 20 to 50 percent of the clad depth from the clad  
23 surface. And it comprised about 30 weight percent,  
24 fairly large fraction.

25 Nickel oxide and nickel ferrite rounded

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1 out the composition, both having about ten percent.  
2 Now, the fact that the nickel ferrite was only ten  
3 weight percent of the structure is unique in itself  
4 because typically nickel ferrite is the predominant  
5 crud oxide.

6 So if we take a look at some observations  
7 --

8 CHAIRMAN POWERS: If I take the nickel  
9 ferrite amount in the heavy deposit and compare it to  
10 the nickel ferrite in a unit that is not having an  
11 AOA, --

12 MR. DESHON: Yes.

13 CHAIRMAN POWERS: -- is it the same  
14 amount?

15 MR. DESHON: It could be. It could be,  
16 yes, because that particular flake of 125, the other  
17 one was only maybe 10 micron. So after looking at  
18 some assemblies with less severe AOA, say modest,  
19 moderate AOA or very low, mild AOA. We come up with  
20 some additional findings.

21 The amount of crud is proportional to  
22 boiling. That I guess is rather intuitive. But the  
23 inventory of crud is greater, five times greater, in  
24 AOA plants than in non-AOA plants. And the crud is  
25 still iron-based for the most part, but the

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1 nickel-to-iron ratio in these moderate AOA plants is  
2 on the order of .7 to .8.

3 Again, the historical crud, the lower-duty  
4 stuff, may be .4 to .6. We're transitioning here with  
5 a modest AOA, .7 to .8 maybe, .9. And then when you  
6 get into the severe AOA cruds, you're approaching up  
7 as high as a ratio of two to one.

8 So from these campaigns, we can at least  
9 come to these following points at this time, again,  
10 crud mass proportional to subcooled nucleate boiling.

11 Since nucleate boiling doesn't start  
12 occurring until typically spans 5 and 6, crud is  
13 typically heavier in those spans. Now, if you will  
14 look at these crud deposits from non-zinc injection  
15 plants, you see very little or no crud in spans 1  
16 through 3, start seeing a little bit in span 4, and  
17 then more crud in spans 5, 6, and a little in 7.

18 Nickel-to-iron ratio increases with rod  
19 power and boiling duties. And something else that we  
20 have seen which is important to us from a crud  
21 modeling standpoint is that the porosities are lower  
22 in the crud flakes closer to the clad than they are to  
23 the coolant.

24 Nickel metal is typically absent in the  
25 thicker cruds. Nickel oxide is more prevalent in

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1 those deposits undergoing high SNB subcooled nucleate  
2 boiling. Thin crud has more chromium than thicker  
3 crud. Why is that? I'll get to that in the next  
4 slide.

5 Thick crud from rods undergoing  
6 significant SNB have fully substituted nickel ferrite.  
7 That's probably more information than you are  
8 interested in, but it still is important to our  
9 studies.

10 CHAIRMAN POWERS: Everything seems to be  
11 pointing toward differences in the oxygen potential  
12 during boiling.

13 MR. DESHON: You're a wise man. That's  
14 right because it could be that and we think it is  
15 probably a combination of these conditions taking  
16 place. Number one, we could be seeing an elevated pH  
17 taking place within those deposits because we know  
18 through our plant experience. And one of the boron  
19 deposit theories is that we're precipitating a  
20 boron-lithium compound.

21 Just to give you a sketch here, during a  
22 power reduction very commonly -- and a characteristic  
23 of AOA plants is that you're not only releasing boron,  
24 but you also see an increase in lithium taking place  
25 in your reactor coolant system.

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1           After that power transient has stopped and  
2       upon ascension to power, you see lithium hideout take  
3       place.   So you actually see a reduction in your  
4       coolant lithium concentration.   So we know that there  
5       is an increased concentration of lithium above the  
6       bulk coolant in these crud deposits that could be  
7       resulting in an elevated pH.

8           Now, to touch on what you were saying is  
9       as you develop these thicker deposits through a  
10      boiling process, you have hydrogen present in these  
11      crud deposits.   But the hydrogen because of its  
12      volatility is being stripped out from the deposit at  
13      a high rate.

14           And we also are aware very locally next to  
15      that clad location that we are producing radiolytic  
16      species, such as free radicals, hydrogen peroxide.  
17      And these are changing electrical chemical potential  
18      within that deposit from a reducing environment to a  
19      more oxidizing environment.

20           And, for that very reason, you're right.  
21      You know, seeing observations such as you're seeing  
22      less chromium in these thicker deposits, you're seeing  
23      a change in iron state going from .2 to .3 all lend  
24      itself to that sort of process taking place.

25           Nickel oxide, for example, we're not

1 seeing it in our coolant samples, but we're seeing it  
2 in these thick deposits. So the generation of nickel  
3 oxide very well could be this mutation from nickel  
4 metal to nickel oxide.

5 MEMBER FORD: So you're almost going to a  
6 BWR.

7 MR. DESHON: I wouldn't say that.

8 MEMBER FORD: All of those things that you  
9 mentioned are --

10 MR. DESHON: Right. And these things are  
11 happening very locally, right at the clad surface,  
12 within just a few microns.

13 All right. Well, I've discussed some of  
14 our activities and intelligence on crud now and  
15 corrosion products. The next several slides will just  
16 demonstrate a few examples of what we are doing in  
17 terms of minimizing crud and hoping to avoid AOA.

18 Rosa mentioned here we've got ultrasonic  
19 fuel cleaning technology available now. And I've got  
20 a few slides on that. We are pursuing an elevated and  
21 constant pH program.

22 Our EPRI primary water chemistry  
23 guidelines now encourage utilities to stop employing  
24 the traditional modified pH program that has been very  
25 common since the late 1980s and transition to a higher

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1 and constant pH within the limits allowed through your  
2 fuel vendor and your materials evaluation for, for  
3 example, your steam generators.

4 So what the guidelines suggest is see if  
5 you can approach a constant pH of 7.1 or 7.2 so that  
6 you have a constant pH throughout the whole cycle.

7 What we have done is taken it a step  
8 further in that we do have a demonstration taking  
9 place at one of our utilities that has increased the  
10 pH to 7.3 throughout the whole cycle and ultimately  
11 will go to 7.4 if everything pans out well. The other  
12 strategy that we are pursuing is zinc addition and,  
13 finally, boric acid, enriched boric acid.

14 Ultrasonic fuel cleaning. And these just  
15 don't show up that well here, but we have installed  
16 the ultrasonic fuel cleaners, as Rosa mentioned, at  
17 Callaway, South Texas project, and this coming week  
18 Vogtle will be applying it at one of their units.

19 The original prototype was installed at  
20 Callaway. And it was a single channel ultrasonic  
21 cleaning unit. And we demonstrated it during, I think  
22 it was, cycle 10 on 16 reload assemblies. And we had  
23 very good success with those assemblies during the  
24 operating cycle. So they went ahead and did a full  
25 reinsert cleaning prior to cycle 12 and cycle 13.

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1           So what this diagram is showing is this is  
2 actually a more advanced unit, one that, let's say,  
3 for example, is employed at South Texas project, but  
4 you have got two chambers here that can accommodate a  
5 fuel assembly for fuel cleaning.

6           Up here you have a pump skid and  
7 filtration unit. And the pump will actually draw  
8 water from the bottom of the ultrasonic fuel cleaner  
9 down here and will draw it up through the filters and  
10 back into the pool.

11           What we have in these units in the South  
12 Texas project unit are 12 ultrasonic transducers that  
13 are vertically mounted inside the cleaning canister.  
14 And when the assembly is inserted into the canister,  
15 you apply the power to it. It takes probably three to  
16 four minutes in order for the material to be fully  
17 removed or removed to their satisfaction.

18           The way that they monitor when they are  
19 done cleaning a particular assembly is that they have  
20 radiation monitors on the hose and on the filter  
21 banks. So they will see initially a very rapid rise  
22 in dose rate or gamma activity on the hose. And once  
23 that subsides, they know at that time that they are  
24 pretty much done.

25           Now, I mentioned to you earlier that that

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1 bonaccordite was essentially impervious to any  
2 shutdown chemistry technique. If a PWR has  
3 bonaccordite, really, the only way to get rid of it --  
4 and we have been able to demonstrate it -- is through  
5 this ultrasonic fuel cleaning. And we were able to  
6 successfully do that at Callaway during a cleaning  
7 efficacy project that we had demonstrated there.

8 This cleaning technology removes at least  
9 85 percent of the fuel deposit on these assemblies and  
10 in most of the cases will remove above 90 percent. So  
11 I have kind of expanded on that, only because I  
12 thought you might be interested in that information.

13 Evidence suggests crud from reload fuel  
14 can redeposit in boiling regions of feed fuel  
15 assembly. We have evidence that that transpires.  
16 What happens when you reinsert fuel, depending on the  
17 relative power of that fuel in a second cycle of  
18 operation, if it's low-duty, then if you've got  
19 material on the rods, it's going to dissolve or it's  
20 going to be released through thermal hydraulic forces  
21 or hydraulic forces going, fluid shear going up the  
22 assembly. And that's because there's nothing really  
23 keeping it there.

24 The subcooled boiling isn't taking place  
25 on that assembly any longer. So the crud, we have

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1       been able to show through our crud scrape campaigns,  
2       actually reduces in that second cycle of operation.  
3       It releases the crud and makes it available to come  
4       back around and deposit on the new feed fuel, where  
5       you do have a lot of subcooled boiling taking place.

6               Early-cycle boron hideout promotes early  
7       onset of AOA and greater chance to degrade. That is  
8       just talking about if you don't have the crud  
9       substrate there early in the cycle, then you are less  
10      likely to encounter AOA on any reinsert fuel also.

11             We have had one case. This was following  
12      Callaway's most severe AOA cycle, cycle 9, that the  
13      reinsert fuel also exhibited AOA in that subsequent  
14      cycle, kind of a unique thing, but because they had  
15      such heavy crud loading that it still promoted the  
16      boiling taking place.

17             Some other aspects that utilities might  
18      want to use ultrasonic fuel cleaning, if you look at  
19      the Callaway case, they have had a progressive  
20      reduction in dose rates occurring at their plant on  
21      ex-core surfaces since employing this ultrasonic fuel  
22      cleaning technology.

23             Now, that data is somewhat muddled by the  
24      fact that they have also reduced the duty of their  
25      core there as well, but you are able to remove a whole

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1 lot of crud on these assemblies when you're doing this  
2 ultrasonic fuel cleaning.

3 Strategy, elevating constant pH. Crud  
4 management is the focus of this. The expected  
5 benefits from an AOA avoidance perspective is a  
6 reduction in the source term, transport and deposition  
7 of corrosion products at the fuel clad.

8 We do believe that if you are able to  
9 raise the pH in your system, say up to 7.3 or 7.4,  
10 that is a better regime to be in than, say, at 6.9 or  
11 7.0. And that's based solely on a solubility and  
12 thermodynamic standpoint. If proven successful, it  
13 may pave the way for similar applications at other  
14 PWRs.

15 Here is the plant that is participating in  
16 this demonstration. These are the pH regimes that  
17 were used in previous cycles here. You can see --  
18 let's see -- this is pH. So they started out here in  
19 this red and blue line early on at 7.0, came up and  
20 held constant at 7.2 through the balance of the cycle.  
21 And in this current cycle, they started out at 7.3.  
22 And they're maintaining that throughout the entire  
23 cycle.

24 We will be performing visual and lift-off  
25 measurements of their fuel coming up this fall in

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1 their outage.

2 CHAIRMAN POWERS: When you cite this pH,  
3 is that pH that is actually measured in the plant or  
4 is that what is measured by sampling and then  
5 subsequently corrected to room temperature?

6 MR. DESHON: These are calculated pH's at  
7 temperature.

8 CHAIRMAN POWERS: At temperature?

9 MR. DESHON: At temperature, right. These  
10 aren't 25 degrees. These are at temperature.  
11 Actually, we use TF.

12 CHAIRMAN POWERS: Okay.

13 MR. DESHON: Okay. We're looking at zinc  
14 addition and how does zinc figure into our AOA  
15 prevention strategy. Well, laboratory studies that  
16 took place before zinc was added at the boilers or in  
17 the PWRs were found to actually reduce the corrosion  
18 rate of your ex-core materials, stainless steel and  
19 inconel, and to make them more stable so you have less  
20 corrosion taking place, less corrosion product  
21 released from those materials.

22 So the end result here is a reduction in  
23 corrosion rates; transport; and, therefore, material  
24 that is available to deposit on your fuel assemblies.

25 Something else that we are intrigued by

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1 based on the fuel observations during our crud scrape  
2 campaigns, oxide measurements is that the crud  
3 deposition pattern in these zinc plants is somewhat  
4 different than they are in your traditional chemistry  
5 programs, insofar as the corrosion products deposit  
6 along the entire length of the fuel assembly and not  
7 restricted to just those spans where you have  
8 subcooled nucleate boiling taking place.

9 So what that means to us is perhaps  
10 through zinc addition, you don't reach that critical  
11 thickness that is necessary to deposit boron in those  
12 upper spans.

13 So we are kind of intrigued from this  
14 potential aspect from zinc addition. So why are we  
15 demonstrating it at one of our high-duty units?  
16 Bottom line is there have been no high-duty units that  
17 have added zinc, firstly. So adding significant  
18 subcooled nucleate boiling into the equation makes us  
19 a little uneasy because we don't know how zinc is  
20 going to be affected under that environment.

21 Additionally, when you add zinc,  
22 especially in that first cycle, it will be rapidly  
23 consumed by system surfaces. And as it does that, it  
24 displaces other transition metals, namely nickel and  
25 iron, from those surfaces. And it gets them into

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1 reactor coolant. That makes them available then to  
2 deposit on the fuel assemblies.

3 So we take a very cautious approach to  
4 zinc injection for this demonstration plant. It's a  
5 step increase. Number one, they didn't start  
6 injecting zinc until six months into the cycle.  
7 Secondly, they added at a very low rate. And once  
8 they started detecting zinc in the coolant, they  
9 stepped the rate up a little bit. But they're doing  
10 it in incremental components so that they don't  
11 encounter any problems.

12 I think I have covered everything with the  
13 zinc addition. And my last two slides here, something  
14 that we are looking at that is not a demonstration  
15 yet, it is still in the research phase, is enriched  
16 boric acid.

17 We have got a program taking place right  
18 now at the Halden reactor project. And I have heard  
19 that facility mentioned here several times yesterday  
20 and today. The project right now is shut down due to  
21 some cracking problems in one of their primary pipes.  
22 So this activity is not taking place at this moment.

23 The objectives behind this particular  
24 project -- and we have received some DOE co-funding.  
25 Glenn is still here. I thought you left, Glenn. We

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1 have received co-funding from DOE for this particular  
2 project.

3 The initial objectives for us were:  
4 first, we're not even injecting enriched boric acid at  
5 the point. Halden needs to be able to demonstrate  
6 that they can actually exhibit the symptoms of AOA.

7 So to do that, they need to show us that  
8 they can deposit crud on their fuel rods under  
9 prototypical PWR conditions that we have prescribed  
10 for them. And, secondly, they need to be able to  
11 exhibit those symptoms of AOA.

12 We are giving them two tries to be able to  
13 address those two issues for us in phase I. Test one  
14 was not successful. So we have made some program  
15 changes for the next test. We're basically throwing  
16 everything but a Chevrolet into the reactor coolant  
17 system to deposit crud.

18 If we are successful in phase I, then the  
19 phase II objective will be to indeed determine whether  
20 or not EBA is a viable chemistry alternative to avoid  
21 AOA.

22 So why are we looking at EBA? A couple of  
23 reasons: number one, EBA allows us to optimize our  
24 reactor coolant pH so that we don't have to increase  
25 lithium above, say, the current three and a half ppm

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1 limit that we apply to our utilities.

2 Now, a utility that has, say, inconel 600  
3 ml anneal tubing might be interested in EBA for that  
4 very reason, because they want to optimize their pH.  
5 But they are a little concerned that raising the  
6 lithium could enhance PWSCC susceptibility. So they  
7 can optimize their pH.

8 The second component here is directed  
9 towards the actual deposit mechanism. Because AOA,  
10 the boron component to it, is through a concentration  
11 process, you have to actually achieve very high  
12 concentration factors in order for the boron to  
13 actually deposit within the crud. So if you are able  
14 to reduce the concentration of your coolant boron,  
15 then you're reducing the concentration for the same  
16 fuel duty at that clad surface. So you can perhaps  
17 delay the deposition process taking place or avoid it  
18 altogether. So these are the two reasons why we're  
19 looking at EBA.

20 Because EBA is such an expensive  
21 proposition for any utility to undertake because of  
22 the capital costs associated, we wanted to verify it  
23 through a research reactor before presenting it as a  
24 potential strategy for our utilities. So I think  
25 that's it.

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1 CHAIRMAN POWERS: One question I should  
2 have asked before. Have we characterized the  
3 double-layer potential on these fuel rods in the  
4 cruadded and uncruadded states at all?

5 MR. DESHON: No. We approached Halden  
6 with that too late into getting into this EBA project  
7 because they would be best suited to do that.  
8 However, it was too late in the game to put in some  
9 sort of probe or anything like that, electrode. It's  
10 an interesting thought and something that we have  
11 considered and may or may not be able to do down the  
12 road.

13 There are some data. Studsvik has  
14 generated some data that we're looking at potential as  
15 well but not in a cruadded environment, just looking  
16 solely at what is the potential right there at the rod  
17 under standard or prototypical PWR conditions.

18 CHAIRMAN POWERS: If you happen to have a  
19 reference to that, I would like to see it. It would  
20 be interesting.

21 MR. DESHON: Okay.

22 CHAIRMAN POWERS: The idea is to get rid  
23 of this, not to study it, but --

24 MR. DESHON: Yes. Yes, I know. Yes, I  
25 know.

1 CHAIRMAN POWERS: Any other questions for  
2 the speaker?

3 (No response.)

4 CHAIRMAN POWERS: Could I propose that we  
5 break for lunch and reassemble here at 1:30? So we're  
6 recessed until 1:30.

7 (Whereupon, at 12:48 p.m., the foregoing  
8 matter was recessed for lunch, to  
9 reconvene at 1:37 p.m. the same day in  
10 Closed Session.)  
11  
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A-F-T-E-R-N-O-O-N S-E-S-S-I-O-N

(3:21 p.m.)

CHAIRMAN POWERS: We're back into session.

And we're going to hear the sad tale of fuel failing. We've got to improve our schools for fuel. You know, it's because they don't study prior to the test. That's why it is. It's lack of parental involvement. We have sibling rods. There must be parents someplace, right?

MEMBER KRESS: Must be.

CHAIRMAN POWERS: Go ahead, sir.

13) FUEL FAILURES

MR. CHENG: Okay. Thank you. My name is Bo Cheng.

