The RBHT just forgot to have an overview for the facility itself. It's a full height bundle. It's a seven by seven assembly of electrically heated rods. The difference between it and previous reflood tests is that this has a complete set of instrumentation, meaning when we want to look at grid spacer effect. FEBA did a nice job of taking a look at that.

In the rod bundle heat transfer tests, there will be thermocouples on the grids. There will be fluid temperatures. There is a very detailed array of DP cells. There are thermocouple regs by which to get the steam temperatures. So we can get the whole package of information on reflood and not have to sift through FLECHT and FLECHT-SEASET and FEBA and G2 to get bits and pieces.

In the next several figures, it shows some of the examples of the data that's coming out. I just want to make a few comments. One is it appears to us that the results are consistent. When we look at what's coming out of the test results and compare it to what we would expect from FLECHT and previous tests, we're seeing those things. It's a relatively long transient for in this case a one inch per second test. That's good because this is intended to help us with the model development.

We looked at the steam probe behaviors. The steam probes were a concern in FLECHT because they quenched up at around 900 degrees Fahrenheit which would put us up in here. (Indicating.) In the Penn State bundle the traversing probes are giving meaningful measurements to at least 600 degrees and in some cases lower than that. It means we can get meaningful vapor temperatures relatively close to the quench front where we didn't always have that previously.

A couple of comments on the results. You can see it in this figure where it shows an axial temperature distribution. There are also steam temperatures and grid temperatures. The grids are a first order effect. They truly dominate what is going on in the bundle. That's somewhat expected in a Y in the facility make up there are windows up and down this facility so that they can use a laser camera and digitally image the droplet field. They focus this on the inside of the bundle.

We found and it's amazing that you could run a reflood test and within minutes of completing the test, you get a droplet distribution. Now, the test matrix moves the camera around in some cases so that we see the effects above the grid and below the grid. We're getting droplet information and a distribution that makes sense. The size tends to match up.

DR. BANERJEE: These even look normal.

DR. BAJOREK: Yes.

DR. BANERJEE: Amazing.

DR. BAJOREK: And the size is very typical of what we had expected from previous experiments. This is a bit confusing but the software that goes along with the camera will give you those distributions as a function of time. Now, in this case, there are enough droplets in this particular test to get a nice smooth curve. This gives us a way to look at different periods of the test and seeing how potentially the droplet distribution may change as the quench front moves in the bundle.

The traversing steam probes. First by way of the bundle itself it's a relatively uniform planer rod for a temperature profile, meaning the housing is not having a very strong effect on the interior rods as we would hope. We are seeing with the steam probes a gradient in the steam profile as we move from the center of the bundle closer to the housing.

We're also able to pick up what I refer to as the subchannel effects where you see higher temperatures when you have the steam probe immediately between two rods as opposed to somewhere out further in the subchannel of the flow. So we're getting what we think is a fairly detailed picture of the vapor temperature distribution across the bundle.

DR. SCHROCK: I don't understand. If this is on the distribution and time, how do you see that?

DR. BAJOREK: This shows two different tests. The only difference is where the traversing steam probes were positioned. This one was in the subchannel, the middle of four rods. For this upper curve, the steam probe was immediately between two rods. So we're able to see the difference in steam temperatures in where the bulk mixing part of the fluid is versus where it is between the rods. As we go from the center of the bundle out to those rows closer to the housing, we would see this pair drop in temperature as you would expect.

MEMBER RANSOM: Are those the droplets hitting the probe?

DR. BAJOREK: Probably.

MEMBER RANSOM: A shoot up in temperature and then down. Although that's kind of a long time.

DR. BAJOREK: That's a fairly long time

and there's a lot of droplets.

MEMBER RANSOM: What explains the scilitory (PH) (PH) nature of the temperature measurements?

DR. BAJOREK: There are some oscillations in the -- itself.

MEMBER RANSOM: Pardon?

DR. BANERJEE: It's quite regular.

MEMBER RANSOM: Are they slugs or drops? I mean, they're actually bubbles I guess because they're higher temperatures so it must be steam and then go down to the liquid temperature.

