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NUCLEAR REGULATORY COMMISSION

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

THERMAL HYDRAULIC PHENOMENA SUBCOMMITTEE MEETING

NRC-RES T/H RESEARCH PERTAINING TO

PTS RULE REEVALUATION

(ACRS)

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WEDNESDAY,

JULY 18, 2001

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CORVALLIS, OREGON

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The ACRS Thermal Hydraulic Phenomena Subcommittee met at Oregon State University, Richardson Hall, Room 313, Corvallis, Oregon, at 8:15 a.m., Dr. Graham B. Wallis, chairman presiding.

COMMITTEE MEMBERS PRESENT:

GRAHAM B. WALLIS, Chairman

THOMAS S. KRESS, Member

WILLIAM J. SHACK, Member

ACRS STAFF PRESENT:

PAUL A. BOEHNERT, ACRS Engineer

JACK ROSENTHAL, U.S. NRC, RES, SMSAB

DAVID BESSETTE, RES/SMSAB

STEPHEN BAJOREK, RES/SMSAB

VIRGIL SCHROCK, ACRS Consultant

ROY WOODS, NRC RES/DRAA/PRN3

NILESH C. CHOKSHI, NRC/RES/DET/MEB

JAMES T. HAN, RES/DSARE/SMSAB

A-G-E-N-D-A

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

(8:15 a.m.)

CHAIRMAN WALLIS: This is the meeting of the Thermal Hydraulic Subcommittee of the ACRS. We're looking forward to hearing from Professor Jose Reyes and his folks.

MR. REYES: Thank you.

LOOP STAGNATION AND FLUID MIXING IN THE REACTOR VESSEL DOWNCOMER

MECHANICS FOR PRIMARY LOOP STAGNATION

MR. REYES: Yesterday we started by discussing a little bit about the overall program and we got into some of the integral test data.

Today we're going to focus more on the separate effects or the local behavior in the downcomer. So the presentations you'll see today all deal with plume mixing and our predictions of plume mixing or plume behavior in the downcomer.

And we'll also talk a little bit about the -- this is kind of the bridge presentation here -- the primary loop stagnation.

What we found was that some of the behavior in the cold leg, as affected by HPI injection, affects overall loop properties, in particular, loop stagnation.

So we've identified the different mechanisms for loop stagnation. So I will talk about -- one of our tests is an inventory-reduction test. And this is like being able to take snapshots of a small break LOCA in progress. And it's similar to some of the tests that performed the Semiscale. And I actually compared some Semiscale data to our facility just to give you a feel for where we lie in comparison for that.

But that gives an idea of as we void the plant and the steam generator tubes drain, at what inventory would stagnation occur. And it coincides with reflux condensation. So we'll look a little bit more at tube voiding then.

Also in terms of one of our tests and what we saw there, how tube draining would result in loop stagnation for us.

And then steam generator reverse heat transfer and then loop seal cooling. And I'll talk a little bit about some of the downcomer behavior we observed and how that affected the integral system.

The reason there's been so much focus on stagnation in the past is that it was identified that under stagnant loop conditions with HPSI injection, that that would most likely be the most severe case for producing cold plumes in a downcomer.

And I think today what you'll see is that we've come to a slightly different opinion for this particular plant, and we'll show you why.

So first the stepped inventory reduction test. This test was performed basically by holding the power constant. We had a constant steam generator pressure, and we opened up a small break on the reactor pressure vessel and we would drain some of the inventory. We would stop the drain, and then we would let the system go through natural circulation. And we've measured the flow rates in each of the cold legs. And we --

CHAIRMAN WALLIS: Do you have a break in the vessel?

MR. REYES: Remarkable. It's just a small little drain valve.

CHAIRMAN WALLIS: It doesn't sound like one of those standard accidents, does it?

MR. REYES: No. It's not a -- this is not a standard accident. This is a drain valve that we use for setting up the plant.

So we would continue in step-wise fashion, drain the plant. We stopped the drain. We let it reach steady-state natural circulation conditions. We go single phase and then we transition to two-phase natural circulation. And then eventually we pass a maximum and then to zero conditions.

And the same tests were performed in Semiscale back in the 19- -- late '70s, early '80s maybe -- a while ago.

MR. SCHROCK: So it's a series of steady-state tests that reduced inventory; is that basically it?

MR. REYES: That's correct.

So we start -- in this corner here, we're starting with a system completely filled or including a pressurizer, and we let it go to natural circulation conditions. And so these are the flow rates, the cold-leg flow rates that you'd see.

This is the sum of all the cold-leg flow rates is the core flow rate. And you see for this region here it's fairly flat. And what we're seeing is just single-phase natural circulation.

We transition then. As we drain our inventory on the bottom, on our x axis here, this is a percent of overall reactor coolant, the primary-loop inventory.

As we drain, we reach a knee here, an inflection point, and now we're starting to go two-phase. And we see an increase in our core flow rates. And this is measured by the flow in the cold legs.

And so what we found in this test is that loop seals play a nice role of separating -- of keeping the cold legs single-phase.

As we continued reducing our inventory, we reach a maximum. And presumably the maximum coincides with the point where you've essentially got two-phase going up the tubes and essentially all-condensed liquid coming down, or something very close to that. So that would give you your maximum flow through the core.

As we continue draining, then we start seeing a decrease in the flow. These dark triangles are steady-state points and the diamonds are actually the transient data.

And we come down further and further as we reduce -- somewhere around 60 percent of our overall primary mass we reach a point where essentially we're in reflux condensation.

And the measured flows then in the cold leg are essentially zero. So injection during this point would produce conditions similar to what's been tested in the past: Cold injection with stagnant conditions in the primary loop.

So our system was about 60 percent of the overall inventory. We want to compare that to what was done in the past with Semiscale. You can see that the trends are very, very similar. We're just a little bit offset to them. This has been normalized to the same maximum there.

We -- somewhere they both around 65 to 70 percent -- my battery's charged -- somewhere around 60 to 65 percent of the mass -- of the total inventory -- now this excludes the pressurizer liquid mass. That's why the number's different here.

Semiscale performed the test with the -- starting with their pressurizer essentially empty. So they -- all their numbers were based on the percentage of primary mass without the pressurizer inventory. So that's what's been done here. So we have very similar results for this design.

Okay. Well, that gives us an idea that if our inventory during a small break LOCA drops to about, in this case, 65 to 70 percent of the plant inventory, of our initial inventory, we would expect it to be in stagnant conditions.

MR. SCHROCK: There's an implicit assumption that the inventory distribution is the same in a steady-state reduced inventory situation as in a transient. What transient, I guess, is the question that comes to mind.

MR. REYES: That's right.

MR. SCHROCK: You have on the previous graph a lot of data points designated as transient data. What is the transient, just --

MR. REYES: Good. The --

Would you turn to the previous slide for me, please? One more.

MR. SCHROCK: The one before that.

MR. REYES: Yeah, that's it. Thanks.

So what we're designating here is -- what we were doing with these steady-state points, we were holding at one position and just repeating the measurement and coming up with an average condition. And that's how the tests were performed at Semiscale.

When we looked at our actual measurements throughout the test, as we were -- as we were draining, we saw that our drain was slow enough to where we actually could use the -- and I'm calling this the transient data, because it includes the time periods when we were actually draining the facility, so the triangles represent the step changes.

We found that the transient data in

between the step changes, because the drain was slow enough, seemed to match the steady-state data rather well.

CHAIRMAN WALLIS: So this isn't some kind of a standard transient. This is a transient that you -- you -- you -- you did --

MR. REYES: That's --

CHAIRMAN WALLIS: -- and you did it slow enough so that it was quasi-steady state?

MR. REYES: That's right. So this is -- that's exactly right. So this is --

MR. SCHROCK: A small break line on the vessel.

MR. REYES: Correct. So we're draining from a low region in the plant.

And the idea was just to see what kind of inventory behavior. So you're absolutely right. Depending on the break location, we would see different -- different behavior, different voiding of the steam generator tubes. The void distribution is important.

This is just a snapshot of a very particular controlled test or controlled small break LOCAs.

MR. SCHROCK: So your transient in this

case is -- appears to be always quasi-steady?

MR. REYES: That's right. That's right.

And originally we were just going to use the steady-state data itself to compare with Semiscale because that's how they performed their test. But as we looked at the overall data we realized that -- actually the test was performed slow enough to where we could use the transient data.

Okay. So that gave us -- at least that gave us some idea of how the loop seals were performing, and they were preventing bubbles from getting into the cold leg, and at what conditions we might expect to see some stagnation occurring.

So loop-stagnation phenomena. When we talk about loop-stagnation phenomena what we're saying is that the flow in the cold -- the flow through the loop seals and up through the cold leg is essentially zero. The flow rates are essentially zero.

You can have HPSI injection, which produces some flow. And that will produce a cold layer on the bottom of the pipe. And that concern, of course, is that the cold layer spills into the downcomer and it produces some plumes. And so you might see it like this.

CHAIRMAN WALLIS: Now again in some of the reactors the HPSI velocity is so great that the momentum will carry it to the right.

MR. REYES: Correct. Yeah. So for example for the side-injection B&W plant they have a very high injection flow rate. It's a small injection nozzle. And you'll actually jet across the pipe and impinge the other side.

CHAIRMAN WALLIS: And it swells up on the wall.

MR. REYES: That's right. So you get a tremendous mixing.

This plant, for the Palisades plant, what we found was that it was the opposite. They have a very large pipe at fairly low injection flow rates. So on a scale -- for their plant the maximum flow rate was about 300 gallons per minute per cold leg of HPI flow. So total injection flow was about 1200 gallons per minute at the maximum.

CHAIRMAN WALLIS: So it makes a big difference whether the stagnation is really zero flow, or a little bit one way, or a little bit the other way. I think that would make quite a difference since your HPI flow is so low.

MR. REYES: That's right. Yeah, our HPI flow is quite low. Yeah.

And there's a few things that we've noticed that, again, we start to couple the separate effects with the integral. And I'll show you what happens with that.

CHAIRMAN WALLIS: I presume with this Froude number criterion about whether any of it flows back, and things like that.

MR. REYES: Right. Right. So the criteria --

CHAIRMAN WALLIS: There must be some condition where all the HPI goes into the vessel. There must be enough. When there's enough flow rate in the cold leg, then all the HPI flow will go to the vessel itself. You've shown it sort of half and half, or something like that.

MR. REYES: Right. This shows spilling over this weird -- this little reactor coolant pipe lip. And for certain conditions below a certain flow rate all the flow will go towards the downcomer.

CHAIRMAN WALLIS: Does it then fill up the loop seal and --

MR. REYES: About -- for higher flow rates, you spill over and then you --

CHAIRMAN WALLIS: But then it eventually fills up the loop seal with cold fluid, and then it all comes back again, doesn't it?

MR. REYES: That's where -- that's where I was surprised.

CHAIRMAN WALLIS: Hmm?

MR. REYES: This is where the data produced a surprise for us, so I'll show you.

CHAIRMAN WALLIS: Okay. So we haven't seen the -- this is just --

MR. REYES: Yeah, you haven't --

CHAIRMAN WALLIS: -- act 1, scene 1 so far.

MR. REYES: That's right. The plot thickens.

MR. SCHROCK: It looks like the plume narrowed, though.

MR. REYES: The plume narrowed, but the plot thickened.

These are the integral system tests that we performed. And we wanted to understand a little bit about the stagnation. One stagnation would occur for these different types of integral system tests.

And so we had the -- numbers 7, 8, and 9, these were essentially small break LOCAs -- well, they are small break LOCAs. For 10 -- 11 and 12 are main steam line breaks. And then number 10, which sits right in the middle there, that was a combination, stuck-open ADV, which would be like a main steam line break, in combination with the stuck-open pressurizer safety release valve. So it's a primary side break. So it's a combination case. We wanted to see what would happen with regard to stagnation.

What we observed in those tests is that for the very small break LOCA, cold legs 1, 2, and 3 stagnated. And it stagnated because of the presence of this cold loop plug in the loop seals, so it's kind of interesting.

For Test Number 8 we saw a combination of things happening as a larger break/small break. In the previous test there was no tube voiding. In this test there was tube draining.

So in the small break, the very small break, what we found was that the HPI could keep up with the break flow. As a result we saw the tubes in the steam generator remaining full.

In the two-inch break we saw draining, so we saw a combination of effects there. Cold leg 1 and 2 stagnated because of steam generator tube voiding.

And cold leg 3 and 4 stagnated a little bit before each of the respective partners because of this cold liquid plug forming in the loop seals.

For the main steam line breaks down below, 11 and 12, we saw 2 and 4 stagnating due to a loss of steam generator heat sink, reverse heat transfer from the steam generator. But we also saw some interesting behavior here with regard to the downcomer.

The same thing with number 12 where we had the break on the other side of the plant. Cold legs 1 and 3 stagnated due to the loss of the heat sink.

The combination, stuck-open ADV and pressurizer safety relief valve, we saw 2 and 4 stagnate due to the -- because of reverse heat transfer in steam generator 2.

So we observed different mechanisms for stagnation for these different tests, which was very nice because that allows us to characterize the downcomer under different situations and plume formation.

MR. ROSENTHAL: I'm sorry.

MR. REYES: Sure.

MR. ROSENTHAL: If you would just go back one slide.

MR. REYES: Yes.

MR. ROSENTHAL: In all these cases the steam generators are full?

MR. REYES: No.

MR. ROSENTHAL: Except for 10?

MR. REYES: In all -- so Test Number 8, which was a two-inch break, in that case we did see --

MR. ROSENTHAL: I'm sorry.

MR. REYES: -- the steam generator tubes drain. In the other test --

MR. ROSENTHAL: I meant the secondary side of the steam generators.

MR. REYES: I'm sorry? The primary --

MR. ROSENTHAL: The secondary side.

MR. REYES: Oh, for the main steam line breaks the secondary sides, of course, drain for the -- for the broken steam generator. We let them drain all the way out.

Now we --

MR. ROSENTHAL: Well, I mean the feed water would keep up with the stuck-up in ADV, so these are just postulated scenarios.

MR. REYES: Correct. Correct. That's right. That's a very important point.

So some of the assumptions for the main steam line breaks we assumed that the operator continued to feed the broken steam generator for 10 minutes. And then we would adjust -- at which point they would diagnose the situation and close the --

close the feed water to the broken steam generator. And then they would work with the intact steam generator to restore the heat transfer to the system.

For most of the cases, because we had such a -- with such a -- in the main steam line break, for most of those cases because we had such a rapid cooldown, the feed-water flow and the steam flow on the intact steam generator was essentially isolated, because we just produced a very cold temperature in the core.

CHAIRMAN WALLIS: Yeah. One steam generator is quite enough to cool it down.

MR. REYES: That's -- that's right.

CHAIRMAN WALLIS: It's no problem at all.

MR. REYES: Absolutely.

Okay. So I wanted to just illustrate a little bit of what we saw. I picked the two-inch break because that had the draining of the steam generator tubes, so I wanted to show that one.

It also had the -- the case of the loop seal cooling, which resulted in stagnation. So I picked this one. It's a little bit more complicated to demonstrate, but I think it's reasonably clear, but...

CHAIRMAN WALLIS: What you mean -- you

don't mean heat transfer from the loops. You mean the cold fluid going into the loops?

MR. REYES: That's right. That's right up where I mean.

CHAIRMAN WALLIS: Because I was really puzzled when you had this had a loop seal coolant. It means that it's got cold water in it.

MR. REYES: Right. It's -- right. It's cold water mixing in the loop seal. Thanks.

So this is the behavior inside the steam generator tubes for the two-inch break case. And what we see is that this is -- we have a set of level measurements, they're just DP cells in -- attached to the long tubes, another set attached to the shorter tubes. So we have the maximum and the minimum basically for those and, as far as we can observe, the draining in both of those, in both cases.

What we do see, and this is an area of interest to us with regards to RELAP, is that the tubes, first of all, they drain at different rates, at different times. And that's what you'd expect.

What it does -- what it does mean, though, is that if you're modeling in RELAP with a single tube, the question comes up, well, which tube are you modeling. Is it some average tube, or how does that work.

So that's kind of interest to us because as long as these short tubes are filled, you still see flow in your primary loop. So there's a range here from about 1500 seconds all the way out to, oh, maybe about 3,000 seconds that you still see some flow --

CHAIRMAN WALLIS: Excuse me. Long tubes, short tubes? There's some long tubes out here and some short tubes in here, or something.

MR. REYES: That's correct. Yes. Long tubes go all the way to the top of the steam generator tube bundle and short tubes are the inner circle, the inner tubes.

CHAIRMAN WALLIS: And you're scaling the way a typical steam generator is in terms of the ratio of the lengths, are you, or is it exaggerated in your facility?

MR. REYES: So our facility, it's about -- the length ratio is constant. It's about 1 to 3.5. So all of our lengths about 1 to 3.5 in the steam generator.

So we're actually a little long compared to -- compared to Palisades -- compared to our normal one-fourth scale.

So that's what we see there. We see this draining really begins somewhere around 1500 seconds or a little bit earlier on the long tubes. But we still see flow in the primary loop. And then we continue to see flow until the shorter tubes start to drain.

MR. BESSETTE: You see the same sort of thing in ROSA at full height. Roughly, basically the same.

CHAIRMAN WALLIS: It means that in RELAP they might be useful to bundle the tubes.

MR. BESSETTE: In RELAP typically the generators model a single tube.

CHAIRMAN WALLIS: Yeah, but that's --

MR. BESSETTE: We have done sensi- --

CHAIRMAN WALLIS: We miss that effect altogether.

MR. REYES: Yeah. We have done sensitivity studies where we model three tubes, or whatever.

MR. BAJOREK: It depends on the sequence.

MR. REYES: So here's a look at the cold-leg flow rates. And looking at cold leg number 2 and cold leg number 4 as a function of time for this test.

And here I've identified when steam

generator tubes and the long tubes begin to drain, at the very onset of draining the tubes. And then -- so these are the two different flow rates. The one on the bottom here, which comes along and -- they match pretty well for this initial portion of the transient. And then we see they kind of split off here. The cold leg number 4, that goes to zero.

Cold leg number 2 experiences a small increase and then continues to decrease down.

What's happening --

CHAIRMAN WALLIS: Where exactly are you measuring this flow rate?

MR. REYES: These are being measured in the cold legs.

CHAIRMAN WALLIS: Yeah, but where?

MR. REYES: Oh, so these are just after the injection location.

Is that right, John?

MR. GROOME: Yeah. They're right after the high-pressure injection --

CHAIRMAN WALLIS: You mean they're upstream?

MR. GROOME: -- before the reactor vessel.

CHAIRMAN WALLIS: Oh, they're on the side of the vessel.

MR. REYES: Right.

CHAIRMAN WALLIS: So --

MR. GROOME: They're on the downstream side of the loop seal.

CHAIRMAN WALLIS: Yeah, but which side of the injection point are they?

MR. REYES: So they sit --

MR. BESSETTE: The vessel side.

CHAIRMAN WALLIS: They're between the injection and the vessel.

MR. REYES: Right.

CHAIRMAN WALLIS: So you could have zero flow in the cold leg, and then you would just pick up the injected flow --

MR. REYES: We would pick up some injected flow.

CHAIRMAN WALLIS: -- which would be about one gpm somewhere.

MR. REYES: Right. And then we have a separate flow meter measuring our injection flow rate also. So we know at all times how to --

CHAIRMAN WALLIS: When you say this goes to zero, if you actually had injection --

MR. REYES: Injection flow.

CHAIRMAN WALLIS: -- it could be zero in

the cold -- in loop seal and then it would be the injection flow where you're measuring it.

MR. REYES: That's right. That's right. Yeah, we haven't subtracted those out.

CHAIRMAN WALLIS: Is that why it bottoms out at one instead of zero?

MR. REYES: At one, yeah. That's right. That's right.

So what we saw happening here, we were interested in how this flow was splitting. We expected that as the tubes drained, the flow in the primary loop would just continue to drop.

Because we're draining 133 tubes, it just kind of goes in a fairly well-behaved manner towards zero. But we saw the split here, and we were curious about how -- what was happening there.

And so what we observed was that this Weir wall, there was spillover over the weir wall, this reactor coolant pump lip. And the cold water would create a plume basically and fall into the loop seal.

And now you're producing a very cold loop seal. So the next figure here shows that, illustrates that. So here both loop seals are warm, both for number 4 and number 2.

When we get to this -- that point, that

transition point there, the 1500 seconds or so, and we see that -- for the cold leg 4 we see some of the plume spilling over into the loop seal and starting to cool that off. And that corresponds exactly with the time that we see that split.

So the loop seal forms -- it's basically a cold-liquid plug which resists -- that gravity head there resists the fairly low flow of the loop. And the flow is diverted then to the other cold leg.

Through the common lower plenum of the steam generator, the flow is diverted to cold leg number 2. And so we see an increase in the flow rate there and a zero flow in cold leg 4.

CHAIRMAN WALLIS: Did you get any kind of loop seal blowout with these cold plugs being blown out at some stage?

MR. REYES: We'll have to look at some of the other tests to see.

CHAIRMAN WALLIS: That might not be too good for the reactor vessel, blew out a plug of cold water.

MR. REYES: If it put out some cold water.

MR. BESSETTE: You need larger breaks to get a loop seal clearing basically in this.

CHAIRMAN WALLIS: You need a larger break for that to happen?

MR. BESSETTE: Yeah, to create loop seals.

MR. ROSENTHAL: I'm not sure that the vessel, given its mass, would even notice a slug.

MR. BESSETTE: Plus you've got to put the break into the cold.

CHAIRMAN WALLIS: Well, it's a question of local cooling, isn't it, and --

MR. BESSETTE: You've also got to put the break in the cold leg. This was a hot leg break.

MR. REYES: Yeah, the thought was if --

CHAIRMAN WALLIS: It was just a thought, I mean. While we're thinking about it, it's sort of like the boron-dilution problem where you've got a slug of something that comes in.

MR. SCHROCK: In the previous diagram you have certain events highlighted, number 2, long tubes begin to drain.

MR. REYES: Yeah.

MR. SCHROCK: Is that something that you see from these traces, or that's just pointing out that this is observed from other evidence at those times?

MR. REYES: This was what was observed from other evidence.

CHAIRMAN WALLIS: What's the big hiccup at about 1100 seconds?

MR. REYES: We know that the initial steam generator tube draining does result in an increase in flow, so we're draining those tubes and they're draining into the cold-leg side and to the hot-leg side. And we expect to see some increase in flow rate. I would suspect that's related to that.

CHAIRMAN WALLIS: Yeah. But how do you --

MR. REYES: And we don't see it in the other one, so --

CHAIRMAN WALLIS: You need to blow-up the scale to see for how long it stayed at zero at around 1100 seconds, if it did. You know you can't see it in here. Eleven hundred seconds is a big hiccup.

MR. REYES: Oh, this -- this spike right here you see. Yeah.

CHAIRMAN WALLIS: Yeah, it goes down to zero, is the point.

MR. REYES: Right. Now the -- these magnetic flow meters, they're very sensitive to voiding. If you have a bubble through the line and it goes past the instrument terminals, you might see a spike like that.

However, I tend to think this might be a real -- we'll look at that a little bit closer. This might be a real...

So what we see is the creation of this cold-liquid plug in the loop seals and the flow being preferentially diverted to the -- through the steam generator lower plenum to the other flowing leg with the warm loop seal.

Later today we're going to show you how this works. We'll take -- when we go to the lab we're going to run this experiment for you. Here we have the -- this Weir wall.

Imagine in the plant that this whole elbow here would be the pump and this would be the outlet of the pump. And you can see that it acts effectively as a dam which keeps the cold water on the reactor vessel side.

Eventually you will spill over, and you will go into this loop seal, and you'll cool it off. We'll show you that phenomena.

CHAIRMAN WALLIS: Now RELAP has great trouble trying to predict that, doesn't it?

MR. REYES: Excuse me?

CHAIRMAN WALLIS: Doesn't RELAP have great trouble trying to predict that, that sort of phenomenon?

MR. REYES: I would say that there's no way.

CHAIRMAN WALLIS: But you can still run RELAP.

MR. REYES: That's right. And I think what we saw in this test with the RELAP calculation is that it did predict reasonably well the steam generator tube voiding on some average basis.

And so it was in the ballpark. But as far as the sequence of -- the timing and the exact sequence, probably would miss. It can't --

CHAIRMAN WALLIS: It just mixes --

MR. REYES: -- it can't calculate this.

CHAIRMAN WALLIS: It just mixes everything, doesn't it?

MR. REYES: Yeah.

We're looking at that, though, to see what RELAP is predicting as a loop seal temperature during the trading and comparing it to what we saw.

So you'll see that test a little bit later. Chris Linrud and Ian Davis are here to do that for us.

Okay. So we saw steam generator tube voiding as a stagnation mechanism. We saw this cold loop seal plug as another stagnation mechanism.

The third one that we observed was this reverse heat transfer. And that's when the steam generator and the main steam line break, we blow that steam generator down on one side. The other intact steam generator is bottled up and becomes a heat source eventually.

And so you see in this schematic here, this is for Test Number 12, a main steam line break at full power. We have steam generator temperature and the hot-leg temperature. We see initially the hot-leg temperature is greater than the steam generator temperature.

As we go through the blowdown, of course, we drop that hot-leg temperature well below the steam generator temperature. And we see stagnation of cold legs 1 and 3 occurring within this band right here. So it doesn't occur immediately. There's a band that -- there's a delay time and then a band. And we were curious about that.

Now later on what we see is the -- as the primary plant reheats and repressurizes, our temperature goes up above the steam generator temperature. And we see a resumption in the cold leg 1 and 3 flow. So it works as expected. And again we see that occurs relatively close to when we cross that

-- when we made that transition.