I would like to share with you the fuel failure experiences in the U.S. light water reactors and our root cause investigations into those issues.

I will share with you first the industry fuel failure trend and talk about failure root causes. And I would like to focus on the investigation of crud-induced cladding corrosion failure because that seems to be the current issue.

I will also discuss somewhat the challenges we are facing today. And the last topic will be the BWR water chemistry changes, NMCA, and the

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1 fuel performance issues associated with it.

2 As you know, most of the fuel failure in  
3 the U.S. imposes economical penalties on the  
4 utilities. They really have never become safety  
5 issues, but the cost of fuel failure can range from  
6 just a small amount up to -- the worst one I heard was  
7 like a \$17 million loss.

8 CHAIRMAN POWERS: Well, you know, the one  
9 area where failures may or may not come into the  
10 regulatory process is if you believe that iodine  
11 spiking in, say, a steam generator tube rupture or  
12 something like that is the result of water intruding  
13 into a perforated rod. Then it comes into the  
14 regulatory process.

15 MR. CHENG: Okay. In the robust fuel  
16 program, we have tried to first work with utilities.  
17 When they have fuel failure, some of them do contact  
18 us. And we provide all of the technical assistance or  
19 is all of the industry database.

20 We evaluate the root cause with them, join  
21 their root cause investigation team. And if there is  
22 a need to send a rod to the hot cell, we'll call into  
23 the effort with the utilities to perform the work.

24 I showed you the trend plot already. Just  
25 basically the last two years, the BWR side has

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1 experienced a substantial fuel failure experience. I  
2 think about 50 percent of the 33 BWRs all have  
3 experienced a certain degree of failure, some with a  
4 lot of rod fail, some with only one failed rod. PWR  
5 seems to be more steady.

6 About the root causes, I'll just show you  
7 a typical PWR assembly, but the BWR assembly is  
8 somewhat different. There are many different root  
9 causes. The first one certainly is associated with  
10 manufacturing. Okay?

11 There are many different manufacturing  
12 defects that lead to fuel failure. The most  
13 outstanding one is internal hydriding, which was a  
14 measure of failure of root cause from the beginning of  
15 fuel operation.

16 Last week I talked to one utility guy.  
17 They think they also have just recently experience  
18 with moisture failure. So although it's really mostly  
19 under control but occasionally we do still experience  
20 a little bit of this manufacturing defect, the end  
21 plug welding was a big issue in the beginning, many  
22 years ago, like three, four decades ago. But mostly  
23 it's under control now.

24 Tube flaw, the low corrosion resistance  
25 cladding. We talk about corrosion. There is a lot of

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1 corrosion there that would actually cause fuel failure  
2 as a common measure of corrosion with others that  
3 caused the fuel failure.

4 Now, we have like missing fuel pellets or  
5 damaged fuel pellets. And there are other material  
6 defects also. But most of the manufacturing defects  
7 have been under control.

8 The second one is foreign material  
9 intrusion. It's actually caused debris fretting. And  
10 in the last ten years, both BWR and PWR have  
11 implemented this debris filter by the nozzle, by the  
12 type plates.

13 In PWR, it seems to be quite effective,  
14 gradually removing this small metallic debris-inducive  
15 failure. Often with debris, you've got caught by the  
16 spacers. And the fret on the fuel rod caused a fuel  
17 failure.

18 In PWR, it seems to be quite effective;  
19 BWR, it's not so sure. The data doesn't conform. You  
20 know, we continue to have failure with even debris  
21 filter by the nozzle. So we still need to see some  
22 more improvement that's need in the BWR side.

23 The grid-rod fretting -- I think Rosa had  
24 mentioned this. This is a vendor-specific issue and  
25 many different causes. Grid design is one of the

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1 major components that cause grid-rod fretting failure.  
2 Particularly, at the core periphery, because of this  
3 jetting, you know, the jetting issues cause fuel  
4 failure on most of the high burnup rods.

5 The chairman had a question why we did not  
6 inspect, so many rods had never been inspected. That  
7 was because utilities believe there's a recurrence of  
8 grid-rod fretting in discharged fuel. So they thought  
9 they didn't know that was the root cause. Somehow  
10 they just don't have time to inspect the discharged  
11 fuel.

12 Then, of course, the next one is local  
13 power change due to control blade movement caused the  
14 PCI failure, pellet-clad interaction failure. Again,  
15 most of it is under control, but I will explain a bit  
16 later. We do occasionally continue to have a problem  
17 on this mechanism.

18 The last one is, as I said, the  
19 interaction with impurities in the coolant, mostly due  
20 to crud interaction with the fuel rod. Again, Rosa  
21 showed you this.

22 MEMBER FORD: Excuse me, Bo. Before you  
23 move on to that, --

24 MR. CHENG: Yes?

25 MEMBER FORD: -- I noticed there was a

1 surprise on Kurt's presentation but also on yours. He  
2 mentioned they were doing some work on fatigue. And  
3 you have shown there that fatigue is not, as I seem to  
4 remember it, a major failure mechanism. Is that  
5 purely because it's a new material, the high burnup  
6 fuels?

7 MR. CHENG: Yes. It's a high burnup fuel  
8 concern. I don't think people attribute any of the  
9 failure to the fatigue.

10 MEMBER FORD: That's right.

11 MR. EDSINGER: It's a margin issue.

12 MEMBER FORD: Okay.

13 MR. CHENG: Okay. If you'll notice here,  
14 we do have fuel. This is the one. It's the different  
15 failures of root cause. The red one was cladding,  
16 corrosion failure, some of it due, probably most of  
17 it, to crud-induced corrosion failures. We have quite  
18 a few incidents of that. Again, we do have a couple  
19 of PCI. I will talk about that.

20 In the PWR side, you see the red ones,  
21 those three crud-induced corrosion failure with the  
22 three incidents, the risk of the major issue that has  
23 been associated with grid-rod fretting.

24 The reason I bring this corrosion failure  
25 up is that when you have fuel failure, typically most

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1 other mechanisms in the last ten years, maybe one or  
2 two or three rods fail.

3 Now, when you have corrosion damage,  
4 crud-induced corrosion damage, you could reduce the  
5 whole reload. Three units in the last, say, five  
6 years essentially lost the whole reload due to the  
7 crud-induced corrosion.

8 I already covered this thing. So I will  
9 not go over. Our focus on the crud/cladding  
10 corrosion, fuel failure. And if you have an interest  
11 on other mechanisms, we can discuss that. I do have  
12 backup slides of other issues.

13 I would like to talk about PWR  
14 crud-induced corrosion failure. As I mentioned, we  
15 had three cases of crud-induced corrosion failure. It  
16 affected mostly the high-power, first-cycle rods in  
17 all three cases. So this is not a high burnup issue.  
18 This is a high-duty fuel issue.

19 Corrosion separation was thermally induced  
20 in at least one case. I will talk about that. We  
21 found it from the hot cell examination. And it  
22 occurred in a couple of cases. In two cases, it  
23 occurred in fresh-to-fresh fuel assembly faces.

24 Another case was because the fuel duty was  
25 pretty high to get to 4.95 enrichment. And this

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1 specific utility did not use so-called intermediate  
2 mixing band. That's the IFM grid. Okay? In the new  
3 design, because the high-duty fuel added three  
4 additional grids in the upper part of the core to  
5 improve the MB margin and also to increase the mixing,  
6 this specific case, they got better high-duty fuel  
7 without IFM grid. So this got this localized  
8 corrosion failure.

9 Out of the three failures, we did hot cell  
10 examination of the first case of failure that occurred  
11 here in 1995. I will show you those hot cell  
12 examination data to show to you how we reached this  
13 failure root cause and how this problem can be  
14 managed.

15 In the TMI cycle trend, they got ten  
16 failures. The first failure occurred about 120 days  
17 into the cycle with nine rods failed at span 6. That  
18 is the hottest span, number 6.

19 In addition to the failed rod, they had  
20 many rods. And the damage is by crud. And you can  
21 see this is visual appearances of crud-induced damage,  
22 the hottest span, number 6.

23 All the failed rods were once burned. And  
24 they failed at the assembly periphery. This  
25 observation is very similar to the second failure

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1 case. I think APS discussed yesterday briefly  
2 observation of those characteristics were very  
3 similar.

4 If you look at a core map, all the failure  
5 occurs -- and I'm sorry this is not very clear, but  
6 the blank, this white blank, area is the fresh fuel.  
7 And in this case, there are four fresh fuels that were  
8 classed together in a so-called T-joint occasion. And  
9 you can see the symmetrical location.

10 All the damages were on the fresh fuel,  
11 mostly between fresh fuel assemblies. And also in  
12 some cases, a fresh fuel assembly is a cold location.  
13 For fail rods, it actually occurred between  
14 fresh-to-fresh fuel assemblies.

15 We sent four rods to the hot cell. One of  
16 the rods, you can see this is a corner rod of an  
17 assembly with four fail rods. And you look at the  
18 corner. This is the corner facing away from the  
19 assembly. It faced the water gap between two fresh  
20 assemblies.

21 This is a corner rod. You can see on the  
22 corner side, you have significant crud-induced damage.  
23 The side facing the bundle interior looks very smooth.  
24 There was no indication of crud-induced damage.

25 Similarly, this peripheral rod also shows

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1 the surface facing the interior side, showing very  
2 smooth surface without any crud-induced damage. It  
3 was the surface facing toward the water gap between  
4 two fresh assemblies showing very significant  
5 crud-induced damage.

6 In the hot cell, we send the rod to the  
7 hot cell, of course. We did quite a few things,  
8 looked at neutron radiography, profilometry, gamma  
9 scan as a means of burnup distribution.

10 We took a fuel pellet. We took micro  
11 samples from the fuel pellet on the side facing the  
12 water gap and also on the side facing the interior.  
13 And the reason we do that is because when people look  
14 at this kind of corrosion damage, this is a dry-out  
15 condition. You have a power distribution problem.

16 Of course, from a utility perspective,  
17 that is a very serious problem. So we need to resolve  
18 whether there is a power distribution problem or maybe  
19 just crud deposit issues.

20 So we did quite a few things. The key  
21 finding was that we look at azimuthal burnup  
22 distribution. And we could not see any variation in  
23 the burnup distribution azimuthally. So the  
24 conclusion was that there was no unexpected burnup  
25 distribution. Inside and outside, it looked

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1 essentially the same.

2 One key observation we found, we cut a  
3 sample across the damage location. And we looked at  
4 the cladding microstructure here and compared the  
5 location behind this damage on the interior side. You  
6 can see that there is a clear difference in the  
7 cladding microstructure, the grain structure. We  
8 crystallized the grain structure.

9 On the back side, on the interior side,  
10 this is cold work structure. This is a cold work  
11 stress relief structure. This is in a fabricated  
12 condition. So in order to transform this  
13 microstructure into this structure, you do need a  
14 temperature greater than 450 degrees Centigrade. And  
15 so the maximum should be less than the 350 C, even  
16 though your structure in the PWR should be less than  
17 350. So clearly the crud has induced a temperature  
18 rise significant enough, maybe 100 degrees Centigrade  
19 or even somewhat higher to induce the localized  
20 corrosion penetration. So that is our conclusion.

21 MEMBER KRESS: You could check that by  
22 some sort of thermal calculation knowing the thickness  
23 of the crud? That seems like an unreasonable  
24 assumption to me, but, of course, I can't argue with  
25 your recrystallization picture.

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1 MR. CHENG: Yes. That's right. That's  
2 right.

3 MEMBER KRESS: But it looks like a thermal  
4 calculation of that crud knowing its thermal  
5 conductivity.

6 MR. CHENG: Right. It depends on the type  
7 of crud. Actually, the thermal conductivity of the  
8 crud all depends on the morphology more than from the  
9 type, the chemical composition because the crud, say,  
10 it comes as a solid, the solid iron oxide conductivity  
11 is better than zirconium by maybe a factor of two to  
12 five.

13 MEMBER KRESS: Yes.

14 MR. CHENG: Okay. But if so, it depends  
15 on morphology. If the morphology is such that it  
16 would cause a steam blanketing, then your steam has  
17 extremely poor conductivity, maybe two orders of  
18 magnitude lower than the --

19 MEMBER KRESS: I see. It might be a very  
20 poorest gap.

21 MR. CHENG: Right. The crud is so  
22 difficult to characterize. And the conductivities all  
23 so much depend on the morphology.

24 So what kind of crud would induce the  
25 failure? We did collect some crud samples and did an

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1 X-ray diffraction study. Basically those are either  
2 magnetite or nickel ferrite. And we also found nickel  
3 oxide.

4 So this is consistent with what Jeff  
5 discussed this morning. It's not unusual crud  
6 deposits. We could not determine the surface loading.  
7 And we really don't know the morphology of the crud.

8 We collected some crud samples. And the  
9 vendor who handled this initial investigation was not  
10 experienced enough, and we lost most of the crud  
11 samples because of that.

12 However, we went back six months later and  
13 tried to collect some crud samples. All the crud  
14 disappeared in the storage before because storage pool  
15 has a pH of about 4.5. So they all disappeared.

16 Also, a lot of crud will dissolve even  
17 during the shutdown. You know, first your boil rate,  
18 the water, and then you get into oxidizing conditions.  
19 You know, a lot of crud will burst out during the  
20 plant shutdown. Something like maybe three or four  
21 kilograms will induce from the fuel rod surface.

22 So typically we really don't know how much  
23 crud was on the fuel surface during operation. That's  
24 probably the most difficult part for the PWR to  
25 quantify how much crud was actually on the fuel

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1 surface.

2 I think the vendor did reload  
3 thermal-hydraulic calculation. They really couldn't  
4 predict subcooled boiling, even the hot span, because  
5 PMI is really the low-temperature PWR. The only  
6 difference is that for this plant, they are making a  
7 transition from I think 18 or 20-month cycles into  
8 24-month cycles. They do increase enrichment to some  
9 extent.

10 However, no matter how we did, the vendor  
11 did a calculation. At EPRI, we also used a VIPRE to  
12 do the calculation. We simply could not predict that  
13 they could have subcooled boiling in the core.

14 However, we did some sort of case study.  
15 And that says that if you have a subcooled boiling to  
16 exist, you will need to have some special hydraulic  
17 effect. And that hydraulic effect is to cause some  
18 sort of flow loss between the fuel assembly gap,  
19 either because of the strip, the side strips, or some  
20 sort of raw tripper that causes actually the water  
21 loss on the gap.

22 It's not fully resolved why you get the  
23 subcooled boiling in such a low-temperature plant.  
24 There is another theory that maybe the water gap, the  
25 flow was slower because of the water gap is wider than

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1 the interior, which would induce the crud to  
2 deposition and led to subcooled boilings because of  
3 the cladding process. But this generally is not  
4 really credible.

5 Really, the issue is that we know from --  
6 we did bring in a lot of experts, like Saul Levy, Dr.  
7 Levy, to look into the condition. Basically a  
8 suggestion is you have to really take the plant data,  
9 say you do have subcooled boiling. And so do  
10 something there.

11 So it's becoming more an empirical  
12 situation to how you mitigate this problem would be an  
13 empirical approach. And so you need to assume when  
14 you put fresh-to-fresh assemblies together and cross  
15 them together, the thermal hydraulic condition may be  
16 more complicated than the model predicts. We really  
17 need to take a more conservative approach.

18 MEMBER KRESS: Does that mean you have to  
19 get circumferential variations in your model?

20 MR. CHENG: Yes, yes. We don't know if  
21 there is a power variation, but it put a hydraulic  
22 condition there. And in the case I mentioned, when  
23 they got to very high enrichment in high-temperature  
24 PWR, I think that additional mixing maybe is  
25 necessary. So IFM grids appear to be necessary to

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1 prevent local hot spots.

2 Of course, there is a chemistry issue here  
3 that we need to avoid total inventory within the  
4 pressurized loop. One of the first things is TMI did  
5 operate the pH something less than 6.9, maybe 6.7, for  
6 the first 100 days. They offer a slightly lower pH.  
7 And the reason was that they were confined by the  
8 lithium limit of 2.2 ppm. So with high 24-month cycle  
9 core without enough persons inside the fuel rod at  
10 Westinghouse design, they have this lithium.

11 In the other design, they rely on  
12 gadolinium. That was not sufficient to control the  
13 reactivity in the beginning of the cycle. So they  
14 start up the cycle with about 1,830 ppm of boron. And  
15 that's pretty high. So as a result, they got a  
16 somewhat lower pH.

17 After this experience, of course, they  
18 made their boron to about 1,750 or 1,800 as the  
19 maximum limit now. Of course, Jeff mentioned this  
20 EPRI's recommendation is to try to operate at a  
21 constant pH of about 7.2.

22 So from the data, it seems the higher pH  
23 total inventory of crud, iron-nickel crud, should be  
24 somewhat less than the low pH condition and should  
25 also reduce the crud transportation in the primary

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1 system.

2 So the PWR failure, we had experienced  
3 those three failures. We think that the problem, that  
4 the root causes were understood. And we think the  
5 problem can be contained.

6 I would like to switch, then, to BWR  
7 corrosion failure. BWR is a little bit difficult to  
8 contain because the feedwater is a single-loop system.  
9 So impurity can easily get into the feedwater into the  
10 core, unlike PWR, which is a closed system.

11 There is no way you can get any impurity  
12 into the closed system in PWR except during a  
13 shutdown. But BWR, there is a chance that impurity  
14 can enter a system through feedwater into the reactor  
15 water. And also there are a lot of changes in water  
16 chemistry conditions.

17 In terms of the crud-induced corrosion  
18 failure, I think the multiple plant/cycle failures  
19 that occur by crud-induced localized corrosion failure  
20 that occur starting in 1978 into mid 1980s affected  
21 many plants at that time was kind of newer plants,  
22 BWR/4 to 6 high-powered plants, those plants equipped  
23 with brass condensers and Powdex cleanup systems.

24 The uniqueness of this Powdex system is  
25 not very efficient in removing the soluble species in

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1 the feedwater. So the feedwater in those plants would  
2 contain somewhat higher soluble species than other  
3 types of cleanup systems. There are two types. The  
4 other type is called deep bed cleanup system, which  
5 can remove the soluble more efficiently.

6 Well, the problem, so-called CILC failures  
7 were mitigated. One of the mitigations was to improve  
8 the corrosion resistance of the cladding. And that  
9 was introduced in the mid 1980s, about '85 or so. And  
10 after that, we had a few fuel failures associated with  
11 this type of cladding corrosion failure.

12 The first one was in 1988, we had one  
13 plant with very significant cladding corrosion damage.  
14 It affected fresh fuel. Then for ten years, we  
15 essentially didn't have this type of corrosion because  
16 I guess the mitigation was quite effective.