DR. BAJOREK: These are bare thermocouples so they do occasionally get wet. There's a lot of liquid. I think when they do get wet there is a time period by which it takes to --

MEMBER RANSOM: Just one quick clarification. You have percent numbers on the droplets. Are they all normalized to 100 percent?

DR. BAJOREK: They are eventually, yes.

MEMBER RANSOM: Okay.

DR. BAJOREK: I guess our point at this point testing is moving along. They've been able to run on the order of seven or eight valid tests at this point. We're taking a look at the data as it's being produced. We're using this to modify the test matrix so these things make sense. The long run moving the camera around to positions of interest.

They're going to do the initial phase of reflood tests consisting of a group of 33. They should have those done in about September. Our proposal to the Committee is that potentially October, maybe November would be an appropriate time to spend a day looking at the reflood test program where we could go through in detail and show you the bundle, show you the results, show you the trends. We probably won't be at the point of developing models at that point, but explaining what's going on.

We think it would be worth having that meeting at Penn State so you could see a test, look at the instrumentation, see how it's done, and look at the facility that's been put together. It's an impressive facility and I think represents a very strong commitment on the part of research to continue advanced model development.

DR. SCHROCK: Could we have the benefit of some documentation on the instrumentation in advance of that meeting?

DR. BAJOREK: Yes.

DR. SCHROCK: I think that would be

helpful.

DR. BAJOREK: It's not bookmarked.

MR. ROSENTHOL: We'll give you what we have.

DR. BAJOREK: This is all on paper at this point.

DR. SCHROCK: We've seen some. But I don't know that it's enough.

CHAIRMAN WALLIS: This is near Philadelphia?

DR. BAJOREK: State College, Pennsylvania.

CHAIRMAN WALLIS: Where's State College? It's out in the boonies somewhere?

DR. BAJOREK: Yes. It's across the state. It's easier to get to than New Hampshire.

(Laughter.)

MEMBER RANSOM: Quick question. Is somebody thinking about how you're going to use this information to improve the TRAC code?

DR. BAJOREK: Yes. Really the entire test matrix which was designed by Joe Kelly is set up in such a way that we get information to develop mechanistic models for dispersed or off the heat transfer, interfacial drag, and inverted annular flow; those areas of the code where we have particular question marks.

MEMBER RANSOM: Precursory cooling out of that?

DR. BAJOREK: In what way?

MEMBER RANSOM: If you have reliable models that calculating precursory cooling for the bundles, I think that's what you had earlier.

DR. BAJOREK: Do we have them now?

MEMBER RANSOM: You will have them.

DR. BAJOREK: We will have them. We need to have them, yes.

CHAIRMAN WALLIS: So, thank you.

MEMBER RANSOM: I'm still puzzled. It's not a reasonable question.

DR. BAJOREK: What? I'm not sure whether your question is whether we have good precursory cooling models now or that's our intention to use this data to develop them.

MEMBER RANSOM: Are there new models of precursory cooling which I think has been a problem for these reflow reductions?

DR. BAJOREK: We would hope to be able to develop them out of this data because we're going to have a much better handle on the development of axial steam temperatures.

MEMBER RANSOM: That's basically part of Joe Kelly's contribution then.

DR. BAJOREK: Yes.

MEMBER RANSOM: Okay.

CHAIRMAN WALLIS: Anything else?

DR. BAJOREK: Okay. Thank you.

CHAIRMAN WALLIS: Thank you. Can we move on before we take a break? Then we'll take a break somewhere after the next presentation or maybe after Marino diMarzo's presentation depending on how things go. We are changing gears completely.

(Discussion away from the microphones.)

CHAIRMAN WALLIS: This is a new play all together.

MR. SCOTT: Yes. In fact you probably thought about alpha all morning, the void fraction creation. This afternoon we're going to be thinking about beta, the reactivity parameter.

I'm going to start off here and give you an overview of the Generic Safety Issue. Then next Dr. DiMarzo who is actually a part time NRC employee in addition to being from Maryland is going to talk a little bit about thermal-hydraulics. Then it sounded like you wanted to take a break. Then Dr. Diamond has a longer presentation in which they've used the PARCS code to make some calculations.