We were -- and that's to be expected. What we were curious about was this little delay here and what might be causing that. Here's looking at the, again, cold-leg flow rates for 1 and 3. And you can see that we start off with our pumps on, come way down. We go to zero, essentially zero flow for the flow meter.

Come -- and we resume our -- this steam generator is a heat source. And here the steam generator is a heat sink again. And we come back to our flow intake.

CHAIRMAN WALLIS: What does negative flow in the cold leg flow area mean?

MR. REYES: Negative flow, I don't think we're seeing negative flow in this. It's just the --

CHAIRMAN WALLIS: Isn't that what it says?

MR. REYES: It certainly does, but I think we're just zeroed. We're a little bit off in our zero.

This flow meter is -- I'll ask John Groome to tell me the range for that flow meter on the test.

Do you remember this one?

We've been struggling with memory lately, myself.

MR. GROOME: Yeah, I'm sure my memory's not any longer than yours though, Jose, so I don't know if I'll be able to answer the question, but my name's John Groome.

And these flow meters are ranged positive to negative 100 gallons per minute. And, you know, there's some interpretation that you have to do with all data.

And I'm of the same opinion as Jose, that's just a zero shift there on that second meter. And that could be not just due to the meter. It could be due to the actual estimate loop that carries the signal back to the data acquisition, so...

CHAIRMAN WALLIS: You really need a more sensitive flow meter because you're talking about low flows in the order of one gallon per minute.

MR. GROOME: Yeah. And, you know, these flow meters are actually quite phenomenal. When we first worked with Westinghouse back in the early '90s we couldn't measure flow in our cold legs. And so part of the problem was our temperature and pressure.

And so we actually worked with them to develop a new flow meter to -- that we put a flow meter in to test, at about $4,000 a test we'd break a flow meter. And so these flow meters have been in for about going on three and a half years, and they've worked for three and a half years successfully.

And, you know, this is a meter that's capable of flow ranges up to about 700 to 800 gallons a minute. So when you're down here looking at zero and you're nitpicking about a gallon-per-minute flow, I think you ought to be happy you have any data.

CHAIRMAN WALLIS: Well, how does a flow meter work when you have, say, a stratified countercurrent flow? Does it --

MR. GROOME: Well, it's a void average. Unfortunately, it measures in gallons per minute. But it's a void average flow, a volume-average flow.

CHAIRMAN WALLIS: So it has -- does a -- is it slices, or something, or --

MR. GROOME: No. It actually has just two, and I can show you some flow meters today if you'd like, but it just has two contact points in the middle. So it assumes that the velocity profile through the -- through this bore of the flow meter is constant.

CHAIRMAN WALLIS: Well, that's very difficult if you've got a countercurrent flow, with cold water going one way and hot the other, --

MR. GROOME: Sure.

CHAIRMAN WALLIS: -- it must get very confused.

MR. GROOME: Sure. And that could be what's happening.

CHAIRMAN WALLIS: So it might well give you a faulty reading.

MR. GROOME: Right. Right.

MR. REYES: Sure. Sure. Yeah.

Thanks, John.

CHAIRMAN WALLIS: So it just measures at one point essentially?

MR. GROOME: Correct.

CHAIRMAN WALLIS: And then assumes a velocity profile?

MR. GROOME: Correct.

CHAIRMAN WALLIS: Oh.

MR. REYES: So reduce the stagnation occurring and then resumption.

CHAIRMAN WALLIS: So what it's measuring is the velocity at the point where it measures what it calls flow. That's what it's really doing.

John, it's --

MR. GROOME: Excuse me?

CHAIRMAN WALLIS: It's really just measuring the velocity at the point where it measures.

MR. GROOME: Correct.

CHAIRMAN WALLIS: And then from that it tries to predict the flow.

MR. GROOME: Right. In those -- in those areas --

CHAIRMAN WALLIS: And if it has an S-shape velocity profile, it's going to go --

MR. GROOME: It doesn't -- it doesn't know how to calculate that, right.

CHAIRMAN WALLIS: But it still knows to calculate the local velocity. That's what you --

MR. GROOME: Right. So it measures essentially a velocity and it knows the area.

CHAIRMAN WALLIS: So you might actually try looking at that velocity and recasting it in terms of what's actually happening in the pipe and getting a better sen- --

MR. REYES: And try to get the better, yeah. Yeah.

MR. SCHROCK: Is it in the proximity of the bend? Most everything is.

CHAIRMAN WALLIS: Everything is, yeah.

MR. REYES: How many -- how many *l* over *d*s, John, from -- did we require for the --

MR. GROOME: It's -- *l* over *d*s, yeah, it's right there on the bend. It's maybe like 2 *d*. Actually I have a slide if you'd want to go back and pull it up and we could actually look at a plan view of it. But it's maybe like one and a half *d* from the bend.

But that's fortunate for magnetic flow meters to have the, you know, the least-required *l* over *d* for flow measurement, or typically anywhere from 1 to 5 *d*.

MR. REYES: Okay. So what we saw then was loop stagnation due to the steam generator, one of the steam generators becoming a heat source instead of heat sink. But there was a delay, and we were curious about that. So we investigated a little bit further.

And what we realized was that we're injecting cold water to downcomer. And so we're cooling off the downcomer. Of course, we have core heat. And so we are creating a density difference in the driving head. So the downcomer driving head, because the system is completely liquid filled, is still driving the flow.

And so what's happening is that the reverse-heat transfer from the steam generator is acting like a break. It's resisting the positive flow, but it's not able to stop the flow. And so that's why we see a continued natural circulation for that period of time.

Eventually we get to a large enough delta T on the steam generator where it is able to overcome the driving head produced by the downcomer injection. So you do have a downcomer recirculation.

That was -- that plays an important part when you're working -- when you're looking at an integral system injection. Because what that means is even when you have "stagnant conditions," as soon as you begin injecting, if you have any core heat, you will create some natural circulation flow. And so you -- by virtue of injecting you're producing a natural circulation flow. So it's kind of --

CHAIRMAN WALLIS: As long as the injection goes the right way.

MR. REYES: That's right, into the downcomer. That's right.

Okay. So we observed those phenomena.

Steam generator tube voiding. That should be the loop -- the cold-liquid plug --

CHAIRMAN WALLIS: If the steam generator wins over the downcomer, then presumably the flow goes the other way, if that's possible.

MR. REYES: The resistance is pretty large in the other direction.

CHAIRMAN WALLIS: I was thinking of the buoyancy. You're saying the buoyancy in the steam generator counteracts the buoyancy in the downcomer.

MR. REYES: Right.

CHAIRMAN WALLIS: Presumably there's a situation where the steam generator could win and the flow could go the other way. Don't pull that cold stuff into the loop seal, --

MR. REYES: Well, I think --

CHAIRMAN WALLIS: -- ready to come back again.

MR. REYES: I think what -- of course, the top of the plant will just get real hot and stay hot and the cold water will stay on the bottom, so...

Okay. So we identified three modes of loop stagnation, which we were interested in understanding for integral tests.

One of them, the loop seal, the cold plug in the loop seal actually is tied to a local phenomenon, which I thought was one of the key findings as far as relating our separate effects test to the integral system test.

The other thing was the presence of this RCP Weir wall. That really does delay the loop seal, the formation of a cold-liquid plug in the loop seal. And hence it delays stagnation in the loops.

So if we didn't have that Weir wall we would have expected possibly to have stagnated a bit earlier, because we would have formed cold plugs in the loop seals. So that's kind of an interesting result. So having them actually delays stagnation.

MR. SCHROCK: Isn't that Weir an attempt at simulating the real plant?

MR. REYES: That's right, yeah.

MR. SCHROCK: And so how do you judge the quality of that simulation?

MR. REYES: Right. Now at this point all we can do is use our, in this case, CFD Codes to see if we can, first of all, benchmark the CFD Code against our test.

And then have a little bit of confidence then that we can go forward and try to do a more accurate model of the real plant.

Now in talking to the folks at Palisades, they do indicate to us -- I mean they gave us the dimension of this lip. And they have indicated to us that, in fact, when they are draining, trying to drain the cold legs they can't drain it completely because of this lip. So we know it's an effect.

The other thing that it does cause -- that we do observe is that the presence of that Weir wall also, with side injection, we're going to see a lot of stratification.

The plume doesn't come in from the top of the pipe and then mix on the way down. So typically the flow is going to be in the positive direction, because it's not mixing on the way down, and you've got this wall, this dam on the other side which, in essence, is driving all the flow towards the downcomer up to a certain point.

We said that reverse-heat transfer can either -- it can reduce or stop the primary loop natural circulation, depending on the available downcomer fluid driving head.

Okay. So that's what we saw in the area of loop stagnation.

CHAIRMAN WALLIS: What are your scaling laws now? I would think that you have some scaling laws for your loop.

MR. REYES: Correct.

CHAIRMAN WALLIS: And then I would think that some sort of Froude numbers scale these, whether it goes over the Weir and the stratification.

MR. REYES: That's right.

CHAIRMAN WALLIS: Is that consistent with your scaling of other things like velocities and dimensions?

MR. REYES: Yes.

CHAIRMAN WALLIS: It is?

MR. REYES: Yes. And so what we're doing now is -- we have run a preliminary series. And we're going to run several just to be sure. We're going to identify the conditions for the onset of the loop seal spillover, which is a very nice project for any volunteering students.

It's a very straightforward effort. And we know basically what the dimension of those groups should be. And I think we can do a good job on that one. So we're gathering that data right now.

MR. BAJOREK: Jose, your pump is down at the bottom --

MR. REYES: Our pump is at the bottom of the --

MR. BAJOREK: -- of the loop seal as opposed to up at the top.

MR. REYES: Correct.

MR. BAJOREK: Are there any additional restrictions in a regular PWR pump lower than the Weir that a positive steam flow through the loop would prevent some of that liquid coming back over the Weir and delaying the cooling?

MR. REYES: Now we're talking steam flow?

MR. BAJOREK: Yes.

MR. REYES: There was a schematic that John had showed us yesterday, and it's a fairly short -- what it is it's kind of a relatively flat --

MR. BAJOREK: Impeller.

MR. REYES: -- impeller with -- in a volute. Okay. I was looking for the right word, a volute. So if that comes -- your cold leg comes out at this angle, and then you've got this -- a short drop and then to the loop seal.

So I don't think there's anything other than the impeller itself that would hinder the steam from getting up there and going out. Is that -- I'm not sure if I understand.

So you're going to have -- you're going to have -- the steam will come in, and if there's water on the bottom of the cold leg, it's basically just a stagnant pool almost, except for right at the surface.

Okay. Now we'll talk a little bit about -- if there's no other questions on stagnation. Again, the reason we looked at stagnation so heavily was because in previous studies the thought was, well, if the primary -- if the cold legs are stagnant, then injection under those conditions would essentially be the worst plume conditions. Okay. As we continued with our study we saw that we came to a different conclusion.

COLD LEG THERMAL STRATIFICATION AND

PLUME FORMATION IN APEX-CE

MR. REYES: So I'll talk a little bit about cold leg thermal stratification first, and then we'll talk about the plume behavior in the downcomer.

Okay. We did these flow visualization tests, which were really very helpful. We started by just doing a series of tests in APEX at pressure and temperature. And we were measuring our -- we had our thermocouple rake in there.

We were seeing constantly that we had cold temperatures at the bottom for most of the flow rates that we generated, the cold-leg flow rates. And we were curious then what was going on. So we built this very simple flow visualization test that allows us to take a look at the similar Froude number conditions, what might be going on in the pipe. And we --

CHAIRMAN WALLIS: This is green salty water; is that what it is?

MR. REYES: That's green salty water. So

we're injecting -- we're using sodium fluorescein to actually give us that green color. And if you hit it with ultraviolet light you get a very bright image with that.

So we've put sodium fluorescein in our salty water. And we're using that to represent our cold injection.

The pipe is initially filled with fresh water. And that whole tank actually is filled with fresh water initially.

So we begin our injection, and this is the type of behavior that we see.

CHAIRMAN WALLIS: Where is the injection here?

MR. REYES: I lost my mouse. Oh, here it is. Thank you. So --

CHAIRMAN WALLIS: It's the pipe that we can't see, which is there?

MR. REYES: Yeah, that's right. It's a side injection. And so from a top view the injection line would be behind the pipe.

CHAIRMAN WALLIS: That's why we can't see it.

MR. REYES: That's right. That's right. So... Thank you.

CHAIRMAN WALLIS: So is this fog flowing down the Columbia Gorge.

MR. REYES: It's the fog coming down the Columbia and out towards the ocean here, I guess.

Here's the Weir wall. So for this injection flow rate and for this combination of cold-leg flow rate, we're not getting it -- well, maybe we are spilling over a little bit here. Here's a side view. So we're not, okay. So for this --

CHAIRMAN WALLIS: It doesn't look like a very flat layer, does it?

MR. REYES: Say again.

CHAIRMAN WALLIS: It doesn't look like a very flat interface between the green and the blank.

MR. REYES: It's not very flat. For this flow rate it's not very flat. That's right. So what we're looking at then is a -- we're at about the 12-gallons per minute in the cold leg. And we're injecting probably somewhere around a gallon per minute here through the -- so you see the side injection.

The plume comes in. It travels both directions, and back towards the vessel and towards the loop seal. But this acts as an effective wall to prevent the flow.

CHAIRMAN WALLIS: I guess the drag from the other flow keeps the -- it's what causes it to flow in this arrangement.

MR. REYES: So here's a closer look at it, and I'll show you the Weir wall.

But here we're injecting again. This is -- you can see this --

CHAIRMAN WALLIS: Well, that shows how stratification inhibits the mixing.

MR. REYES: Right. Here's a close-up of the -- of that --

CHAIRMAN WALLIS: You can't just use the normal CFD in a stratified flow like that. K-epsilon doesn't work in their stratified interface.

MR. REYES: That's one of the -- this is where -- this is -- Ian's nodding his head yeah.

Working with CFD Codes, and we'll talk about that a little bit later, but that's some of the challenges that we face with using these types of codes. And so we're going to be looking for some advice from experts.

CHAIRMAN WALLIS: The turbulence is really suppressed at the interface.

MR. REYES: Yeah. So this is at the Weir wall, and we see that basically the cold fluid from the cold leg -- I mean the cold-leg fluid is sweeping all that fluid back.

Okay, another look here. We have a little bit of spillover in this case. We've got the flow rate. And then this is looking again at the spillover into the loop seal. So we'll perform some of those visualizations for you when we go over there after lunch.

Okay. So let's talk a little bit about what we saw with regards to the stratification in the cold legs, some of the measurements from APEX-CE.

So we did --

CHAIRMAN WALLIS: Now are you going to tell us about analysis of this in terms of some math and some predictions?

MR. REYES: Yes.

CHAIRMAN WALLIS: Somebody -- somebody is.

MR. REYES: When we talk about the plumes.

CHAIRMAN WALLIS: Somebody is. Well, what about the cold-leg behavior and the stratification and all that?

MR. REYES: We have some predictions to show you later on if you -- we can chart --

CHAIRMAN WALLIS: Any comparisons with data?

MR. REYES: We have lots of data.

CHAIRMAN WALLIS: Do you have -- well, come on.

MR. REYES: We'll give you some. You'd like some theoretical...

Well, we have looked at the plumes in the downcomer, and I'll present some equations there.

In the stratified region, we're still looking at developing what's going on in that section.

We have a -- there was a -- I think I know what you're referring to. Early on in the development of this project we were real curious about the onset of thermal stratification and came up with pretty good criteria that was used -- that you could use to predict when you have essentially well-mixed conditions in the cold leg.

Now the presence of this Weir wall has changed that somewhat. So we're looking -- that's why we're changing the theory some, to examine that Weir wall more closely and understand how that's affecting the flow and what that really means in terms of a stratification criteria.

CHAIRMAN WALLIS: It looks like a real candidate for the Kelvin-Helmholtz instability type of analysis.

MR. REYES: That's right. That's right. So now you've got -- I mean that's exactly right. So that's what we're looking at right now.

So what this tells me then is that the stratification criteria that we use that P. F. Foss had developed, and then the modified version which I had developed, which was based on the Froude number of the cold-leg stream squared plus the Froude number of the hot leg squared equal to one.

With the presence of that Weir wall we need to look at that and say, okay, now we've got a slightly different situation.

CHAIRMAN WALLIS: What is 10 gpm in terms of Froude number, using the density difference.

MR. REYES: Oh, 10, that -- with using that combination, I think it's like .04. That's that modified Froude number. That --

CHAIRMAN WALLIS: You're using the density difference between the fluids?

MR. REYES: Density difference between the fluids. And using --

CHAIRMAN WALLIS: That's the only Froude number. It's not modified. That is the Froude number.

MR. REYES: Well, this -- they're modified in terms of -- it uses the HPI injection.

CHAIRMAN WALLIS: Density.

MR. REYES: Density --

CHAIRMAN WALLIS: Minus --

MR. REYES: -- with the cold leg --

CHAIRMAN WALLIS: Minus the density of the --

MR. REYES: Oh, okay, I'm sorry. The Froude for the cold leg. Yeah, I'll have to look that one up. I was giving you the injection, injection Froude. Yeah, I can look that up for you.

CHAIRMAN WALLIS: You can tell us after the break.

MR. REYES: You bet. We've got lots of calculators.

So what we found, though, is that the presence of the Weir wall results in some stratification for the full range of conditions that we studied.

So this test 003, what we were doing was we were putting -- we were parametrically varying the cold-leg flow rate and the injection flow rate for 16 different cases. We wanted to see what we would observe as far as stratification in the cold leg.

So what we saw was that at the presence of the Weir wall there was always some stratification for the flow conditions that we looked at. And we were looking at essentially from one and a half percent to K to four percent to K powers over a range of about 30- to 100-percent HPSI injection flow rates.

The spillover was not observed in any of these tests, which meant that our -- above 30-percent HPSI for us, what we saw was that we had enough flow. It was greater than 10 gallons per minute in the -- excuse me -- for one-and-a-half percent to K power, our flow in the cold legs was greater than 10 gallons per minute.

So we always kept flowing in the direction of the reactor vessel. And there was no spillover for any of these tests. So this is the range of conditions we cited.

We would vary the K power. That would change our natural circulation of flow rate in the loop. And in between each test we would turn our pumps for a while and get everything back to uniform temperature and then do another parametric study.

So here's that --

CHAIRMAN WALLIS: What's the basis of these HPSI flow rates? What's the basis for choosing these values?

MR. REYES: Oh, that's -- that basically was the limits of what we could do. Yeah. So 30 percent, when you drop below 30 percent on our injection, we have difficulty controlling our -- well, for -- for the cases that we looked at, I guess we can get down to --

CHAIRMAN WALLIS: Presumably it's a scaled HPSI from reactor conditions.

MR. REYES: Right. Right. So point -- the lowest we did was .35 gallons per minute, which corresponds to about 30 percent of one injection flow. So that was what --

CHAIRMAN WALLIS: So this is a throttled HPSI of --

MR. REYES: Right.

This shows the range of tests that we did. And in between each test, again, we operated our reactor coolant pumps.

Once we put in several hundred gallons per minute through the loops. Of course, everything warms up pretty uniformly. All our thermocouples matched up.

This is looking at the top of the cold leg number 3 and this is the bottom of cold leg number 3, so we're going -- we're looking at the temperature stratification in the cold legs.

And this shows that for the different conditions we saw we always saw some stratification. Even at our minimum being .35 gallons per minute, we saw some stratification in cold leg number 3.

Again, this being the bottom of the cold leg here and all the way up at the top would be the top, so they actually went in order. So we saw that stratification for our tests.

Here we are at -- for cold leg number 4, the same test, we were running -- we ran two different injection flow rates for that --

CHAIRMAN WALLIS: What is your temperature of your HPSI?

MR. REYES: HPSI temperature is about 65 degrees Fahrenheit.

CHAIRMAN WALLIS: So this is a lot hotter than the HPSI itself.

MR. REYES: Oh, much, much hotter, right. Yeah. So what we're seeing is by the time we get to this -- the typical rates, we are seeing some -- quite a bit of mixing.

And the total -- well, I mean this is 150 degree delta T from the bottom of the pipe to the top of the pipe, so it's a pretty big stratification.

This case and this case, we also used to model with STAR-CD. So these two cases we modeled with STAR-CD. And later on you'll see the results of those comparisons.

CHAIRMAN WALLIS: So maybe if you had bottom injection you might actually have those minima going down to something like the HPSI temperature. Because presumably it's bottom injection; it doesn't mix with anything.

MR. REYES: That's right.

Now I'm not sure if there are any plants that do bottom --

CHAIRMAN WALLIS: I don't think there are, but just for comparison sake.

MR. REYES: -- with the big --

CHAIRMAN WALLIS: I mean you said with top injection there's more mixing and side injection you get more of this.

MR. REYES: Right. So the bottom might be --

CHAIRMAN WALLIS: Presumably there's one limit where you just ooze the cold water in and it flows along without mixing with anything.

MR. WACHS: You get conducted heating from the metal in the cold leg.

MR. REYES: Dan.

MR. WACHS: I said you'll still get conducted heating from the metal in the cold leg, so there will still be some warming. You won't -- you're unlikely to --

CHAIRMAN WALLIS: Yes. Yes.

MR. WACHS: -- get that small.

CHAIRMAN WALLIS: Yeah, I guess you need to estimate that, too.

MR. REYES: Okay. So the upshot of it for us for these series of tests was that for all the natural circulation cases that we examined, we always saw some stratification.

And this case here being the maximum stratification we observed, which was not the -- not the lowest flow rate, but it was -- it was essentially close to the highest flow rate, but not the -- not necessarily the lowest. Well, like big yeah, the trend is getting bigger as we go to lower -- lower cold-leg flows.

Okay. So we always see some stratification, which was different than what we've seen in the past. If we kept the criteria, the stratification criteria the way it was, it would predict good mixing for some of these tests.

So we see that the Weir wall has no -- has an effect. And we need to change that theoretical model.

Okay. Now we'll talk a little bit what's going on in the downcomer as far as plumes.

I'll start off with kind of a typical analysis and what's been done in the past. The classic analysis is you have a single planar plume falling into a stagnant, uniform ambient fluid.

Okay. That would be the classic analysis. And it's been done -- it's been done for a long time. Bachelor did a study on it and Morton and Rouse and --

CHAIRMAN WALLIS: You say, "planar." You mean it's 2 *d*?

MR. REYES: Correct. Yeah, they're 2 *d*.

CHAIRMAN WALLIS: They're also cylindrically symmetrical. The simple ones are --

MR. REYES: Right. The --

CHAIRMAN WALLIS: -- planar or --

MR. REYES: Right, the axisymmetric --

CHAIRMAN WALLIS: -- axisymmetric.

MR. REYES: Right, axisymmetric case. You just change the coordinates and unwrap it and get a planar. Yeah, so the 2 *d* case.

And these involve some very classic

assumptions, some very -- which work very well for the single planar plumes and also for the axisymmetric plumes.

CHAIRMAN WALLIS: Oh, review that for me. If I have, say, a faucet, the plume actually accelerates instead of -- because the density difference is so enormous.

MR. REYES: Right. Yeah.

CHAIRMAN WALLIS: And then if I have a very low-density difference, presumably the buoyancy is not so big and the plume spreads a lot. What sort of range are you in in terms of the density difference, in terms of, you know, whether the plume spreads a lot or --

MR. REYES: Right.

CHAIRMAN WALLIS: -- doesn't because of the gravity accelerating it?

MR. REYES: Right. For these tests, our delta rho over rho was like .18. So I'd have to go back and see what just a delta rho is. But -- so it's comparable to what you would see in the plant, not -- not as large, but it's within 10 percent.

CHAIRMAN WALLIS: But it's something like the plume from a cigarette, or something, in terms of what you --

MR. REYES: Oh, no.

CHAIRMAN WALLIS: -- imagine in terms of things you know about?

MR. REYES: Okay. So smoke and air, maybe -- maybe like --

CHAIRMAN WALLIS: Smoke from a chimney, from -- on a clear day. Something like that.

MR. REYES: Yeah. I'm thinking of my backyard.

CHAIRMAN WALLIS: Yes, something like that.

MR. REYES: I'm looking at the stack way out there.

CHAIRMAN WALLIS: But, you see, if you have a hot enough fire --

MR. REYES: I'm looking at the stack way down there.

CHAIRMAN WALLIS: -- your plume actually --

MR. REYES: Yeah, it would be similar --

CHAIRMAN WALLIS: -- can go up and concentrate.

MR. REYES: Right. So --

CHAIRMAN WALLIS: Before it spreads.

MR. REYES: -- you'll see a lot of

examples of the reverse. You'll see a hot plume --

CHAIRMAN WALLIS: Right.

MR. REYES: -- going up in air.

CHAIRMAN WALLIS: Depends on how hot it is.

MR. REYES: So it -- from the shape of it, I'd say --

CHAIRMAN WALLIS: So I'm trying to get a feel for which kind of a plume is it. I think it's a spreading plume.

MR. REYES: It's a spreading plume.

CHAIRMAN WALLIS: Yeah. You have the fire, the density difference is two to one or something. So it's...

MR. SCHROCK: These theories pertain to, as you've said, a large field. You've got the downcomer walls that are confining the plume. Are you going to address that?

MR. REYES: I'll cite the difficulties with those things, right. Yeah.

We'll go on, and I'll show you some of the problems we're facing --

CHAIRMAN WALLIS: There's a good -- there's a good book on this by some German whose name I forget, who studied all kinds of plumes and all the

--

MR. REYES: I've got it in my bag.

CHAIRMAN WALLIS: Okay.

MR. REYES: It's Rodi and Chatney.