17 But in 1998, we had one plant that had a  
18 very significant crud, very heavy crud, deposit that  
19 caused a failure. This plant again experienced the  
20 same type of failure just sometime this year, early  
21 part of this year. So we had a repeat of this similar  
22 failure this year by similar mechanisms.

23 Last year, we had two plants: Vermont  
24 Yankee and Browns Ferry II. Both experienced fuel  
25 failure of second-cycle fuel. And we will discuss.

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1 this CILC failure mechanism a little bit to give you  
2 some sort of background.

3 We thought we were out of the  
4 corrosion-induced failures. Somehow they keep coming  
5 back. And I think these CILC failures were  
6 investigated very, very thoroughly by General  
7 Electric. So I think the understanding is pretty  
8 good.

9 However, the information here we learned  
10 I think is applicable probably to some extent to those  
11 CILC failure mechanisms, too. So I will talk a little  
12 bit on the CILC failure mechanism. Then I will talk  
13 about a new type of crud failure. Then I will come  
14 back to this more mysterious failure.

15 MR. CARUSO: The 1998 plant, that is River  
16 Bend, right?

17 MR. CHENG: That's right.

18 MR. CARUSO: You're saying that was CILC?

19 MR. CHENG: No. That's different. I  
20 mentioned that's a heavy crud-induced failure.

21 MR. CARUSO: Okay. But not CILC?

22 MR. CHENG: It's different. It's  
23 detailed.

24 Okay. So I'll give you a brief update on  
25 the CILC failures. As you know, CILC failure was due

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1 to cladding at a very significant nodular corrosion.  
2 And you can see this nodule corrosion, the spots, the  
3 nodule corrosion, grew at a rate much higher than the  
4 typical protective black oxide.

5 In this rod, you've got corrosion damage  
6 fail. When you look at it in a hot cell, you can see  
7 that a failure occurred due to corrosion pitting types  
8 of defect. And this is just to show you this metal  
9 loss at this location.

10 MEMBER RANSOM: Has anybody suggested that  
11 that may be due to subcooled boiling, you know, sort  
12 of the opposite of cavitation? You know, you get  
13 collapsing of the micro bubbles and then fatiguing of  
14 the metal surface.

15 MR. CHENG: I think because there is a PWR  
16 course, there is a lot of boron. I can see here and  
17 show you here, if you look at the location, some rods  
18 show nucleus nodule corrosion at about 20 to 40. And  
19 then the corrosion went down.

20 Other rods show the two peaks boiling  
21 under the peak here. There you can see here right  
22 from each location, this is the place you have  
23 vigorous subcooled boiling. It occurred about 30 to  
24 40 at each location. So the boiling occurred on the  
25 fuel rod surface. That is to strip off a lot of crud.

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1 I don't know if fatigue was involved, but if you look  
2 at a cross-section, it's really metal loss.

3 So this is kind of puzzling, right? You  
4 have a double peak here. I can come back a little bit  
5 on that. But, anyway, if you look at the rod in the  
6 hot cell, there is a lot of cross-section. There is  
7 some very heavy modular corrosion.

8 If you cut a cross-section, you have a  
9 nodular oxide here. A nodular oxide is locally  
10 penetrating into the cladding. Between nodules, it's  
11 forming this kind of crud deposit here. And there is  
12 a heat perturbation.

13 If you do the heat calculation, you will  
14 see because the nodule is getting so close, you start  
15 getting really high peaks. The boiling rate was much  
16 higher here than on the nodular oxide surface.

17 When you look at a cross-section exam with  
18 a scanning electron microscope, you can see here there  
19 is crud imbedded inside zirconium oxide.

20 This is the EDX. Using this SEM, you can  
21 see the zirconium oxide here. And this is Zircaloy  
22 cladding. Inside, there is nothing in between. Then  
23 you've got this porous deposit with a lot of copper  
24 here and also some zinc, and actually also some  
25 manganese, some cobalt, some nickel, found mostly all

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1 the soluble species in the reactor wall. They got  
2 stripped out by the boiling process.

3 If you look at this cross-section -- I'm  
4 sorry the quality is not very good -- you can extend  
5 a very large area with zirconium oxide on the outside  
6 and on the inside. In between, you have a layer of  
7 this type of porous crud embedded there.

8 So then we come to what then was this  
9 structure. Then you will say, "Okay. If you have  
10 water come" -- I'm sorry. Outside of this area, there  
11 was some sort of fluffy site but removed or lost.

12 But, you know, under this boiling  
13 condition, of course, with the porous crud, you can  
14 contain steam, but water cannot come inside. So the  
15 conductivity, thermal conductivity of this will be  
16 mixed structure of some dry steam in here, taking dry  
17 steam, mixing it with a copper-zinc oxide mixture  
18 here. And some of it is difficult to measure how much  
19 it is.

20 If you have enough steam pocket here,  
21 locally heat will not go through very effectively. So  
22 you are bound to have sort of local temperature rises.  
23 And with this type of structure, Zircaloy becomes very  
24 soluble oxide with growth very fast.

25 Somewhere about 500 degrees Centigrade,

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1 you can perforate cladding in just a few days at 500  
2 C. with poor nodular corrosion-resistant cladding.

3 In laboratory tests, this oxide will grow  
4 like 10 ml per day for 24 hours. So you can perforate  
5 the cladding if you overheated cladding over 400  
6 degrees Centigrade.

7 So this clad mechanism I believe is  
8 well-established through quite extensive study. In  
9 the old days, during this investigation, General  
10 Electric actually retrieved 12 rods from Vermont  
11 Yankee and did very extensive testing, even testing  
12 sample for corrosion, for everything in controlled  
13 radioactive environment because it was much cheaper to  
14 do this type of work a long time ago.

15 So the solution, mitigation, was to  
16 implement is the heat treatment and the belt-polished  
17 cladding. So there are two things. You heat-treat  
18 the cladding and you finish the surface with  
19 belt-polish versus the old cladding, which was not  
20 well heat-treated and the cladding was autoclaved.

21 In addition, many plants re-tubed the  
22 brass condensers to remove the copper source. Some of  
23 them did not repress the brass condenser. They put a  
24 pre-filter for the condensate cleanup to reduce all  
25 the impurity sources before the water gets into the

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1 feedwater stream. And so, thus, the solution becomes  
2 quite effective.

3 After the implementation, some fuel  
4 surveillance programs of those heat-treated cladding  
5 show that, actually, you can really eliminate nodular  
6 corrosion in the reactor by using this heat-treated  
7 cladding. Even before the brass condenser was changed  
8 out, many plants show very low or no nodule offset at  
9 the change-out.

10 There are some unresolved issues. The  
11 issue is why nodular corrosion or the CILC occurred  
12 predominantly to gadolinium fuel rods? A large  
13 percentage in the first CILC failures, all the  
14 failures occur to the gadolinium rods. But then the  
15 subsequent failures start somewhere to also show  
16 failure in the damages.

17 Why does gadolinium play a significant  
18 role in the failure mechanism? A second one is why it  
19 occurs also at 100-inch elevation. And this is kind  
20 of an interesting mystery.

21 Okay. So that's the CILC failure. Then  
22 I want to talk --

23 DR. MEYER: Could I interrupt and ask a  
24 question?

25 MR. CHENG: Sure.

1 DR. MEYER: This is Ralph Meyer from NRC.

2 On the previous slide, you showed  
3 heat-treated belt-polished cladding. Do I understand  
4 from that that in the mid '80s, they started polishing  
5 the surface of the cladding during fabrication?

6 MR. CHENG: Yes, yes. As a finished  
7 product, all the vendors switched to belt polish.  
8 Before the mid 1980s, all the vendors used autoclave.

9 DR. MEYER: Because this is entirely  
10 consistent with what we saw with the E110 cladding,  
11 which was developing nodular corrosion.

12 MR. CHENG: Yes, yes.

13 DR. MEYER: When it was polished, it  
14 improved the situation dramatically. Thank you.

15 MR. CHENG: Right, yes. Cladding surface  
16 can be a very major part of the whole corrosion  
17 equation.

18 Okay. Now I will switch to this heavy  
19 crud-induced corrosion failure. Again, this first  
20 occurred in 1998. We helped the utility a bit. And  
21 the data was published in this meeting in year 2000.

22 The crud was very heavy crud. You can see  
23 here in the picture here some of the crud was so heavy  
24 that this is about a 40, 50-inch elevation from the  
25 bottom. The crud was so heavy, some of them, between

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1 the two, they would almost touch each other. So it  
2 almost crossed the gap in some of the rods.

3 It occurred to the first cycle high-power  
4 rods. When you brush it off the rod, you see this is  
5 opening damage. One thing interesting, you don't see  
6 the nodule type of corrosion on those damaged rods.  
7 So the detailed mechanism is somewhat different.

8 The main constituents are iron, copper,  
9 and zinc. This is a brass condenser is not a typical  
10 CILC plant in that it has a deep bed cleanup system  
11 and supposedly is more efficient in removing copper.  
12 But, yet, they still have about .2 to .3 ppb of copper  
13 in the feedwater. So they still have copper less than  
14 the subpipe of copper in the system, but it still has  
15 some copper.

16 And they inject zinc. Okay? Of course,  
17 the zinc injection was for dose rate reduction  
18 consideration. They inject zinc into the feedwater  
19 and enter into the reactor water.

20 They have a lot of crud deposit.  
21 Actually, they have mass balance. And they say that  
22 they think they may have some sort of iron intrusion.

23 So at that time, it was not so clear what  
24 really triggered the failure except they believed that  
25 maybe they have a significant iron intrusion during

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1 the start-up period that caused this iron to go to the  
2 fuel rod surface.

3 But, yet, if you look at the total iron,  
4 however, it is really not the highest there. There  
5 are other plants with higher iron deposits. Yet, they  
6 didn't have fuel failure.

7 Look at the copper itself was not the  
8 highest either. We had a similar copper deposit. We  
9 had a similar zinc deposit. However, they're unique  
10 in the combination of iron, copper, and zinc.  
11 Combined together, they were very unique in the  
12 industry.

13 So there was some sort of belief that they  
14 had to do with the copper hideout in tenacious iron  
15 oxide crud. This crud was very tenacious. It's very  
16 difficult to brush off. So this is somewhat  
17 different.

18 I'm sorry?

19 MEMBER KRESS: Do you gather that from the  
20 clue that the copper and the zinc curves tend to be  
21 mirror images of each other? Is that a clue that you  
22 --

23 MR. CHENG: Yes. I think what happened is  
24 I will come back when I talk about NMCA. When you  
25 inject zinc, the crud can become very tenacious.

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1 Without zinc, crud tends to be very fluffy. I think  
2 when you add zinc into the reactor, zinc will interact  
3 with iron to form a very tenacious zinc ferrite.  
4 Okay?

5 With the porous tenacious crud, copper  
6 found a place to hide out. And maybe that copper  
7 plugs up this porous tenacious crud to cause a steam  
8 blanketing, too.

9 Okay. So I will come back to the next  
10 slide to --

11 MEMBER KRESS: The copper and zinc are  
12 definitely related to each other. You can see that.

13 MR. CHENG: Yes, here, certainly.

14 MEMBER KRESS: Yes.

15 MR. CHENG: But the source of zinc in this  
16 case came mostly from zinc injection, although there  
17 is some zinc in the system because brass contains it.  
18 But the majority of the zinc came from the zinc  
19 injection.

20 CHAIRMAN POWERS: Yes. I was just looking  
21 at the shape of the curves. High copper means low  
22 zinc and low copper means high zinc. So they're  
23 related. And that gives you a clue as to how they're  
24 interacting with each other.

25 MR. CHENG: Yes. Okay.

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1 MEMBER KRESS: I'm not sure what clue that  
2 is.

3 CHAIRMAN POWERS: Well, I'm not either,  
4 but there is a clue there that we need to look at.

5 MEMBER FORD: The zinc displaces in the  
6 magnetite. That is the basis of the GeSiC process.

7 MEMBER KRESS: And then, therefore, the  
8 copper can't get to it.

9 MEMBER FORD: Yes.

10 MEMBER KRESS: Yes. That's the clue.

11 MR. CHENG: Well, I think the problem,  
12 they had a similar experience this year. And they're  
13 still working on the root cause, the final root cause.  
14 So the utility is actually taking the lead.

15 You know, previously the vendor made it  
16 more strong inference in the final root cause and here  
17 decided that this is their plant they have to have  
18 their voice, their stronger voice. So they took over  
19 the root cause investigation and lead the effort.

20 We are providing them the root cause  
21 analysis. And also we are helping them to analyze  
22 this tenacious crud, particularly to try to understand  
23 the morphology.

24 In addition to that, the plant already  
25 installed this full-flow filter to remove copper and

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1 iron. So right now the plant has very low iron and  
2 very low copper. So we think the problem should just  
3 go away by that.

4 In addition, I will come back on this. We  
5 have requests as to the chemistry guidelines to be  
6 revised to limit the zinc, how much zinc you can put  
7 into the reactor water.

8 MEMBER FORD: At less than .4 ppb, you can  
9 still control the cobalt 60?

10 MR. CHENG: Well, that is something that  
11 could be a problem for a high-iron plants. Some  
12 plants may have to take exception to this limit. For  
13 a plant with copper, we like to stick to .4 or even  
14 lower.

15 So I would like to summarize the crud  
16 corrosion failure here, historical case, including the  
17 high crud-induced case I just mentioned. I think that  
18 it's the localized corrosion acceleration will occur  
19 when stagnant steam pockets are formed.

20 There are two ways to form closer from the  
21 data details. In the delaminated nodular oxide layer,  
22 like we found at the -- due to intrusion of soluble  
23 species outside that caused this steam blanketing.

24 The second case is tenacious crud, where  
25 the pores got partially blocked. And we still think

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1 and I think this type of conclusion, this we're still  
2 working on the cross-sample characterization, but we  
3 think the case probably is very similar to what  
4 happened at SGHWR in the 1970s is a heavy water,  
5 steam-generating reactor.

6 They had a very tenacious iron oxide crud.  
7 And then they got this copper oxide plug up this crud  
8 area from the outside. So it created a steam pocket  
9 here that the dry steam escaped. So water cannot come  
10 in. So you are creating a heat barrier in between.

11 So we think copper can cause this  
12 delamination in the plug of the tenacious crud. And  
13 the reason is the copper is the most abundant soluble  
14 species. You go in. You've got boiled and  
15 precipitate iron oxide plus copper oxide.

16 However, iron is different. You know, all  
17 the species behave differently. Iron when it goes to  
18 the BWR core, it precipitates out as a colloid of iron  
19 oxide. It's not a soluble. So the position  
20 characteristic of iron oxide is very different.  
21 Mostly it would occur at the bottom part of the core,  
22 like a 20 to 40-inch location in the subcooled boiling  
23 regime or most of the insoluble iron oxide will be  
24 stripped out. We have a lot of crud data that  
25 indicate that to be the case.

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1                   So the equation is how about other  
2                   solubles? We are adding zinc. And zinc is also  
3                   soluble. So that's the equation that we need to  
4                   address.

5                   How do we deal with this tenacious crud  
6                   issue? If we look at the history of all the BWR crud  
7                   data that we have collected, we can safely say that  
8                   before zinc injection that was started in 1986, we had  
9                   seen tenacious crud. Most crud, you brush it, it  
10                  comes off.

11                 Occasionally in some of the brass  
12                 condenser plants, you had natural zinc. But a zinc  
13                 concentration is substantially low such that you don't  
14                 really form a tenacious crud there.

15                 So only zinc injection in the last many  
16                 years, we start seeing very tenacious crud formation.  
17                 Other crud formation characteristics also have to do  
18                 with the thermal hydraulic condition in the BWR core  
19                 because it's a two-phase flow boiler.

20                 You have a subcooled boiling at the bottom  
21                 part of the core up to about maybe 40, 50 inches into  
22                 about 40 inches. You've got bulk boiling. But that  
23                 region, there the two-phase flow depends on this film  
24                 boiling. There is a very thin film on the water, on  
25                 the fuel while keeping it thermodynamically stable.

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1 If we produce the water film, we can get into the  
2 dry-out condition.

3 But this also could potentially become  
4 location for a hideout because water droplets deposit  
5 on the fuel rod surface and they'll vaporize as pure  
6 steam. So it will leave behind some of the  
7 impurities.

8 So there is some sort of hideout condition  
9 here. We talk about nodular oxide. We have got  
10 tenacious crud. We also have been looking into this  
11 thermal hydraulic-driven type of hideout as a  
12 possibility here. So this is an issue, the raw  
13 thermal hydraulics. It's not so clear and is a  
14 subject that we need to look into further.

15 The nodular corrosion issue, as we see,  
16 fabrication through heat treatment, through proper  
17 reduction, we can control the nodular corrosion, clear  
18 data to support that, but that's another story.

19 Sometimes I don't know. For whatever  
20 reason, we start seeing evidence of nodular corrosion  
21 more recently. And the possibility of some sort of  
22 chemical impurity in the water may reduce the nodular  
23 corrosion again. However, we really don't know about  
24 other species. This is another area we need to work  
25 further.

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1           Then the last issue, again, I mentioned is  
2 gadolinium. White gadolinium would induce a lot of  
3 nodular oxide. So there is something on this issue.  
4 However, certainly we can certainly contain those  
5 problems. And the key is to make sure that we don't  
6 have excessive tenacious crud. We don't have very  
7 excessive nodular corrosion.

8           So that's the corrosion issue. You know,  
9 I want to come back to talk about the current issues.  
10 That's the corrosion failure I mentioned. Last year  
11 we had two plants with cladding corrosion failure.  
12 And Rosa also mentioned this earlier today.

13           We had three plants with PCI-like failures  
14 and then in a water chemistry modification. We'll  
15 touch on those three topics. The BWR corrosion  
16 failure, okay. The two failures occurred at two  
17 different plants, both at BWR/4. Both plants were  
18 CILC-susceptible, but one of the plants re-tubed the  
19 brass condensers. So they don't have copper source  
20 anymore. In about 1990, they re-tubed the brass  
21 condenser. So they don't have copper.

22           The corrosion failure occurs at about 95  
23 to 110-inch location. Remember, I showed you the  
24 double peak. This is the case. There was no damage  
25 at the bottom part. Twenty to 40-inch only occurred

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1 in 95 to 110-inch elevation. So this is kind of a new  
2 situation.

3 We see some sort of crud deposit, but  
4 there was nothing excessive. You know, visually it  
5 looks kind of typical, noting very unusual to speak  
6 of. The fuel design is the same. Damages occur  
7 predominantly to the part-length rods.

8 This is fuel rod nine by nine design with  
9 a total of eight rods inside a core, which is 4.95  
10 enrichments or is the high peaking rod.

11 An interesting part that Peter asked me  
12 was because both plants had NMCA applications during  
13 outage before fuel failures. And in both cases,  
14 failure started about six, seven months into the  
15 cycle. So the timing was consistent. You know, both  
16 plants had failures that started seven months into the  
17 cycle.