This slide is just for the benefit of people that are going to read a transcript later. So let me put up a diagram of a steam generator coolant and just talk a little bit. This event starts with a small break LOCA. For example, a two inch break is about the right size. That's about 20 square centimeters.

CHAIRMAN WALLIS: Does it matter where it is?

MR. SCOTT: It doesn't seem to. Well, it may matter where it is. Some scenarios would not result in boron dilution and some would. We didn't look into exactly which scenarios resulted in this.

MEMBER RANSOM: It looks like it would be pretty important whether liquid is leaving out the break or steam is leaving out the break. If it's steam leaving, no boron is leaving. If liquid is leaving, boron is leaving.

MR. SCOTT: Well, but the steam has to go over the candy cane and then condense here to put unborated water down where this green is. (Indicating.)

MEMBER RANSOM: No. The question is what leaves the system? Where is the break?

MR. SCOTT: I guess I don't know for sure in which calculation that BNW did where the break was.

MEMBER RANSOM: I know in the documentation I couldn't find out where the break was.

MR. SCOTT: Well, we don't say exactly where the break is.

MEMBER RANSOM: What do they assume, the liquid leaves or paper leaves? The importance of this question is you're trying to figure out if boron is leaving the system I think.

MR. SCOTT: No. What we're trying to find out --

MEMBER RANSOM: As well as dilution. I understand that.

MR. SCOTT: How much water that does not have boron in it can accumulate in the steam generator.

CHAIRMAN WALLIS: This thing is looking like a still.

MEMBER RANSOM: Yes. My point is that the boron inventory is also important if it all stays in the core.

DR. DIMARZO: Right. The scenario which is depicted here is a situation that occurs late in the transient where basically the inventor is being reduced.

MEMBER RANSOM: By liquid draining out.

DR. DIAMOND: By liquid draining out. You have lost most of the liquid at this point. All you have is liquid in the core because you have to clear the hot leg in order to have an installation process if you wish or -- at BCN type process. So it is necessary for that hot leg to be substantially empty.

If you have 20 percent collapse liquid leveling in the hot leg, you are bound to have now and then presumption of natural circulation. That would basically foul up the deborate water that you have accumulated because it would put borated water on top of it and it's mixing. So it's a very tight scenario in order to generate a slug of this magnitude.

That inventory cannot be too high otherwise you start getting two-phase natural circulation. It doesn't have to be too low otherwise your transitions is a severe accident. That's a very narrow bend. It has to be maintained long enough, that interval of --

MEMBER RANSOM: So you gather the worst case is a small break, like two inches in the liquid at some point. So you're losing boron as well as liquid.

DR. DIMARZO: You have some HBI capability.

MR. SCOTT: And it also has to be early in the core life because at the end of it's cycle the boron concentration normally is down.

MEMBER RANSOM: Right.

MR. SCOTT: So therefore if you could get a little bit of boron in, you'll be okay. Dr. Schrock, ten years ago when we did the CSAU with RELAP, I don't think this issue ever came up. We did assume only one HBI pump. We did BCN phase. I don't recall that there was any discussion. A little bit later I'll mention some of these scenarios and say about what time people brought them up if you want to talk about that.

At some point the natural circulation had stopped. You developed this as I showed unborated water in the tubes and in these legs. Just before the circulation is done, this may move up and then come back down. (Indicating.) We're assuming that the pumps don't start. Once you've refilled the system, the natural circulation starts again and now this slug of unborated water moves into the core. That's the assumption. You also get this same scenario in a steam generator plant. I don't know if I have a figure of that or not.

Also I should point out that the vent valves in the BNW reactor as long as there's no natural circulation flow that they are doing some mixing. There is some mixing going on in the core itself.

DR. BANERJEE: Are you going to show us a little diagram where there's vent valves?

MR. SCOTT: I don't have one with me. I can dig one out later.

DR. BANERJEE: Yes. It would be useful because there's a lot of appeal to the vent valves here.

MR. SCOTT: And as I recall from the write up it depends where the level is. If the level is up either at the vent valve level or higher, they may be more or less affected. But this was one of the things that BNW did later on to show that the transient is more benign as they get more effectiveness from the vent valves.

DR. BANERJEE: So it would be worth seeing the geometry of this.