CHAIRMAN WALLIS: Rodi, that's right. Rodi.

MR. REYES: They did a ton of work in -- you're welcome to look at the book. Yeah.

CHAIRMAN WALLIS: It's pretty comprehensive.

MR. REYES: It is. It was a very nice -- one of the few that covered a wide range of axisymmetric and -- but I'll show you another paper today, which is fairly new, which is closer to our situation.

CHAIRMAN WALLIS: It's got too many *n*s.

MR. REYES: So we're familiar with the classic assumptions for the planar plumes. The idea that there's a linear spread of plume radius with axial position, because you have a constant entrainment rate. And that assumption works reasonably well for the planar plumes in stagnant media.

You've used the similarity of velocity and buoyancy profiles. And you can come up with some universal curves that way. And in REMIX they kind of use that technique of producing these universal curves. And then at different locations it says, okay, for this set of dimension groups you kind of convert it back into what you should be reading there, so that works well.

And, of course, they always -- you typically assume the Gaussian-shaped profile for this stagnant media. I'll show you a couple of pictures.

Back in 1934, we've got some data which shows the same situation. Here you have the velocity measurements inside the plume. The scale's missing here. That should be centimeters per second on the *y* axis.

The velocity measurements for the plumes at different axial locations. And if you -- you can actually scale it with a mean velocity of plume and come up with a single shape, a single universal Gaussian curve. So we know that that theory works very well.

So the thought was, well, we can apply to some of the similar concepts to our test --

CHAIRMAN WALLIS: Well, I'm trying to think, though. When you pour -- pull this stuff over the lip of a pipe, --

MR. REYES: Right.

CHAIRMAN WALLIS: -- you don't have the sort of starting condition of a uniform velocity. It has to sort of accelerate out of the pipe. So it's accelerating for a little while before it does this mixing.

MR. REYES: That's right.

CHAIRMAN WALLIS: Isn't it?

MR. REYES: So -- yeah, I was --

CHAIRMAN WALLIS: I don't quite know how you modeled the starting condition for coming out of the pipe and going over the lip and into the downcomer. How do you start your plume for an analysis like this?

MR. REYES: For an analysis like this what we think is actually happening is that the plume is jumping the gap. Eventually it's --

CHAIRMAN WALLIS: It hits the other wall.

MR. REYES: -- it hits the core barrel wall. Now you've got another, another problem. So that's what we believe happened.

CHAIRMAN WALLIS: This is like the experiments that we did with the injection of water into a steam down- -- filled downcomer. It jumps to the wall and goes down the other side.

MR. REYES: Which test was that?

CHAIRMAN WALLIS: When was that done?

MR. REYES: Yeah.

CHAIRMAN WALLIS: 7-70, or something like that. 1970 maybe.

MR. REYES: Yeah. For our test number 13 we're thinking of something similar, so I'll ask you a little bit more about that.

The -- so that's right. There's some type of flow establishment region. If you have a forced flow, you have a momentum dominated, then some kind of a transition. And then you eventually gets to this buoyancy-dominated region for the plume.

So this region actually could be fairly short. And where you'd like to be is kind of in this region as far as analysis. So you've got this spreading plume. But again that's for a stagnant medium.

If you have -- if you have any complications to it, you really have to -- I mean it complicates the analysis quite a bit. If you're impinging onto a core barrel wall, well, how do you analyze that.

So we very quickly got -- as we started looking at the different complications, that's where we said, well, we need to use to some of the CFD and see if we could understand that a little bit better.

CHAIRMAN WALLIS: Now let's look at Mr. Foerthamnn's experiment.

MR. REYES: Sure. Can you go back?

CHAIRMAN WALLIS: Now it seems as if the width of the plume is about four centimeters, or something, but the velocity in the middle hasn't died to half the initial one until it's gone 75 centimeters. So this is a plume that's very persistent. It's gone an awful long way before its velocity in the middle has gone down by a half.

MR. REYES: Right.

CHAIRMAN WALLIS: So your plumes aren't anything like that. Yours --

MR. REYES: No.

CHAIRMAN WALLIS: -- spread much more rapidly, don't they?

MR. REYES: Correct. Correct.

CHAIRMAN WALLIS: Why is that? There's something different about some dimensionless number in your experiment than in this one?

MR. REYES: Right. Now for this experiment --

CHAIRMAN WALLIS: There must be something.

MR. REYES: I think -- yeah. There -- I'm not exactly familiar with the delta rho over rho in this test or the density difference in this test and what was going on as far as the buoyancy.

CHAIRMAN WALLIS: I think this is actually spreading less than the jet would in just -- the shrifting-type jet with no buoyancy at all. This one is actually buoyant, so it's spreading less than a jet. And --

MR. REYES: Than the actual.

CHAIRMAN WALLIS: -- that's why it's so surprising that your plumes spread so rapidly.

MR. REYES: Well, there's other -- so there's other -- right. So there has to be other mechanisms that are --

CHAIRMAN WALLIS: You think about the plume from the stack from the incinerator next to your -- do you have an incinerator next to your building?

MR. REYES: It's a -- well, I can see it from --

CHAIRMAN WALLIS: That probably goes quite a long way on a clear day before it spreads much.

MR. REYES: That's right.

So what we -- we started looking at our plumes and realized that there's something -- it's significantly more complicated, especially for the conditions that we were looking at, because we had multiple asymmetric plume interactions. We actually had some cases where we had cold flow.

So now instead of a stagnant downcomer, what you actually have is hot-leg flow. You're putting hot water -- the way this was stratified, you're -- basically the cold water is pouring -- pouring out the bottom of the pipe.

You still had positive hot-water flow on the top of the cold leg going into the downcomer. And you were forcing this flow through the downcomer co-current with the plume. So now you've got a could-current situation.

CHAIRMAN WALLIS: That could be worse.

MR. REYES: Yeah. So now I'm starting thinking relevant velocity between the plume and your medium. If you have a stagnant case, your plume comes in and the relative velocity for that case is going to be larger than if the media traveling with the plume is at nearly the same velocity. So now the relative velocity between the plume -- and that's a well documented -- that's this plume behavior in cold flow.

And so we searched the literature for that, and we found a paper that was fairly recent that tried to address that, by Wood.

So potentially with some cold flow you can actually have less -- you'll preserve the plume further under certain conditions, okay.

There are other compounding conditions, of course. We -- and our tests, of course, as opposed to some of the studies done previously, we have a core with a core barrel. And that's dumping heat into the downcomer. So there are other things which are heating up this plume and causing it to dissipate a bit earlier.

So you have these -- all these different factors, some trying to preserve the plume and some trying to destroy the plume. Okay.

So we very quickly came to realize that if we wanted to do a realistic or something realistic, that maybe we can bound the problem asymptotically and look at some of the ranges of the plume spreading.

But, in fact, the thought then came, we need to do some type of CFD work. And that, of course, brought with it its own set of problems, how to understand CFD and who would volunteer to do the work.

And so we'll present that later on. And we're wide open to suggestions on that. But you'll see some of the comparisons, and you can be the judge of what the problems might be or what went right.

Okay. So, in essence, there is a test facility in Finland, Imatran Voima Oy, which in the good old days they did these flow visualizations. And I guess they had an artist watching the stuff, because this is an artist sketching. He must have been very fast.

CHAIRMAN WALLIS: Well, Leonardo did it all 500 and some odd years ago.

MR. REYES: That's right. I think this may be a da Vinci.

CHAIRMAN WALLIS: But Creare did something like this, too, didn't he?

MR. REYES: Yeah. So Creare had that -- well, they only had the single.

CHAIRMAN WALLIS: It was red or blue, that stuff that they used, but it was -- they had pictures like this, I think.

MR. REYES: They did? I don't think -- I think they had a single injection, a single --

CHAIRMAN WALLIS: Unwrapped?

MR. REYES: -- cold leg.

CHAIRMAN WALLIS: I thought they had an unwrapped --

MR. REYES: Well, maybe they did have two.

CHAIRMAN WALLIS: Maybe -- well, go back and find out.

MR. REYES: I don't know if they ever -- I never saw they had for two. Yeah, I saw two tests that they did.

But they had -- they were using that red dye and they were injecting into each of the cold legs and sometimes they flow, but they were getting some -- they were getting plume merging. And so, of course, that -- you know, what's the strength of the plume where they -- when they merge and how does that affect heat-transfer coefficient, da-da-da. It goes on and on.

So in terms of simple analyses, they very quickly -- it became obvious that it was beyond what you can do on the back of an envelope --

CHAIRMAN WALLIS: That plume seems to be going a lot more than 4 *ds*. You were talking about mixing by 5 *ds*. Or the beltline is at 5 *ds* from the pipe, or something?

MR. REYES: Right. For Palisades it's somewhere up there --

CHAIRMAN WALLIS: And this one seems to be going down a lot more than that --

MR. REYES: This -- this -- yeah, this looks like it's going down for -- now the flow rates for the -- for what they were doing were very, very high in these tests. So that's a big part of it.

And I think we have a picture later on that we'll show you that kind of goes back to this test. And, of course, we saw similar behavior as far as merging, but we didn't see the plumes, you know, getting --

MR. BESSETTE: You have to remember also this is an artist's rendition.

MR. REYES: So da Vinci --

MR. BESSETTE: Done by -- Actually it was done by Tuemisto himself.

MR. REYES: Tuemisto, okay.

MR. BESSETTE: Yeah.

MR. REYES: Tuemisto da Vinci.

CHAIRMAN WALLIS: They didn't have photography in those days.

MR. REYES: We have some --

MR. BESSETTE: Not -- well, I don't know. Like I say, he'd interpreted what he saw, and he did it by drawing.

MR. REYES: So when we started looking at the plumes we were having difficulty interpreting what was going on in the downcomer. So Kent Abel, one of our graduate students, came up with this idea of putting together this, an unwrapped map.

And so each -- this shows all four of the cold legs. On top of it, it gives you the flow rate through the cold leg, and then the HPSI flow rate for each of the cold legs. So those are listed up on top. And then along side here he's got a color code for the different temperatures.

And then here in the cold leg you can see if the cold leg is stratified or not, so again by temperature. So we can observe stratification. When this light is green, it means that the HPSI is flowing for that particular transit.

You can pull up any one of the tests that we've performed into this format, and it'll just play the downcomer for you, which I love it. I can -- I sit there and watch the lights.

CHAIRMAN WALLIS: Do you have music?

MR. REYES: HPSI, HPSI. You get hypnotized kind of by it.

But this is just an example. If we have time I think we can run one of these or two to show you a couple of different scenarios and what we see.

It's useful because we break it up into a gradient, a delta T that your eye can actually catch instead of a continuous type of a thing.

And what we see in this particular snapshot, we see this plume, we see cold temperature over here and cold temperature over here, so we're in the dark, this dark blue region over here.

CHAIRMAN WALLIS: It's not very obvious.

MR. REYES: It's not real obvious, but it does interact --

CHAIRMAN WALLIS: Can't you get more contrast?

MR. REYES: Right. In some of the other -- I think in some of the others we'll see more contrast.

CHAIRMAN WALLIS: Yeah.

MR. REYES: But the thing is that the temperature difference is not -- you're within -- they're typically within 10 degrees or so, 10 or 15 degrees. And so we could do some more contrast.

So what we see is a kind of interaction here, and then we do see colder here and some cold down here. So we kind of see a merging plume over here. But then again the ambient is relatively cold also.

So in terms of a delta rho, we're not

looking at a very large delta rho. However, we are seeing this merging and then getting down blow here. So you can imagine that if we had a couple thousand more thermocouples, that would have been ideal.

So that's one example.

Now you can see it a little bit better as we run -- is that the next -- yeah. We'll run this for you, and then you can see a little bit better the temperature changes. And this was for the -- this was for the main steam line break case, so you'll see eventually everything will turn blue because the --

CHAIRMAN WALLIS: Yeah. I think if it's dynamic it will be easier to see.

MR. REYES: Right. And I think that's what we'll do.

Okay. So it's running right now. We're getting -- the time on the upper left-hand corner is the time to start the test. And so it's jumping. We're jumping about -- every step is about eight seconds or so.

And this is the main steam line break. So we've opened up the break, and so you see all the temperatures are uniform. Now the break's open. We're starting to see cooling, but that's not cooling to the HPSI.

Now the green -- the HPSI's on now at this point, and so you'll start seeing colder temperatures underneath the cold legs. So there you go. So you see some of the yellow and the green, so it's getting colder underneath there.

CHAIRMAN WALLIS: Can you -- uh-huh, okay.

MR. REYES: And we can step through it if you want to go slower. So you see --

CHAIRMAN WALLIS: So this is typically the whole downcomer, so the beltline is sort of where in this, in the middle --

MR. REYES: The beltline is between the 4 *d* and the 8 *d*.

CHAIRMAN WALLIS: Somewhere in the middle of the page.

MR. REYES: Yeah. And we -- and that's actually where our beltline is. We have a big flange sitting there so we couldn't get thermocouples in it.

And so you can see at this point the cold leg number 3 there is still so much stratified. Cold leg number 4 is completely cold, but then that was where the broken steam generator was. So you're seeing some cold flows there.

So now that the whole downcomer is overwhelmed basically by the transient itself, the steam line break. Looking --

MR. BOEHNERT: So that was every eight seconds, was it?

MR. REYES: Correct. Correct. Yeah, I think we're -- were we jumping eight seconds there, Ken? Yeah.

CHAIRMAN WALLIS: If you go back to about one or two seconds after it began to turn yellow, --

MR. REYES: Okay.

CHAIRMAN WALLIS: -- you've got some -- some spludges pretty low down of the -- a really different color from the surroundings. I got the impression that there was some plume activity down to maybe 10 *d* or something. Not insignificant.

MR. REYES: Right. Well, -- yeah. In fact, we'll talk about what happens when you have that cold-leg flow and you're trying to preserve the plume. We see it -- the behavior is somewhat different. I won't steal -- I won't steal their thunder.

But, yeah, we do see a different behavior for cases where your cold legs are flowing and -- for this plant.

(Discussion held away from the microphone and simultaneous talking.)

MR. HAN: One of the things to keep in

mind --

MR. REYES: It was one of our thermocouples --

MR. HAN: -- in terms of the vessel is that transient --

(Discussion held away from the microphone.)

MR. HAN: -- behavior is not important because of the time constant of the vessel wall --

MR. REYES: This is James Han.

MR. HAN: -- things that happened over the time of, say, one minute, for example, don't matter because you don't build up a stress. So you can have these plumes. Let's say, if they're moving and whatever, that the transient behavior doesn't matter. It's the longer-term behavior that's important, things that happen over the course of 15 minutes to 45 minutes.

CHAIRMAN WALLIS: It's a question of the balance between the surface *h* and what you think of sort of internal heat transfer distance of the wall.

MR. BESSETTE: And it's conduction -- it's conduction --

CHAIRMAN WALLIS: It's certainly not an infinite *h* on the surface.

MR. BESSETTE: No, but if it does -- the

h doesn't matter. It's because it's so conduction controlled.

CHAIRMAN WALLIS: Yeah. So it's like an infinite *h*?

MR. BESSETTE: It's like an infinite *h*. If you had an infinite *h* or not an infinite *h*, it doesn't really matter too much.

CHAIRMAN WALLIS: So you're immediately chilling the surface to the temperature of the water?

MR. BESSETTE: Essentially your boundary layer doesn't matter that much. It's the ambient --

CHAIRMAN WALLIS: But you had to know *h* because if you assumed *h* is infinite it's not very nice.

MR. BESSETTE: Well, --

CHAIRMAN WALLIS: You have to know *h*.

MR. BESSETTE: -- if H is infinite -- if *h* is infinite, it means you have no boundary layer. It means your ambient temperature is the temperature of the surface of the wall.

CHAIRMAN WALLIS: I don't think you want that.

MR. BESSETTE: It doesn't matter that much.

CHAIRMAN WALLIS: It stresses the wall.

That temperature difference is what stresses the wall, the difference from surface from the average, is it?

MR. REYES: There is a thermal penetration of time that --

MR. BESSETTE: The difference between the ambient fluid temperature and the wall surface temperature is never large, no matter what *h* is.

CHAIRMAN WALLIS: Then you might as well assume *h* is infinite for your -- and forget about everything else as long as you know what the temperature is.

MR. BESSETTE: That's right. You can do that.

CHAIRMAN WALLIS: I don't think that's very good for -- well, maybe we -- that's a different discussion somewhere else.

I thought it was pretty critical what *h* was.

MR. BESSETTE: No. In fact, we've done those sensitivity studies already --

CHAIRMAN WALLIS: Okay. So we'll go back to that some time.

MR. BESSETTE: -- to show that *h* is not important.

MR. SHACK: I mean that's good news.

MR. BESSETTE: Yeah.

MR. HAN: That's good news, yeah.

CHAIRMAN WALLIS: So we just forget about thermal hydraulics.

MR. SHACK: No, no. You had to set the temperature.

MR. KRESS: No, you need the temperature.

CHAIRMAN WALLIS: Okay.

MR. BESSETTE: We've been trying to tell you that.

(Laughter.)

MR. SHACK: But it's still your penetration depth that you're interested in, isn't --

CHAIRMAN WALLIS: See, there's a white -- there's a light-colored one way down there, right? Presumably that -- what's happening there? It looks very strange to me. You've got colder stuff down there than you've got --

MR. KRESS: At the middle it curled over.

CHAIRMAN WALLIS: Yeah. But it's just going to warm again at the top, isn't it? Or, no, maybe I've -- yeah, it's going to warm again at the top. There's a plug, sort of a lump of cold fluid in there not even connected to the pipe.

MR. REYES: Yeah. And sometimes what you

see is -- well, our thermocouples -- that's a good -- that's a good point.

Our thermocouples are closer to the vessel wall because that's where we wanted to measure, what was impacting the wall.

CHAIRMAN WALLIS: Oh, so if it jumps away to the inside, --

MR. REYES: If it jumps --

CHAIRMAN WALLIS: -- you won't see it?

MR. REYES: Yeah. So quite often -- that's right. So quite often what we see is when we're injecting -- it'll jump that first thermocouple. And that one will read hot. And all the thermocouples below will read cold. And so it's impacting the barrel wall, mixing up, and then it's --

CHAIRMAN WALLIS: But here we have -- do those yellow things -- are they those things -- they look -- that doesn't look like a plume. It just looks like a -- sort of a odd-shaped lump of fluid.

MR. REYES: It's not like the -- well, again we don't have -- we don't have a lot of thermocouples to get a good fine detail of this thing.

But you're right, the shapes are not going to be nicely-spreading plumes. There are going to be some meandering --

MR. SHACK: Will we see this in the CFD calculation, something like this?

MR. REYES: Well, yeah, I think you'll see that the CFD calculation does more of the meandering and the curling-type behavior, so...

Okay. I'll let them get us back to the presentation.

Okay. So one of the things that we've observed is that at least as far as -- in terms of an asymptotic solution or trying to imagine a little bit of what's going on, there was a paper recently by Wood. It was called, "Asymptotic Solutions and the Behavior of Outfall Plumes."

And it was very nice -- nicely done because you don't -- it was the only one I found that was fairly recent that talked about the spreading of the plume under some unusual conditions, either crossflow or co-flow.

So what is done basically is the b represents the half width of the plume. Okay, and z is the axial position of the plume as it comes down.

And so this basically describes the spreading of the plume. So for a stagnant case, u subinfinite here, that's a stream velocity. U_p is the plume centerline velocity. And k_s is the spread constant.

And so for a stagnant media where you're injecting these plumes, *k* is a constant. I mean this goes to zero. The u_ps cancel in case. So he was able to kind of unify that behavior.

Whenever you have a flow, this is the angle between the trajectory of the plume versus your flow. So if it's co-flow, that would be -- the cosine's zero is one. So you'd have u_p over u_p plus u infinite.

So what this is telling us then is it's a factor that makes this constant smaller and as a result you get a plume width which is smaller, tighter as you go down in your axial position.

So this confirmed an idea that, well, for co-flow you would expect to see tighter plumes. They might be preserved a little bit longer than you'd expect to see in a stagnant media.

So this suggests that for certain -- so now a scenario comes to mind. You have stagnant conditions in your -- in your downcomer. You inject the plume.

You'll get very good mixing because the relative velocity between the plume and the ambient is going to be higher than the case when you have co-flow at low-flow rates. When you've got a co-flowing plume, so you'd expect the plume to be preserved a little longer. And we'll talk about the phenomena that we see in co-flow versus stagnant because we did both cases.

Of course, if your stream-flow rate continues to increase, eventually something's going to -- this model wouldn't apply. So there's got to be a limit to this. And so that would be on the asymptotic end of this study.

So if you'd get enough crossflow or enough downflow, you'd expect the plume to break up because of it. So again it's probably -- you've got a relative velocity criteria and -- if I come up with something that works reasonably well.

So again this just explains what I just said, that the spreading for the stagnant condition, you expect it to be greater than spreading for a co-flow.

Now this is -- again this is a nice uniform co-flow, so we have some other behavior which could complicate this -- this -- what we see in our test.

Okay. So what we did see, we did see downcomer thermal stratification under the flowing case. And we had a presentation on that which describes what we saw when we were injecting these plumes for the co-flow case and why that data looks different, the downcomer profile looks different than what we saw for --

CHAIRMAN WALLIS: Actually going db/dz when you have these very irregular plumes must be a little bit awkward. It's not as if you just have a cone.

MR. REYES: Yeah. We --

CHAIRMAN WALLIS: You measure the db/dz, this thing is swirling around.

MR. REYES: That's right.

CHAIRMAN WALLIS: So you had to -- do you actually measure db/dz some --

MR. REYES: No, not with --

CHAIRMAN WALLIS: So this statement here is inference from the theory.

MR. REYES: Inferred -- is inferred from theory. It's inferred from theory.

CHAIRMAN WALLIS: Okay. I thought you meant you had measured it.

MR. REYES: Yeah. That would -- that's my dream.

If we could set up a -- this would be

simple enough to set up with a flow visualization. I think it's something that --

CHAIRMAN WALLIS: With one plume?

MR. REYES: Just one plume, yeah. We wouldn't see --

CHAIRMAN WALLIS: Once you start --

MR. REYES: Then grow to two plumes --

CHAIRMAN WALLIS: Once you start setting up swirlies in the downcomer, all the plumes are going to start wandering around.

MR. REYES: "Swirlies," I like that.

Okay. There's an appendix I have added to this which deals with a little more details of what we were seeing as far as the plume stratification or cold leg -- excuse me -- cold-leg influ- --

CHAIRMAN WALLIS: Well, let's see. So far it's kind of qualitative, isn't it? I mean I didn't get anything I can grasp which is something I can use yet.

MR. REYES: Right.

CHAIRMAN WALLIS: But you're going to give us something which is more quantitative.

MR. REYES: Right. Now we're getting into some more of the measured -- what we're seeing for the different scenarios, the flow case and the stagnant case.

So this is a stagnant loop case. We did Tests Numbers 4, 5, and 6. We had the system essentially stagnant. And we're injecting cold water. There was no core heat. The system was hot initially. We had all of our structure. Everything was hot in that pressure. And we just started injecting cold water into the cold leg and watch it spill into the downcomer.

What this represents are all the temperatures, and that's this part. Okay. These are all the temperatures that lie underneath cold leg 1. So directly beneath it and to the sides of it, everything that's underneath cold leg number 1, all the way down to the 8 *d* mark.

And on the -- of course, we're looking at a decay situation. And so at first glance it looks like everything is fairly tight. And this is kind of what you'd expect to see. But at the very beginning what happens is that your density difference, of course, is the greatest. Okay. So you inject this cold plume into the stagnant media.

And what happens, of course, is as time goes on you're cooling off the whole system. And so your delta rho is getting smaller and smaller as time goes on. So you expect that difference to narrow. I mean the plumes are, in essence, -- it's as if the plumes are getting weaker, because the ambient is getting colder.

So we see the largest temperature differences initially, and this could persist for a while, but some of the thermocouples we'll read. So here we are at that 275 or so. We're looking at only about a 25-degree-Fahrenheit difference from the coldest point in the plume -- or the coldest location in the downcomer, which is the 1.3 *d* for a lot of these tests, and then down to about 4 *d* -- well, this actually goes only 8 *d*.

So we're not seeing a very large -- except maybe at the beginning, we see 50 degrees or so.

So when you first come in and the system's hot, you really see a large temperature difference. So you'd expect --

CHAIRMAN WALLIS: You've got so many colors it's very hard to figure out anything.

MR. REYES: Oh, yeah. Yeah, this -- yeah, that's a good point.

What I'd like to -- what I'd just want to point out is the shape of this thing. Okay. How well it's -- how tight it is, okay.

So what you see is kind of the -- throughout the test, these --

CHAIRMAN WALLIS: Which are the worst spikes? Which ones are they?

MR. REYES: These bottom -- so what you see are these bottom --

CHAIRMAN WALLIS: Which are the worst spikes in terms of where they are, the location? Are they at 2, or 3, or 4, or 8?

MR. REYES: They're all above the 4 *d*.

CHAIRMAN WALLIS: They're at 3 maybe?

MR. REYES: No, 2.

CHAIRMAN WALLIS: At 2?

MR. REYES: At 2 and 1.

CHAIRMAN WALLIS: 2 and 1?

MR. REYES: And that 1.3, it jumps and sometimes it mixes back up. So you see -- you'll see it come on and off basically. So we're still looking for the --

MR. KRESS: And like David said, those spikes don't matter. You can just ignore them.

MR. BESSETTE: I think, you know, to me this one plot says that we have no plume problem.

MR. REYES: Yeah. It says it's relatively tight all the way through. And you'd expect it to get tighter --

CHAIRMAN WALLIS: Well, see if you had bottom injection in that of ACC or -- you might have a problem. The temperature differences would be much bigger.