18 The chemistry, plant chemistry, is  
19 different. As I say, one plant still had copper  
20 because of the brass condenser. But they did not have  
21 hydrogen water chemistry, no zinc injection.

22 Other plants had no copper, but they  
23 injected zinc. There was a high level amount of zinc  
24 injection. And they have hydrogen water chemistry.  
25 So the chemistry condition is somewhat different.

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1           The cladding material, the vendor looked  
2           into the material. They found some of the failed rods  
3           tended to have somewhat lower iron concentration in  
4           the alloys, but, actually, they were always in the  
5           specification, not really highly distinctive there.

6           So that all the root cause investigation,  
7           initial phase of our investigation, showed that maybe  
8           there are quite a few contributors, like water  
9           chemistry, like cladding material and the fuel duty,  
10          but really cannot pinpoint which one, what are the  
11          predominant triggers.

12          So robust fuel decided to fund this hot  
13          cell program to send funds to the hot cell  
14          examination. So that's the current situation. We  
15          need to do hot cell examination hopefully to reveal  
16          the root cause. I want to talk about --

17                 MEMBER LEITCH: How many pins were failed  
18                 in this situation?

19                 MR. CHENG: Okay. The first plant, the  
20                 first outage, and they got five pins in the four  
21                 bundles fail. And they took out all the bundles in  
22                 the high-power location in addition to the four  
23                 bundles that failed. So I think it's total. The  
24                 reload was maybe 200 bundles. They took maybe almost  
25                 half of it.

1           The second plant first had a four-bundle  
2 failure, four bundles. They took out the four  
3 bundles. They restarted right away. And they it kept  
4 failing in the rod. So they had a second missed cycle  
5 outage, unscheduled outage.

6           And they took out I think 25 bundles,  
7 failed bundles. And they didn't have enough fuel to  
8 redesign the core. So they restarted by fabricating  
9 new fuel.

10           So at the end of the cycle, they took out  
11 a whole reload. I think in the end, they may have, I  
12 think, maybe 40 bundles fail.

13           So the first plant, if they didn't pick up  
14 all the high-powered locations, the bundles, they  
15 might fail a lot of bundles. So it depends on how  
16 they manage this.

17           MEMBER LEITCH: Did either of these plants  
18 have excursions in their chemistry, like a major  
19 condenser tube leak or foreign material?

20           I had an experience once with lube oil  
21 getting into the reactor coolant system. Any of that  
22 kind of history?

23           MR. CHENG: Hydraulic fluid.

24           MEMBER LEITCH: Hydraulic fluid?

25           MR. CHENG: Yes. Well, in the first

1 plant, no, they did not have the hydraulic fluid in  
2 leakage. They did not report a condenser failure. So  
3 it was they said just burn no more operation. With  
4 chemistry, look at chemistry, very typical, very  
5 clean.

6 The second plant, they had the hydraulic  
7 fluid intrusion, but it occurred I think the prior  
8 cycle. And they were able to isolate. So they don't  
9 believe it entered into the feedwater strain.

10 So it was not so clear, you know. People  
11 would say, "Oh, that was the cause," but they were  
12 able to isolate it.

13 MEMBER LEITCH: Yes.

14 MR. CHENG: Okay. The PCI-like failures,  
15 this is in the three BWRs. They used a single  
16 product. It's called iron-enriched zirconium liner.  
17 As you know, in order to prevent the PCI failure  
18 during control rod pole, people used zirconium liner  
19 as a soft liner to prevent a PCI.

20 Because of the zirconium iron liner in the  
21 late '80s into the '90s, there are a lot, a  
22 substantial number, maybe one-third of the failed  
23 zirconium liner rod that suffered a very long axial  
24 split. And they lost few pellets since.

25 So at that time, a vendor introduced a

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1 different kind of liner. They thought the zirconium  
2 liner was iron. And with that additional iron, the  
3 corrosion resistance of the liner is improved  
4 substantially.

5 So after fuel failure, they believe that  
6 the corrosion rate will be much lower. The hydrogen  
7 generation inside the fuel rod will be much smaller,  
8 lower. So that won't cause damage to the fuel rod.

9 And so they use that, but somehow they  
10 suffer mostly I think at about 15 gigawatt-days.  
11 After about 30 gigawatt-days, in that burnup range,  
12 many rods fail during power change. However,  
13 utilities do stick to these limits. They do have  
14 limits. They can pull the control blade type of  
15 thing.

16 One of the pictures show just a hair line.  
17 White lines you have to brush the fuel rod to look at  
18 it. Several rods showed this type of feature. But,  
19 in addition to that, because there is hydride damage  
20 at other locations, but, anyway, possible root cause  
21 from failure model evaluation, I think they look at  
22 three plants as monitor pool-side inspections, most  
23 likely failure of root causes, pellet defects due to  
24 when the pellets were loading into the fuel cladding,  
25 maybe because of chipping, maybe make the rods more

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1 susceptible to PCI. That's one possible scenario.

2 The second one, of course, the possibility  
3 of maybe this liner only reaches iron after  
4 irradiation because the iron dissolution or those  
5 kinds of things may affect this PCI resistance of the  
6 liner.

7 Another thing that the fuel vendor says  
8 is, "Well, maybe it's hydride-assisted cracking  
9 because you put noble metal into the reactor. And  
10 maybe noble metal causes hydrogen absorption." And,  
11 therefore, the outer layer of the cladding may  
12 accumulate hydrogen and fuel in the PIE changes, that  
13 may induce initial cracking of the cladding.

14 Now, this is the theory that the Japanese  
15 seem to be very concerned about this type of  
16 hydride-induced cracking from outside propagating into  
17 the inside.

18 Those are three potential failure root  
19 causes.

20 MEMBER FORD: Sorry. These are Japanese  
21 reactors?

22 MR. CHENG: No. This is all domestic.

23 MEMBER FORD: I'm sorry?

24 MR. CHENG: These are --

25 MEMBER FORD: United States?

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1 MR. CHENG: Yes, U.S. So we think most  
2 likely it would probably be the first one, maybe petty  
3 differences. But, again, I was just looking at the  
4 pool-side. How do you tell? There is no way you can  
5 tell. So we sent in the fuel rod to the hot cell for  
6 the PIE.

7 MEMBER LEITCH: Was that last picture the  
8 inside we're looking at?

9 MR. CHENG: This is outside. This is the  
10 fuel rod you are looking at from outside.

11 MEMBER LEITCH: From the outside?

12 MR. CHENG: From the outside. And that is  
13 the brushing. So typically you have a reddish outside  
14 rod there. You won't see anything. So you brush it.  
15 And they were able to see.

16 I think, in addition to this, there was  
17 profilometry, eddy current measurement. And coupled  
18 with visual, you are able to see this type of feature.

19 MEMBER LEITCH: But what's this down on  
20 the right here? Is that where the --

21 MR. CHENG: Oh, I'm sorry. This is just  
22 the picture. I chopped off the picture and maybe just  
23 the lighting condition.

24 MEMBER LEITCH: Oh, okay. This is not --

25 MR. CHENG: Sorry.

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1 MEMBER LEITCH: Okay.

2 MR. CHENG: So the schedule I want to show  
3 you, we are sending the fuel rods by the end of this  
4 year in both cases. We are hoping to get the results  
5 sometime next year, but we have this robust fuel  
6 committee who would actively participate in all the  
7 work and review the results.

8 As soon as we get a result, we disseminate  
9 all the results to the utility members so they will be  
10 able to get firsthand the results and hopefully help  
11 them resolve their issues.

12 So that is the fuel failure. Now I want  
13 to touch on the water chemistry issue. This is the  
14 last topic. On the BWR side, unlike PWR, it's almost  
15 a uniform chemistry across the whole industry with  
16 minor changes in lithium and pH.

17 BWRs domestically, we have 33 different  
18 chemistry conditions. Every plant is somewhat  
19 different in all the impurity levels. And if you look  
20 at it back in the 1970s, a lot of plants had recent  
21 intrusion, condenser failures, a lot of gas, oxygen,  
22 nitrogen in their system, carbon dioxide or carbonate  
23 measure in the water.

24 So in the '70s and '80s, it was a major  
25 effort to try to clean up the water to make sure that

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1 the industry operates with nice clean water. And one  
2 indicator is the conductivity. The reason to clean up  
3 water mainly was driven by system material cracking.

4 We keep cracking the piping. And the  
5 conductivity, one of the indicators, you've got a lot  
6 of soluble and that is a problem. And the soluble  
7 sometimes comes from chloride or sulfate. Those are  
8 major efforts. And the measure, as I say, is to plug  
9 up the condenser tube to make sure the condenser tube  
10 doesn't keep leaking.

11 The second one is the reason the cleanup.  
12 The filtration system, the reason often break down and  
13 release of the fines, reason fines, into the  
14 feedwater, into the reactor and the reason and then a  
15 lot of sulfate, a lot of silica.

16 MEMBER LEITCH: Are there some plants  
17 today? It says "current levels." Are there some  
18 plants actually operating at .3 ppb copper?

19 MR. CHENG: Right now we have probably, I  
20 would say, maybe on the high end, the cycle average is  
21 less than this. It may be .2, but, as I say,  
22 sometimes it would go up a little bit higher, .3, .4.

23 We right now have probably two plants  
24 still with brass condenser.

25 MEMBER LEITCH: Yes.

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1 MR. CHENG: Yes. They would have. Well,  
2 actually, including the one that this  
3 corrosion-induced failure would be three, but that  
4 plant already put a filter in. And they are able to  
5 knock the copper way down.

6 So we have two plants, probably .2, .3  
7 type of range.

8 MEMBER LEITCH: Yes.

9 MR. CHENG: If you take a cycle average,  
10 I would say .2, but the range. So the iron actually  
11 comes down from like a 10 ppb in the feedwater and the  
12 maximum maybe 3 to 4 ppb. Okay? And the iron  
13 recommended is .25 to 1.5 ppb.

14 It's interesting, you know. When the  
15 plant runs iron below this level, they are saying that  
16 the dose rate will start increasing. So they have to  
17 inject iron to bring the iron back to .25

18 So right now nobody is injecting now, but  
19 in the last five years, I would say three plants  
20 inject iron oxalate into the coolant, try to bring up  
21 the iron level. We are trying to reduce the boiling  
22 limit so that they don't have to inject iron again.  
23 So this is a range we prefer.

24 But most plants can meet this range now.  
25 A fuel plant may be on the high side. Copper, as I

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1 say, maybe of them, I would say that 31 plants have  
2 less than .1 ppb now and about 2 of them maybe 2 and  
3 another one may be .1 or slightly higher.

4 And zinc, without a zinc injection, the  
5 zinc, even with brass condenser, they say zinc in the  
6 water is about half of copper in the brass condenser  
7 tube. So without zinc injection, maybe it will be  
8 about .15. And copper plant may be in this category  
9 but without zinc injection. So the water quality is  
10 much better now. And I think it does help the fuel  
11 performance also substantially.

12 In 1983, hydrogen water chemistry was  
13 first introduced at the Dresden 2. And the purpose  
14 was to mitigate stress corrosion cracking of the  
15 piping system. Hydrogen addition, at that time the  
16 first demonstration was started at about 1.4 ppm added  
17 into the feedwater stream. And they're going to the  
18 reactor water to suppress oxygen in the piping system.  
19 So that was introduced.

20 We conducted a very significant fuel  
21 surveillance program. And we found this was benign to  
22 the fuel. We didn't see any problem with the fuel.  
23 If there is anything, we think maybe it would be  
24 somewhat beneficial to the fuel. It makes the crud  
25 very fluffy. So it may be somewhat beneficial.

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1 Zinc injection was introduced in 1986. I  
2 think the first plant was Hope Creek. And it was  
3 introduced. The vendor suggested the control was in  
4 the reactor water, rather than the feedwater.

5 Feedwater is not really controlled. It's  
6 reactor water controlled to 5 to 10 ppb. This can be  
7 a problem because if you are running 5 ppb, you are  
8 probably at like a .2 ppb of zinc in your feedwater to  
9 get this.

10 If you want to get a 10 ppb, you probably  
11 have to increase the feedwater concentration by 10  
12 times in order to get the double reactor water. And  
13 most of the zinc will load on the fuel rod surface.  
14 So this can be a problem. And right now we tried to  
15 mitigate this problem.

16 Noble metal chemical addition, NMCA, was  
17 introduced in 1996. Again, this is to increase the  
18 efficiency of hydrogen in stress corrosion cracking  
19 mitigation. The theory is once you treated a system  
20 with NMCA, you only need a small amount of hydrogen  
21 into the feedwater.

22 You don't have to go to 1.8. You can go  
23 down as low as 0.2, 0.3 ppb. I'm sorry. This has got  
24 to be ppm in the feedwater to control the stress  
25 corrosion cracking by reducing its chemical potential.

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1 I think Rosa showed you this already. I  
2 think there was a problem with this. We have to come  
3 back. Let me come back. How this works is the  
4 platinum and rhodium in chemical form, soluble  
5 chemical form, added to the BWR reactor water, it's  
6 about 160 degrees Centigrade when the plant is coming  
7 down. They injected chemicals into the line for 48  
8 hours to circulate inside the reactor coil for 48  
9 hours.

10 During that time, platinum and rhodium  
11 metal will fold into monolayers on the piping system.  
12 However, the majority of the noble metal will deposit  
13 on the fuel surface during the treatment because the  
14 fuel surface still has a gamma heating and temperature  
15 is hotter.

16 Because of the crud, the effective surface  
17 area is much larger than the piping system. So most  
18 of it will go down to the fuel surface.

19 During the application, if you calculate  
20 total amount of noble metal added to the core, divided  
21 by total reactive fuel rod surface area, you can come  
22 down to like a microgram per centimeter<sup>2</sup>. And there  
23 is a variation.

24 Some trends had treated very  
25 conservatively, like the bowing is much lower, like

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1 10, and others started with like 62. Okay. And right  
2 now I will come back to say right now we try to limit  
3 to 30, no more than 30, but they do have a large  
4 variability here.

5 This is equivalent to maybe like one to  
6 four kilograms of noble metal added to the core during  
7 the treatments, about one to four kilograms.

8 We know that everybody worries about what  
9 happened to the noble metal. You put in platinum and  
10 rhodium, this is a catalyst that can cause a lot of  
11 change in the water chemical reaction.

12 So the concern is about the accelerated  
13 hydriding of Zircaloy, concerned about its crud  
14 transport and deposition because as a catalyst, it  
15 could cause a lot of deposition. And we also worry  
16 about cladding corrosion.

17 So we did fuel surveillance at the three  
18 BWRs by BWRVIP and robust fuel together to do fuel  
19 surveillance at three plants. And, of course, also  
20 some utilities did their own surveillance and provided  
21 data to the industry for the overall assessment. In  
22 this process, we also did hot cell examination twice.  
23 We examined the condition of the fuel rods.

24 To just summarize the condition that we  
25 observed after the NMCA, we actually saw increased

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1 frequency of surface spallation at several plants.  
2 And I will show you this picture.

3 This is one case with a high noble metal  
4 injection. And this is before brass. We've got some  
5 crud loss, some sort of tenacious crud. This is an  
6 indication of the surface texture. This is a thick  
7 tenacious crud here. It could be like 20 microns, 30,  
8 40 microns, thick crud there. And in some cases,  
9 there is a tenacious crud spall. And you can see all  
10 of those spotty surfaces because of that.

11 We think the spallation, those with  
12 tenacious crud may have to do with the zinc injection.  
13 One problem was that after they put NMCA into the  
14 core, some see the soluble iron start to increase.  
15 And they think maybe the dose rate is also increasing  
16 because of that. And they start adding more zinc than  
17 they used to.

18 Rosa said at one of the plants they used  
19 to have in the feedwater, they used to put like a 0.2  
20 ppb and suddenly after the NMCA, they increased up to  
21 about 0.8 to 1.5 ppb. So plants started adding more  
22 zinc after they did the noble metal because they  
23 probably got compounded by increasing the injection of  
24 zinc. And in one case, we saw some increased oxide  
25 spallation. Also corrosion is spallation when you get

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1 a very high noble metal treatment.

2 However, from the hot cell work, we found  
3 NMCA did not increase hydrogen absorption. After  
4 three cycles, we looked at it as doing our own rod.  
5 We did not see any increase in the hydrogen injection.  
6 So that's a plus in information.

7 Out of those 28 plants, -- that's 24 in  
8 the U.S., 4 in foreign BWRs -- 2 plants in the U.S.  
9 experienced corrosion failure. Domestically, 22 had  
10 no NMCA-related failures. However, we are not sure  
11 that an NMCA was the root cause. As I say, the  
12 chemistry will change. The zinc injection was  
13 increased. I cannot say it was attributable to NMCA.

14 But, again, until we found the root cause,  
15 it is just difficult to say what to do. So we do have  
16 very close committee to oversee this whole NMCA  
17 transition. Zinc injection changes.

18 When we prepare a white paper and we also  
19 develop this guideline for the BWRVIP on the fuel  
20 issues. And our recommendation was to limit the noble  
21 metal loading to less than 30 micrograms per  
22 centimeter<sup>2</sup>.

23 I showed you before this some had 50 to 60  
24 micrograms. So we try to limit it to no more than 30.  
25 We also ask to limit zinc to less than 0.4 ppb in the

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1 feedwater. As we say, up to today, there is no  
2 controlling the feedwater. It's all in the reactor  
3 water. And we are imposing a limit of zinc in the  
4 feedwater. I think some plants may have trouble, but  
5 I think they have to review their situations case by  
6 case.

7 We also asked the plant to reduce iron to  
8 minimize tenacious crud. And, of course, they need to  
9 talk to fuel vendors to assess the overall situation.  
10 A very important issue is they should keep the  
11 hydrogen available all the time to prevent the crud  
12 transport.

13 Okay. So I touched on several issues.  
14 I'll give you a summary. We think the fuel failure  
15 induced by manufacturing defects have mostly been  
16 under control. Fuel duty and water chemistry failures  
17 continue to occur. And we think it will be more  
18 challenging, particularly in the BWR side.

19 The preventive measures, of course, we  
20 have robust tests and in-plant demonstration for any  
21 changes and technical and experience basis guidelines.  
22 We need to continue to fine-tune that. Any duty  
23 changes or the peaking for the particular when  
24 increased, there was some discussion about how about  
25 enrichment of over five percent.

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1 I think, of course, when you increase the  
2 enrichment, the first thing, of course, is fuel  
3 economics. You want to reduce the batch size. And  
4 that would certainly increase the peaking in the whole  
5 core. This is something we need to watch out.

6 Okay. Thank you.

7 CHAIRMAN POWERS: Thank you. That was a  
8 survey of all problems that your noble metal chemistry  
9 can cause.

10 MEMBER FORD: We don't know that. Sorry.  
11 I can't say it.

12 CHAIRMAN POWERS: That was very generous.  
13 The other way of putting it is that we don't know that  
14 it doesn't cause problems.