MR. ROSENTHOL: But it isn't quintessential to the larger that we will be explaining to hopefully resolve the issue.

DR. BANERJEE: Right.

DR. DIMARZO: There's a lot of stuff in the BNW report that we don't pretty much subscribe as you'll see later on.

MR. SCOTT: Okay. I'm just going to summarize here what Brookhaven has found now with several calculations. We did go above prompt-critical. We did reach its power of 80 percent. I think the only thing that we changed was 37 calories per gram. So the total was about 50. BNW in their report calculated about 90.

That's part of the reason this scenario came onto the scene. Harold Vander Molen was asked to prioritize it because 90 or 100 calorie per gram is in the range where we think now about fuel damage for irradiated fuel. With this level of 37 calories per gram, we do not expect any fuel damage.

DR. SCHROCK: You don't give any information on the length of time this reactivity gain required.

MR. SCOTT: Dr. Diamond will cover all that.

CHAIRMAN WALLIS: It doesn't last very long at all.

MR. SCOTT: It's five or ten seconds. I'm sorry. The pulse itself?

DR. SCHROCK: The rise in reactivity to $1.02 happens over some period of time during which a lot of negative feedback occurs as well.

MR. SCOTT: Yes. But that would be real short.

DR. SCHROCK: But one of the things as I read the material sent to us, it occurred to me that there's never mentioned that maybe something like the SL1 accident could occur in a BNW system to this boron dilution. If the reactivity could be inserted rapidly enough, I don't think it could. You know what I'm referring to.

MR. SCOTT: Yes.

DR. SCHROCK: SL1 blew its lid essentially because it was half full when it received a prompt reactivity dose in a matter milliseconds.

MR. SCOTT: There is another aspect of the scenario which is you run the pumps. You pump the primary pumps.

DR. SCHROCK: That's what I'm getting at. When you use that --

MR. SCOTT: At which point --

(Inaudible.)

DR. SCHROCK: Reactivity insertion passed enough to give you that kind of phenomenon. If so, it should be considered.

DR. DIMARZO: Okay. The history of this particular issue. The BNW owners group essentially claim that pump restart would be a problem. So they decided to take the pump out. That's fuzzy at this point. But the idea would be that if you enter BCM or if you have the probability of generating such a slug your variant would be prevented from turning the pump on. That's where they are.

That's okay. But we are not happy with just leaving it at that. So we have concocted a slug that would be pumped. We passed this information to Brookhaven. They are going to run that calculation just to see what that would entail.

DR. SCHROCK: That's something to be done in the future.

DR. DIMARZO: That's something to be done between now and September.

DR. SCHROCK: So would it be looking at the possibility of an SL1 type?

DR. DIAMOND: It's still in the orders of magnitude slower now.

DR. SCHROCK: I think it's too slow.

DR. DIAMOND: Right. We're in a different regime here.

MR. SCOTT: I'm going to now mention some other scenarios just to give you some perspective. You may have heard these before or not. Let me just this put up. (Indicating.) Let me say this is a 22, the first one up here. The second one is the french. Let's say this one here is the french. This one is the GSI-185. Let's say this is the Swedish one here. (Indicating.) This is just pictorially.

What I can do now if you want to or maybe you want to save time, I can go down and describe a little bit about these. Would you like me to skip that?

CHAIRMAN WALLIS: Do they help us understand GSI-185?

MR. SCOTT: Not particularly.

CHAIRMAN WALLIS: Maybe we should just move right on then.

MR. SCOTT: All of them result in unborated water which eventually goes into the --

CHAIRMAN WALLIS: But we're trying to resolve GSI-185.

CHAIRMAN WALLIS: Right. Let me now jump into the process that we used in trying to do this. This little diamond here is acceptable. (Indicating.)

If we assume and calculate some ex-vessel mixing, do the neutronics, if we get a small pulse, no fuel damage, then we can show issue closure. We expect to go down this path. We've been going down this path.

If in fact at this point you got a high value of fuel enthalpy or fuel high temperatures then you could proceed over here and say let's see if we can get more mixing in the vessel between the down cover inlet and the core inlet which would make the pulse be broader or slower. Then you could do some calculations. Other people are doing this in Europe. Then you could come around here and get this one. (Indicating.)