MR. REYES: Yeah. If the concern is duration of temperature.

CHAIRMAN WALLIS: Yes.

MR. REYES: And when we look at the flowing case --

CHAIRMAN WALLIS: And also magnitude. I mean you're actual driv- -- your different temperature differences in the cold leg aren't that big, anyway.

MR. REYES: That's right. Right. When we look at the stratification.

So the rest of the plots, I'm going to just skim through, but you see similar results.

CHAIRMAN WALLIS: Yeah. There are one or two that look worse.

MR. REYES: Okay. That one was a little bit more severe, but...

Again these are -- typically it's early on in the transient, so we can just go through. So let's jump over to the flowing case. So we'll jump over to the natural circulation case.

So those tests represent essentially -- I'll say essentially stagnant plume. Again, what we saw when we -- as soon as we injected it generated initial loop flow which gradually stopped, so it was hard to get -- for the tests that we did, because we had system full, we saw a little bit of flow in the cold legs initially, and that tapered off.

Okay. Now to the circulation case. This was a series of parametric tests that we performed. And what we had going on there is we used the core power to generate a natural circulation flow rate through the loops.

And then we varied our HPI in a stepped fashion. And we produced 16 different cases, 8 cases under cold leg 3 and 8 different cases for cold leg 4. Okay. So they're on opposite ends of the plant under different steam generators. So we were trying -- we were watching both of these for the two situations.

And the idea is that we would hold it for a small period of time and we would observe what type of downcomer behavior, what type of plumes we would generate.

So what you can see here is for one of the more severe cases here about 200 kilowatts of core power, which corresponds to about two-percent decay heat for us and about half a gpm, which is about 50-percent HPI flow for that one leg.

We get about 300 -- about a 30-degree temperature difference. And these top lines here, again it's hard to see with this, but the bottom ones are typically the 1.3 right at the outlet. And the tops, it's kind of a merger of the -- between 4 and 8.

So we're seeing that the plumes have essentially dissipated by the time you get to 4. And I can show you individual plots with just -- which would be a little bit easier to see, but this shows all the data.

So that was -- the most severe case was under 4, I think. Let's see -- no, so 3 was the more severe case.

So we're seeing here only about 20 degrees of temperature difference --

CHAIRMAN WALLIS: So 8, I can't see where 8 is because of where the color is.

MR. REYES: Oh, okay. Yeah, 8 merges all the way up on top here. Yeah, 8's up on top.

And I can certainly -- we can pick any one of these and blow it up.

CHAIRMAN WALLIS: And those are much less than the stratification in the cold leg which you showed us on another figure.

MR. REYES: Correct.

CHAIRMAN WALLIS: Much less.

MR. REYES: So the same test. First we looked at the cold leg and then we looked at the downcomer.

CHAIRMAN WALLIS: At most 30 percent or so.

MR. REYES: Right. So we are seeing -- now the difference in this, in terms of a scenario -- okay. So if you have a reactor plant and you're concerned about cooling at a -- for duration, well, potentially in this situation you can have natural circulation through a core. The core's producing hot water. And so you're continually feeding hot water to the cold leg.

So the difference between this and the stagnant case is that in the stagnant case the plumes will decay over time because the whole system is cooling down. In this one you're using the hot water from the cold leg to essentially keep your downcomer warm. And so you can make these plumes persist a lot longer. I think that's just an important point. But we're seeing that temperature difference is not very large.

Okay. And so if you get to even much higher flow rates or -- with pumps on, it's not going to be a big effect. But the difference is that you can make these persist a lot longer because you've got flow. You're replenishing your downcomers with hot water. So that's the big difference there in terms of an integral system.

CHAIRMAN WALLIS: Well, how big a temperature difference do we need to see for Dave Bessette to get worried?

MR. ROSENTHAL: Well, yeah, if I can interject, it's not a question of Dave Bessette getting worried but Nilesh Chokshi getting worried. And we're talking -- what were you saying, 25 *c*, some numbers like that.

CHAIRMAN WALLIS: So 25 *c* is bad?

MR. ROSENTHAL: Well, I mean --

MR. BESSETTE: Noticeable.

MR. ROSENTHAL: That's where it's starting -- it will show up in their probabilistic fracture mechanics case.

CHAIRMAN WALLIS: So these are less -- these are all less than 15 and maybe more.

MR. ROSENTHAL: Half.

CHAIRMAN WALLIS: In fact, the way you

worry about it is more like 2 or 3 *c*, isn't it?

MR. ROSENTHAL: Well, this is all good news, but let me --

MR. REYES: Now --

MR. ROSENTHAL: -- let me back up a little bit if I might just for a moment because I'm worried. You know, if we go read this transcript two years from now, the --

CHAIRMAN WALLIS: We should, yes.

MR. ROSENTHAL: -- we ought to put it into a little bit of perspective.

We're talking about pressurized thermal shocks. We're talking about low temperatures at some higher pressure. We're talking about cases that would have to persist for some period of time.

Roy Woods' probabilistic work will tell us the probability of sequences. But here we're focused on a small break LOCA sequence where the break is big enough that you don't refill it and depressurize, but not so big that you depressurize the system, so it would be a case again. So it's sort of a perverse-size break.

And then the issue comes up: Okay, we know that under force-flow conditions we think that we can predict things rather well. Under conditions where you don't have force flow are you going to have a problem with plumes and stagnant conditions and whatnot.

CHAIRMAN WALLIS: Like you said, this was an -- it's an artificial kind of break, but isn't it --

MR. ROSENTHAL: No. It's just a purp- --

CHAIRMAN WALLIS: -- artificially made to be a pretty bad break from the point of view of --

MR. ROSENTHAL: Of PTS.

CHAIRMAN WALLIS: -- of PTS.

MR. ROSENTHAL: Right. Right. But it's --

CHAIRMAN WALLIS: And, of course, the risk -- the risk-informed people will probably say it's never going to happen anyway, so...

MR. ROSENTHAL: Well, he's going to give us the probability of this thing some day. And then when you throttle HPSI flow, then there's some associated HRA numbers associated with that.

But from a thermal hydraulic standpoint, it's still very interesting, so -- okay.

CHAIRMAN WALLIS: But you're trying to look at the worst case, or something close to the worst case in that?

MR. ROSENTHAL: Well, in this. I mean we --

MR. REYES: Right.

MR. ROSENTHAL: Because I think that we have confidence that in force-flow situations that the codes will do a better job predicting --

CHAIRMAN WALLIS: So it is only if we could say that this is something like the worst case or very close to the worst case, and the temperature differences here are so small that they don't challenge in any way the vessel, then --

MR. ROSENTHAL: Okay. But stagnant --

CHAIRMAN WALLIS: -- we don't need any PRA. We can forget it.

MR. ROSENTHAL: Well, fine. Okay. But --

CHAIRMAN WALLIS: And then we're really happy then.

MR. ROSENTHAL: But the -- yeah. But the stagnant thing was something of true concern, --

CHAIRMAN WALLIS: Yes.

MR. ROSENTHAL: -- so I'm glad that we --

CHAIRMAN WALLIS: Yes. Oh, yes.

MR. ROSENTHAL: -- had the experiments.

CHAIRMAN WALLIS: Yes, indeed. Indeed.

MR. ROSENTHAL: And --

CHAIRMAN WALLIS: Otherwise, you could argue about it forever.

MR. BESSETTE: Yeah. And it's worth noting, we didn't do these experiments by accident.

(Laughter.)

CHAIRMAN WALLIS: Well, I hope you don't do many experiments by accident.

MR. ROSENTHAL: David keeps whispering little insights in my ear about the timing, et cetera. I mean --

CHAIRMAN WALLIS: Someday --

MR. SHACK: Again this is all for Palisades. You know, you're going to have to somehow do the calculations to convince us that it's this good for everybody.

MR. ROSENTHAL: Okay. But this is where -- and we'll do lots of calcs, but I mean this is really very good benchmark stuff. And even if you take the broader perspective, we have relatively little data on steam line break experiments. So the fact that we're generating these have a broader applications in terms of --

MR. SHACK: Well, that, I guess, was another question --

MR. ROSENTHAL: -- code validation.

MR. SHACK: -- is I assume you're getting all this in a nice optical disk somewhere so someday in the future if somebody wants to benchmark calculations, this won't disappear.

MR. BESSETTE: It's all going on our databank, yes.

MR. ROSENTHAL: Oh, so you can get it right off the web.

MR. SHACK: Yeah, I could. From the NRC website. Good luck. Or you're going to put it in Adams.

(Laughter.)

MR. REYES: There is one qualifier that -- I just want to remind you, that this is -- we are a reduced-pressure facility. And so as a result our delta rhos over rho are somewhat less. What you'd expect to see in Palisades is something on the order of 10 percent or more.

CHAIRMAN WALLIS: That's when we get into the question of when you get a big enough delta rho do things change significantly, or is it still the same?

MR. REYES: Is there a transition somewhere. So that's just a -- just as a qualifier.

We're fairly close. I mean .18 is relatively typical. But I think for Palisades plant we're going to see they start up at a higher temperature, 570 and -- or hot leg 570, the cold leg 530. So they're 530, we're at 420. So there is some difference.

CHAIRMAN WALLIS: But it's not as if you're way off.

MR. REYES: Right. That's right. Okay.

CHAIRMAN WALLIS: And if you have a good theory, then maybe extrapolating it that far isn't too bad.

MR. REYES: That's not so bad, no.

Okay. So concluding with this one, what we saw was that the downcomer plumes were -- we saw it both for the stagnant case and natural circulation flow conditions.

For the range of natural circulation flows we examined from one and a half percent to four percent decay power in this test number 3 and about 30 to 100 percent HPSI flow.

The plumes were, for all those cases, they were well mixed by about four cold-leg diameters, is what we saw. Okay. Everything was relatively back to the ambient temperature.

CHAIRMAN WALLIS: How does that compare with what we started out with? You know, we started out with a theoretical plot for the infinite plume. You said Rodi or someone has all these different conditions.

Does yours fit in in any way with the classical experiments with isolated plumes?

MR. REYES: With the -- we haven't -- right. We haven't done that comparison yet.

CHAIRMAN WALLIS: But this seems to be a very rapid mixing.

MR. REYES: It's a very rapid mixing. We haven't -- my first thought was to use the co-flow work and the isotonic models to compare, just to see if that makes a difference. But I haven't done that yet.

But we have done calculations with REMIX and with STAR-CD, our CFD codes, to try and see if we can predict some of the meandering behavior in some of the --

CHAIRMAN WALLIS: This is funny, because jets are sort of well mixed by 10 diameters, aren't they? And you'd expect plumes to go further because the buoyancy is driving them. So it's kind of surprising that four diameters are enough to --

MR. REYES: To mix this --

CHAIRMAN WALLIS: -- to wear out these

plumes.

MR. REYES: These are -- again, this is for the flow rates that we're looking at. And, again, for the CE Plant that they're a very low injection flow compared to what we see in other plants, so...

Dave suggested that --

CHAIRMAN WALLIS: Well, it may well be -- excuse me -- but the actual plume, when it starts out, is much smaller than --

MR. REYES: I know, just --

CHAIRMAN WALLIS: -- the whole cold-leg diameter.

MR. REYES: Right. That's right.

CHAIRMAN WALLIS: For instance, this spills out --

MR. REYES: That's right.

CHAIRMAN WALLIS: -- and maybe you should take -- if you took a quarter of a cold leg diameter, this would look like 16 diameters.

MR. BESSETTE: That's right, yeah.

MR. REYES: That's right.

CHAIRMAN WALLIS: Maybe that makes more sense.

MR. BESSETTE: It's not evident that the cold-leg diameter has any particular significance.

MR. REYES: Okay. Today --

CHAIRMAN WALLIS: Well, it's **a** way of scaling things, isn't it? It's just...

MR. REYES: You're right. It's a good idea.

Today when we run the test I'll need someone take a look in the tank and I think, you know, we'll be able to see as it pours into the sides of the -- I think you're right. It doesn't fill the pipe.

CHAIRMAN WALLIS: We'll see a plume?

MR. REYES: You'll see a plume. Well, one person will.

CHAIRMAN WALLIS: Only one person, no independent check on that?

MR. REYES: That's right.

CHAIRMAN WALLIS: One person goes in the tank and looks through the wall?

MR. REYES: One in the tank.

Okay.

CHAIRMAN WALLIS: Do you need a volunteer?

MR. REYES: Well, we've got two.

Okay. Are any other questions on what I've presented?

(No audible response.)

MR. REYES: If not, then we'll move to the next presentation.

Brandon is going to talk, Brandon Haugh will be talking a little bit about what we saw for these force flows or natural circulation flows, what we saw happening in the downcomer that was a bit different than when you had the stagnant flow.

MR. HAUGH: Just give me one second here.

DOWNCOMER THERMAL STRATIFICATION IN APEX-CE

MR. HAUGH: Good morning, everybody. My name is Brandon Haugh. I'm a graduate student in the Department of Nuclear Engineering. I'll be giving you a presentation on downcomer thermal stratification we observed in our CE Tests in the APEX facility.

I am going to talk about a description of what downcomer thermal stratification is. I have a diagram and some tests from the IVO facility in Finland, observations of what we saw in our test facility. And we're also going to run another one of those transient temperature maps that we saw in a previous presentation, and it will help to easily demonstrate what thermal stratification is. And then I'll come to a few conclusions.

The figure here is rather dramatic. It doesn't actually look that stratified. This is just for an appearance of -- it looks good in black and white, so we'll leave it at that.

And the plume isn't this concentrated. It obviously spreads and dissipates some. But you'll see that there's co-flow of velocity in the downcomer and velocity in the plume when we see a stratified layer in the lower portion of the downcomer.

We observed in our tests that this occurred in the presence of natural circulation flow. It didn't happen in any of the stagnant cases. And it seems the co-flow of the downcomer fluid stream in the plume reduces the mixing and seems to permit the onset of downcomer thermal stratification.

It seems to help confine the plume, and it seems to just go to the bottom and start cooling the bottom and working its way up.

These figures here are taken from the IVO facility. I would say the full name, but I would probably butcher it.

This is from Test Number 102. In some of the tests they used photography so it was just not all artist rendition. But for this test they had one injection in one cold leg and then cold-leg flow in a different cold leg. But it was a rather high flow rate, so you can see it's pretty dramatic, the stratification they see --

CHAIRMAN WALLIS: Well, that plume isn't mixing much at all, is it, unless I'm mistaken.

MR. HAUGH: Yeah, exactly. There's a 66 gallons per minute cold-leg flow and 6.6 gallons per minute HPI flow. So this is much larger than we see in our facility.

CHAIRMAN WALLIS: What we see on the left is --

MR. HAUGH: Yeah. You'll see the plume almost penetrates fully to the bottom.

CHAIRMAN WALLIS: The plume doesn't seem to spread at all.

MR. HAUGH: Yeah, exactly. And that's kind of the argument of the co-flow case. It seems to help confine the plume.

And you'll see the stratification. I mean it's rather dramatic because of the dye. You can't really tell kind of how much it mixed at the bottom.

CHAIRMAN WALLIS: Then you say, "Temperature gradient observed in the downcomer" are similar?

MR. HAUGH: Yeah, we see similar in our facility, but it's not quite as dramatic.

CHAIRMAN WALLIS: What's this? I would think that you'd actually get cold temperatures lower down with that, a plume like that.

MR. HAUGH: Yeah, that's what we see. You know, in the transient temperature map you'll see that we don't seem to catch the plumes due to maybe our thermocouple spacing or it jumping and may be sticking to the core barrel side. But we definitely see the stratification. Okay.

For the test that we ran, an integral systems test, and some of the separate effects test, this is just kind of a map of what we did and what we saw related to downcomer thermal stratification.

The first three, 4, 5, and 6, were the stagnant cases with no cold-leg flow. And we observed basically no downcomer thermal stratification.

In tests 7, 8, and 9, those were the small break LOCAs, where we had natural circulation flow in at least some of the cold legs, we did observe some downcomer thermal stratification.

CHAIRMAN WALLIS: And by "thermal stratification," you mean temperature as a function of z, or as a function of Froude? So the pool --

MR. HAUGH: Yeah, in an axial measurement. So from the bottom of the lowest point --

CHAIRMAN WALLIS: -- a pool of cold s- --

MR. HAUGH: -- in the downcomer to the

top.

CHAIRMAN WALLIS: Why doesn't that wash out when you have circulation?

MR. HAUGH: That's -- we don't quite -- I don't quite understand that. I think Dr. Reyes might be able to field that.

MR. REYES: What we've got is a relatively low natural circulation flow. And that's introducing the hot water into the top of the downcomer. And that water is -- at the bottom you do see some of that, that mixing occurring. And so it's constantly replenishing that mixing region which is a little bit lower in the downcomer.

CHAIRMAN WALLIS: So the hot water is getting out by mixing with the cold, presumably. Otherwise --

MR. REYES: Right. That's right.

CHAIRMAN WALLIS: -- it would --

MR. HAUGH: You'll notice that the stratification we observed isn't very significant in terms of the delta T, from 8 diameters to 1.3 diameters; in tests 7, 8, and 9 it was between 35 and 40 degrees Fahrenheit.

In Test Number 10 -- that was a combination test of a safety relief valve in the pressurizer and an atmospheric dump valve on the steam generator side -- we saw a little, of a slightly less stratification, but it was observed.

In the hot zero power main steam line break due to the -- we have no core power basically. Well, it was very low, like 45 kilowatts, we weren't replenishing the hot water in the top of the downcomer. So we didn't observe the thermal stratification. It appeared to be relatively well mixed.

In Test Number 12 in the main steam line break from full power while the steam generator was blowing down, the downcomer was relatively well mixed because the cold legs feeding in were relatively cold from the broken side.

But after the steam generator finished flowing down and we started reheating the plant after we repressurized, we saw the onset of thermal stratification because we started feeding hot water into the top of the downcomer. But it was very minor and not significant delta T from the top to the bottom.

This is a snapshot of one of the transient temperature maps from Test Number 9, which was a stuck-open safety relief valve on the pressurizer.

This is the initial conditions. We can see it's relatively all the same temperature. I'll move quickly to the next slide.

This is 3500 seconds into the test, and it's pretty obvious to see. You can see the stratification in the downcomer. It's easy to note that it's, you know, only 30 degrees Fahrenheit, but it is there.

Later on in the test we can see that the bottom is cooling up, but we're still replenishing hot water due to the core power to the top, so it's stratified. But the stratification layer is getting much closer to the cold legs at this point.

CHAIRMAN WALLIS: With the stratification that high it really kills the plume, doesn't it? The plume goes right into the --

MR. HAUGH: Yeah, we --

CHAIRMAN WALLIS: -- stratified thing, and then --

MR. HAUGH: In the facility and in some of the plots that we don't have. But when we play the transient temperature map, you can -- you won't even notice that there's a plume there. It just seems that you just see the stratification, and that's about all.

And then for Test Number 6, which was one of the stagnant cases where we didn't observe thermal stratification, this is about 800 seconds into the test, you can see that it's all relatively well mixed.

And at this point the delta rho over rho is a -- well, the delta rho between the downcomer fluid and the plume is relatively low, so you don't really see much plume activity, either.

And now we'll play the transient temperature map from Test Number 9. And I'm starting about 2,000 seconds into the test, because that's when it's easiest to see this onset of the stratification. And you can see that the bottom is slightly colder than the top. And it'll build as it runs.

You can also notice the stratification in the cold legs from the injection. And it seems to be pretty much -- above the Weir wall height it's relatively constant temperature fluid. But due to the side injection below the Weir wall height it's stratified.

And when you've seen enough, just let me know.

CHAIRMAN WALLIS: If you gave each one of those dots a note you could play music.

(Laughter.)

MR. HAUGH: Next time.

And as you can see, it's starting to cool as we go up. That's probably... I mean would you like to see more? It's entertaining.

That's probably enough, Kent.

Just click on "Resume Slide Show" up above. There you go. Okay.

Now that we've seen that, I hope it was entertaining.

So the conclusions about downcomer thermal stratification, DTS, we observed it in the APEX facility in tests where we had natural circulation. And we noticed it did not occur in the stagnant loop cases or when we had a very high cool-down rate, such as in a main steam line break.

But after the blowdown ceased in Test Number 12, when we started reheating, we saw the onset of thermal stratification.

We have come to the conclusion that a probable mechanism for downcomer thermal stratification is the co-flow of the downcomer fluid stream and the plume, which tends to preserve the plume and helps it get to the bottom.

And also we have the replenishment of the hot fluid from the core power heating up the top of the downcomer.

CHAIRMAN WALLIS: There's more to it than at that time, though, isn't there? I mean it somehow has to go through almost a shock wave. The plume comes down and then it all mixes up in this colder thing at the bottom.

MR. HAUGH: Yeah, there's a mixing -- with a thermal stratify decay there's like a mixing -- there's probably some penetration.

CHAIRMAN WALLIS: I would think you'd have to explain that. It's not just a fact that the plume is helped by the co-flow. Why does it stop? Why does this mixing occur at that level?

MR. HAUGH: That's a good question.

This was just a preliminary conclusion. There's obviously more mechanisms present that -- there's the plume interaction with the thermal stratified layer also hitting the core barrel. There's several other things that will probably need to be examined to further define this phenomena.

That concludes my presentation. Is there any more questions I can field?

(No audible response.)

MR. HAUGH: Okay.

CHAIRMAN WALLIS: Well, we're looking forward to a really good theoretical model.

MR. HAUGH: And the work is in progress.

(Aside comments off the record.)

CHAIRMAN WALLIS: I think we have one more presentation before the break.

MR. BOEHNERT: That's correct.

REMIX CALCULATIONS OF APEX-CE TESTS

MR. YOUNG: My name is Eric Young. I'm a graduate student here, a graduate student of Dr. Reyes. I'd like to take this opportunity to thank Dr. Reyes for giving me this opportunity for presenting in front of the council -- or the Committee.

I'll be presenting on the REMIX calculations or predictions on the STAR- -- or on the APEX-CE facility. The presentation will progress in the following manner.

I'd like to describe the objectives of the study; go through a description of the REMIX model; a description of the APEX-CE stagnation tests that we did a comparison with, these being Tests 4, 5, and 6; some insight into the effects of the core barrel heat transfer and effective thickness; and the recommended summary -- or summary and conclusions.

The objectives of the study was to benchmark STAR-CD against the integral test facility, this being the APEX-CE facility here at Oregon State

University; identify any of the code limitations in predicting downcomer and well-mixed temperatures at an integral test facility; --

CHAIRMAN WALLIS: You said STAR-CD, did you, or REMIX?

MR. YOUNG: Did I?

MR. REYES: Yeah, REMIX.

MR. YOUNG: REMIX. Sorry. I worked on both things. I might put the two together sometimes.

...benchmark REMIX against the APEX-CE facility; and assess the applicability of the code for integral system geometries.

The REMIX Computer Code is used for calculating well-mixed core inlet temperatures along with downcomer temperatures in any specified locations below the cold-leg injection into the downcomer.

It's based on the regional mixing model originally designed by Dr. Theophanus and is described in the following figure.

CHAIRMAN WALLIS: Dr. who?

MR. ROSENTHAL: Theophanus.

CHAIRMAN WALLIS: Theophanus?

MR. YOUNG: And it's described in the following figure. This is out of the REMIX Manual.

It assumes that the cold stream originates at the high-pressure safety injection site, forming a cold stream along the bottom of the cold leg, which then flows towards the downcomer and the loop seal portions of the primary system.

At these two jump locations it generates a buoyant plume, which decay into the loop seal and into the downcomer. Most of the mixing -- or the mixing is most intense at certain mixing regions, and these are the regions that REMIX calculates mix and entrainment, which it uses to then determine the cold stream temperature that enters into the downcomer, and it also does a global system calculation for the well-mixed temperature inlet to the core.

CHAIRMAN WALLIS: Is there some kind of coefficients which describe the mixing --

MR. YOUNG: Yes. Yes, sir. This is --

CHAIRMAN WALLIS: -- which are different in the different regions and determined in some empirical way?

MR. YOUNG: I'm sorry?

CHAIRMAN WALLIS: Are they determined empirically, these mixing coefficients?

MR. YOUNG: Yes, sir.

CHAIRMAN WALLIS: So the data are made to fit these experiments, or...?

MR. YOUNG: It was pitted against --

CHAIRMAN WALLIS: Some similar...?

MR. YOUNG: It was originally validated against the Creare one-fifth, I think, scale test, and it was again modified using some mixing experiments at Perdue University, I believe.

MR. SCHROCK: Could you go back and explain this pump? What is this description of the pump all about? I don't understand it.

MR. YOUNG: Okay. In REMIX you're able to specify a certain pump volume in the pump heat transfer area to take into account any contribution that the pump material or structure would have in contributing to the temperature of the system, of the coolant inside the system.

It's an option allowed in REMIX.

MR. SCHROCK: I don't understand what this diagram is intending to convey with a stratification situation. It looks like it's spilling over in a reverse flow and then an arrow showing something else moving forward.

MR. YOUNG: Okay. In the calculation of the amount of mixing entrainment from the cold stream, there needs to be a countercurrent hot stream flow from the downcomer and the loop seal portion.

The countercurrent flow from the loop seal portion is generated from the inventory that's in the loop seal during the injection and is then mixed with a cold stream.

The cold stream was injected from the high-pressure safety injection location and flows towards both ends of the cold leg.

The hot stream that finds the mix and entrainment region flows from the upper downcomer -- the upper plenum in the downcomer into the top of the cold leg. And that finds the mix and entrainment at the falling plume location, which is the high-pressure safety injection location.