15 Are there any other questions for the  
16 speaker?

17 (No response.)

18 CHAIRMAN POWERS: Thank you very much.  
19 Most interesting stuff we don't ordinarily get to hear  
20 about, and it gives us ammunition for harassing Peter  
21 for several months now.

22 And, Rosa, I want to thank you for  
23 bringing everybody here and giving us a very  
24 interesting talk. This is really fun stuff that  
25 you've got here. And it's obvious that you have got

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1 more than your hands full with all of these activities  
2 going on.

3 . At this point, I think we need to go off  
4 the recorded record and discuss what the  
5 subcommittee's strategy is for the future.

6 (Whereupon, at 4:47 p.m., the foregoing  
7 matter was adjourned.)

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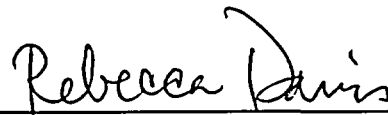
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This is to certify that the attached proceedings  
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in the matter of:

Name of Proceeding: Advisory Committee on  
Reactor Safeguards  
Reactor Fuels Subcommittee  
OPEN SESSION

Docket Number: n/a  
Location: Rockville, MD

were held as herein appears, and that this is the  
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Rebecca Davis  
Official Reporter  
Neal R. Gross & Co., Inc.



## Robust Fuel Program

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### Utilities Formed The Robust Fuel Program In 1998

- Today's demanding operating conditions have reduced operating margins
- Competitive environment lessens ability to fund R & D to ensure fuel performs "as advertised"
- RFP is aimed at ensuring
  - Optimal fuel performance; avoiding operational surprises
  - Regulatory stability
  - Operating flexibility
  - Burnup extension



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## More Demanding Environment

- Increasing discharge burnups and long cycle length
- Increased fuel peaking and enrichment
- Plant uprates
- New water chemistry environments
  - Elevated pH/lithium and Zn injection for PWRs
  - NMCA, hydrogen water chemistry and Zn injection for BWRs
- Fuel design changes and introduction of new materials

Reduced margins and increased unknowns

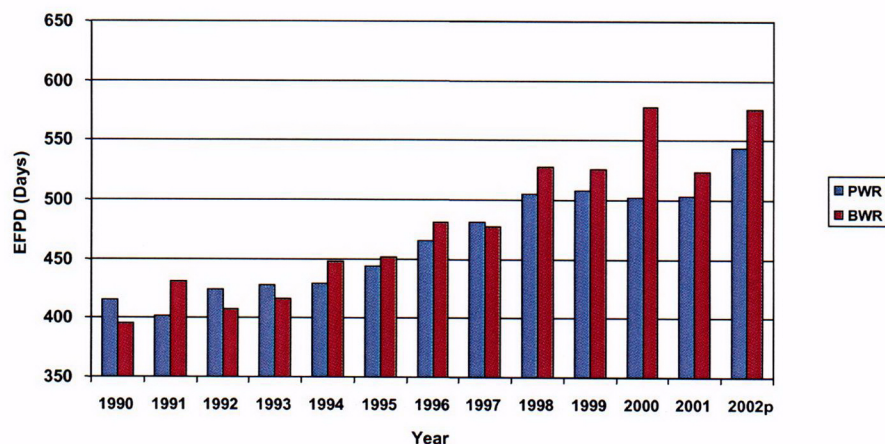
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## Trends In Cycle Length -U.S.



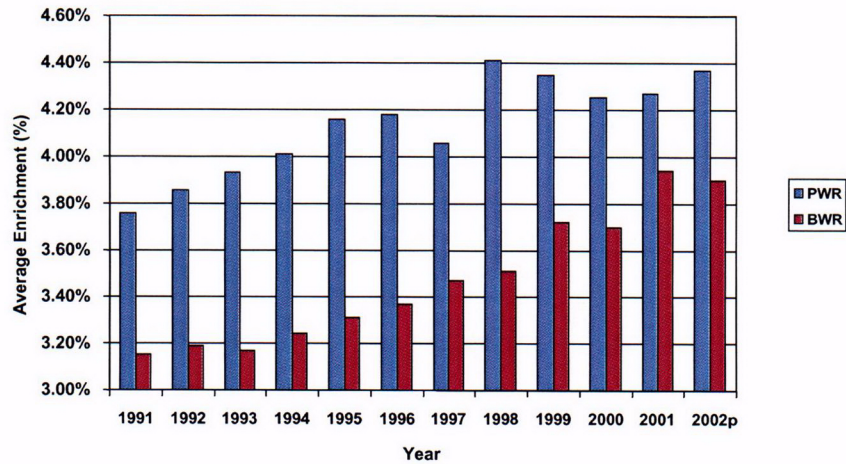
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## Trends In Average Initial Enrichment -U.S.



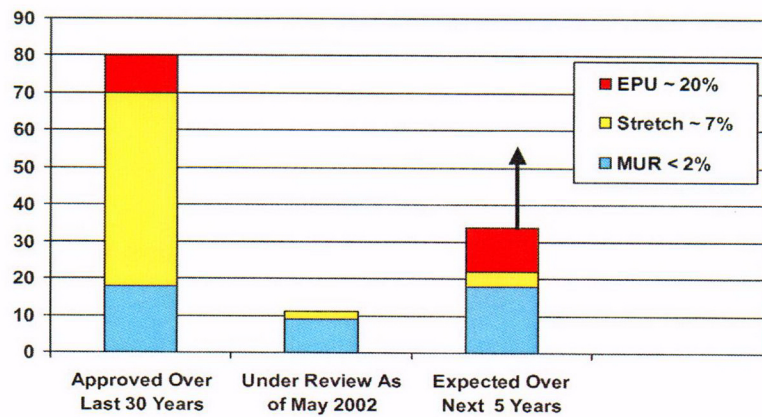
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## Number Of Uprated Applications In U.S.



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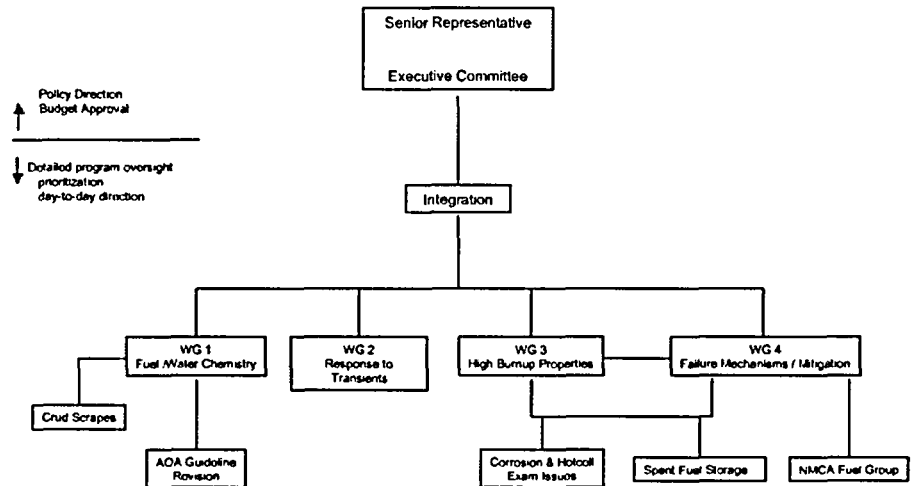
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## Robust Fuel Program Utility Steering Committee



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## Executive Committee Members

Lyle Bohn, Nuclear Management Company  
 Ken Canady, Duke Energy  
 Bill Eaton, Entergy  
 Lou Long, Southern Nuclear  
 Jim Malone, Exelon Corp  
 Joe Sheppard, South Texas Project (Chairman)  
 Ausaf Husain, Fuelco

Gary Fader, INPO  
 Alex Marion, NEI

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## Chairmen/Vice-Chairmen & Project Managers

	<u>Chairman</u>	<u>Vice Chairman</u>	<u>Project Manager</u>
Working Group 1	Dan Bryant (South Texas)	Kenny Epperson (Duke Power)	Jeff Deshon
Working Group 2	Nicolas Waeckel (EdF)	Bob Tsai (Exelon)	Odelli Ozer
Working Group 3	Dave Hoppes (South Texas)		Kurt Edsinger
Working Group 4	Bruce Hunt (Southern Nuclear)	Ed Armstrong (Exelon)	Bo Cheng

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## International Participation

### 2004 Members

<u>US</u> (19 utilities, 80 units)		<u>International</u> (9 utilities, 113 units)
AmerenUE	Pacific Gas & Electric Co.	EdF (France)
Constellation Energy	PPL Corporation	Japan Atomic Power Co. (Japan)
Detroit Edison	Public Service Elec. & Gas	Kansai Electric Power Co. (Japan)
Duke Energy	So. Tx. Project Nucl. Oper. Co	Kyushu Electric Power Co. (Japan)
Energy Northwest	Southern California Edison Co	Leibstadt (Switzerland)
Entergy	Southern Nuclear Operating	Shikoku Electric Power Co. (Japan)
Exelon	Tennessee Valley Authority	Tokyo Electric Power Co. (Japan)
FirstEnergy Corp.	TXU Electric	UNESA (Spain)
Nuclear Management Corp	Wolf Creek Nucl. Oper. Corp	Vattenfall (Sweden)

### Close Collaboration with

INPO; NEI; NRC Research; Global Nuclear Fuel; Westinghouse and Framatome ANP

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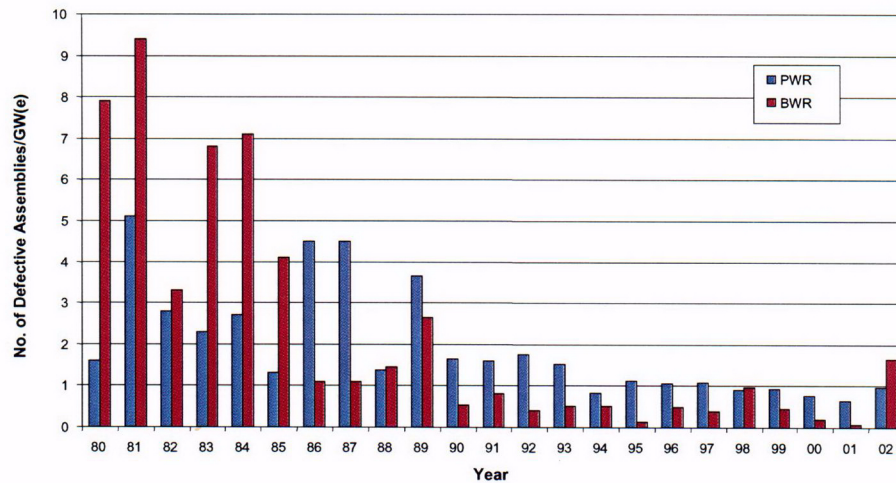
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## Key Issues Addressed

## Key Fuel Performance Issues

- BWR :
  - Large number of BWRs experiencing fuel failures, and many of the root causes are unknown
  - Needs to assess the impact of Noble Metal Chemical Application (NMCA) and Zn injection on fuel performance
  - Excessive channel bow interferes with control blade insertion at some BWRs
- PWR :
  - Grid-rod fretting continues to be the main failure root cause
  - Axial offset anomaly (AOA) persists but occurrence frequency and severity are down significantly
  - RCCA cracking and deformation

## Fuel Failure Trend 1980 To 2002



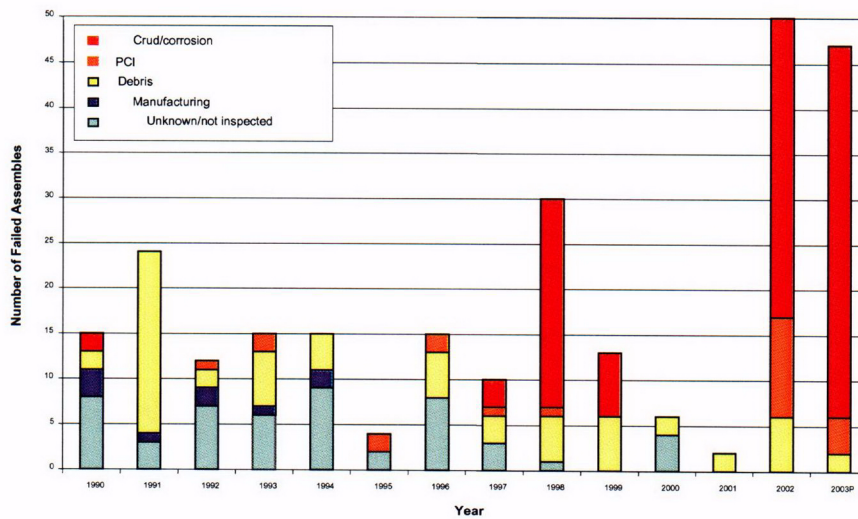
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## Trend In BWR Fuel Failure Root Causes



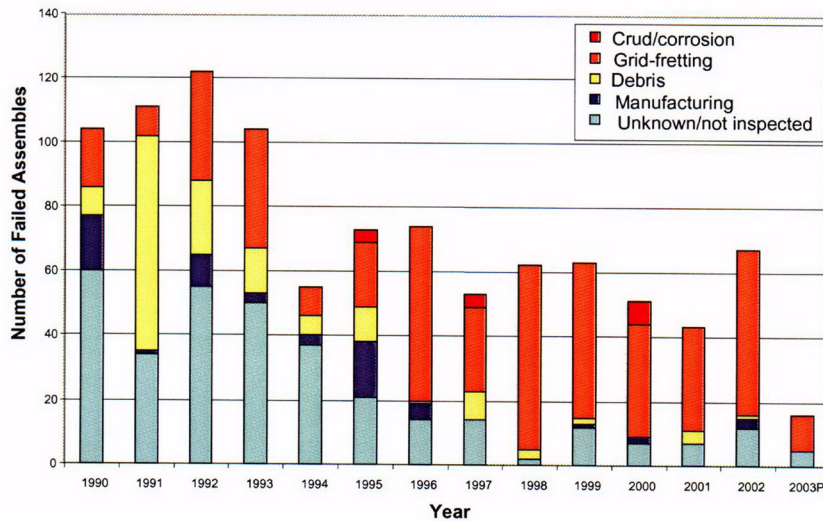
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## Trend In PWR Fuel Failure Root Causes



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## RFP Focus

- Resolve existing operation and reliability problems
  - Failure root cause investigations
    - Two hot cell shipments planned in late 2003 to identify BWR failure root causes
    - Assisted members in failure root cause investigations
  - Impact of NMCA and Zinc injection on fuel performance
    - Data indicate apparent increase in clad corrosion and crud
    - Collect data to quantify the impact
    - Work with BWRVIP and Chemistry group to issue guidelines
    - Conduct tests to identify alternatives
  - Mitigate axial offset anomalies (AOA) and crud deposits
    - Interim mitigation measures available-UT cleaning, reload core design, chemistry control, mitigation tool available (BOA code)
    - Potential solutions are being investigated

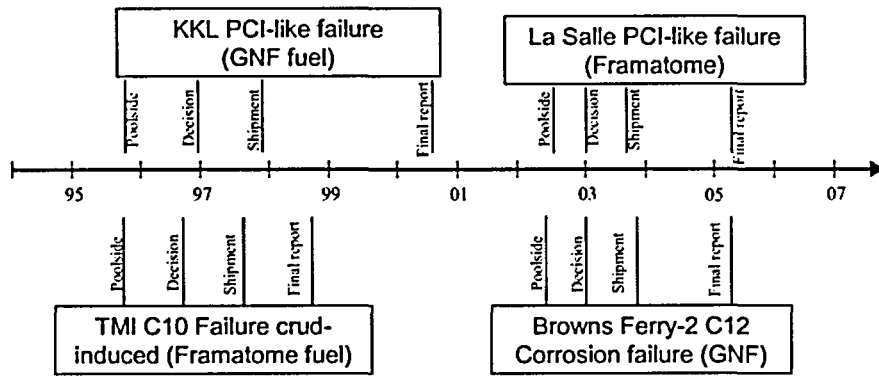
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## Hot Cell Projects To Determine Failure Root Cause



Hot cell exams have been successful in identifying failure root causes

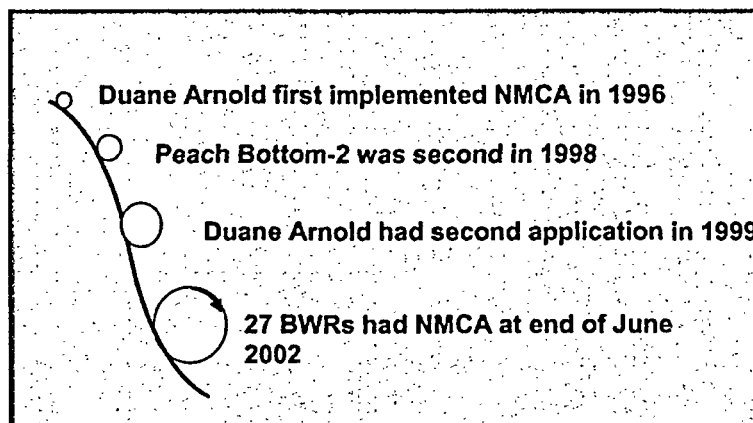
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## NMCA Implementation Status



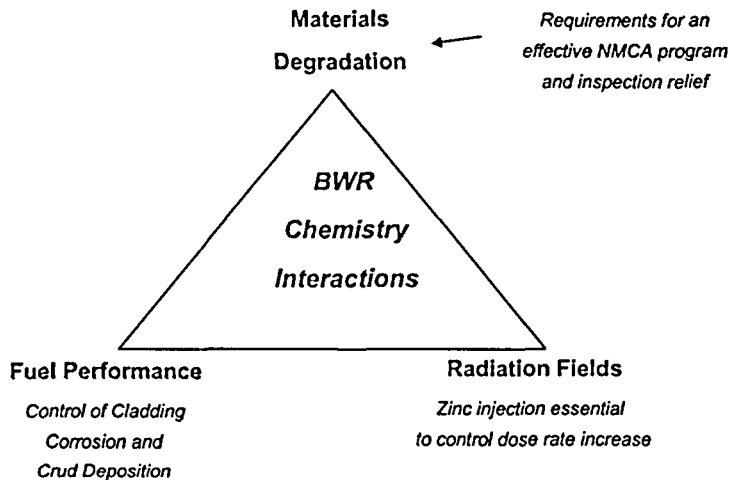
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## BWR Chemistry Optimization



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## RFP Focus (cont'd)

- Proactively collect data to ensure margins under high duty conditions
  - No data available for modern high-duty fuel
  - Minimum number and scope hot cell campaigns performed/planned
  - The data are crucial to ensure margins AND can also be used for burnup extension
- Regulatory stability
  - NRR wants improved technical basis for licenses already granted
  - RES and regulatory agencies worldwide are funding research to revise regulatory criteria for RIA & LOCA
    - RFP submitted a RIA Topical to NRC for review in 2002
    - RFP is working closely with NRC to develop the LOCA criteria for advanced high burnup fuel

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## Quantify Operating Margins By Hot cell Exams

Quantify margins of key fuel designs under prototypical and limiting conditions by examining fuel with

- Minimum time to reach practical discharge limits (i.e., achievable within 5% enrichment limit)
  - High power
  - Long cycles
- Representative water chemistry
- High temperature (PWR)

The program is designed to avoid the really big surprises!