Now I'm going to put up a graph that's from the report that you saw. When Dr. Diamond gets up here, he'll give you more details about this scenario and some other scenarios. Here's one note that I had. When Dr. Vander Molen did the prioritization he got two times ten to the minus five per reactor year for this GSI-185. That's the level that we're talking about as why it was considered to be worth further study.

CHAIRMAN WALLIS: Now, you're not showing here the reactor power.

MR. SCOTT: No. This is the reactivity

and the boron concentration.

CHAIRMAN WALLIS: The reactor power is a more dramatic figure presumably.

MR. SCOTT: So in this case now this blue line and on your handout it's black and white but it has circles is an input guide to the code. The code doesn't calculate that. We didn't take RELAP and calculate the whole scenario. We just have a core that has the PARCS and the kinetics and you drive it with the RELAP boundary conditions. Correct?

DR. DIAMOND: Sort of. Something like that.

MR. SCOTT: Okay.

DR. SCHROCK: So it's a burst of boiling that causes that precipitous drop in reactivity.

MR. SCOTT: This would be the Doppler comes on and takes you down. You still have positive reactivity so you can get another pulse. At this point I guess you're getting heating and it can take you down. You'll describe this.

DR. DIAMOND: Yes.

CHAIRMAN WALLIS: Boron concentration doesn't look like a slug. You're saying this is some kind of an average or something.

MR. SCOTT: Well, it's going to diffuse as it starts in because it's mixed as it starts out before the pump. It has to come in through the pump, come down a leg, come down again. We didn't assume any further mixing in the down-comer. So it doesn't have a sharp edge on it and in the tail of it.

DR. BANERJEE: Why is it mixed in the pump?

DR. DIMARZO: Let me go and explain what's going on here. This particular curve I think is --

MR. SCOTT: Very benign.

DR. DIMARZO: Benign and is the original claimed curve by the owners group. This was based on some -- mixing that was happening between the steam generator and the core inlet.

DR. BANERJEE: The by-process.

DR. DIMARZO: No. Basically the slug was coming from a steam generator, coming out the cold leg, going through the pump, and then flowing into the down-comer, mixing in the down-comer, mixing in the low head and then entering the core. What you get there is the core. So initially the slug was characterized as pretty shot. By the time you went through all these geometries, it was pretty diffused. That's what they claim.

When you see the slide of the approach

that we have taken, we have taken no credit for any mixing happening into the down-comer or into the lower head of the vessel which is a pretty substantial amount of mixing. But the problem is that in order to know how much that is you would have to do a full blown calculation and scale it to plant. That's a route that we did not decide to take. What we did was just simply consider the movement of the slug from the steam generator to the entrance of the down-comer which basically involved the steam generator, the cold leg, the pump, and the remaining part of the cold leg to the vessel.

MR. SCOTT: You also have the borated ECCSs coming in and mixing with that as it flows.

DR. DIMARZO: Yes. But we didn't take credit for that either.

MR. SCOTT: Also we should say that this curve assumes that it's symmetric at the core inlet. In other words, the left half of the core is exactly the same as the right half of the core. Some of these experiments have shown that if you're just getting one LOOP to start up that has the unborated water it wouldn't be symmetrical. But we didn't try to make any assumptions about that.

The velocity into the core is around two percent of rated core flow. The size of this slug is 1000 cubic feet or about 28 cubic meters. We think that there are several scenarios where you may have less cubic meters than some other scenarios. So you can figure out here knowing the densities and the volumes it runs for about 100 seconds given these velocities. As I said, Dr. Diamond will tell you some more about the intricacies about the red curve.

Okay. Now I think I'm going to go to my last slide. Closing the issue. Let me say first a few words about my personal bullet here. It's additional calculation that we want to do. As we said earlier, we've already assumed natural circulation. But we will do a calculation where we've assumed pump bumping.

This was considered in the prioritization report. So for completeness, we need to do both these calculations. But we did the one first just to see where we were at. If we get a large pulse, then we'll show that these emergency operating procedures that say leave the pump off, that should be continued. The other possibility is that even with this scenario the fuel enthalpy will be such that it could be interpreted as giving fuel damage no worse then that from the rod ejection accident. In that case if they make the mistake of starting the pumps, it wouldn't be the end of the world.