CHAIRMAN WALLIS: So these MR 1, 3, and 4 are the areas which have some kind of a coefficient to describe mixing, which is different for each region?

MR. YOUNG: Yes, sir. These are regions that are assumed to be determinant in how much mixing occurs between the cold stream and hot stream. Any mixing at other locations of the system are negligible.

It's assumed that there is a stationary interface between the cold and hot streams on -- in any locations, other than these mixing regions.

MR. SCHROCK: MR5 is insignificant or

significant?

MR. YOUNG: MR5 is calculated in REMIX, and the only insignificant mixing region is MR2. It isn't shown in this map, but it's between the high-pressure safety injection and the vessel in that length of cold leg.

Okay. Some of the limitations of the --

MR. SCHROCK: The code chops this up into elements and calculates something? It's kind of a sketchy description of what the code is.

CHAIRMAN WALLIS: I presume it has nodes and --

MR. BESSETTE: Volumes.

CHAIRMAN WALLIS: -- cold volumes.

MR. YOUNG: Yeah. In the -- in order for REMIX to calculate the temperature transients at the downcomer locations and the well-mixed temperature transient at the core inlet, it is required that you specify certain volume, the total volume, participating volume, of the system; the total mixing volume of the system, which is considered to be in well-mixed conditions.

Any material structures that are masses indirectly specified by their wall thickness and their material properties, which is the conductivity and the diffusivity of the material structures, which allows any conduction calculation to be calculated along with the transient temperature of that material.

MR. SCHROCK: Okay. I'm exhausted.

MR. YOUNG: Is that sufficient?

CHAIRMAN WALLIS: I presume there's a document somewhere that describes REMIX.

MR. YOUNG: Yes, there is, sir. I have two REMIX Manuals, if you'd like to look at them.

MR. BOEHNERT: We can get that for you as soon as you get back to the office.

CHAIRMAN WALLIS: Yet another code to review.

(Laughter.)

MR. SCHROCK: I'm not sure I'd like to review it, but I'd like to be reminded of something that I did look at more than 10 years ago. I'm not getting very much from this.

MR. BOEHNERT: I'll get you a copy.

MR. BESSETTE: You might say that each of those mixing regions that are labeled, you might say, are distinct calculations that REMIX does.

MR. YOUNG: It predicts -- a plume is assumed to be developed within two diameters down from the cold-leg injection. This temperature is calculated and many other specified locations in the downcomer which are desired are then calculated from this location.

And then a lumped parameter calculation is made to determine the well-mixed core inlet temperature, which is simply an exponential decay to a stable temperature.

Some of the limitations of the code in the version that we're using. The version that we used for the comparison is the code -- is the 1986 version. And some of the limitations in this code is that it was not designed to predict the effects of multiple plume interactions.

It's not designed to predict temperatures or calculate temperatures in the presence of cold-leg flow. The only output that's available from this REMIX is the cold centerline temperatures and the core inlet well-mixed temperature.

You can't specify locations that are any different as a myth of location, so -- in between two of the cold-leg injections; it's only along the centerline.

And it doesn't predict plume velocities or any other flow characteristics. It uses a fixed-heat transfer coefficient, which we'll see later to be negligible or really not that important in the calculation.

And it does a 1-D conduction heat-transfer analysis in the metal structures.

The three tests that we compared with REMIX were tests OSU-CE-004, 5, and 6. The superficial Froude number for these tests range anywhere from .019 to .0402.

The temperature difference between the high-pressure safety injection and the primary inventory gave delta rho over rho values of .18.

Between the three tests, the first test, 004, only had one injection location, where Tests 5 and 6 used all four high-pressure safety injection systems.

CHAIRMAN WALLIS: Q_{hpsi} is per injection?

MR. YOUNG: I'm sorry, sir?

CHAIRMAN WALLIS: Q_{hpsi} is the flow rate per site, so we have --

MR. YOUNG: It's per site.

CHAIRMAN WALLIS: Okay.

MR. YOUNG: And in the case of four high-pressure safety nozzles being operated it's an average flow rate between the four, because there is some variance between them.

The input data to describe the APEX-CE facility model in REMIX was created by specifying the volumes for the -- in the one high-pressure safety injection case the entire downcomer and lower plenum was considered as a portion of the total volume.

In the four high-pressure safety injection case, the lower plenum and downcomer region was partitioned into four equal volumes.

The material properties for the structures, which I mentioned before were the conductivity and diffusivity, were specified: The HPSI flow rates and relative flow temperatures or fluid temperatures; initial system temperature; heat transfer areas in each of the regions along with their respectful heat transfer coefficients.

CHAIRMAN WALLIS: You input those; they're not calculated in some way? You just put some number in?

MR. YOUNG: These are variables that you have to put in to describe the facility to REMIX. So you have to specify a certain amount of volume that you consider to participate in this calculation. And a well-mixed volume, which I mentioned, is considered to be well mixed during --

CHAIRMAN WALLIS: Well, how do you figure heat-transfer coefficient?

MR. YOUNG: The heat-transfer coefficients that I calculated were calculated using analytic plume velocity in the downcomer region. And in the cold leg I used the flow rate over the area of the cold stream for that velocity.

CHAIRMAN WALLIS: These are just at the wall; they're not between streams, aren't they? Just at the wall?

MR. YOUNG: This is not between the streams.

MR. SCHROCK: I thought David told us that's essentially infinite heat-transfer coefficient.

MR. YOUNG: That is -- we did a heat-transfer coefficient sensitivity, which I'll show you towards the end of this presentation, and it's fairly insensitive to any changes in heat transfer.

In calculating -- or in properly describing the REMIX facility or the APEX-CE facility with REMIX, we considered the core region to be participating in the heating of the downcomer fluid.

As you can see in the figure in front of you that there is a ceramic annulus, which is of nonuniform thickness, around the core. It's directly in contact with the core barrel and supplies energy to the core barrel for heat transfer to the downcomer.

In order to maintain a correct description of the heat conductance in our -- during our test, we used an equivalent material which would include the downcomer stainless steel and the ceramic of the reflector.

We considered these to be homogeneously mixed. And we calculated an effective thermal conductivity for this material to specify in REMIX. And then we increased the core barrel thickness to include the thickness of both of the materials.

This is to account for any energy stored in the reflector that is available for heat transfer to the downcomer fluid.

Now I'd like to show you some of the comparisons between these four -- three tests.

CHAIRMAN WALLIS: So even in the transient you can use just conduction here to the core barrel reflector?

MR. YOUNG: Yes, sir. We gave -- we specified an effective diffusivity so that REMIX would be able to calculate the temperature transient of the material and from that the heat transfer to the downcomer fluid.

And the heat-transfer coefficient was

again the calculated heat-transfer coefficients used in the plume velocities.

In the first graph, this is the core inlet well-mixed temperature for Test 4. This is with one HPSI being operated.

As you can see, REMIX underpredicts the temperatures at all the locations within 40 degrees of the actual well-mixed core inlet temperature.

CHAIRMAN WALLIS: Well, the well-mixed temperature is simply mixing the fluid and having some heat transfer from the wall to change it?

MR. YOUNG: Yes, sir.

CHAIRMAN WALLIS: And so the only variable really is the heat transfer from the wall. The mixing is this first law conservation of energy.

MR. YOUNG: Yes, sir.

CHAIRMAN WALLIS: So what, so the difference is presumably in getting the heat-transfer coefficient right.

MR. YOUNG: It is in correctly modeling the amount of heat transfer that the --

CHAIRMAN WALLIS: Right.

MR. YOUNG: -- core region contributes to the downcomer.

In REMIX calculations and in the Manual

it's recommended that a core barrel thickness be specified. This is specified in any previous literature with validation. Only the thickness of the core barrel itself was described.

It's seen in some of these plots that a portion of the core region and energy stored in the material and possibly even some of the primary inventory in the core region is contributing to heat transfer through the downcomer region.

This next plot is a temperature comparison between 1.3 cold-leg diameters below the cold leg injection into the downcomer for the case of one high-pressure safety injection being operated.

Again, REMIX initially underpredicts the temperature of the plume at the location and throughout the entire test. It's within 60 degrees of the actual calculations.

CHAIRMAN WALLIS: But REMIX is predicting far bigger temperature differences than you actually get.

MR. YOUNG: Yes, sir.

CHAIRMAN WALLIS: So it seems to be way off, rather.

MR. YOUNG: Well, it's much more accurate in predicting a four high-pressure safety injection case than it is a single high-pressure safety injection case.

I think this is due to -- maybe I'm not completely understanding the mixing volumes that are participating in the one case.

This is for four cold-leg diameters below the cold-leg injection into the downcomer. And again REMIX underpredicts the temperatures within 40 degrees.

The same calculations were carried out previous to increasing the core barrel thickness to include the mass.

CHAIRMAN WALLIS: Excuse me.

MR. YOUNG: Yes, sir.

CHAIRMAN WALLIS: I think that Professor Reyes showed us that this 4-D temperature is very close to the mixed temperature.

MR. YOUNG: In the facility?

CHAIRMAN WALLIS: Yeah, right. So that, in fact, REMIX is getting the mixed temperature wrong. It's really giving it a tremendous difference. It very well matters really. So the difference between the 4-D temperature and the mixed temperature, is what you're worried about, which we know to be very small. So REMIX --

MR. YOUNG: After approximate- -- yes, sir.

CHAIRMAN WALLIS: -- on that basis is way off, isn't it?

MR. YOUNG: Yes, sir.

MR. BESSETTE: And you'll notice the offset seems to occur from time, from your initial time.

MR. YOUNG: We noticed in the stagnation cases that after approximately 500 seconds into the test the plume had seemed to have been completely diminished.

So at that point REMIX doesn't calculate any other flow configurations which would enable it to determine whether or not the plume existed.

The next --

MR. ROSENTHAL: Yeah, if you'd just flip back one slide. So this is the centerline, roughly? This is along the centerline?

CHAIRMAN WALLIS: It probably gets too cold, the plume just coming out of the pipe.

MR. BESSETTE: That's right. I think that's what the problem is. If you -- I -- you know, what REMIX does for this, if you go back to Viewgraph Number 4, what REMIX does for mixing Region 3 is arbitrary. And I think it's getting that --

CHAIRMAN WALLIS: It doesn't mix enough.

MR. BESSETTE: Yeah.

MR. ROSENTHAL: Okay. But, you know, last week and the week before we're running RELAP and REMIX calculations. And if you look at 4,000 seconds you see about a 50F difference on that graph. And so that's now something that we would start to see in the fracture mechanics stuff.

So the offset is important to us. And we had, you know, RELAP Code and REMIX Code. And we're scratching our heads whether we should believe any of it.

So now we've got some REMIX versus some experimental data, which will allow us to come to some conclusions about what we should do with the REMIX.

CHAIRMAN WALLIS: So your strategy might be --

MR. ROSENTHAL: So I'm just pointing out that, you know, where this fits in the grander scheme.

CHAIRMAN WALLIS: So your strategy might be to try to fix up REMIX to represent these experiments.

MR. ROSENTHAL: Or shuck it and go to CFD's stuff --

CHAIRMAN WALLIS: Or go to something else, yes.

MR. ROSENTHAL: -- that you couldn't have done in the mid-'80s.

CHAIRMAN WALLIS: All right.

MR. YOUNG: If you're able to --

CHAIRMAN WALLIS: If no one else wants to speak, is it your objective to just run REMIX and see how it does, or is it to fix up REMIX to be more realistic?

MR. YOUNG: Well, it was originally to use the recommended REMIX or the -- what REMIX recommended for the volumes and structural materials to see how accurately it could determine integral test facility with either a heated core region --

CHAIRMAN WALLIS: So then an assessment of REMIX, yeah.

MR. YOUNG: -- or mix.

An assessment. And in doing this, describe any limitations and fix these limitations that REMIX might have. And this was -- in my first attempt -- was to increase the core-barrel thickness to include any of the mass.

CHAIRMAN WALLIS: Right, right. So you are fixing it up, as well?

MR. YOUNG: I'm trying to -- I'm trying to find if REMIX is applicable to an integral test facility, since there are only basically two different conditions that can change the fluid temperatures. And that's the mixing and the thermal conduction from the wall.

CHAIRMAN WALLIS: Right.

MR. REYES: Now there appears to be limitations to what we're seeing in the experiment compared to what REMIX can predict.

You know plume interactions and things like that REMIX cannot do, so Eric's been working, of course, with STAR-CD. And you'll hear another talk on that, trying to see if we can come up with some better -- better tools to predict the behavior, because we think there are some limitations to what the code was designed to do.

It was really for a stagnant condition, a single plume. And he'll show you some more plots looking at one plume versus four plumes. But we see big differences in the behaviors -- in the calculation versus the behavior.

MR. YOUNG: As we've seen in a lot of the CFD calculations or we will see later on today, the ability for REMIX to predict the location of the coldest transient is almost impossible with REMIX, because it predicts only centerline temperatures.

We're finding our coldest downcomer or our coldest vessel-wall temperatures to be located between two interactive plumes after they have merged. So it's not really applicable to the case where there's more than one injection.

CHAIRMAN WALLIS: Now you're going to show us all the graphs. They all look very similar.

MR. YOUNG: I'll just show you a couple more, and I'll go on to the --

CHAIRMAN WALLIS: Right. Then go on to --

MR. YOUNG: -- transfer system.

CHAIRMAN WALLIS: -- improvements, such as bringing in the core barrel, or whatever.

MR. YOUNG: Yes, sir.

CHAIRMAN WALLIS: Thank you.

MR. YOUNG: I'll just flip through these quickly then to show you that REMIX does underpredict because it is, indeed, calculating that there is a plume there. That's inherent in the code.

Pick one of the well-mixed temperatures here. Here's a case where four injection -- HPSI injections were being operated. You can see that it predicts the well-mixed temperature or the coolant temperature much more accurately.

CHAIRMAN WALLIS: If it starts right it seems to do better.

MR. YOUNG: Yes.

CHAIRMAN WALLIS: It has to start right at the top.

MR. YOUNG: Yes.

Yet it still underpredicts the downcomer locations. These are more accurate. They're still under by 25 to 30 degrees.

One of the things that we found very important in these REMIX calculations was the effects of the core barrel or the core region or any materials in the core region that had stored energy that could be supplied to the downcomer.

We did a heat-transfer coefficient sensitivity study along with downcomer thickness, wall-thickness sensitivity.

In this first slide we varied the heat-transfer coefficient from 100 watts from *u* squared degree Kelvin up to 6,000 watts from *u* squared degrees Kelvin.

You notice that the difference in temperatures calculated for the core inlet temperature are very negligible. They're only within a couple degrees, maybe 5, 10 degrees.

This, indeed, is the case because, as David Bessette had mentioned, that we are conduction-limited and there are the skin effects of the heat transfer, removing the energy from the skin of the materials.

Yet when we vary the thickness of the core barrel to include the mass of the reflector, we see that we calculate temperature differences up to 35 to 40 degrees Fahrenheit. So the material or the energy stored in the core region is, indeed, important in these calculations.

MR. KRESS: So did you vary the mixing rate in the downcomer?

MR. YOUNG: That's not available in the code that I'm aware of, sir. I think it's hard-coded in it. They have I think a linear segregation of the plume from the injection location down to two diameters.

MR. KRESS: That would -- that would certainly be a way to bring the codes -- the cores together.

MR. YOUNG: If we were able --

MR. KRESS: Yeah.

MR. YOUNG: -- to understand a little bit more of how the mixing occurred and to introduce that into the code.

CHAIRMAN WALLIS: Now there's Mixing Regions 1 and 3 you need to do right. You have the starting condition right.

MR. KRESS: Well, he also gets -- needs to do it in the plume, because --

CHAIRMAN WALLIS: Yeah.

MR. KRESS: -- because that's why it cools -- cools off faster than --

CHAIRMAN WALLIS: But by now he's probably got four tuning coefficients. He should be able to do very well.

MR. KRESS: Yeah. You ought to be able to match it exactly.

(Laughter.)

MR. KRESS: He's only got one for the plume.

MR. YOUNG: So, in summary, the REMIX model was developed and applied for three of the stagnant loop conditions. In the comparisons for the one high-pressure safety injection operation, REMIX underpredicted both the core inlet and the downcomer locations.

For the cases of tests 5 and 6 where four high-pressure safety injections were operated, the predicted -- or calculated temperatures were much more accurate, yet REMIX still underpredicted all of them.

One of the reasonings behind the underprediction of the 1.3 location is again that we believe the cold stream entering into the downcomer jumps over this location, so the temperature or thermocouple in the APEX facility isn't reading the cold stream temperature. It's rather reading the wall -- near-the-wall temperature. And --

CHAIRMAN WALLIS: So you're saying in reality the plume jumps and REMIX doesn't consider this?

MR. YOUNG: No, it doesn't, sir.

And REMIX generally underpredicted all the fluid downcomer temperatures. One of the reasons may be that these locations -- the temperatures of the centerline of the plume isn't located below the downcomer injection but rather between two of the cold legs.

That about wraps up what --

CHAIRMAN WALLIS: So the question is what happens now. Are you going to keep working with REMIX?

MR. YOUNG: No, sir. I don't believe --

I don't --

CHAIRMAN WALLIS: You --

MR. YOUNG: I don't believe that REMIX is going to be able to consider all the physics involved in determining the downcomer temperature transients.

CHAIRMAN WALLIS: So your conclusion is that we should replace REMIX with something better?

MR. YOUNG: Yes, sir.

CHAIRMAN WALLIS: Okay.

MR. SHACK: Well, I mean if the -- if the temperature differences are always as small as they seem to be as in these experiments, I mean RELAP does just as well, doesn't it?

MR. ROSENTHAL: I think the point is that RELAP doesn't model the mixing. See, you wanted to explore this aspect. And we back on the East Coast tried REMIX also and we got offsets very, very similar to their showing, and they were enough to be important in the wrong direction.

We would have to have incorporated it into the uncertainty analysis that we passed on to the fracture mechanics.

And you do it -- you know, we did it because it's cheap and fast, and whatnot. But I think we'll have to make a decision with what we do REMIX now.

And the point was that you couldn't -- I mean Theo put it together to solve a problem in the mid-'80s. He just -- you didn't have the options you have today.

MR. YOUNG: We'll see in comparison to the CFD Codes that the calculated temperatures are not in the same accuracy of the CFD Codes.

Thank you.

CHAIRMAN WALLIS: Well, we have one more minute.

Anyone have anything more to say? NRC want to say anything more?

MR. BESSETTE: Well, I guess, you know, --

CHAIRMAN WALLIS: One minute.

(Laughter.)

MR. SHACK: Forty seconds.

MR. BESSETTE: You know, of course we wanted to run REMIX because this was a code we developed for PTS -- for the purpose of PTS analysis.

So, if nothing else, somebody along the line would have said, well, why don't you run REMIX. So we wanted to run REMIX against actual data and just to see how it does.

But like we said, you know, when we

developed REMIX in 1985 we couldn't do CFD analysis, but now we can.

MR. KRESS: And was -- REMIX was fitted to real data back in '85. What this is telling me is this data gives different results than the '85 data, presuming the REMIX --

MR. SHACK: The Creare one-fifth test, yeah.

MR. BESSETTE: Well, yeah. But, see, REMIX was always run against the fluid-mixing experiments, which were designed to look kind of like REMIX. They incorporated only that part of the system that REMIX models, so the cold leg and downcomer.

So that the experiments, the configuration of the experiments matched the part of the system that REMIX models. So maybe that helped REMIX to model those experiments.

And this system is more of a -- you have more of an integral system even when we're running these sort of separate effects kind of tests where we're just looking at the -- trying to focus on the HPI injection and the plumes.

MR. YOUNG: And I'd like to mention is --

MR. REYES: Get to a mic here, Eric.

MR. YOUNG: Oh, I'm sorry. This is Eric

Young. I'd like to mention that the facilities that REMIX was validated against didn't include any core region and were simplified plume geometries, a planar plume, and a rectangular duct, and didn't include any of the endless geometry or heat from the core region that we're seeing here. So it's not able to do that.

CHAIRMAN WALLIS: So I will declare a break and we will remix here at quarter to 11:00.

(Recess taken from 10:30 a.m. to 10:45 a.m.)

STAR-CD AND CREARE HALF SCALE BENCHMARK CALCULATIONS

MR. HAUGH: I'll dim the lights just slightly so you can better see the animations and everything in the presentation.

I'm doing a presentation on STAR-CD and the Creare half-scale PTS test facility benchmark calculations. My name is Brandon Haugh. I was here earlier.

The objectives of this presentation are to introduce the STAR-CD CFD Code and basically just a preliminary of what it is; a description of the test facility that was compared; a description of the tests that I ran and calculated; a description of the model, the computational maps that I generated; and a comparison of the results from calculation with actual data from the test facility.

And I will make some conclusions about how it compared.

CHAIRMAN WALLIS: Do you remember when the Creare tests were run?

MR. HAUGH: These half-scale tests were run, I believe, in 1987.

CHAIRMAN WALLIS: '87?

MR. HAUGH: Yeah.

Okay. Well, the objectives here are to benchmark STAR-CD; provide insights into the CFD Code operation to help with the APEX-CE simulations; and also to establish a learning curve for the STAR-CD Code.

CFD Codes are tricky to run, and so there's a lot of things that you learn along the way.

The STAR-CD CFD Code is from a computational fluid dynamics code. The acronym "STAR" stands for simulation of turbulent flow in arbitrary regions.

The code consists of three major components: A preprocessor/postprocessor called Prostar, which is where you build a mesh and it sets up the problem.

CHAIRMAN WALLIS: Does it have automatic

grid generation also to stuff that makes it easy?

MR. HAUGH: It does, yeah. It makes it easier. It's never easy, the CFE, but there's a package called ISM CFD, which will allow you to take a 3D like ProE-generated models and insert them and it will generate the mesh automatically.

For the purpose of this study we're kind of -- for the entire learning curve, I was using the built-in mesh generating tools and built it by hand.

There's the analysis package called STAR which is a Fortran Base Code that runs the problem and does the calculations.

And there's also a parallel computing interface called Pro-HPC, which is important in CFD because you need a lot of computational horsepower.

CHAIRMAN WALLIS: Is this one that converges on the answer; it does all kinds of iterations?

MR. HAUGH: Yes, it does a lot of internal sweeps --

CHAIRMAN WALLIS: And tells you what the residuals are or --

MR. HAUGH: -- for every iteration. Like it does sweeps --

CHAIRMAN WALLIS: Sometimes in these

problems it doesn't converge. I mean if the plumes are wandering around all over the place, it won't converge on any answer at all.

MR. HAUGH: Yeah. And it will let you know if it diverges. It produces an error file, and it will let you determine -- it will help you determine what parameters you might have set up incorrectly, or if your timed step was off, things of that nature, yes.

The code has the capability of handling many types of fluid flow, dispersed flow, and chemical reactions, compressible flow, moving meshes, all kinds of things.

The Creare half-scale test facility, which ran their tests in 1987, was built to not model any particular PWR but to be flexible with interchangeable cold legs and injections, to be able to do different PWRs.

The configuration used in the MAY-105 and -106 tests is displayed here to the right. On the next slide I will give you some characteristic dimensions since they didn't show up too well. But you can kind of see it's a planar downcomer, a cold leg that's horizontal, top injection with a loop seal and a pump simulator.

CHAIRMAN WALLIS: Because it's a downcomer with walls on the side, that's what restricts the plume, doesn't it?

MR. HAUGH: Exactly. Yeah. So it will make a difference. It's different than an integral facility or a full-scale plant.

Some of the characteristic dimensions from the test facility, the cold leg inside diameter was 14.3 inches. HPI inside diameter, 4.5 inches. Downcomer width, 63.7 inches. The gap 5.4. Thermal shield thickness, one and a half inches. There was a thermal shield in place, which also had a height of 100 -- let's see -- I forgot to put in -- of 95 inches. And vessel wall thickness for the core side and the vessel side of 2.75 inches, and that was carbon steel.

Now the MAY-105 test --

CHAIRMAN WALLIS: I think that was scaled so that it was big enough so that it was thermally thick and it didn't have to be any thicker.

MR. HAUGH: Exactly. Yeah. So you still had -- you had a conduction-limited period and 8 *d* back -- 8 *d* back period.

The test that was ran for the MAY-105 was a stagnant loop, 462 *k* or 189 *c*. That's 372 degrees

Fahrenheit.

It had a constant HPI injection flow of 5.17 ten to the minus third meters cubed per second, which is about 1.37 gallons per minute; at 14.2 degrees C, which is about around 70 degrees F.

The test duration was --

CHAIRMAN WALLIS: That's pretty low velocity.

MR. HAUGH: Yeah. It was still pretty low velocity. It was actually kind of comparable to the APEX test. The velocity for the injection ended up being about half a meter per second or about 1.6 feet per second. So not terribly high, but actually I think it will help compare to the APEX facility.

And test duration was a little over 2,000 seconds.

For the STAR-CD model a computational grid was generated using the built-in tools in STAR-CD. The resulting grid consisted of a little over 200,000 fluid cells and 60,000 solid cells representing the steel.

I'll show here, this is what the computational grid looks like, the red representing the fluid cells and then the yellow representing the steel. Sorry you can't see the refinement better.

It's kind of hard to get it on a PowerPoint slide, but you can see that the downcomer -- actually you probably can -- is far more refined than the loop seal or the cold leg, because I wanted to try to capture the plume behavior very well.

You can see the thermal shield in place. And I only inserted steel on the core side and vessel side of the downcomer since that was comprised of most of the volume.

CHAIRMAN WALLIS: Now your nozzle here, now their nozzle was more characteristic of a PWR, it wasn't just a pipe stuck in with a sharp corner?

MR. HAUGH: Exactly. Yeah, it has the gradient of a typical nozzle.