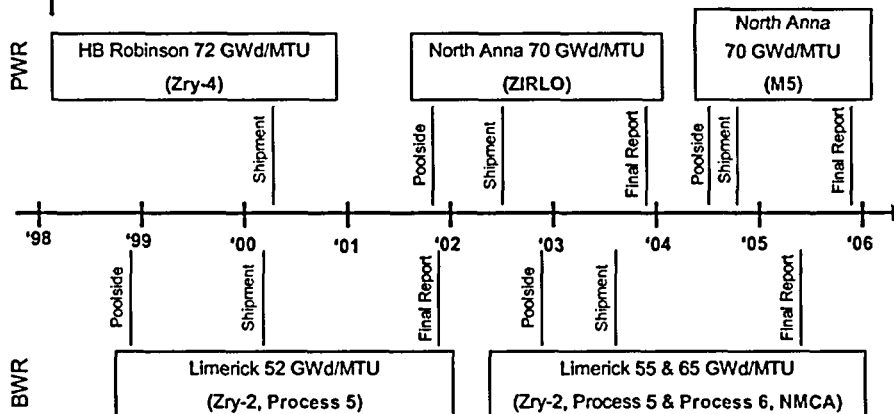
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## Hot Cell Projects To Quantify Margins



Major designs covered with minimum number of programs  
All hot cell exams complete in 2006

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## Strategies: Ultrasonic Fuel Cleaning

### PWRs that have now ultrasonically cleaned fuel:

#### Callaway

Purpose: AOA avoidance

- Callaway experienced varying degrees of AOA from Cycle 4 through 11. In combination with reducing fuel duty, CY12 was free of AOA and CY13 has had no indications through 7500 MWD/MTU

#### South Texas Project Unit 1

Purpose: AOA avoidance, allowed a reduction in fuel assembly purchases

- First cleaning performed in October 2002

#### South Texas Project Unit 2

Purpose: AOA avoidance following SG replacement & up-rate, allowed a reduction in fuel assembly purchases

- First cleaning performed in April 2003

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## Strategies: Ultrasonic Fuel Cleaning

### Next PWR planning to ultrasonically clean fuel:

#### Vogtle Unit 1

Planned Date: October 2003

Purpose: AOA avoidance (in anticipation of injecting Zn) and dose rate reduction

.....

### First BWR planning to ultrasonically clean fuel:

#### Quad Cities Unit 2

Planned Date: Spring 2004

Purpose: Dose rate reduction

- Mock-up testing taking place at Vallecitos, 16 discharged assemblies will be cleaned on a pre-trial basis in Fall 2003. Anticipate cleaning first reload assemblies in Spring 2004.

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## Mission Of WG2 (Response To Transients)

RFP WG2 is the industry's interface with NRC  
on fuel related regulatory and technical issues

### NRR

-Through NEI on regulatory and licensing issues

### RES

-MOU between EPRI and RES

>LOCA tests in ANL

>Cabri International Program

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## Three Main Regulatory Focus Areas

- **RIA**
  - Submitted RIA Topical Report on licensing criteria at high burnup (for Zr-4)
  - Participated in the Cabri International Project to confirm margins
- **LOCA**
  - Work with NRC to define appropriate LOCA limits for high burnup fuel rods
  - Tests on representative high-burnup rods and LOCA tests in Japan, France and Norway
  - LOCA response of advanced claddings (eg. Zirlo, M5)
- **Industry Guide for licensing burnup extensions**
  - Identify burnup-dependent fuel design criteria and how to demonstrate compliance at high-burnup

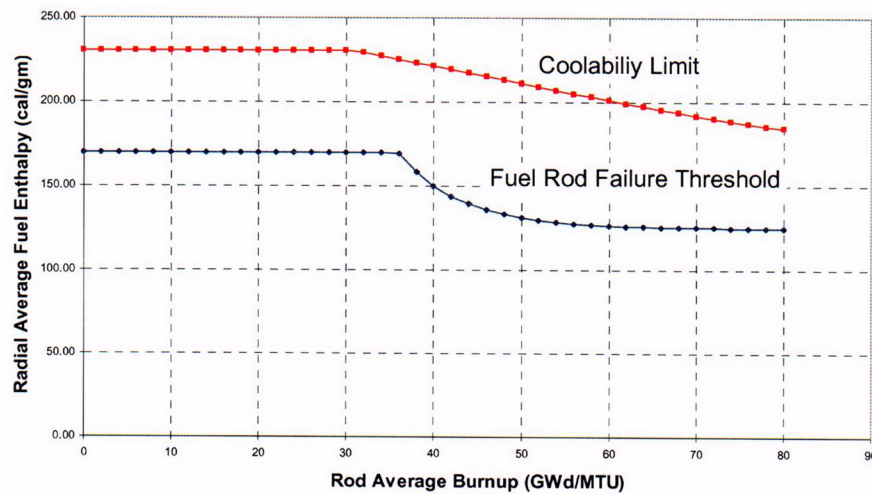
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## Proposed RIA Criteria



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## Ongoing LOCA Experimental Programs

- Four major international experimental LOCA programs
  - 1) **NRC-ANL LOCA** criteria-related tests on irradiated fuel
    - Industry collaborate closely with NRC
      - Provided Robinson and Limerick high-burnup rods and un-irradiated Zircaloy archive material from Robinson, Limerick
      - Framatome and W provided M5 and Zirlo
      - Selected tests with irradiated M5 and Zirlo
  - 2) **Separate-effects tests at EDF/CEA** in France on unirradiated & pre-hydrided Robinson and Limerick claddings (RFP funded) as well as M5 and Zr-4 to study oxidation, quench and phase transformation kinetics
  - 3) **JAERI LOCA** test program (ALPS) on irradiated fuel
  - 4) **HALDEN LOCA** tests using high burnup fuel rods

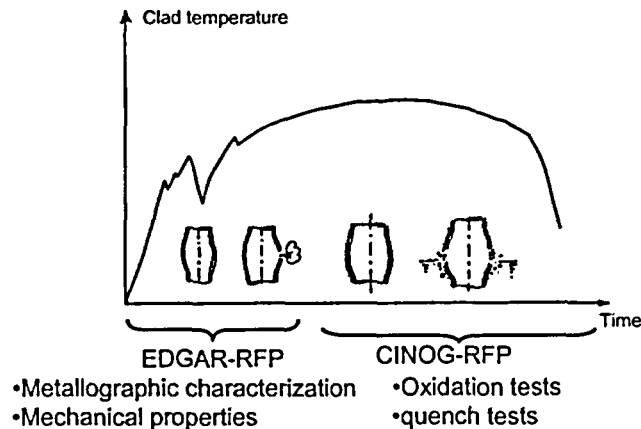
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## Separate Effects Tests- Collaboration With EdF



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## Industry Guide For Burnup Extension

- Being prepared in response to NRC's mandate for an industry-wide, consistent approach to the licensing of burnup extensions
  - 75 GWD/T rod average for PWR and 70 GWD/T for BWR
- Approach :
  - Reviewed current criteria and design limits (SRP 4.2 and non-proprietary vendor topicals) – Determined which criteria depend on burnup
  - Determine what changes (if any) are needed and what data will be required to demonstrate compliance with the new limits
- Status :
  - The draft Industry Guide is complete except for LOCA-dependent "cladding residual ductility" criterion
  - The LOCA section is being drafted by a "focus group" including utilities and vendor LOCA experts
  - To be submitted to NRC in 2004

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## Summary

- Active International participation
- Have addressed several key industry operational and technical issues and are well-positioned to obtain data to ensure margins and avoid big surprises
  - UT cleaning and AOA model & guidelines
  - NMCA data and BWR water chemistry guidelines on NMCA & Zn concentrations
  - RIA Topical report
- Robust Fuel Program is aimed to ensure
  - Reliable and efficient fuel operations
  - Industry wide collaboration to resolve safety & regulatory issues in an integrated and effective manner

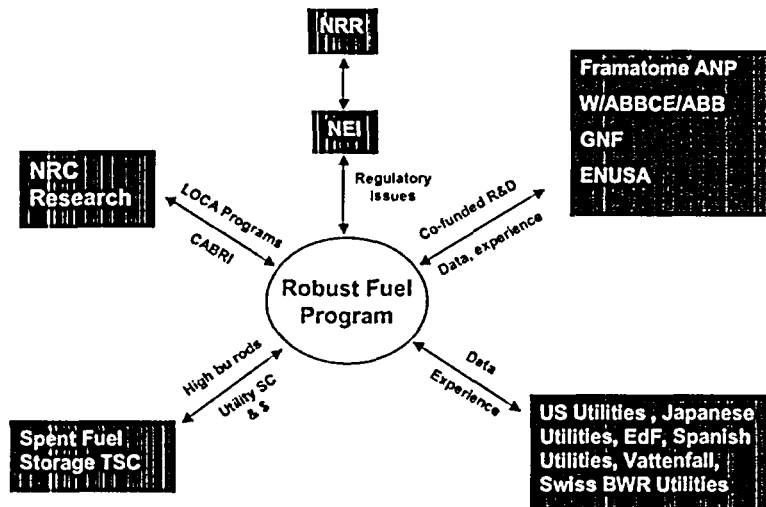
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## Industry Interactions

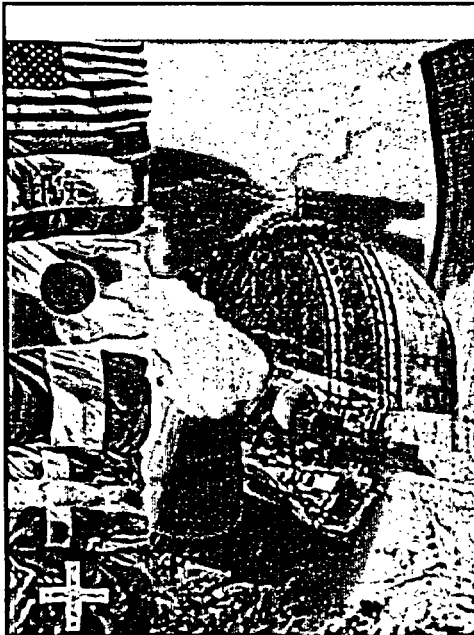


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## PWR Axial Offset Anomaly & Crud

ACRS Meeting  
Washington D.C.

September 30, 2003

J. Deshon  
EPRI

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## PRESENTATION OUTLINE

- Objectives and Focus of Working Group 1
- Background: PWR Axial Offset Anomaly
  - What is it? How is it detected?
  - History
  - Implications
- Corrosion Product Transport and Deposits
- Strategies to Reduce Crud (and avoid AOA)

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## Robust Fuel Program Working Group 1

### OBJECTIVE

Minimize the threat of the PWR Axial Offset Anomaly (AOA) through the management of core crud deposits.

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## Background: Axial Offset Anomaly

### Definitions

Axial Offset (AO) is normally defined as follows:

$$(P_t - P_b) / (P_t + P_b)$$

P<sub>t</sub> = integrated power in the top half of the core

P<sub>b</sub> = integrated power in the bottom half of the core

**Axial Offset *Anomaly* (AOA)** is a significant deviation between measured flux map power data to predicted values.

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## Background: Axial Offset Anomaly

### Definitions

For PWRs of original Combustion Engineering design and fuel, AO is referred to as **Axial Shape Index (ASI)**.

AO equals the negative ASI, or...

$$ASI = (P_b - P_t) / (P_t + P_b) = -AO$$

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## Background: Axial Offset Anomaly

- Every core design has an associated AO prediction curve. Nuclear codes such as ANC (Westinghouse) and Simulate (Studsvik) are used to predict, at various burn-ups during the cycle, what the AO should be
- On a monthly or more frequent basis, operators conduct "flux maps" using movable in-core neutron detectors and compare the data against the predicted value for the given burn-up point in the cycle
  - A few utilities have fixed in-core detectors

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## Background: Axial Offset Anomaly

Axial Offset *Anomaly* (AOA) is a significant deviation between the measured power data to the predicted values. This deviation results from a phenomenon where boron concentrates in corrosion product deposits on the upper spans of the fuel assemblies. Once sufficient boron has accumulated, measurable shifts in neutron flux occur.

In order for the reactor to maintain power, these shifts occur axially downward to the lower half of the core. It results in a more negative AO ( $P_b$  becomes greater) than predicted (designed).

Historically, a plant experiencing a core deviation of  $-3\%$  or greater between predicted and measured AO is considered to have AOA.

- However, if the unit has a core AOA of  $-3\%$ , then there are individual assemblies that will be exhibiting considerably greater deviations.

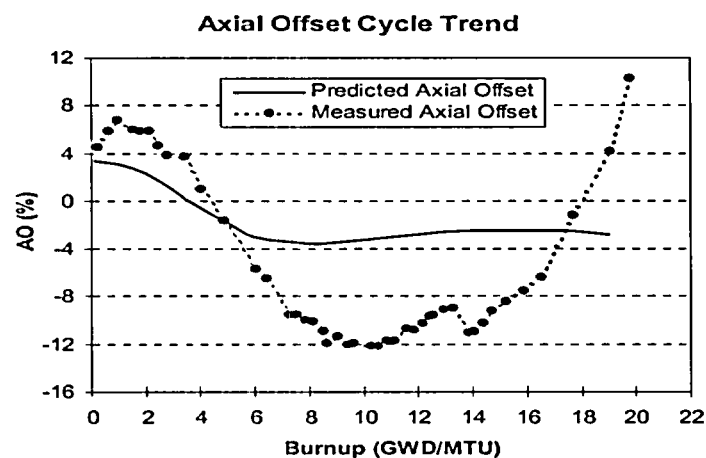
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## Background: Axial Offset Anomaly Plant Observations



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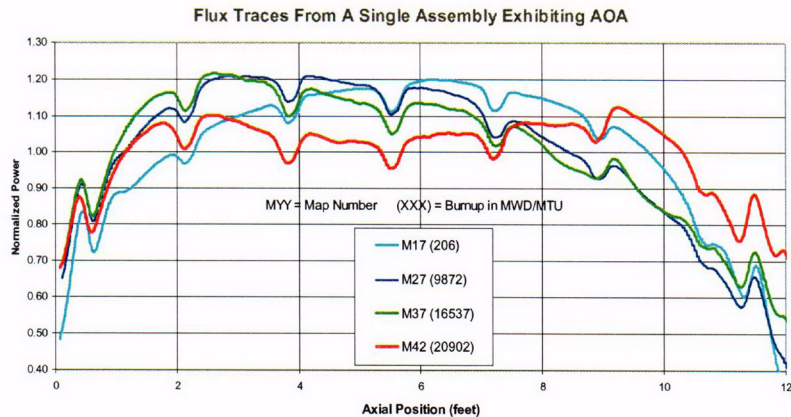
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## Background: Axial Offset Anomaly

### Plant Observations



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## Background: Axial Offset Anomaly

### History

The first documented evidence of AOA took place at a German reactor in the early '70s.

- Cause: Adequate hydrogen overpressure was not maintained allowing a persistent presence of oxygen in the system. Heavy crud deposits formed on the upper spans of the fuel assemblies.

The first domestic evidence of AOA is believed to have occurred in the late '70s.

- Cause: A large oxygen ingress into the reactor coolant was believed to have occurred causing excessive corrosion and heavy crud deposition in the core.

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## Background: Axial Offset Anomaly History

AOA didn't start becoming a common phenomenon until the '90s. Why?

To remain competitive, utilities extended their operating cycles to 18 - 24 months.

To improve fuel cycle economy and uranium utilization, these cycles required higher duty cores - with higher assembly power and higher thermal duty. In some cases, fewer assemblies were loaded for additional economic savings. This further raised the "duty" of these cores.

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## Background: Axial Offset Anomaly History

Connecting the Why to the Root Cause of AOA:

- ↑ Accompanying the transition to higher duty fuel, enhanced sub-cooled nucleate boiling in the upper spans of feed fuel became routine - resulting in more aggressive core designs.
- ↑ Circulating corrosion products deposit at the clad surface (regardless of fuel duty). The *rate* of deposition is *enhanced* in the regions of high sub-cooled nucleate boiling.
- ↑ Once a sufficient crud thickness is established, the local conditions (e.g. temperature, morphology) within the crud create an environment that allows boron to concentrate, then deposit either through a precipitation process or by adsorption.

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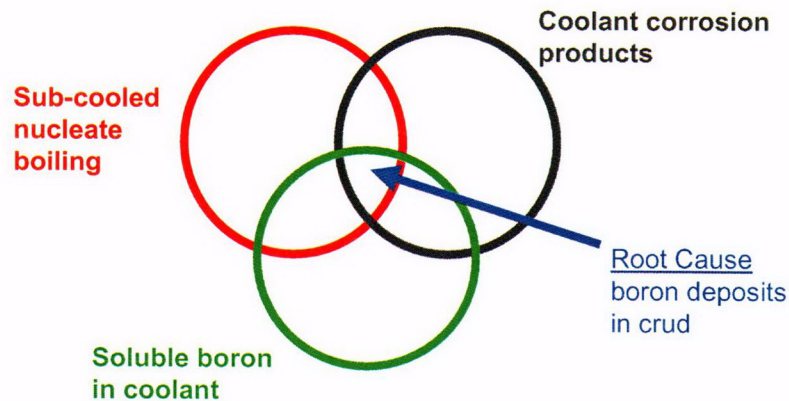
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## Background: Axial Offset Anomaly

### Root Cause of AOA



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## Background: Axial Offset Anomaly Implications

So what if a PWR encounters AOA?

### Steady-State Operations

Normal full power operations with AOA may or may not pose a challenge to plant operations depending upon the severity of AOA.

As the reactor coolant boron concentration decreases near the end of core life, and the fuel in the bottom of the core becomes significantly more depleted than that in the top of the core, the axial offset moves in the positive direction. For a severe AOA cycle, the AO may approach the positive limit and require insertion of control rods to maintain AO below the positive T.S. limit. A power coast down at end-of-life may make this situation worse as temperature in the top of the core decreases, adding positive reactivity and driving AO even more positive.

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## Background: Axial Offset Anomaly Implications

So what if a PWR encounters AOA?

### Power Transient Conditions

Depending on the severity of AOA, a down power maneuver may require deeper control rod insertion at reduced powers than previous operating experience to maintain axial offset within the control bands. In severe cases, the control rod insertion limits may be insufficient to permit operation within the axial flux difference (AFD) control bands.