Warren Lyon from NRR is the person that's been following this issue for a number of years. In fact, this scenario and I skipped over that before was identified in '91 or '92. So the scenario has been around a long time. It just didn't come up for a relook until a couple of years ago.

If we're done here with these items, then in September we can come to the full committee. Then the process is that we prepare a closeout memo to EDO assuming that there's no action that we're going to recommend to NRR. Okay. Thank you.

CHAIRMAN WALLIS: I thought you were recommending for the work. Maybe I missed this.

MR. SCOTT: We're going to do one more calculation.

CHAIRMAN WALLIS: That's all. I thought it was more than that. Maybe I got the wrong impression from what I read.

MR. ROSENTHOL: If I could make a couple of comments. Dr. Wallis, you were absolutely right. We're trying to sell GSI-185 and not all boron dilution events. So your earlier comment was right on and very important.

In the course of preparing to go we thought to the full committee, now we decided to go to the subcommittee first, we were briefing our office director. He said what happens if they turn the pumps on. We said that's a different scenario. He said for completeness, you really ought to understand that one also with its commensurate frequency.

Then there was a discussion about how many other scenarios we should do. We said no, this is GSI-185. Boron dilution at cold shut down or something else is some other GSI. So it was only really the recognition and preparation from meeting with you that we recognize that for completeness we really ought to do the assumed operators don't follow their emergency procedures and turn the pumps on. That's the stuff of the additional work.

I want to make one other comment because I think that Marino would be too modest. That is that a lot of people around the world are doing a lot of thermal-hydraulic calculations looking at the distribution of boron water in the system as a function of time. He's the one who said wait a minute, let me come up with some sort of bounding slug, and let's take advantage of this new physics tool that we have to do 3-D space kinetics. If we can show that the results for the pessimistic slug are okay, then we don't have to get into all the detail.

So at the very same time we're trying to resolve this reasonable narrow generic issue. There are people around the world doing lots of fancy calcs which is good stuff but maybe more applicable to other scenarios.

CHAIRMAN WALLIS: Maybe I misread, I thought I read a tough action plan which calls for more experiments and OSU, those sorts of things.

MR. SCOTT: Let me tell you about that. Those other tasks in there all had a prerequisite that said if --

DR. DIMARZO: No. He's referring to a correct one. As you will see, I have two slides. It's not going to be much. But basically I have formulated a simple model to characterize the mixing ex-vessel, in other words, from the steam generator to the vessel.

Then I add some LOOP data, some Maryland data which were repeatable and reliable at least to me at that point. I used that to validate against. That's inbreeding. So at that particular point I said maybe we ought to run a couple of tests blind and check whether the same model is able to predicate that in a blind fashion. In other words, it would be me running the calculation data and they are doing the experiment and then match.

Unfortunately AP1000 came on the scene at that point. We lost the window of opportunity to run those tests in OSU. So the only validation we have is data from Maryland basically which were obtained three or four years before. That basically is the base for the validation on the model which I'll describe to you all if you want right away.

CHAIRMAN WALLIS: Maybe I just didn't spend enough time reading it. I got the impression that you folks were not closing the issue, but you were asking for more work. They've had a task action plan that specified all this work to be done. That is not the case. You're actually proposing to close the issue with what you know now.

DR. DIMARZO: Yes. If we put through the pump a slug and we don't get anything dramatic, there is no point in trying to finagle the thermal-hydraulic to get the same answer.

CHAIRMAN WALLIS: Okay. We never fanagle thermal-hydraulic.

(Laughter.)

DR. DIMARZO: Okay. What I'm talking

about here is reported in a paper that came out on engineering and design. I have a few copies of it.

MR. BOEHNERT: They got copies.

DR. DIMARZO: So the idea here is to characterize the mixing that occurs between the steam generator and the entrance of the down-comer. The geometry that you are looking at is the steam generator, the steam generator upper plenum, the cold leg in the suction portion leading to the pump, the cold leg in the discharged section. That's it.