It's still a sharp edge. I didn't incorporate a smooth edge, so there's some difference there.

MR. SCHROCK: And you put your boundary condition for the injection back up in the pipe there somewhere?

MR. HAUGH: Yeah.

MR. SCHROCK: Is that what that shows?

MR. HAUGH: Yeah. Right at the top of the pipe here is where the boundary condition for the injection of the HPI was.

There was also a boundary condition here, but the velocity was specified as zero, so it did the correct pressure, back-flow stuff.

Now the outlet is different. You'll notice the lower plenum isn't the same as the test facilities. Theirs kind of came out here and was more -- it was triangular.

Due to the built-in mesh-entering tools in STAR-CD, that wasn't really a possible geometry to replicate. So I tried to preserve volumes as best as possible. And along with the curvature right here to promote the mixing.

MR. SCHROCK: And this grid is cylindrical in the downcomer?

MR. HAUGH: It's -- no, it's planar.

MR. SCHROCK: Planar.

MR. HAUGH: Yeah, which is what the test facility was, too.

MR. SCHROCK: Oh, yeah. That was an unwrapped in it, yeah.

MR. HAUGH: Yeah. And so the outlet is actually right here. You can't see it. It's actually more characteristic. It's right here. It consists of six cell faces which comprise within three percent the same area as the outlet of the standpipe on the Creare facility.

CHAIRMAN WALLIS: It's a constant pressure with a hydrostatic term or something there?

MR. HAUGH: Yeah. It's just -- it's treated as an outlet so it won't let it drain. Just kind of -- it's the same pressure as what the fluid is in the lo- --

CHAIRMAN WALLIS: And there's no -- there's no problem with reverse flow. The problem with outlets is if you can reverse flow it everything gets confused.

MR. HAUGH: The code will get confused if you have that, which I initially had, but I adjusted some parameters and no longer see that in my runs. But, yeah, there will be some problems with that.

Here's the volume comparison. I'm pretty close in most things except for the pump simulator, and that was user error. This was the first time I was running CFD and the first mesh I had ever generated. And so I was concentrating on the cold legs and the downcomer and basically the lower plenum and loop seal. And for some reason I lost my mind on the pump simulator, and that's a large part of the mixing volume there.

So you will be able to see the slight

discrepancies in the comparisons I'll show later, but --

CHAIRMAN WALLIS: So you're going to fix that?

MR. HAUGH: Yeah, I will. I was in the process of it. But due to the geometry and how the grid was, it became more time-consuming, so I couldn't get it done in time, but I will have better results for you.

The STAR-CD model inputs, you get to establish some parameters for the model to be able to run the problem, such as a turbulence model.

I chose to use a high Reynold's number, k-epsilon model but, as Dr. Wallis pointed out earlier, I didn't have a lot of experience in turbulence modeling, so it might not predict the correct interface in the stratified cold leg, so there might be some errors associated with that.

There are several different turbulence models that can be applied and any input that you can provide would be very valuable.

The density was treated just as a function of temperature, not pressure. It's basically a constant pressure system so it's isobaric, just function of the thermal expansion coefficient.

I used a time step of a quarter second. I ran 4,280 iterations for about half of the tests. Basically at that point in the test the facility was almost all the way cooled down and so we capture most of the important transient I think in this first part. I can run the rest of it, I was just under a time crunch --

CHAIRMAN WALLIS: My experience of CFD is it's pretty grid dependent.

MR. HAUGH: Yeah. Yeah, exactly. Your time step is related to your mesh size. And so this produced sufficient convergence for me that I felt the accuracy was okay.

I also used only an upwards difference numerical discreditization scheme. And so it's just a single-step first-order accurate method.

CHAIRMAN WALLIS: You're supposed to try sort of good refinement in various areas --

MR. HAUGH: Exactly.

CHAIRMAN WALLIS: -- and also to see if it makes any difference.

MR. HAUGH: Yeah. There's some gradients around the thermal shield that probably need to be refined, but as the first time in CFD, this is kind of my best effort at this point.

MR. SHACK: What were your run times like?

MR. BOEHNERT: The next page.

MR. SHACK: Oh, never mind.

MR. HAUGH: Yeah, I'm getting there.

It ran for 7.7 days on -- I ran it in parallel, so two processors. It's a Sun Blade 1000 work station, 750-megahertz processors, and one gig of RAM. It's a UNIX terminal.

The results I'm going to present here are some of the cold-leg stratification predictions, some downcomer temperatures. I have some animations showing the plume activity on both sides of the downcom- -- over both sides of the thermal shield, so the core side and the vessel side. It's pretty interesting.

And just a couple of snapshots of some of the convection circulation patterns around the base of the thermal shield.

For my cold-leg stratification comparison, there is a cold-leg raking in the Creare test facility 9.1 inches after injection towards the vessel. The rake is centerlined, the spacing being about 1.43 inches between thermocouples. And they're labeled 1 through 10 starting at the bottom.

This is the greater representation at that same location in STAR-CD, so you can see that my grid isn't quite encapsulating every thermocouple location. Sometimes two thermocouples will fall in one cell.

And also that I didn't have cells right on the centerline, so in my comparisons I used both cells. Since they were pretty close in temperature they'll both be on the box.

And I'll show you, I compared position 1, position 10, and position 4, which is right here, which is this set of cells.

For position 1, the bottom of the cold leg, I seemed to predict that pretty well in STAR-CD. It looks like it may be slightly under the average of -- read by the Creare facility, but the mesh was also pretty course, so I feel that it did a fairly good job representing that.

The next location of position 4, which is slightly below centerline, I still did pretty well. I even captured the step phenomenon that they captured in their data for the mixing --

CHAIRMAN WALLIS: The wiggles are the data, aren't they? The wiggly curve is the data.

MR. HAUGH: Yeah. The wiggly curve is the data, due to the splashing in the interface and stuff. And in my model, probably do the turbulence model, I don't see that kind of --

CHAIRMAN WALLIS: Now you didn't fudge anything? I mean you didn't change dials on the model, or anything? This is just straightforward using whatever's in the code?

MR. HAUGH: Yeah. I just specified a mixing length --

CHAIRMAN WALLIS: You didn't have to tune anything or --

MR. HAUGH: -- and a turbulent energy and that was all.

There's lots of knobs you can turn, but it kind of -- I think the kind of idea was, well, let's see just straight out of the box what kind of -- well, how good will it do. And it seems to do okay here, but you notice the next plot, this is the top of the cold leg, I seemed to not predict this very well.

Initially I do, but later I dip down pretty good. It's as much as almost 50 degrees Fahrenheit, so it's probably due to the mixing in my turbulence model in the cold leg.

And possibly the cell on the top of my pipe is quite large, and I didn't include steel on my cold leg. So there might be some conduction there affecting that. But I don't think it would bring it up quite so much. So there's a little bit of investigation that needs to be done into why I was so far off, considering the other two locations seemed to be pretty good. I just kind of still in the process of figuring it out.

For the downcomer temperatures I created an animation of the model to visualize the plume activity, which is a nice thing about CFD is it will give you some visualization which a lot of other types of codes can't.

The first animation is via the vessel side, which is the side that's important for pressurized thermal shock and the second is the core side.

CHAIRMAN WALLIS: Is there any other option in this k-epsilon model you might use?

MR. HAUGH: Well, I can specify different turbulent energies and mixing lengths. And I can also --

CHAIRMAN WALLIS: But you can't account for stratification, though, can you?

MR. HAUGH: There's different turbulence model I might be able to use.

CHAIRMAN WALLIS: Does it have effective thermal stratification on the turbulence itself? I don't think --

MR. HAUGH: No, it doesn't incorporate that.

CHAIRMAN WALLIS: It probably doesn't.

MR. HAUGH: Yeah.

CHAIRMAN WALLIS: That's well known to be a problem.

MR. HAUGH: Yeah.

CHAIRMAN WALLIS: All the CFD people will tell you it's a problem, --

MR. HAUGH: Yeah, but the --

CHAIRMAN WALLIS: -- but they won't give you much of a solution to it.

MR. HAUGH: Yeah. They're good at that. They say, oh, it can do anything, but maybe it won't do that, but they won't tell you why.

So -- yeah, so there's probably some work. The company that distributes this in the United States has been pretty good at working with us for support and stuff. And they're always interested in other things they could add to their code.

CHAIRMAN WALLIS: Do you mind if I show this to Creare?

MR. HAUGH: No, I don't mind at all. Yeah, that would be fine.

So I'll start the animation here. I recorded data every five seconds. And so to play the whole test it's playing rather quickly. But you can see that the plume activity on that vessel side isn't terribly significant in terms of the gradient on the side here. I mean really as the test goes on and it cools down, it's maybe 10 to 15 degrees Kelvin in the scale.

You can kind of see -- you can also see that the loop seal riser and the top of the downcomer don't participate in the mixing volume, which is expected.

CHAIRMAN WALLIS: A real illustration of sort of thermal waves are clearly different from the fluid flow direction.

MR. HAUGH: Yeah, exactly. It's --

CHAIRMAN WALLIS: And nothing's moving up in the downcomer.

MR. HAUGH: Yeah, so it's kind of neat.

CHAIRMAN WALLIS: This is distorted. Have you made the downcomer extra fat in order to show what's happening there?

MR. HAUGH: Well, I twisted it.

CHAIRMAN WALLIS: You twisted it? Ah, okay.

MR. HAUGH: Yeah. So it's --

CHAIRMAN WALLIS: So we're looking at different --

MR. HAUGH: -- a slightly angled so you can see the --

CHAIRMAN WALLIS: Okay.

MR. HAUGH: -- the cold leg and the downcomer.

Yeah. And these lines here represent the top and bottom of the thermal shield.

What was interesting to see is in the next animation that the thermal shield actually plays a big role. It seems that the plume comes out of the cold leg and hits basically right in the middle of the top of the thermal shield and kind of splits and washes back and forth. But it also has enough momentum that it seems to -- you'll see right here -- it impinged definitely more on the core side as the plume -- much more significant --

CHAIRMAN WALLIS: Oh, yeah, it goes a long way down there. Doesn't it?

MR. HAUGH: Yeah. But this is on the core-barrel side, where in the PTS phenomena we don't really care, so --

CHAIRMAN WALLIS: Hey, it looks like some sort of a dancer there.

MR. HAUGH: Yeah, but it is. It's still only like 20, 30 degrees Fahrenheit -- I mean Kelvin. But it is.

CHAIRMAN WALLIS: But that -- look at that, I mean that looks like a plume that's getting narrow at the bottom.

MR. HAUGH: Yeah. It is. It's not --

CHAIRMAN WALLIS: Accelerate.

MR. HAUGH: -- what you'd conventionally think of the rising. So it could be the CFD model and the turbulence or --

MR. WACHS: So it's a temperature probe -- that's just the peak temperature in the center is getting narrower.

MR. HAUGH: Yeah.

MR. WACHS: It's actually just sporadic --

CHAIRMAN WALLIS: Right. That's right. We're just looking at temperature.

MR. HAUGH: Yeah. When you come over this afternoon, I have much more information available. Like I can show you velocity distribution of the plume. And it's actually -- it does widen.

CHAIRMAN WALLIS: I think Walt Disney could really put that to music.

(Laughter.)

MR. HAUGH: We could make millions. Yeah, so it's pretty interesting.

Now for a comparison in the plots of the actual data, this is a map of some of the thermocouples in the Creare downcomer. They did have more in this row, but these are just the ones I chose for comparison, to not overdo you with too many plots.

I'm going to be comparing rows 5 and 9 just for -- to keep it brief.

In this plot I've included both -- there's thermocouples on both sides of the thermal shield in the center of the downcomer gap in that region. So I've presented both the vessel and the core side.

I think -- probably in black and white it's not very easy to see on the paper. It's a little easier in color here. The Creare is the blue and the pink. This is the row 5, column 7. So this is centerline below the cold leg. And then the STAR-CD data is the black and the red.

But you can see for the core side that STAR-CD seems to do pretty well. It even predicts some of the plume behavior. And due to the fact that I recorded data every five seconds, it's not going to get all the plume behavior, so just keep that in mind.

But it seems to do a reasonably well job. At the bottom here I'm slightly below, and that could be due to my mixing volume being slightly off. But on the vessel side I seem to be underpredicting what Creare does. I get the plume that he did pretty well, but as the test goes on, you'll see I'm below what the actual data presents. But I mean it's really not too bad. It's maybe --

CHAIRMAN WALLIS: Which would -- which would indicate there's really more mixing than you're predicting?

MR. HAUGH: That's kind of what I'm kind of leaning towards. Or it could be the mixing volume, and so my cool -- cool-down rate is a little bit faster than what it was in the real facility.

I'm working on producing these in a nondimensional format with the mixing volume or the mixing time on the bottom. And so I'm hoping that will clash the data a little tighter, but we'll have to wait and see.

This is pretty much the bottom of the downcomer, or really close, centerline as well. And you'll see that on the core side I'm pretty much right on until the end. And of course that comes back up, but I kind of stay down.

And on the vessel side I'm pretty much below the whole time.

The order of magnitude is not too bad. It's maybe 20 degrees Fahrenheit.

CHAIRMAN WALLIS: This is really quite good for CFD and the new problem --

MR. HAUGH: Yeah.

CHAIRMAN WALLIS: -- without any kind of tuning or --

MR. HAUGH: Yeah, without turning the knobs or anything.

CHAIRMAN WALLIS: -- tweaking.

MR. HAUGH: I mean relatively it's pretty good.

I mean in terms of the overall like a power plant operation, this is a much simplified model, with the planar geometry, stagnant loop, and just the injection. So --

CHAIRMAN WALLIS: And you've still got that piece that you modeled wrong, too?

MR. HAUGH: Exactly. So when I correct that I'm hoping the data will be much more agreeable, I mean given the fact that it's so good now, hopefully it should get better.

And here's the well-mixed temperature for the inlet of the core, which is -- which would be the standpipe temperature in the Creare facility, which is just the outlet of my model.

CHAIRMAN WALLIS: This is just a heat balance, isn't it?

MR. HAUGH: Yeah.

CHAIRMAN WALLIS: So you think you should get that pretty --

MR. HAUGH: Well, if my volumes are off, --

CHAIRMAN WALLIS: Yeah.

MR. HAUGH: -- you can see it right there. So I think when I nondimensionalize it and fix my models, I think it should be just about right on. So it seems to be meeting that pretty well.

Okay. Now for the velocities on the thermal shield, this is just kind of interesting to note. I'll kind of explain it a little more.

Now this is the opposite side of the plume entry. So the plum, the cold leg was not in the center of their planar section downcomer, it was more to one side. So on the opposite side of that at the bottom of the thermal shield, you noticed we have a convection pattern so we have upflow. So there's a cell that built inside of the downcomer.

Now if you'll look at the other side where the plume is we see the downflow, but there's still a slight -- a swirl on the core side right here. But I just thought it was interesting to point out. And the velocity magnitudes are given here. So it has decayed and slowed down a little bit because of the density difference.

This is also at 60 seconds into that transfer --

CHAIRMAN WALLIS: That could be a bit awkward because somewhere in that -- that swirl, on the edges of it, you've got stagnation points, --

MR. HAUGH: Yeah. Well, actually I --

CHAIRMAN WALLIS: -- and most-heat transfer correlations would --

MR. HAUGH: -- this is more looking this way. And I can show you later that these velocities are actually impinging the wall.

CHAIRMAN WALLIS: They are?

MR. HAUGH: Yeah.

CHAIRMAN WALLIS: They can't go through it. So somewhat there you've got a stagnation point --

MR. HAUGH: Yeah.

CHAIRMAN WALLIS: -- because you know it

devised. And so I think your heat transfer and your CFD would probably predict there's no heat transfer there or very, very low H.

MR. HAUGH: Yeah, it probably will. I do have heat-flux data that I didn't present here because it's very new, but I can show you later if you want to see.

Just to mention it, my heat fluxes that the CFD predicted were pretty -- on order of two in some locations greater than what the Creare reported. But their measurement was kind of, well, here's the thermocouple in the middle of the fluid. Here's the thermocouple at the wall, and they guessed the heat flux.

CHAIRMAN WALLIS: Now this is an instantaneous picture. If you did it 20 seconds later it would probably look quite a lot different.

MR. HAUGH: Yeah, it would look completely different given the transient case. I can show you an animation back in the lab if you'd like to see what it looks like. It's pretty interesting.

Some preliminary conclusions I made is STAR-CD is a benchmark against the Creare data for a first-case, rudimentary analysis.

The well-mixed temperatures were slightly underpredicted, but that's most likely due to my model's mixing volume being 6.7 percent less than the Creare facility. So I apologize for that. That's my error.

Predictions of plume temperatures in the downcomer compared reasonably well with the data. Considering that I didn't do much adjustments or anything, I felt it was reasonably good.

CHAIRMAN WALLIS: How long did it take you to get to the point where you actually could --

MR. HAUGH: I started doing this last summer, and so about a year. And I'm getting reasonable results.

CHAIRMAN WALLIS: And you ran it last week or --

MR. HAUGH: I ran it and finished a month ago.

CHAIRMAN WALLIS: A month ago, okay.

MR. HAUGH: Yeah. And I've been running jobs throughout and just -- just kind of -- initially I had my turbulence wrong because I was learning. And so as you learn, you go, oh, well, that wasn't very smart, and so you rerun it. And then it takes some time --

CHAIRMAN WALLIS: Did you learn on this or did you learn by running a lot of other problems first?

MR. HAUGH: Well, I kind of learned on this just seeing, well, that doesn't look right. And then with information from Adapco and Dan Wachs helping with the input, people with more experience than myself helped me do a better job at establishing the correct parameters for the model.

And it's probably a good thing to point out the CFD is largely an experience based kind of usage of the code. The more you learn about -- I mean because you need to know about a good background in turbulence and things like that to be able to apply phenomena in models to correct circumstances. So -- so I learned how to use STAR-CD using parallel processing, which was kind of interesting on its own.

Parallel computing is kind of relatively complicated. I'd like to acknowledge the computer support staff at the College of Engineering helping out with that. They did a great job.

But it was obviously -- the parallel computing helped me speed up the problem quite a bit.

And the benchmark calculations aided in the selection of turbulence models, the selection of the fusion links, and turbulent intensities for preliminary runs. You can see that things weren't quite as they were supposed to be.

And that's the end of my presentation.

CHAIRMAN WALLIS: If you look at various weather patterns you can see how stratification kills the mixing and you get distinct layers and they go a long way.

MR. HAUGH: Yeah. And something interesting that I was thinking might be able to help, this was kind of after the fact, is the Oceanography Department here does extensive meteorological research on vast supercomputers. And they might be able to give better insight into what models they use to represent stratification.

CHAIRMAN WALLIS: Yes. yes.

MR. HAUGH: Yeah. Well, thank you.

CHAIRMAN WALLIS: Thank you very much.

3-D CFD MODEL OF THE APEX-CE TEST FACILITY

MR. WACHS: Okay. I guess I get to finish up here. We're going to talk about the 3-D CFD model we used for the APEX-CE facility. And on this work I worked with both Eric Young and Brandon. And we got quite a bit of help from the Adapco folks for the U.S. distributors for computational fluid dynamics.

I'm a grad from Oregon State. I'm now at

Argonne, so I have to do a little shift in gears from sodium pool fast reactors back to water reactors. I think I can make the switch.

First off, I'll talk a little bit about what our goals were with this model.

We wanted to explore the potential of CFD modeling, to treat some of these individual phenomena that we were seeing in the reactor out there that we didn't think codes like RELAP and REMIX were going to be able to capture.

And to do that we chose one particular test, we chose the OSU-CE-3 test to try to model and see what we could come up with. After I talk about that a little bit I'll talk about our particular model and the components we included in the model and things we did with that.

I will look at a couple of the phenomena that we were able to observe in both the model and the APEX facility, including stratification of the cold legs, comparison of the core inlet temperature, the downcomer temperature profiles. And then we'll try to extrapolate to some -- some data that they used in the Creare facility with some models they used to look at plume velocities and heat-transfer coefficients. I will summarize that.

And then after that we'll speak just a little bit about some of the lessons we learned on CFD.

On this particular test the objective was to look at cold-leg stratification and the downcomer profiles. And that's why it was a good one for us to attack with CFD. In the particular test the reactor coolant pumps were turned off and natural circulation was driven entirely by -- by core decay heat.

We did a couple of different tests, and this is the one Dr. Reyes showed where he had five or six different stratification plots.

We chose to go with the 200-kilowatt case because that gave us the greatest amount of stratification experimentally, and we wanted to see if we could capture that.

Describing the model, it's -- the objective of the model is to capture all this thermal hydraulic behavior in just the cold legs and the downcomer. But in order to do that we had to include some of the peripheral pieces of the facility for either reasons of convenient boundary conditions or we thought that it might be participating in behavior to a certain extent.

In particular, for inlet conditions we

needed to include the loop seal and the HPSI. We couldn't inject directly into the cold leg; you weren't going to get a real good profile.

And we had to assume adiabatic walls outside of the model.

CHAIRMAN WALLIS: You had to assume that?

MR. WACHS: Well, you don't have to, but you can -- you can specify heat fluxes on the walls. But you're not necessarily going to know those beforehand.

CHAIRMAN WALLIS: Unless you model them. Didn't we learn from some of the earlier presentations that the heat transfer from the wall matters?

MR. WACHS: Oh, yeah. Oh, yeah, we have the wall included and we have the outer vessel wall included. But on the outer vessel wall.

CHAIRMAN WALLIS: Oh, the outer of the outer vessel wall altogether.

MR. WACHS: So convecting off to the environment. Right. So it's insulated, but there's still a certain amount of convective loss.

CHAIRMAN WALLIS: Oh, I see. I thought you meant --

MR. WACHS: Yeah.

CHAIRMAN WALLIS: -- the inside, too. So, no. No, your -- where it matters you actually modeled the heat transfer.

MR. WACHS: Yeah -- well, yes and no, because we included the outer wall but not the inner wall, and that shows up as a problem later on. That's something that would certainly be added in the future.

The boundary conditions we treated in this particular test. I think that's a typo on the initial temperature. I think it was closer to 400 Fahrenheit. But the loop-flow rates, in cold leg 3 we had 14 gallons per minute in the HPS -- or through the loop, and 12 in the other cold leg. The HPSI lines were about a half gallon per minute and a gallon per minute.

And these were extracted directly from the test facility. So we ran a test, got our boundary condition and applied it to this -- to this model.

Now here's a picture of the model. You can see the two cold legs on each side. We have a loop seal attached to each. The HPSI lines are coming in at an angle on the horizontal plane.

We have the downcomer. We have the full region of the downcomer. And in the center we had to include pieces of -- well, we had to include the core region in order to keep away from numerical problems with changing directions and backflow, which Dr. Wallis mentioned earlier.

And we also have a half of the core vessel overlayed on top of that as solid cells.

One thing that's important to note, though. Since we were initially just treating the internal core region as a stop gap for numerical problems, it's adiabatic, those cells are not connected. Okay, so there's no communication temperature-wise between those two regions.

Now here's a closer look at what we used and where we assigned boundary conditions. Here's the cold leg, and we assigned a boundary condition right at the edge of the HPSI line directly from our facility. The HPSI line is long enough so we can get a pretty full developed flow and get a good idea of what the mixing may be like. And the steam generator inlet boundary condition was the loop-flow rate.

One thing you might note is that we did try to maintain as much of the geometry as we could reasonably include, so the injection nozzle does have the tapered approach. There are sharp angles on the inside, though. You start rounding them, the cells get to be really difficult to draw and maintain.

One thing you might notice that right at the HPSI injection, it's really hard to see the mesh density in here. We doubled -- well, actually we quadrupled the density of the mesh at HPSI injection. And I think that that was a good first step, but in the end I don't think it was enough. We should have done some more. The injection region was larger than that.

CHAIRMAN WALLIS: Maybe you need to get a smaller mesh just where -- where the jets coming in and then --

MR. WACHS: Right. Right, and that's what we tried to accomplish there, but the jet I think ends up being a little bit longer.

CHAIRMAN WALLIS: Does this STAR-CD enable you to refine the jet in places where you say have big velocity gradients, or something?

MR. WACHS: Yeah, you can do adapted meshing.

CHAIRMAN WALLIS: Automatically, yeah.

MR. WACHS: And one of the problems -- and you had mentioned this problem earlier in that one of the things you always want to do with the CFD is you want to prove that it's mesh independent and just keep increasing the density of the mesh till you see it doesn't change.

CHAIRMAN WALLIS: So the answer doesn't change, right.

MR. WACHS: But in this case it took 10 days to run. And when we --

CHAIRMAN WALLIS: So you'd either run out of money or the answer doesn't change.

(Laughter.)

MR. WACHS: Yeah, that's right.

CHAIRMAN WALLIS: Or time, right.

MR. WACHS: And --

MR. ROSENTHAL: Ten days to run on your laptop?

MR. WACHS: No, on -- on a four processor Sun. So it's -- we have substantially machinery we're running it on.

MR. YOUNG: A four-parallel processor.

MR. WACHS: Yeah, right.

So -- but absolutely, that's something that needs to be done. And I think that we need to address our computational ability in order to be able to do those things. Until we can do that it's hard to really say we have the right answer. But we're working on pieces of that. I think that's coming along.

So in this case we wanted to extract some of this data from the model after it had been run this transient over -- I think we went between 3- and 400 seconds. I can't remember, it was like 600 time steps.

(Brief discussion held beyond the range of the microphone.)

MR. WACHS: Okay. So we wanted to extract some of the data from the model and compare it to what we saw with the APEX test facility in the thermocouple rakes. And this next plot -- and these are the -- and these are the cells that would coincide with those particular temperature thermocouples.