During the subsequent ascension to full power, boron uptake may occur within the crud as power and sub-cooled nucleate boiling increases. When full power is achieved axial offset may be more negative than before the power maneuver.

These effects are not easy to model – making it difficult to provide Operators with accurate predictions of core behavior (response).

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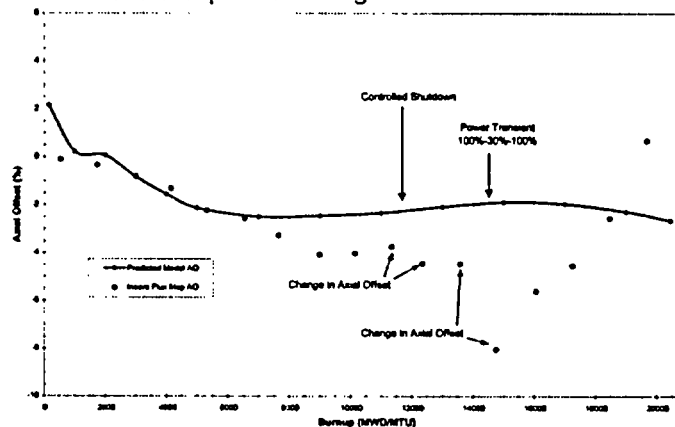
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## Background: Axial Offset Anomaly Implications

AO Response During a Power Transient



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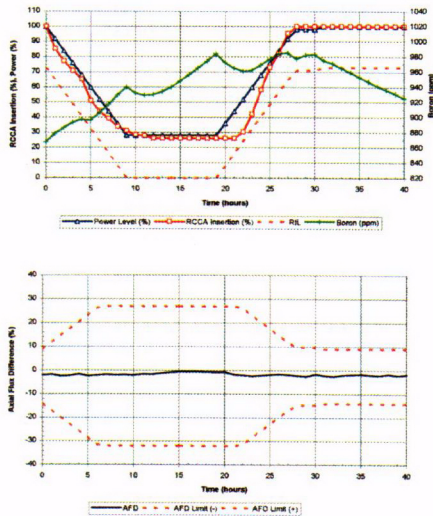
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## Background: Axial Offset Anomaly Implications



### Example of a Power Maneuver for a Plant *Without* AOA

- The initial conditions for the power maneuver are hot full power, control rods fully withdrawn near middle of cycle.
- The plant power is reduced to 28% power at a rate of 8%/hour. A 10-hour hold at 28% power is followed by a power increase at a rate of 8%/hour.
- The control rod insertion limits (RIL) and AFD operating bands are shown on the figure. In this example, the power maneuver is performed without encroaching on the AFD and RIL Technical Specifications limits.

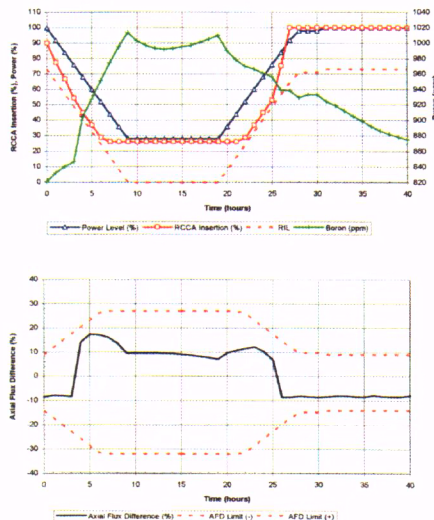
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## Background: Axial Offset Anomaly Implications



### Example of a Similar Power Maneuver for a Plant *With* AOA

- This example demonstrates the loss of operational flexibility due to the presence of AOA.
- Deeper rod insertion is required during the power transient.
- The positive side of the AFD band and RIL are nearly violated during the power reduction and subsequent power increase.
- Controlling the axial xenon or power oscillation following the return to full power is much more difficult.

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## Background: Axial Offset Anomaly Implications

So what if a PWR encounters AOA?

### Erosion of Shutdown Margin

The presence of sustained AOA in the core will impact the calculated shutdown margin.

- The bottom skewed axial power distribution results in a faster depletion of fuel in the bottom of the core relative to the top.
- Associated with this power shift is a skewing of the xenon distribution.
- During a reactor trip, boron is released from the crud in the upper spans and the core becomes more reactive at zero power (than it would w/o AOA).
- Also, the temperature redistribution at hot zero power results in a highly positive shift in neutron flux; moving the flux into the more reactive upper region of the core. This effect is magnified by the pre-trip axial distribution of xenon which will also peak in the bottom of the core after the trip.
- The net effect is some degree of shutdown margin is lost following a reactor trip as compared to operation without AOA.

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## Background: Axial Offset Anomaly Implications

Also,

- Crud played a contributing role in fuel cladding failures at three PWRs during the '90s. In these three cases, AOA was present during the cycle.
  - Note that there have been nearly 40 cases of known PWR AOA since 1990 and only in the three above cases did failures occur.
- Several PWRs that have encountered AOA have experienced uncontrolled releases of crud from fuel during shutdowns for refueling. These releases caused elevated radiation fields and occupational exposures at these units during the refuelings.

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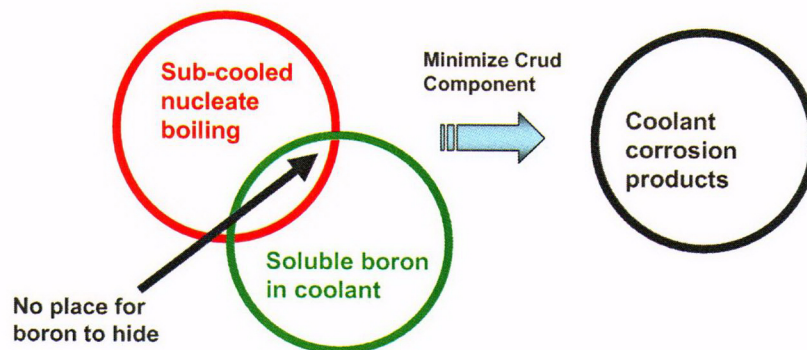
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## Working Group 1 Objective

### WG1 Mitigation Focus:



## Corrosion Product Transport and Deposits

Working Group 1 has devoted significant resources to understanding circulating corrosion products in the reactor coolant and deposits on the fuel clad. We hope to utilize this knowledge to improve our modeling capability to assess AOA risk.

### High Temperature Sampler Installations

- Catawba 1
- Diablo Canyon 1 (Zn injection unit)

### Crud Scrape Efforts

- Callaway CY9, CY10
- VC Summer CY12
- Vogtle 2 CY8 & CY9
- Vogtle 1 CY10
- Diablo Canyon 1 CY11



## Corrosion Product Transport

### High Temperature Corrosion Product Sampling

High temperature particulate samplers have been installed at two PWRs (one is a zinc injection plant) to sample circulating corrosion products at power

#### OBJECTIVES

- To gain a clearer picture of the form and chemical composition of circulating corrosion products and fuel crud without the dramatic thermal and chemical changes of normal coolant sampling.
- To better understand the transport of crud during the fuel cycle (e.g. BOC vs. EOC)

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## Corrosion Product Transport

### High Temperature Corrosion Product Sampling

The samplers have the following attributes:

- Sample lines are on continuous by-pass flow from RCS hot leg
- During sample collection, coolant stream passes through and concentrates particulates on a 0.45 or 0.2 um silver membrane filter
- Temperature at point of collection is 220 – 230 °C (430 – 445 °F)
- At the conclusion of sampling, the filter housing is isolated at temperature, drained immediately while being purged with Argon.

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## Corrosion Product Transport

### High Temperature Corrosion Product Sampling



Non Zn-Plant

#### Beginning of Cycle

- Few well-formed crystals with sharp crystal faces
- Crystal size varied greatly

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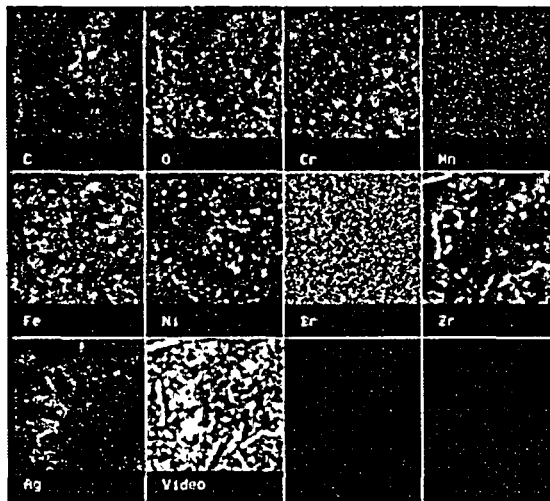
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## Corrosion Product Transport

### High Temperature Corrosion Product Sampling



Non Zn-Plant

#### Beginning-of-Cycle

- Metallic nickel wide-spread
- Cr, when present, is part of an iron oxide phase
- Zr-rich particles composed a significant fraction of sample

Elemental Mapping

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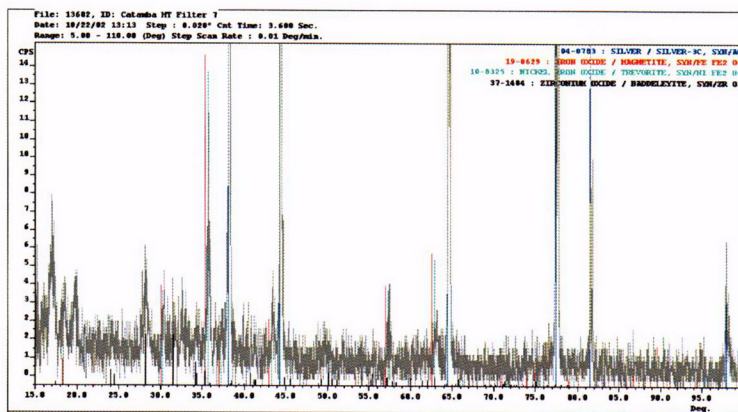
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## Corrosion Product Transport

### High Temperature Corrosion Product Sampling



Non Zn-Plant

Beginning-of-Cycle

\* Highly substituted Ni ferrite was a major phase.

\*  $ZrO_2$  was a major phase

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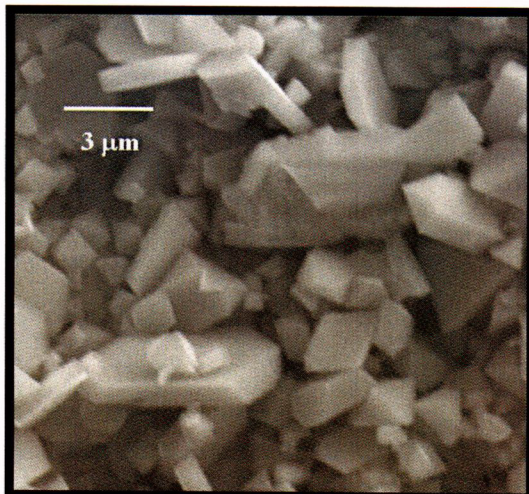
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## Corrosion Product Transport

### High Temperature Corrosion Product Sampling



Non Zn-Plant

End-of-Cycle

- Large plate-like crystals, octahedral shape similar to spinels
- Mainly nickel ferrite with low Ni
- XRD detected only nickel ferrite
- SEM suggested minor  $ZrO_2$ , metallic Ni and chromium rich oxide (see elemental maps)

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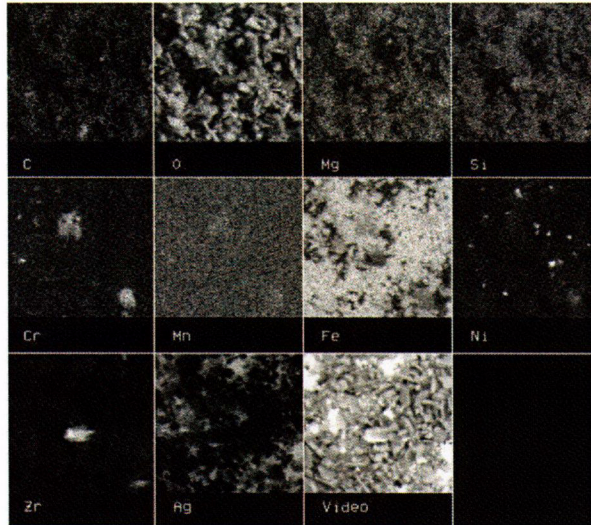
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## Corrosion Product Transport

High Temperature Corrosion Product Sampling



Non Zn-Plant  
End-of-Cycle

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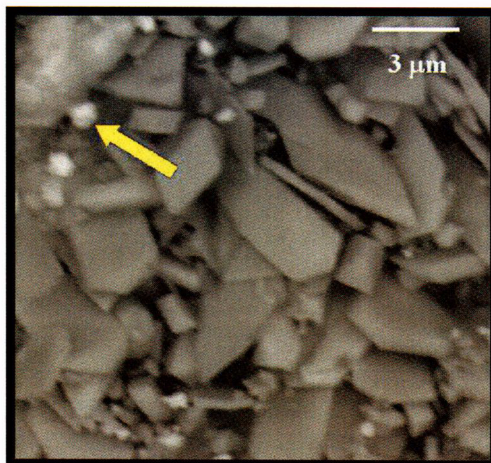
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## Corrosion Product Transport

High Temperature Corrosion Product Sampling



Non Zn-Plant  
End-of-Cycle

- Metallic nickel is common crud constituent

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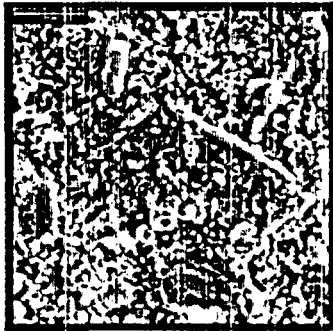


## Corrosion Product Transport

High Temperature Corrosion Product Sampling



High Ni in Ferrites More  $ZrO_2$



Low Ni in Ferrites and Less  $ZrO_2$



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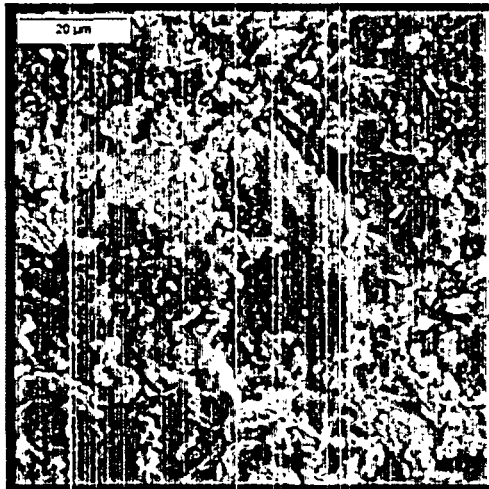
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## Corrosion Product Transport

High Temperature Corrosion Product Sampling



Zn-Plant

Middle-of-Cycle

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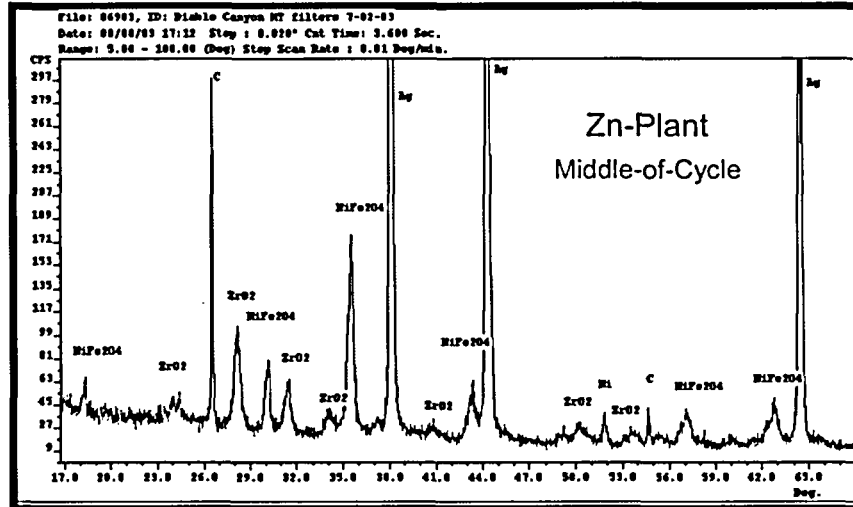
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## Corrosion Product Transport

### High Temperature Corrosion Product Sampling



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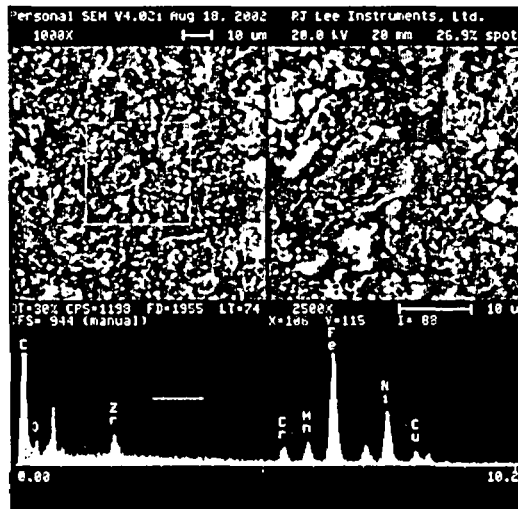
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## Corrosion Product Transport

### High Temperature Corrosion Product Sampling



Zn-Plant  
Middle-of-Cycle

Carbon is a constituent  
of circulating material –  
likely from the reduction  
of zinc acetate

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## Corrosion Product Transport

### High Temperature Corrosion Product Sampling

- Cr-Ni-Ferrites are a major component of circulating crud in the RCS
- The end-of-cycle ferrites were similar to magnetite in structure (low substitution of other elements) and had well defined crystalline structure
- The beginning-of-cycle ferrites were more highly substituted with less defined crystalline structure
- No NiO was detected in any samples (Catawba or Diablo Canyon)
- Sub-micron metallic nickel particles are an important part of RCS circulating corrosion product chemistry. These are not frequently observed in crud scrapes and may likely be responsible for much of the Ni released during a shutdown
- Zirconium oxide is a common component of circulating crud. It was found at higher concentrations in the beginning-of-cycle samples than in the end-of-cycle samples