So basically this is nothing strange. I took something that is old and very well known. I went to Levenspiel back there. I said there are two possibilities.

CHAIRMAN WALLIS: Other OSU work.

DR. DIMARZO: Yes. There are two possibilities here. Either we have volumes that are completely mixed or there are volumes that are completely unmixed. So either we go to a plug flow or we go to a backmixed flow.

CHAIRMAN WALLIS: I suspect that plug flow is the worst condition.

DR. DIMARZO: Plug flow is the worst condition.

DR. BANERJEE: You are saying some

components --

DR. DIMARZO: Some components will be one way. Some components will be the other way. The reason why I elected to do that is that if you do anything modeling wise more complex then the question becomes how much mixing do you allow in a component. That's subjected to scaling problem. I didn't want to touch that.

So I said we have two volumes which I believe are fully mixed. One is the pump because basically you have veins in there. Even at fixed flow you have enough turbulence generated that which would cause mixing in that volume. Then you have the steam generator of the plenum which is also subjected to mixing because you feed it from all the tubes which basically are like little jets in that particular volume.

I made the assumption that those two volumes were completely mixed and everything else was completely unmixed. It was just a transfer.

DR. BANERJEE: Including the down-comer.

DR. DIMARZO: The down-comer I didn't touch. This is fed directly to the core.

CHAIRMAN WALLIS: This is ex-vessel.

DR. DIMARZO: The ex-vessel is fed into

the core. There is no down-comer. There is no lower head which has a substantial amount of mixing. So it was a very conservative position. It wasn't a top hat type thing. But it was next to that, the most conservative thing that you could do.

CHAIRMAN WALLIS: Is it conservative to assume backmixed volumes say in the steam generator at that plan?

DR. DIMARZO: Right.

CHAIRMAN WALLIS: And maybe it's not perfectly --

DR. DIMARZO: Right. So I had the test in Maryland that was conceived like this. The slug was filling the steam generator, the steam generator upper plenum, and was somewhere in the leg filling to the pump. So when that slug moved, the front of the slug would go to the pump only and the back of the slug would go to the steam generator upper plenum and to the pump.

CHAIRMAN WALLIS: But it's already a pure water slug, so it doesn't really matter.

DR. DIMARZO: No. Two interfaces. In other words, in the middle I have this water which has two interfaces; the front and the back. The front goes through the pump only. The back has to go through the steam generator upper plenum and through the pump.

CHAIRMAN WALLIS: Because there's borated water following it. Is that right?

DR. DIMARZO: Right. In our case, it wasn't borated. It was a temperature type situation.

CHAIRMAN WALLIS: Okay.

DR. BANERJEE: But in this case the slug is just pure water with borated water in front. Do you have any at the back?

DR. DIMARZO: Yes. Again, you have the same situation that you have at the front at the back.

DR. BANERJEE: Can you put that diagram up?

CHAIRMAN WALLIS: How does it get to the back?

DR. DIMARZO: No. We constructed a slug which was based on temperature in the Maryland facility.

DR. BANERJEE: Yes. I know what you did.

DR. DIMARZO: Okay. So basically we had salt and temperature. So the temperature is the tracer. The salt is such that it enables you to keep stuff where you want it initially.

DR. BANERJEE: Yes. Just to clarify the

geometry.

DR. DIMARZO: Okay.

MR. SCOTT: I'm looking for the --

CHAIRMAN WALLIS: The back of the slide is much less important.

MEMBER RANSOM: The event's over by the back of the slide probably.

CHAIRMAN WALLIS: So you've put borated water on top of the green.

DR. DIMARZO: Okay. So in the Maryland test, the green stops right here at the beginning and you have water which is cold back up here again. (Indicating.)

CHAIRMAN WALLIS: But in the real thing you have borated water way up --

DR. DIMARZO: In this scenario when you go in natural circulation what happens is this, you reseal the system. All these things are moved up here. (Indicating.) When finally the water fills up completely, the system natural circulation can resume. In other words, your generate your slug and it looks like this. (Indicating.)

DR. BANERJEE: But in natural circulation or just --

DR. DIMARZO: No. In order to generate a

slug, you are in BCM. There is no natural circulation. You're boiling the core. You're condensing the --

CHAIRMAN WALLIS: The slug doesn't move until you but in enough borated water from ECCS.