All you could see are the red lines are our model. And the black lines are from the APEX facility. You could see that the -- well, we are getting thermal stratification. It doesn't match up as well as we'd like, unfortunately. And I think that's driven by the fact that we didn't include enough cells in the region to really show a fully developed mixing region. Maybe the size of the cells were smaller than the -- or larger than the scale of the mixing phenomena, or something.

Anyway, that's an area where increasing the grid density may be an effect. In fact, Eric did some tests --

MR. SHACK: And you're at k-epsilon again?

MR. WACHS: I'm sorry. Go ahead.

MR. SHACK: You're at k-epsilon turbulence?

MR. WACHS: Yeah, we used k-epsilon in this case. You know like we said before, we started with a default, the ones that generally worked the best, to see what would happen.

And it would be nice to do a parametric study on several other of the models they have available and see how it works. And I think it's been shown time and time again that changing the turbulence model changes your results, and you want to find the one that works best for your case.

CHAIRMAN WALLIS: There seem to be more of these calculations or six of them, then there are five of the APEX data. So is something missing in the APEX data there?

MR. WACHS: I think some of the upper ones may be overlaying on top of each other.

CHAIRMAN WALLIS: That close? They do have wiggles. It would be unusual for the wiggles to overlay. It looks as if there are five APEX groups here and six -- is there one reason the -- it looks as if there's an APEX missing in the middle or there's an extra CD where there isn't an APEX measurement or something.

MR. WACHS: I had to change -- I changed the colors on them. I may have grabbed the one and changed it incorrectly to a wrong color and just had it disappear. I can -- I can replot that for you this afternoon if you'd like.

MR. YOUNG: One thing is -- this is Eric Young. One of the things we'd like to mention is we did do a refinement on the cold leg with the loop seal geometry and everything and reran it for a stagnant-loop condition and achieved very accurate results in this cold-leg stratification or the temperature grading across the cold leg for the same geometry.

MR. WACHS: Right. And by just looking at the cold leg we were able to get the cell small enough that you could run the test relatively quickly, in the course of a day easily.

MR. YOUNG: Two days to make that right.

MR. WACHS: Two days? Yeah. So that lends to that effect, but I -- yeah.

CHAIRMAN WALLIS: So it stratifies more in reality than you predict?

MR. WACHS: Yeah. We saw a greater degree of stratification. I think the model showed more mixing than there really was.

CHAIRMAN WALLIS: And that's what you'd expect.

MR. WACHS: Yeah, right.

I go onto the next one. Looking at the core inlet temperatures, the APEX facility shows warmer inlet temperatures than we saw in the STAR-CD model. And one of the reasons that we're postulating for that is that we didn't include communication with the downcomer or the core barrel, okay.

And had we included thermal communication between those two -- two pieces, we would expect the temperature for the STAR-CD model to shift up. And whether it would reach and match, we don't know, but I think it was partially to move it in the right direction.

CHAIRMAN WALLIS: You should get this fairly well. This is an energy balancing --

MR. WACHS: Yeah, I think so too. I think so too -- well, --

CHAIRMAN WALLIS: It's not so sensitive --

MR. WACHS: Yeah, at that point --

CHAIRMAN WALLIS: -- to the plumes and all that stuff.

MR. WACHS: -- it's all well mixed, that's right.

CHAIRMAN WALLIS: It's all mixed up, isn't it, by now?

MR. WACHS: Yeah. I would think that that's a fair estimate.

MR. YOUNG: One thing that needs to be mentioned about the core inlet temperature is that the location that you choose to actually compare this, the -- you can just choose one node or cell at the core region. Now if you went and chose a cell at a different location and with the plume interaction and hitting it, you're going to get different temperatures.

CHAIRMAN WALLIS: Well, the plume doesn't go that far.

MR. WACHS: So there's still some mixing behavior going on in the lower plenum.

MR. YOUNG: Yeah. So there is some mixing behavior going on in the lower plenum. So the choice of the cell location with the temperature --

CHAIRMAN WALLIS: I thought it was well mixed long before that.

MR. YOUNG: There's -- it's well mixed, yes, sir. It is well mixed. But have certain stunts of plume and interaction where it will fold down into the region. And large recirculation zones will occur and you will get kind of a stunt of water go down.

The temperatures between those stunts aren't that much, but it will change the accuracy slightly.

MR. WACHS: Yeah. If you look at the temperature distribution it's only 10-degrees difference. It doesn't change a whole lot. So if you get just a mild recirculation where maybe this half of the downcomer is cool and it's falling in, it's still going to be displacing some hot fluid that's sitting in there, so it's a dynamic behavior.

CHAIRMAN WALLIS: Well, then you'd expect more wiggles perhaps in the data, wouldn't you?

MR. WACHS: Yeah. Well, the facility, I don't think it's got some of these -- I think we're overpredicting some of the convective behavior --

CHAIRMAN WALLIS: Something is wrong about the heat input or something here, because you're off by a large amount in the temperature change at the end, by almost a factor of 2. So it looks as if some source of heat or something's missing in the model.

MR. WACHS: Oh, yeah, absolutely. That's -- I agree. That's where the --

CHAIRMAN WALLIS: That's what you said at the beginning, I think.

MR. WACHS: The core barrel effect is I think important then.

CHAIRMAN WALLIS: You could estimate that, couldn't you?

MR. WACHS: What's that?

CHAIRMAN WALLIS: Can't you estimate that? Do some --

MR. WACHS: Off the top of my head, no.

CHAIRMAN WALLIS: Some quick -- yeah, back of the envelope, transient heat transfer.

MR. WACHS: I don't know what the total mass is of that, so --

CHAIRMAN WALLIS: But you can find that out if you --

MR. WACHS: Yeah.

CHAIRMAN WALLIS: Someone will tell you its shape and size, and you can just do a calculation.

MR. WACHS: Oh, yeah, sure. If you know what the injection flow rates in the initial -- yeah, I agree.

Looking at the downcomer temperatures, if you look at 1.3 cold-leg diameters below and we tried to compare the flows, the STAR-CD calculation is -- is a bit lower than what we're --

CHAIRMAN WALLIS: It seems to suddenly go wrong at one point and never recover.

MR. WACHS: This one does?

CHAIRMAN WALLIS: Yeah. It seems to go wrong at about 80 seconds and then it never comes back to --

MR. WACHS: To lift back up to that --

CHAIRMAN WALLIS: Something happened at 80 seconds to get it wrong.

MR. WACHS: Well, that's where injection begins, where you start to see the cold fluid falling in.

CHAIRMAN WALLIS: Oh, okay.

MR. WACHS: And I think that this is clearly the worst agreement between the downcomer ones, this one right below. And I think we see some dipping behavior in the --

CHAIRMAN WALLIS: Well, isn't this the business of it hitting -- going across and hitting the inner wall?

MR. WACHS: The thermocouple, yeah. So that's kind of the problem with these -- with comparing these analyses. You'd have to grab a single point out of the facility and hope that your phenomena you're looking for crosses it. And it may or may not.

Because realistically we can't expect with this kind of behavior STAR-CD to exactly match what -- what's happening at the facility because it's somewhat unstable behavior.

CHAIRMAN WALLIS: So you don't have many nodes across the downcomer, do you?

MR. WACHS: Radially or axially?

CHAIRMAN WALLIS: Radially?

MR. WACHS: Or azimuthally? Not very many.

CHAIRMAN WALLIS: No. So --

MR. WACHS: But you saw with Kent Abel's work, when he had the plot in Excel with the single data points, those were our points. And you could see the plume moving from place to place.

MR. YOUNG: Dr. Wallis, the number of nodal locations crossed down by the gap is 8.

MR. WACHS: Oh, okay.

CHAIRMAN WALLIS: Oh, so you should be able to pick up the difference between the inside and the outside?

MR. WACHS: Oh, yeah. Oh, yeah. Definitely. And I have -- I'll talk about that a little later.

CHAIRMAN WALLIS: You're actually -- this is STAR-CD predicted at the location on the outside --

MR. WACHS: Yes.

CHAIRMAN WALLIS: -- where the thermocouple is. Oh, so that's not the explanation then.

MR. WACHS: On the next slide you're looking at two diameters below. It seems to do a little bit better. Kind of crosses through the middle of all the wiggles.

And at three diameters it's still pretty good.

MR. SCHROCK: Your calculation seems to smear out some oscillations in the actual --

MR. WACHS: Yeah. I -- that's definitely true. I don't think that it's -- well, again we're looking at the effect of turbulence and some of these eddies and whether the code will be able to capture that, I don't know whether it will or not. Apparently it looks like it doesn't catch it as well as reality, but we still get -- the mean behavior is similar.

So at four diameters it looks pretty similar also. We're in the right ballpark at the very least.

This is a vector plot of the plume velocity at a cross section in the downcomer. So we're in the middle of a downcomer. We've peeled off the layers. And you can see where these plumes are going. They're obviously merging together and interacting into a single plume. And we actually see a convection cell around --

CHAIRMAN WALLIS: And those colors are what? They're velocities?

MR. WACHS: It didn't come across very good. The darker -- or the redder colors are faster velocities in the Z direction.

CHAIRMAN WALLIS: So it gets faster as it goes down?

MR. WACHS: Well, that's kind of -- one of the problems with this is that we have several layers to choose from. And by choosing this middle layer it seems to be fastest at the bottom, where if you choose the layer -- chose a layer closer to the inside of the core barrel it would be higher up.

CHAIRMAN WALLIS: Well, that's very funny because we were told that the plumes dissipate after about 4Ds and here they are going faster at the bottom.

MR. WACHS: Well, you have to consider the scale.

CHAIRMAN WALLIS: I'm not sure any --

there's any excuse for it, is there? It just seems to be different altogether.

MR. WACHS: Yeah. Well, we actually see some temperature -- well, this is just a model, too. And we haven't really had an opportunity to compare velocities from the model to that of the facility.

CHAIRMAN WALLIS: Yeah, but the STAR-CD did so well in the more detailed analysis we just saw.

MR. WACHS: In the Creare facility?

CHAIRMAN WALLIS: Yeah.

MR. WACHS: Yeah. And that's a smaller facility, too. And I think that the geometry --

CHAIRMAN WALLIS: Well, this is kind of surprising. You're saying that you get these big velocities at the bottom of the downcomer?

MR. WACHS: Well, in this particular slice, --

CHAIRMAN WALLIS: And someone else --

MR. WACHS: -- that's where the peak velocities are.

CHAIRMAN WALLIS: -- is telling us that the plumes die --

MR. WACHS: I'm sorry. Go ahead.

CHAIRMAN WALLIS: -- four *d*s below the injection point.

MR. WACHS: Say it again. I'm sorry, I didn't get it.

CHAIRMAN WALLIS: I'm just trying to reconcile it. We were told earlier that the plumes essentially die and everything is well mixed up to about 4 *ds*.

MR. WOODS: Well, there's --

CHAIRMAN WALLIS: And here we've got to these plunging plumes which are more intense at the bottom than the top.

MR. WACHS: Yeah. I guess I'm not really willing to say that that's the most intense region.

CHAIRMAN WALLIS: Well, that's what that red flash showed us.

MR. WACHS: Right, in this particular slice. I think if we took a slice in a different location, it would change that -- that look.

CHAIRMAN WALLIS: Could you back up and show us that again, that red --

MR. WACHS: Yeah, I can show you that.

MR. REYES: I think the other thing is that this test we had a plume with cold flow.

CHAIRMAN WALLIS: Yes.

MR. REYES: So you have downcomer flow due to the cold-leg flow. And I think we're seeing kind of a mixing due to that.

CHAIRMAN WALLIS: Yes. But still you've got these intense velocities.

Could you go back? And if you could tell us what the red magnitude is compared with the red there, the background?

MR. WACHS: Okay, it's a radial.

CHAIRMAN WALLIS: We saw a red thing in the middle there, then. That velocity is very much -- well, that yellow patch, how -- what's that.

MR. HAUGH: That's about a point -- looks like .21.

MR. WACHS: Yeah, that's about right.

CHAIRMAN WALLIS: What's the average velocity?

MR. HAUGH: The average velocity looks to be about .1 --

MR. KRESS: Two, big red.

MR. HAUGH: -- .1 --

CHAIRMAN WALLIS: Go back to that red one, there. Go back to that big red smudge there. Another one, there's another one. Well, it happened twice.

MR. WACHS: Yeah.

CHAIRMAN WALLIS: So it's not -- it's not just erratic.

MR. WACHS: Yeah. It's about two-tenths of a meter per second.

CHAIRMAN WALLIS: Compared with an average of --

MR. HAUGH: Of .15, it looks like.

MR. WACHS: Right, I think that's about there.

CHAIRMAN WALLIS: So it's another big deal.

MR. WACHS: Yeah. So it's -- yeah, I would agree. I think that's a strange behavior from a model.

But, again, this is -- before we were talking about some stagnant cases. And it's possible that -- I don't know -- maybe we're missing the plume with the 8 *d* thermocouples. I think it will be a little clearer when we get to later on we'll see --

CHAIRMAN WALLIS: Well, I thought that some of the conclusion we seemed to be coming to from the previous presentation was that we should replace REMIX with CFD, because CFD does better and models more things, catch they data better.

MR. WACHS: Yeah.

CHAIRMAN WALLIS: And this seems to be showing that CFD can also predict things which may be

--

MR. WACHS: Oh, absolutely. There's no question about that.

CHAIRMAN WALLIS: -- we could lose faith in its ability.

MR. WACHS: Yeah. Well, we should. You should -- yeah, I am sure you guys know that CFD is not a black box. These codes are not black-box codes.

CHAIRMAN WALLIS: Well, I think we have to make an assessment of the probability of CFD giving good enough answers.

MR. WACHS: Right. I think what -- it just hits me. In my personal opinion I think what we would need to do is if we were ever going to incorporate the CFD Code is we would have to develop a mature code that worked well for a particular set of geometries.

And we would want to understand that code and feel comfortable with the results it gave us before we actually went out and applied it to a general case, or to another case. I don't really think we're at a mature stage on this code yet. I think that it still lies on the young state of this particular model.

CHAIRMAN WALLIS: Well, the remarkable

thing was Brandon did something which was as immature as possible. In fact, he hadn't tuned anything.

MR. WACHS: Right.

CHAIRMAN WALLIS: He just took something out of the box and raised it. And it seemed to work very nicely.

MR. WACHS: Oh, yeah, right. I agree. It's hit and miss.

CHAIRMAN WALLIS: And it's the same code that you are running here.

MR. WACHS: It's the same code, but it's a different model, so --

CHAIRMAN WALLIS: Different person.

MR. WACHS: Well, I would -- well, I don't know.

CHAIRMAN WALLIS: So it's used as a dependent.

MR. WACHS: He helped.

Yeah, -- no, it is used to depend, that's definitely true. And does the model you apply capture the behavior you're looking for? So on this case we have loop flow. In Brandon's case we didn't have loop flow.

CHAIRMAN WALLIS: I know what is. It's that he's a student. You're working for ANL. Isn't it?

MR. WACHS: I'm a student, too, still.

CHAIRMAN WALLIS: Oh, okay. I thought you were --

MR. WACHS: I just transferred to a new location.

CHAIRMAN WALLIS: It's an ANL effect, is it?

MR. WACHS: Yes. So -- but, yeah, I definitely think that -- you know, we talked about the size of Brandon's model. He used about 2,000 nodes, and we're about 750,000 nodes. And that may have some impact as well.

MR. REYES: This is a more complicated case, though.

MR. WACHS: Yeah. There's --

MR. REYES: The other case was a stagnant injection -- injection into a stagnant region. And this is a flowing case, but not only flowing, but some asymmetric injection --

CHAIRMAN WALLIS: In a sense none of these are explanations as to excuses --

MR. REYES: Right.

CHAIRMAN WALLIS: -- or possible hypotheses and --

MR. REYES: Hypotheses as to why we don't.

CHAIRMAN WALLIS: So it would be interesting to resolve this.

MR. REYES: Absolutely.

MR. WACHS: Sure. Because we came in, we even stated a couple of times that it's an exploratory issue. We're trying to see how well it will do. And I think it's important to note that it worked really well in one case and it's not working so well in the other case. So there's a certain level of confidence that you should try to extract from that.

The next thing I tried to --

CHAIRMAN WALLIS: You're not seeing -- you're not seeing this stratification effect that we heard about before, are you?

MR. WACHS: In the downcomer?

CHAIRMAN WALLIS: You are, you're getting more of it than was predicted. I thought earlier you were predicting -- your red code showed more stratification.

MR. WACHS: That's only in the cold leg. That was the cold-leg behavior.

CHAIRMAN WALLIS: Oh, that was in the cold leg.

MR. WACHS: Yeah.

CHAIRMAN WALLIS: But not in the downcomer?

MR. WACHS: Not in the downcomer. Actually, the downcomer, it seemed to work pretty well. Other than that first node right below, it -- no -- was so-so. But the other node seemed to work pretty well.

Then from these velocity profiles we went in and tried to extract the peak velocity for the plume in order to compare to some of the work that they did at the Creare facility in modeling with what they saw experimentally. So we took off this peak velocity and got a Reynold's number for the flow.

And that what they do at Creare, they use these Reynold's numbers. Well, they picked out their peak velocity and tried to compare it to -- they tried to calculate a peak velocity and compare it to their actual facility. And we tried to do that same thing here.

In our case, we -- looking at each individual cold leg as an independent plume generator, and using this model that the Creare people used to come up with a maximum plume velocity, you know, in one case we would have two plumes. We got the lower of the two curves here. So we got two independent plumes of moderate velocity.

When you combine those two plumes and you see they have the same strength, they have the Q_{HPI}, it goes together, you get a larger plume as you'd expect. And this larger plume, the model predicted, seems to match better with what we saw in the model, whatever that's worth.

CHAIRMAN WALLIS: I'm not quite sure what I'm looking at here, these points way down the left-hand side there.

MR. WACHS: Yeah. I'll get it for you.

Yeah. Now what do I have to do to roll. These points down here, these are from the model. And what this is showing is it's showing the --

CHAIRMAN WALLIS: Model's warming up, or something?

MR. WACHS: Yeah. It's getting started. The plume is forming. So the velocities are low as it's forming, initially. In terms of the model that they, the Creare people, which we are trying to apply, it doesn't treat that. It just said the plume was there and it's performing in a certain way.

CHAIRMAN WALLIS: Well, once it gets going this isn't all that bad, then?

MR. WACHS: No. Yeah, right. And it

developed, you know, a pseudo-developed plume. It seemed to match okay. Now that's just a check to see a guess what they got. And it's kind of interesting that you have to combine the plumes in order to get that similar behavior.

CHAIRMAN WALLIS: Where do you recall this maximum plume velocity?

MR. WACHS: Well, as you saw in the --

CHAIRMAN WALLIS: Is it that red flash, is the maximum plume?

MR. WACHS: Yeah, basically that's what you have to do, because the plume is always moving around. You look for the hot spot, and you say, "Oh, that's the peak velocity at this particular point in time."

And so you have a group of cells which you grab, and you say the velocity is something like that. And that's one of the real challenges with comparing this type of model data to real data. It's...

Now this is a look at the downcomer fluid temperature. In this case, I superimposed to the mesh over the top. And they look better out in the sun than they did on the presentation. Again, this is a mid-plane temperature in the middle of the downcomer.

CHAIRMAN WALLIS: So here we've got a

plume which is going way down.

MR. WACHS: Well, the temperature gradients here, it's like 475 to 468.

CHAIRMAN WALLIS: Can we freeze it? Let's see -- no, go back. Go back one or two.

MR. WACHS: See, I don't know if we have to let it finish before we can --

CHAIRMAN WALLIS: Go back -- you have to go through?

MR. HAUGH: Yeah, and it will finish, then.

MR. WACHS: I think we do. It's a movie file in place.

CHAIRMAN WALLIS: You have to start again, or something?

MR. HAUGH: Yes.

CHAIRMAN WALLIS: Because there was a time there where you had a plume which seemed to bring -- again, it's difficult to see the colors, but there's a yellow plume that seemed to go all the way down.

MR. HAUGH: Yes, exactly.

MR. WACHS: Um-hum.

MR. SHACK: Yeah, but the whole temperature range is what, 468 to 474?

MR. WACHS: Yeah, it's not a very big

temperature range, right.

CHAIRMAN WALLIS: So it's very little.

MR. WACHS: So, you know, if you see it cooling you're going to see profiles. It's not a very strong plume.

CHAIRMAN WALLIS: So what's the temperature of the fluid coming out of the cold leg?

MR. WACHS: Yeah, like I said, this is a mid-plane, so it's jumping over the plane that we are looking at.

CHAIRMAN WALLIS: But what's it coming in at?

MR. WACHS: What's it coming in at; the temperature rise of the plume?

CHAIRMAN WALLIS: Yeah, what's the temperature when it comes out of the cold leg?

MR. WACHS: I would assume it was coming in at about what the thermal -- or the cold leg, cold stream, the same.

CHAIRMAN WALLIS: Is that the 468, or something, whatever is at the bottom there?

MR. WACHS: I would say that it would be a little bit cooler than that. I think there's certain amount of mixing that has gone on before it gets back to this plane.

It's coming in through these holes here (indicating). These are a couple of cells that were part of a different part of the model.

CHAIRMAN WALLIS: It may be there is something which is just distorted here. It may be that there's a big temperature change at the top, which you're not really seeing.

MR. WACHS: Right.

CHAIRMAN WALLIS: And then there is a survival of a plume at the bottom, because there is some mixing, even though it's stratified. And we are just focusing on that because that's all we can see.

MR. WACHS: Yeah, I agree.

CHAIRMAN WALLIS: I don't know.

MR. WACHS: That's probably true.

CHAIRMAN WALLIS: Hard to tell.

MR. WACHS: I think that, yeah, a majority of the mixing is going to go on in this initial falling area where it's impinging on the far wall.

CHAIRMAN WALLIS: It doesn't mean to say that there's no mixing velocities below that. There seem to be a lot of mixing velocities below that. Bi because it's all about the same temperature it doesn't matter.

MR. WACHS: Right.

CHAIRMAN WALLIS: So it seems to be that you have to really separate out your idea about what the velocities are doing from what the temperatures are doing.

MR. WACHS: Right. Yes. It's the post-processing. There's a lot of data to sift through and choose which ones you want.

Did you want to see that again?

MR. SHACK: Was it possible to refine the mesh right up in that region, right at the nozzle?

MR. WACHS: Oh yeah, absolutely.

MR. SHACK: I mean it --

MR. WACHS: That's a thing you can do.

MR. SHACK: And that seems to be where the action is.

MR. WACHS: Yeah, that's one of the things that you'll want to beforehand. We'll talk of little bit about that when we get to some of the summary, how we would do that.

Now this is a movie of the vessel wall temperature. So the temperature differences here are on the order of four degrees from top to bottom on the range. You can see they seem to mimic the temperature profiles in the fluid pretty well. But the gradients are really small, what it's expecting to see.

CHAIRMAN WALLIS: Again, this is emphasizing what maybe a rather small changes at the bottom of the annulus.

MR. WACHS: Yes.

CHAIRMAN WALLIS: And not really showing you that the mixing is occurring at the top.

MR. WACHS: Yeah. Well, this is actually the steel, the first node of steel. So showing the overall cooldown of that body.

CHAIRMAN WALLIS: Because it's surprising the steel is changing temperatures so rapidly.

MR. WACHS: Well, it's not changing much.

CHAIRMAN WALLIS: It's not?

MR. WACHS: No. This is the -- the full-scale from red to black is less than four degrees.

CHAIRMAN WALLIS: Okay. That's part of it. You've magnified it.

MR. WACHS: Yeah. That's essentially what it does.

MR. SHACK: If you look at it close enough, there's always big differences.

MR. WACHS: Yeah. And, you know, if I hadn't done that it would be red. You know, you don't really see any of the behavior.

CHAIRMAN WALLIS: If you go long enough,

he's going to write OSU in the annulus.

(Laughter.)

MR. WACHS: Yeah. I'll have to play that on the scoreboard at the football game.

The next step that we wanted to try to accomplish there was to try to extract some heat transfer coefficients and see what we could look at. In order to do that --

CHAIRMAN WALLIS: Now who is this guy Newton? Is that a reputed reference?

MR. WACHS: Yeah, that's by name-dropping.

So we want to extract it. In order to come up with this we have to extract a heat flux from the problem, and we have to find some way to demonstrate the delta *t*. And heat flux isn't too bad. You just take a delta *t* over the reactor vessel wall. And we know the thermal conductivity of that particular material so we can extract the heat flux.

And again you'll want to do that at the -- or I did that at the area of the peak velocity, a plume velocity we chose.

Then you just plug it in and choose an ambience temperature. I chose the temperature at the mid-plane, just to have something to work with. And you can translate that into a Nusselt number.

In the Creare work they compared their Nusselt numbers that they calculated and measured to -- so they Spelter equation. They didn't get good agreement, either. And we tend to not see -- be off by about -- well, we're around a hundred and they were around two hundred.

MR. SCHROCK: Well, that's kind of a casual determination of the representative fluid temperature.

MR. WACHS: Yeah, it is.

MR. SCHROCK: You need something more definitive than that.

MR. WACHS: Absolutely, I agree. And one of the hard things with doing that is you get a nonuniform temperature profile. Ideally you would like to choose a mixed mean temperature of the plume. And how to do that is not trivial.

CHAIRMAN WALLIS: Maybe this is one of the problems with REMIX. And REMIX has to do things like get an average heat transfer coefficient in this sort of way.

MR. WACHS: Right.

CHAIRMAN WALLIS: And this is kind of indicating that that is not a very good representation.