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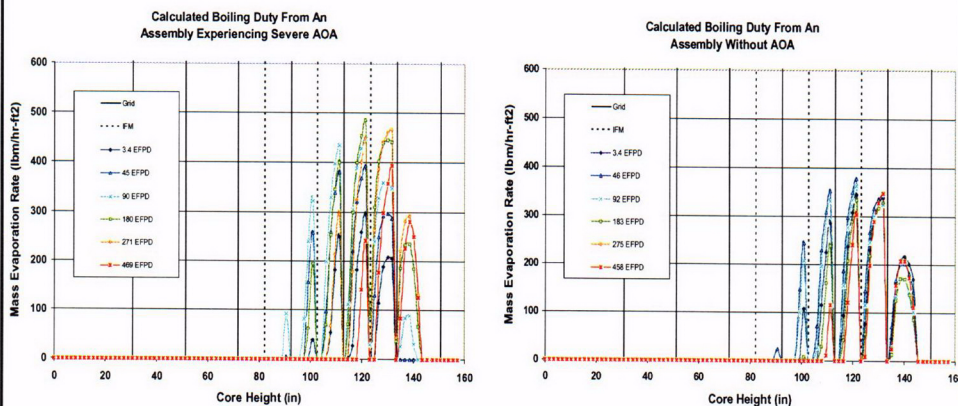
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## Fuel Corrosion Product Deposits

### Fuel Duty Comparison



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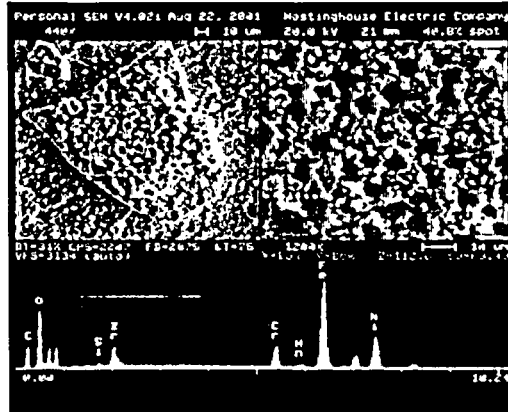
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## Fuel Corrosion Product Deposits

SEM/EDX: boiling chimneys evident from sub-cooled nucleate boiling



Crud from an assembly without AOA

- moderate - high duty
- comprised of particles
- boiling chimneys
- thickness generally <10um

Element	Wt%
O	26.9
Al	0.1
Si	0.4
Cr	5.1
Mn	0.1
Fe	40.0
Ni	22.9
Zr	4.3
Ni/Fe	0.57

Deposits from this assembly essentially Nickel Ferrite

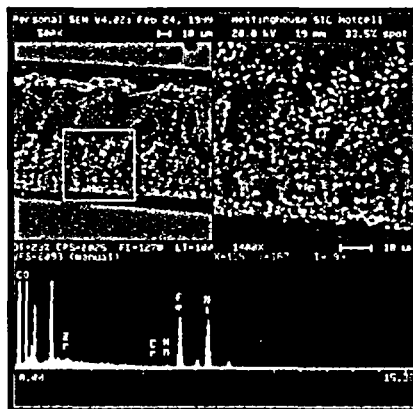
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## Fuel Corrosion Product Deposits



Cross Sectional View of Crud From an Assembly with Severe AOA (-18 %)

- Heavy crud deposits
- Flakes up to 125 microns thick.
- Dense population of boiling chimneys of variable size.
- Layered structure
- $ZrO_2$  layer approximately 25 microns from clad interface
- High Ni/Fe ratio (generally between 1.5 and 2.5)

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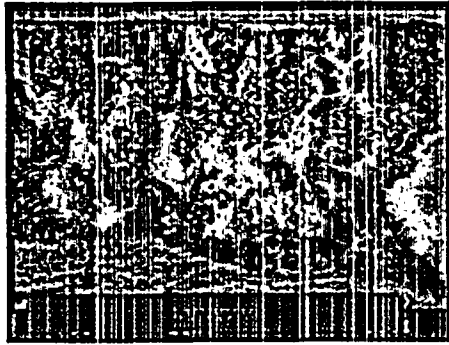
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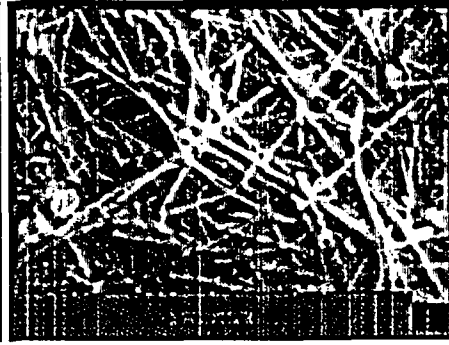
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## Fuel Corrosion Product Deposits



750X Mag



10,000X Mag

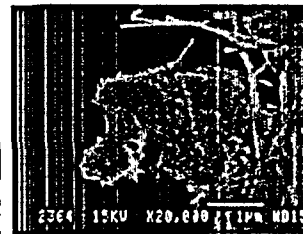
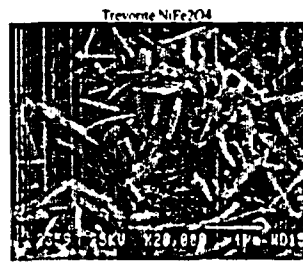
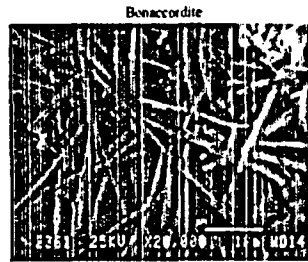
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## Fuel Corrosion Product Deposits



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## Corrosion Product Deposits

### Review of Crud From a Severe AOA Assembly:

- Bonaccordite,  $\text{Ni}_2\text{FeBO}_5$ , forms at clad - crud interface, ~50 wt%, very insoluble
- Zirconia,  $m\text{-ZrO}_2$ , found mostly between wick boiling chimneys at 20 - 50% of the crud depth from the clad surface, ~30 wt%
- Nickel Oxide,  $\text{NiO}$ , concentrated at the crud - coolant interface, ~10 wt%
- Nickel Ferrite,  $\text{NiFe}_2\text{O}_4$ , was interspersed throughout crud at ~10 wt%

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## Corrosion Product Deposits

### Crud Observations From Assemblies with Less Severe AOA

- Amount of crud is proportional to boiling (and observed AOA)
- Inventory of crud greater than 5X over non-AOA plants
- Crud is Fe-based, but Ni/Fe ratio is ~ 0.7 - 0.8

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## Corrosion Product Deposits

### General Observations of PWR Crud

- Crud mass is proportional to the degree of sub-cooled nucleate boiling
  - Since SNB doesn't start until the upper spans, crud is typically heavier in spans 5 and 6
- Ni/Fe ratio in crud from upper spans increases with rod power and boiling duty
- Porosities within crud are lower near the clad and higher near the coolant interface

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## Corrosion Product Deposits

### General Observations of PWR Crud

- Ni<sup>0</sup> is typically absent in [thicker] deposits on rods undergoing significant SNB, while Ni<sup>0</sup> has been measured in thinner deposits from low powered feed rods and from twice and thrice burned rods
- NiO is more prevalent in deposits undergoing SNB
- Thin crud has more Cr than thicker crud
- Thick crud from rods undergoing significant SNB have fully substituted nickel ferrite (Fe<sup>2+</sup> does not exist), whereas thinner crud contains partially substituted Nickel ferrite (contains both Fe<sup>2+</sup> and Fe<sup>3+</sup>) – note this information based on inference rather than direct measurement

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## Corrosion Product Deposits

### General Observations of PWR Crud

- These last four observations suggest the local environment within thick deposits from rods undergoing significant SNB are different than the bulk coolant. This local chemistry shift could be the result from either of the following:
  1. elevated pH from concentrating Li within the deposit
  2. radiolytically-produced oxidizing species formed in small but sufficient concentration to change the electrochemical potential of the deposit, and hence deposit composition
  3. a combination of #1 and #2, other possibilities

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## Strategies Available and Being Pursued to Reduce Crud (and avoid AOA)

### Crud Minimization

1. Ultrasonic Fuel Cleaning (available now)
2. Elevated and Constant pH (demonstration ongoing)
3. Zinc Addition (demonstration ongoing)
4. Enriched Boric Acid (being conducted at the Halden Research Reactor)

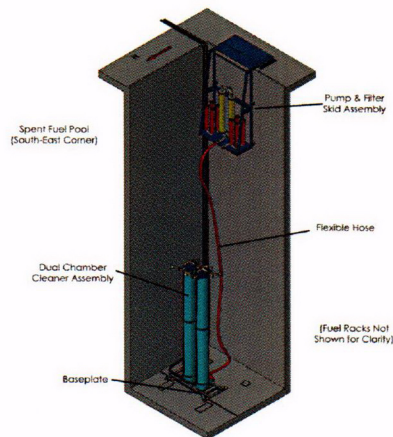
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## Strategies: Ultrasonic Fuel Cleaning



### Why Ultrasonically Clean PWR Fuel?

- Heavy deposits in AOA cores are difficult to remove via traditional shutdown chemistry evolutions
- Evidence suggests crud from reload fuel can redeposit in boiling regions of feed fuel early in cycle
- Early-cycle boron hideout (when boron concentration is high) promotes early onset of AOA and greater chance to degrade

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## Strategies: Ultrasonic Fuel Cleaning



*Before  
cleaning*



*After  
cleaning*

### Why Ultrasonically Clean PWR Fuel?

With fuel cleaning....

- Can design for higher duty on reload fuel early in cycle
- Reduce boiling-induced deposition on feed fuel
- Postpone boron hideout mechanism until later in cycle
- Help prevent elevated radiation fields and contamination events

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## Strategies: Elevated and Constant pH

### Plant Demonstration

- Crud management is the focus of this program
- The expected benefits from an AOA avoidance perspective are a reduction in source term, transport, and deposition of corrosion products at the fuel clad.
- If proven successful (no AOA, no enhanced corrosion), this may pave the way for similar applications at other PWRs

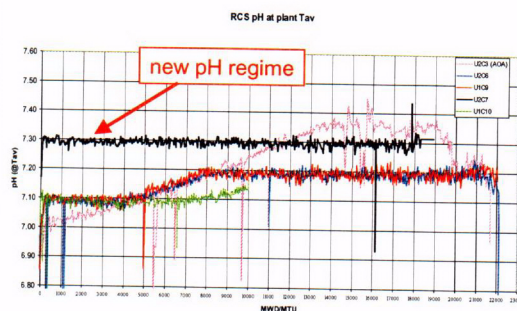
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## Strategies: Elevated and Constant pH



### Plant Demonstration:

- Baseline and two operating cycle fuel examinations are being performed: Scope includes visual and oxide measurements. May perform a 3<sup>rd</sup> cycle exam
- Initial 18 month cycle constant pH 7.3 (@Tave) started May 2002

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## Strategies: Zinc Addition

### Plant Demonstration

How does zinc addition figure as an AOA prevention strategy?

- Zinc works by modifying oxide films of stainless steel and inconel surfaces and results in more stable films.
- The end result is reduced corrosion rates and therefore less corrosion products transported in the reactor coolant.....that are available to deposit in-core.

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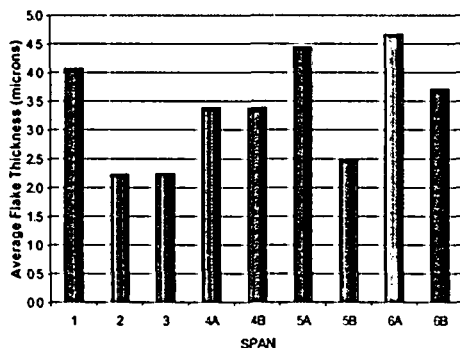
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## Strategies: Zinc Addition

Crud Thickness Measurements From a Low-Duty Zinc Plant (sponsored by RFP)



Also,

Crud deposition patterns can be significantly different in plants injecting zinc. The differences *could* be beneficial.

Recent crud scrape results from a Zn-Plant confirmed previous observations:

- Thicknesses were relatively uniform from span to span.
- Perhaps critical crud thickness can be avoided in AOA susceptible units?

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## Strategies: Zinc Addition

### Reasons for conducting a demonstration at a high-duty unit:

- Because of the high affinity to incorporate into the lattice structure of ex-core surface oxides, zinc will displace some transition metals (e.g. Ni and Fe) comprising that structure. This leads to a release of these metals into the coolant.....to potentially deposit in-core.
- While fuel surveillances conducted at PWR plants injecting zinc have indicated no adverse effect on fuel performance, none of the units have been "high-duty".

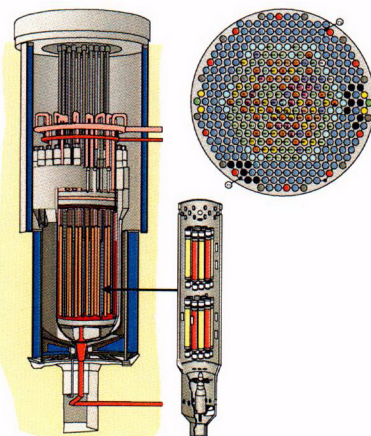
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## Strategies: Enriched Boric Acid



Tests are being conducted at the **Halden Reactor Project** to determine whether the use of EBA can avoid AOA.

Tests are being conducted in two phases:

### Phase 1 Objectives

- Deposit crud on irradiated fuel rods under proto-typical PWR conditions
- Exhibit symptoms of AOA via various in-core detector capabilities

### Phase 2 Objective

- Determine whether the use of EBA is a viable chemistry additive to reduce the chance of AOA or avoid it entirely

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## Strategies: Enriched Boric Acid

### EBA Test Motivation

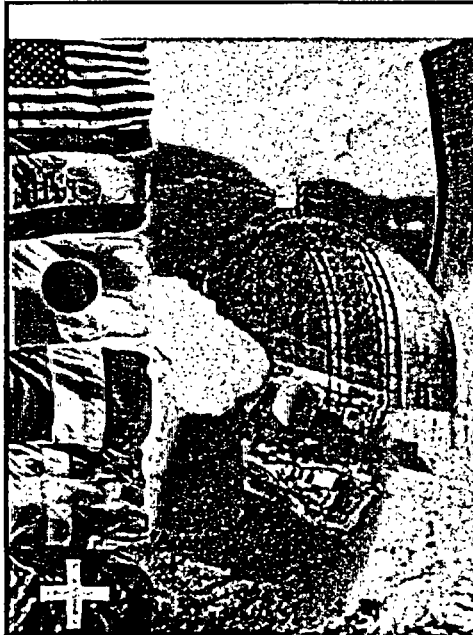
- A potential solution for the AOA problem is to reduce the bulk coolant boron concentration (and lithium).
  - Reactor coolant pH can be optimized to reduce ex-core corrosion rates,
  - Reduced coolant boron corresponds to less boron concentrated in the crud for the same fuel duty and should at least delay the onset or avoid AOA entirely

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## Industry's Position on The Need for LOCA Tests on Irradiated Fuel

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### LOCA (ECCS) Criteria

- Objective of the criteria:
  - Ensure fuel rod damage is limited during LOCA
  - Ensure coolable geometry
- Criteria established in 1973 (ECCS Rulemaking Hearings)
  - Good agreement among the industrial participants that the limit on total oxidation should be around 17%.
    - Data heavily influenced by thermal quench tests and some mechanical property tests
  - Regulatory Staff in their concluding statement compared various measures of oxidation and concluded that a 17% total oxidation limit is satisfactory (if calculated by the Baker-Just equation)
  - A maximum temperature criterion of 1204 °C (2200 °F) was established to further assure survival during thermal quench and guarantee some remaining post-quench ductility
    - Hobson's study showed that embrittlement was not just a function of the extent of oxidation, but was also related to the exposure temperature

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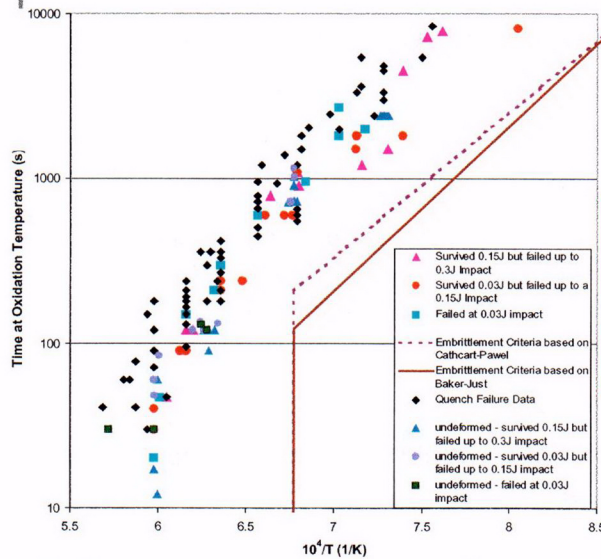
## Evolution of the LOCA Criteria

- The 1973 criteria were based on limited information
  - PCT and ECR criteria were established to incorporate conservatisms
  - AEC considered the database concerning oxidation embrittlement to be insufficient at that time
- Considerable amount of experimental evidence developed since 1973 (ANL, JAERI, INEL)
- Confirmatory Experiments conducted by Chung and Kassner in 1980
  - Series of thermal shock quench tests and impact test performed on post-quench specimens
  - Confirmed the conservatism inherent in Hobson's ring compression tests
  - Validated the conservatism of PCT and ECR limits established in 1973

## Current Basis of LOCA Criteria

- In mid-1980s, the NRC staff reviewed the large amount of data generated since the 1973 hearings
  - Concluded that sufficient data was available to assess the extent of conservatism
  - Based on thermal shock quench and post-quench impact tests NRC concluded that PCT and ECR criteria established in 1973 are sufficiently conservative
  - Summarized in: "NUREG-1230 – Compendium of ECCS Research for Realistic LOCA Analysis"
- Following staff review, 10CFR50.46 was revised based on NUREG-1230
  - PCT and ECR criteria retained (PCT:2200F, ECR:17%)
  - Allowed use of best estimate models including consideration of uncertainties in modeling
  - Provides suitably conservative basis when used with demonstrated safety margins in the cladding embrittlement criteria

## Thermal Shock and Impact Failure Data



Conservatism is evident even when best-estimate (Cathcart-Pawel) oxidation models are used to define criteria

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## Industry's Position Relative to LOCA Research Needs

Position expressed in 9/9/03 Letter (Modeen to Thadani)

- Current regulations are based on the 1988 assessment which relied on quench and impact tests.
- Impact tests on irradiated fuel are necessary to provide a tie-in to the reference for current regulation
  - Irradiated vs. unirradiated (reference)
  - Irradiated vs. pre-hydrated (unirradiated)
- Impact tests are more representative of expected post-LOCA loads

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## Industry's Position Relative to LOCA Research Needs (continued)

- Reliance on ring-compression tests is problematic
  - Qualitative results / subject to interpretation
  - No clear way to relate to the 1980's data
  - Recent use limited to inter-comparison of different material types (unirradiated)
  - Uncertainties will be introduced by defueling of high-burnup fuel for ring specimens
    - Extensive fuel-cladding bonding at high burnups
    - Impact of rigidity provided by fuel pellets in fuel rod response ignored
  - Questionable relevance to post-LOCA loads
- Propose "stakeholder" meeting to ensure appropriate input is considered