MR. WACHS: Right. It's a constructive parameter. Extracting a heat transfer coefficient is not -- you know, this kind of code isn't intended to do that kind of thing.

CHAIRMAN WALLIS: Your CFD has to do something about predicting the wall heat transfer coefficient.

MR. WACHS: Not really. It's just -- it's looking at nodes.

CHAIRMAN WALLIS: Yes, it does. You can't just -- you know, but that doesn't give you a coefficient of the wall. There's got to be some model that goes from the velocities in the nodes to a heat transfer coefficient at the wall.

MR. WACHS: Well, use a strict convection of and conduction between the two.

CHAIRMAN WALLIS: It uses some kind of a law of the wall. It uses some kind of a model of what's happening in the boundary there.

MR. WACHS: Yeah. It does use the law of the wall. That's incorporated into there.

CHAIRMAN WALLIS: Right. It's not clear that that applies when these plumes are doing what they are doing here.

MR. WACHS: Right. I agree.

CHAIRMAN WALLIS: So that you've got the same problem with CFD, but there's a different level than that.

MR. SCHROCK: Dave says just use infinity. Is that universal, then?

MR. WACHS: Between all the codes?

I'm sorry, I didn't get that.

MR. BESSETTE: Well, I think what we've shown is that if you're within a factor of 2, then that's plenty good enough. If so, if you choose -- that's why -- like in REMIX, you know, in REMIX you input the heat transfer coefficient.

So you can just choose something like a thousand-watt square meter degree *k*. And if you're off by a factor of 2, it doesn't matter. It's 500 or 2000.

CHAIRMAN WALLIS: Don't use an infinity of it because then you'll find that five different calculations will give you infinite changes in the step and you'll be in real trouble.

MR. KRESS: I'm surprised that the data is below the Dittus-Boelter.

MR. WACHS: But in this next slide we'll talk about that a little bit, how that works, and why that is.

CHAIRMAN WALLIS: Or a lot.

MR. KRESS: Yeah. I would have thought it would have been above it.

MR. WACHS: Just a little bit on the Dittus-Boelter equation. It's based a fully-developed flow, and that's not really the case we are looking at. In our case --

MR. KRESS: Yeah, you've got an interest region.

MR. WACHS: -- if you look here, one of these is --

MR. KRESS: How do you calculate the Reynold's number?

MR. WACHS: -- the one on the left --

CHAIRMAN WALLIS: Well, that's the whole point.

MR. KRESS: I think that's the issue there.

MR. WACHS: On the left side here we've got an axial slice of the temperature profile. On the right, we've got an access slice of the velocity profile in the *z* direction.

If you look in the upper-right quadrant there you can see where the cold plume is located at. And, you know, that's about five degrees. And this is about mid-plane. You can see that it's attached to the inner wall. It's clearly not running down the center of the vessel -- of the annulus.

And you can see on the velocity profile that the plume is moving with that cold stream just like you would expect.

MR. SHACK: Where am I at in z again?

MR. WACHS: This is right by the mid-plane of the downcomer. So I don't know. What's the total depth of the downcomer?

MR. HAUGH: Total diameter is 86 inches.

MR. WACHS: It's like 71 inches, but I don't -- so it's probably around 35 inches. So that's about 10 diameters from the upper-vessel head, not from the downcomer, or from of the cold leg injection plane.

So we can see that the actual velocity next to the outer wall is relatively small. And thus you'd expect the heat transfer coefficients of the model was -- would you extrapolate from the model would be smaller than what you'd get with a fully-developed flow with the cold plume running down the middle as opposed to the far side. So the effective diameter for the Reynold's number is probably different.

CHAIRMAN WALLIS: These two plots correlate pretty well, don't they?

MR. WACHS: Yeah. Oh, I think so, with the velocity and the --

CHAIRMAN WALLIS: Which I think means that they're calculating the heat transfer coefficient from the velocity. And that gives you the temperature. So you would expect them to correlate pretty well.

MR. WACHS: With the Dittus-Boelter equation?

CHAIRMAN WALLIS: Well, whatever model they have in CFD for the heat transfer coefficient.

MR. WACHS: Oh, oh, I didn't use the --

CHAIRMAN WALLIS: It's probably -- is probably --

MR. WACHS: The CFD model didn't extract the *h* coefficient. I extracted that from the data.

CHAIRMAN WALLIS: Oh, you extracted that?

MR. WACHS: Yeah.

CHAIRMAN WALLIS: You extracted that.

MR. WACHS: Yeah. You have to do some special things beforehand in order for it to calculate an *h* value. You have to --

CHAIRMAN WALLIS: I think CFD would make *h* roughly proportional to *v*.

MR. HAUGH: Yeah. I did that in my Creare model on the last run. What you have to do is between the solid and the fluid cells you insert a wall boundary. And it's just zero resistance. That's just a point for the code to monitor heat flux. And then from the heat flux you can provide a mix mean temperature, and it will give you a heat transfer coefficient.

MR. WACHS: Right. Yeah, it will calculate the *y* plus value and then try to extract the heat transfer coefficient. But it's something you have to do before you run the model really early on in the development.

Just some of the conclusions we could make: Like we said before the nodalization was a little bit coarse in the cold leg, and I think we could get better results if we were to densen that up. And as a part of that we need to show great independence.

The downcomer temperatures seem to be in pretty good agreement.

The core inlet temperatures were mildly underpredicted. And, as we postulated before, I think that's due to the omission of the core barrel.

Now in terms of phenomena base we do see plume interactions, which is something that we think we've seen in the facility from the data that we have available. And those interactions should be affecting the plume velocities.

In addition, the plume doesn't necessarily run right down the middle of the downcomer. It moves in its radial location from inside to outside, primarily down the outside. Generally that affects the agreement with some of the standard convective coefficient -- heat transfer coefficient models.

We also really need to run some more runs and tweak the model a little bit to include some of the physics that we want to make it match the data a little bit better, or to model the same problem, essentially. Essentially, we are not treating the same set of problems. And we also need to show that the cell density is appropriate.

MR. SCHROCK: So your heat transfer --

MR. WACHS: There should be one more on lessons learned.

Any questions?

MR. SCHROCK: Your Nusselt number comparison is even worse when you recognize the Dittus-Boelter equation is for the length average in a long tube, fully-developed conditions. And you're applying it in developing conditions.

MR. WACHS: Right, I agree. They don't really treat the same problem. The only reason I put that on there is because the Creare people put that on there when they looked at their data. I just wanted to compare how well our model was working against how well the model they used.

This should be another one lessons learned that you've got in there.

MR. HAUGH: What's the name?

All right, I got it.

MR. WACHS: Also I'll talk a little bit about the lessons we learned from this stuff, with Brandon -- it took Brandon and Eric and I working on it for the last year. There's some significant things to take with us.

On the CFD methodology there's some distinct steps to that you need to go through in creating a model. And each one of those steps has got its own set of problems and difficulties that you can face.

The first step is you really need to define your problem well. You need to know exactly what behavior you're looking for. You need to know exactly what your geometry is going to be like, where you know inlet conditions and boundary conditions.

And so you need to be familiar with the system before you come in. It's going to be really difficult to get any reasonable results if you come into a system fully blind on the physics.

The next step that you have to go through is you really need to construct the mesh. You'd have to construct the mesh. And the way you construct that mesh needs to be attached to the way you want to model the physics and the physics you want to capture.

Finally, you need to set up your problem. So you need to choose your models, what physics do you want to include, which turbulence parameters you want to -- or turbulence models for you want to run. And then you need to run the problem. And that goes into the computational ability that you have in your facility, how you go about doing that and what you can do. And then post-processing presents its own set of problems.

So things to consider, but you have to understand the physics before you go in. It's not going to be something that you treat as a black box and you just take somebody who knows how to run software, and you put them on it and try to run the problem and expect to get anything that's worth anything.

In terms of mesh building, one thing we found -- that Brandon found -- was that he found it easier to import the geometry from some CAD program that was more suited to generating rough geometry.

In general, the CD or the STAR -- or the CFD codes are not real good at generating initial geometries. They're good at generating meshes, but they're not good at initiating initial geometries. You don't have the same amount of tools. And you can be more efficient and more complete in representing a geometry when you do that.

Now your mesh gradients need to match the physical gradients of the phenomena. It's really important to do that.

And a lot of times people think of CFD as you put more nodes in, and you make time step smaller, it's going to work better. And that's not always going to be the case. You can get too small just as well as you can get too large. So you need to be careful about that as well.

In terms of running the codes, modeling large --

CHAIRMAN WALLIS: So interesting. You can refine the cells in local places but you have to run everything at the same time, that you step --

MR. WACHS: Right. You have to rerun the entire problem. Yeah, because there are all communicating with each other.

CHAIRMAN WALLIS: You can't refine the time in certain regions?

MR. WACHS: Well, yeah. I guess -- yeah, I guess I'm thinking of time -- transient time scales.

CHAIRMAN WALLIS: I guess you could, but I don't think they ever do that.

MR. WACHS: Do what, vary time?

CHAIRMAN WALLIS: Refine the time.

MR. WACHS: Oh, oh, yeah.

CHAIRMAN WALLIS: In certain regions you run the very small time set only in this region, --

MR. WACHS: Oh, okay, yeah.

CHAIRMAN WALLIS: -- but the rest you're on --

MR. WACHS: Yeah, you're right. You have to vary the time globally. You can't vary it in time.

CHAIRMAN WALLIS: Globally but not locally.

MR. WACHS: Yeah, you're right. At least not at this time. I wouldn't be surprised if they decided that they could do that, whether they could or not.

The next thing, when you dealing have large systems and have large numbers of nodes, you need a lot of computing power to be able to treat those models. That's where parallel computing really came in useful for us. Had we not had the parallel computing capability we'd still be running models probably months ago. You know, it would be -- our particular model with the APEX-CE facility took 10 days to run on a four processor parallel machine.

So you take that onto a single processor and you're talking about order of months. So that's a significant advantage.

Now another thing we found was that you needed to have your computing platforms homogeneous. You couldn't work with an HP and a Sun separately. The code didn't like that. It wants to stay on the same platform all the time.

And in terms of post-processing, one of the main difficulties in comparing to experimental data, even in a very well-instrumented facility like ours, we are on the order of hundreds of data nodes, okay, with the -- with the CFD we're on the order of a hundred thousand locations.

So how you take this two-dimensional or

even three-dimensional behavior and try to benchmark it against basically one point in time and really get an idea of whether you're seeing the same behavior. And that's difficult. I think that that's --

CHAIRMAN WALLIS: Which is always a problem with code assessment --

MR. WACHS: Yeah.

CHAIRMAN WALLIS: -- with RELAP or anything else. I mean you get a whole lot of data points and a whole lot of predicted points and how you assess the comparison between them --

MR. WACHS: Right. It's not trivial.

CHAIRMAN WALLIS: -- in other than some sort of superficial way, or you just look at a few pictures and say, "All right, it's good enough."

MR. WACHS: Right.

Let's see. Yeah. So we were talking about multi-dimensional behavior. I think that's it. That's -- because we've add sections.

CHAIRMAN WALLIS: So we are getting very close to the end.

MR. WACHS: What's that?

CHAIRMAN WALLIS: We're getting very close to the end here.

MR. WACHS: Yeah. Any questions on that

at all?

CHAIRMAN WALLIS: Any questions?

(No response.)

CHAIRMAN WALLIS: So, Jose, are you ready to wind this up for us?

MR. REYES: I'm ready to do that.

MR. SCHROCK: So we have a new NRC dilemma. When is enough CFD enough? Never.

MR. SHACK: When you run out of money.

SUMMARY AND REPORTING SCHEDULE

MR. REYES: As I went through this I realized there's a lot to summarize. And I'll kind of hit on some of the highlights that I think we saw as far as observed phenomena and what we've learned in the process.

In terms of separate-affects-type behavior, we've taken a look at using this both APEX-CE and the flow visualization group. We take a look at a specific mixing behavior in the cold legs. We looked at thermal stratification.

We found that the effect of the Weir wall was very important. So that was something that was -- originally we didn't think that much about, but as we went into the testing and we observed the results, especially in the flow visualization group, we realized that that was an important part.

The separate affects can be integrated now with the integral system test, because we see that the formation of a cold liquid plug in the loop seal can affect integral system behavior. It affects stagnation in the loop. So that's a very important piece of our research, I think. And so we will continue development in that area as far as analytical models.

In terms of the integral system testing one of the things we observed there, or some of the key points that we observed for the integral system test, were for all the small break LOCAs, the main streamline breaks, and then the combination breaks, what we observed with regards to the mixing in the downcomer was that the plume basically within four diameters was well mixed.

For cases where we had flowing cold legs in conjunction with injection we also saw thermal stratification. And that ranged -- the maximum we saw was about 40 degrees F from the bottom of the downcomer to the cold-leg location. So we were seeing small temperature differences.

We recognized the unique design of the facility we're scaled here to, the Palisades plant.

It does have a lower HPI than some of the other plants that are out there today. And so we recognize that aspect of it. And so we are seeing some of that effect.

We generally tend to produce relatively weak plumes which mix relatively quickly in the downcomer. That's what we're seeing.

With regards to the two situations, the stagnant injection in a stagnant media as opposed to a cold flow. For a stagnant media case what happens is that initially you see good-sized temperature differences between the -- within one or two *d*, about 15 degree F difference between the ambient temperature and the plume temperature.

But as time goes on you're -- in the stagnant case you're mixing that volume, and it's becoming more and more cold. And so you're seeing a smaller delta *t* with time and a weakening of the plume with time.

With regards to the situation we have of flow in the cold legs, what we see there is a possibility of having a prolonged contact with the downcomer vessel, because you are resupplying that hot fluid. And so you're maintaining a larger delta *t* for a prolonged period of time.

So as long as you're feeding hot water into the downcomer region, you're able to keep this plume relatively strong because you're continuing to inject.

However, we saw maximum case of about -- I think we saw between 30 and -- I think 30 to 35 degrees was the maximum we saw for the situations that we were setting.

However, it does provide an opportunity for a prolonged contact but it's fairly small, temperature-wise.

With regards to our analytical capabilities, we looked at RELAP5 Code, the Gamma version. And for the main streamline breaks, the prediction seemed to compare very well. There were a few areas that we still need to look at.

In particular, the pressurizer liquid level we saw didn't predict exactly as we measured in the test.

And then there are some issues with regards to break flow, for the small break LOCA that we wanted check into also as far as comparisons there.

So there's still some work in that area that needs to be done with regards to the integral system modeling.

In general, we observed that RELAP predicted the stagnations reasonably well as far as the stagnation occurring. The mechanism was typically either reverse heat transfer or steam generator tube draining.

It could not take into account the effect of the cold loop seal plug because of spillover over the Weir wall. So we noticed that.

With regards to the separate-effects-type modeling, we used to two codes. We used REMIX Code and we used STAR-CD.

REMIX is a control volume lump parameter type of a regional-mixing mode, which is significantly simplified. It just addresses certain regions within the mixing volume of a cold leg loop seal and downcomer.

And we observed, in comparing to our data, that it didn't -- it underpredicted basically all of the temperature is in the downcomer that we were looking at.

We also observed that with REMIX you can include and you should include a section of the core barrel to model the core stored-energy release or the barrel stored-energy release into the fluid. And that played an important part. And that effect was also carried over, we saw, into the STAR-CD calculations.

For STAR-CD we used a -- we did two calculations. We benchmarked the code first with the Creare half-scale data. And we saw a very good comparisons right out of the box with that.

And I think if you look at the APEX-CE the temperature scaled was fairly tight. And so I think the comparisons are actually better than they appeared on the screen.

So if you go back to that again, I think you'll see you're still within about plus or minus -- within 10 degrees of the actual measured. So go back to that and look at the scale, and you'll see that it's a little bit tighter than the picture tends to reveal.

So we do see a better prediction than I think was the image portrayed somewhat. Would we think we are seeing some reasonable predictions with the STAR-CD code.

There's more to learn with regards to the turbulence models and what's being done there.

Overall, if you look at the project as a whole and what we were trying to accomplish and where we are right now, I think we've accomplished quite a bit. And so I'm pleased with that.

We will be documenting all of this and providing you with the Final Report. And we'd like to make it fairly comprehensive so it's a standalone document. So it will describe the entire project in its entirety.

There's some additional work that's going on right now. We are still looking at some theoretical models for the plume.

We're also looking at a theoretical model for a prediction of loop seal spillover.

We're also looking at some refinements that have been done, I guess, already on the cold leg to see if we can't -- using STAR-CD to predict better comparisons of stratification by refining the cold leg a bit more. So we have those.

And we also have one test which right now we still need to specify a little bit better, Test Number 13. And we're looking at discussions with NRC as to what's the best way to portray that. That would be basically a cold injection of HPI into essentially a steam environment where you have a level in the downcomer. So we'd like to take a look at that to understand that better.

So that's kind of where we're at.

With that I'll talk about the reporting

schedule. The Scaling Analysis Report is completed. We've submitted it to the NRC. And it's actually gone through the technical review. And now it's going through an editorial review. So we are waiting for comments back from NRC Publications. Not comments from technical but the publications folks to get back with us and get us into the right format for the report.

The Final Report, we are planning to -- we'll probably have several, at least one or two drafts before the Final Report, which we'll provide to NRC for their review. We hope to issue that by the end of the year. That will include the following information:

Review of the previous PTS research. That will be a section in there.

Description of our test facilities.

An overview of Palisades operations, what we learned as far as operations of the Palisades plant.

The results for all of our tests. It will include the RELAP5 comparisons. And that includes all the comparisons. We didn't show you all of them.

We will include the REMIX and STAR-CD final calculations.

And then, of course, we'll have a CD with all of our data and all of our drawings for the facility. So typically we can bundle that essentially on three CDs. So you'll get a three-CD set. You can pick up your copy at the door. So that's how we'll document this project.

So I think it's a fairly comprehensive piece of work. And hopefully you will be able to benefit from this.

But I would like to express my thanks to the Committee for being here. And it's always a pleasure to get a review. And on behalf of our students, who have worked very hard and I think they themselves have learned quite a bit from this process, I extend the thanks to the Committee and hope we can interact with you again in the future.

CHAIRMAN WALLIS: Well, thank you.

I think we've enjoyed hearing from you and your colleagues and students. You've given us a lot to think about.

I think the Agenda calls for a Subcommittee caucus. I think what I'd like to ask is what the ACRS role will be in the future.

Usually we review things like this in the context of our review of RES programs when this happens once or twice a year. This will be very useful input, I think, for that purpose.

But I don't think the whole ACRS is specifically going to focus on this project at any particular time, except in the context of PTS or some safety issue when we will really get involved.

So I see this mostly as contributing to our decisions we have to make about PTS, any rulemaking, particularly, and any regulatory action which the Agency is going to make.

MR. BESSETTE: Well, I think that's right. I think this -- you know, the PTS work here is -- it's very issue-oriented as opposed to generic, like -- so it's different than when you review the code development or something like code consolidation.

This feeds into the -- this was intended to feed into the work on the thermal hydraulics aspects of PTS and it was a key part of it.

CHAIRMAN WALLIS: Now down the road I can see -- we've been reviewing vendor codes. As you know, we've got three or four of them we're doing now. And presumably down the road the NRC, or the licensees, or somebody may wish to approve in some formal fashion the use of CFD in various forms, just the way that they approved the use of GE Code, or

Westinghouse Code, and so on.

So I can see down the road we may have to face that question. And these sorts of results will presumably be part of a review of that type. But that's probably down the road somewhere.

I assume that what we are going to do is we're going to go back and at the next full Committee meeting we'll make a report as a Subcommittee, which will be 15, 20 minutes, half-an-hour, summarizing what we heard here, anything that the whole Committee needs to know.

MR. ROSENTHAL: Yeah, let me just reiterate. I mean, with respect to PTS, you know, we've got a schedule. We'd like to continue on. We're doing plant-specific RELAP calculations.

We're going to do some benchmark against this facility, price the calcs we're doing, but based on the work that they did with RELAP. But I would expect that that would come out rather well.

We had some show-stopper questions in terms of plumes and stagnation, which I'm encouraged in terms of getting some answers. So we start PF- --

MR. CHOKSHI: The thermal hydraulics condition in September.

MR. ROSENTHAL: In September. And then we are due to come to the ACRS in September, also.

MR. CHOKSHI: In other words, the methodological --

MR. ROSENTHAL: And what I think you've asked us to do is spread out, you know, a beginning-to-end for some sample case. So it would involve three divisions in Research. And I don't think we would belabor the thermal hydraulics very much, given what the Subcommittee has heard.

MR. SHACK: Well, it seems to me you've gotten lots of visual insights into thermal hydraulics and PTS from this room.

But what are your next steps now in the thermal hydraulics part of the PTS analysis?

MR. BESSETTE: Well, basically we've done our analysis of Oconee, which is the B&W design. We've run about 60 transients, call them scenarios, or whatever, PTS, potentially PTS-significant transients to map out the plant.

MR. SCHROCK: Using RELAP?

MR. BESSETTE: Using RELAP.

We've done selected transients as well with TRAC. So we have a TRAC RELAP comparison. So that work is done.

We've started our calculations on Beaver

Valley and Calvert Cliffs. Beaver Valley is a Westinghouse 3 plan and Calvert Cliffs is a CE. And we hope to be well along in those analyses by, let's say, October, which is when the fracture mechanics people need the results to run through FAVOR.

And so that's where we stand.

MR. SCHROCK: And they need a --

MR. SHACK: But what kind of calculations are you going to do assure yourself that the plume behavior you see in those other plants is comparable to the plume behavior -- I mean, the conclusions here, I think, are that, you know, the PFM guys don't have to -- you know, they're golden. And, you know -- but can you reach that conclusion generically yet?

MR. BESSETTE: Well, as far as -- you know, as far as a downcomer goes, basically, you know, you have your initial conditions, which is what enters from the cold leg.

And we would expect to cover the range of conditions that we could expect from -- you know, for a B&W plant you've got a high-mixing region when HPI comes in.

CE and Westinghouse is similar in that you get the stratified flow coming into the downcomer.

The HPI flows are slightly higher in the

Westinghouse Plant and CE, but we'll, you know, we'll cover that, that range.

CHAIRMAN WALLIS: So are you going to accept Westinghouse CFD calculations, something like what we saw here, which are actually, you know, reflecting the conditions in their plume, which is somewhat different than there.

Are you going to except those predictions for temperature, and so on, as inputs into --

MR. BESSETTE: Well, actually, we aren't even getting any submittals from Westinghouse.

CHAIRMAN WALLIS: No, but I mean, what are you going to do about the plumes, then? Is someone going to make a calculation of what the plumes are doing in a different plant?

MR. SHACK: I mean, Jack mentioned you were looking at REMIX, which doesn't look very promi- -- very good here, I mean.

MR. ROSENTHAL: Well, you know, I always -- first of all, we are not getting -- let me just clear. We're not getting anything, any calcs from Westinghouse. We're doing the Westinghouse calcs.

CHAIRMAN WALLIS: Well, I was just hypothesizing.

MR. ROSENTHAL: Yeah. Now --

CHAIRMAN WALLIS: But somebody is responsible for facing the issue of: Is there a plume and how big is it, and what are their temperatures?

MR. ROSENTHAL: Well, I think of the three, I am, but I'm going to enlist the two people to my right.

But I always saw this as a question of we would do some RELAP calculations, and we would have to associate an uncertainty with those calculations.

And I always saw that it wouldn't be a constant uncertainty. Dave has pointed out to me more than once that when -- for those sequences in which you have pumps running, for example, you have a very well-mixed case. And the uncertainties ought to be smaller than in the stagnant cases, et cetera.

So I always, at least in my head, thought there would be that qualification on which sequences and we'll know the associated probabilities of those sequences.

Now, should it come to pass that we have some critical cases, either in terms of extremes of pressures or temperatures, with high-enough probabilities that you care about, then we're going to have to do some more homework.

And REMIX we could always run, and it's

cheap. And as long as we have sequences in which you don't cool down very much, or the pressures aren't very high, and they can live with 25 *c*, or 50 *c* uncertainty, then I don't -- I'm not convinced that we should do any more.

But as soon as I get less than twen- -- if they start telling me that 25 *c* delta really matters in some sequence, then I think we're going to have to do some more work.

CHAIRMAN WALLIS: From what you've seen here, the work that's being done here, by the time that you can extrapolate to the Final Report, you think the information in that Final Report is going to be just what you need to make these decisions?

MR. BESSETTE: I think so.

CHAIRMAN WALLIS: You think so?

MR. BESSETTE: Yeah.

CHAIRMAN WALLIS: That sounds very good, then, as an output from this research work.

MR. ROSENTHAL: Oh, yeah, it's very encouraging.

CHAIRMAN WALLIS: So, Jose, you heard that. I think that's a very good outcome. These are getting to be more internal NRC-type discussions that you're just listening to.

Does the Subcommittee have anything else to say at this time, or shall I just wind things up by complimenting all the speakers.

It's been very interesting. It's very, very nice for us to see technical work done from theory, and experiment, and asking questions, and getting answers. It's been a good couple of days.

Thank you.

(Whereupon, the meeting was adjourned at 12:17 p.m. on July 18, 2001.)

CERTIFICATE

This is to certify that the attached proceedings before the United States Nuclear Regulatory Commission in the matter of:

Name of Proceeding: ACRS Thermal Hydraulic Phenomena Subcommittee

Docket Number: (Not Applicable)

Location: Corvallis, Oregon

were held as herein appears, and that this is the original transcript thereof for the file of the United States Nuclear Regulatory Commission taken by me and, thereafter reduced to typewriting by me or under the direction of the court reporting company, and that the transcript is a true and accurate record of the foregoing proceedings.

Nancy Palmer

Nancy Palmer
Official Reporter
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