DR. DIMARZO: When you put the water in from ECCS, you basically push it up in the steam generator and you put borated water on the other side. At some point they meet on top and that's a condition required for single phase natural circulation which is what we're talking about. At that point the slug starts to move.

DR. BANERJEE: You're not talking about starting the pumps.

DR. DIMARZO: That's what the assumption is if they take the pumps out. If you imagine to start the pump, then basically you keep filling the pump at this point. They don't need to do all this business. You just turn on the pump. What happens is that now you pump water on top of the candy cane which joins the slug as it's being pumped out and the process happens similarly.

CHAIRMAN WALLIS: The worst thing you could do presumably is to bump the pump, put the slug into the reactor, and then turn it off.

DR. DIMARZO: And then stop. Right. Okay.

CHAIRMAN WALLIS: Because you get scared.

DR. DIMARZO: Right. What we did at Maryland was this. We had data on the front of the slug and data on the back of the slug. I had an assumption that says the two mixing volume are those two. I know those two volumes. Basically what I did is to generate a curve based on those two volumes and along that theory. That is the validation shown here which is pretty good. The Tao, τ, is the slug transient time. It's the ration between the volume of the slug.

DR. BANERJEE: It's space time.

DR. DIMARZO: Yes. Basically it's how long it takes for the slug to go through one section if it's totally unmixed. So the formulation is very simple because it's not relying on the dispersion factor which is what makes it very amenable to calculation. Clearly you can use any type of input in the function C of lambda, $C(\lambda)$ that you want and basically you get your output that way.

So I took this approach and I applied it to the initial condition that was supplied by the BNW owner group. That is what Diamond will refer to in his presentation here as the second case or third case. Right?

DR. DIAMOND: The second case.

DR. DIMARZO: The second case. So you'll have a comparison between this artificially mixed thing that the owners group came up with and this type of curve fed directly into the core. That's what you're going to see.

The next thing would be to pump. So what happens? First of all the slug that was proposed by the BNW owner group is a 22.3 meter cubed slug. The maximum amount of water that you can physically store there unmixed is 28 meters cubed. So I took 28 meters cubed and pumped.

CHAIRMAN WALLIS: So the only place it's mixing in your model is in the pump.

DR. DIMARZO: And in the steam generator upper plenum.

CHAIRMAN WALLIS: Upper plenum.

DR. DIMARZO: If it was mixing only in the pump, the back of the slug would look identical to the front.

DR. BANERJEE: He's made a very simple reactor model.

CHAIRMAN WALLIS: But the back of the slug doesn't come in until after you get to the right hand side.

DR. DIMARZO: Yes. After one transient time, the back starts to show up.

CHAIRMAN WALLIS: Right. I'm trying to think why you have such a gradual increase in the beginning there.

DR. DIMARZO: Because the first one is going through the pump which is a mixing volume.

CHAIRMAN WALLIS: It can only mix with the boron which is left in the pump. It only flushes it out.

DR. DIMARZO: Yes. Basically what it means is that the slug comes in and mixes with whatever is in there and comes out. That's the model.

DR. BANERJEE: What's the volume of the pump relative to the volume of the --

DR. DIMARZO: The volume of the pump is, let's see in that particular calculation --

DR. BANERJEE: Compared to the volume in the pipe.

DR. DIMARZO: Yes. That's the characteristic N that you're talking about.

CHAIRMAN WALLIS: Yes. Or the volume of the 1000 cubic feet.

DR. DIMARZO: No. In Maryland, it's not 1000 cubic feet. But the transient time for the pump is the volume of the slug divided by the volume of the pump is about seven.

CHAIRMAN WALLIS: Seven.

DR. BANERJEE: Transient time through the pump.

DR. DIMARZO: Transient time is very small because that transient --

DR. BANERJEE: This is natural circulation.

DR. DIMARZO: No. The point is this. In this model it doesn't matter how fast it goes. The model is formulated in terms of just one dimensional type. The time is essentially scaled by the flow rate as in the transient time. So you don't really need to know that.

To put this in perspective, the owners group made 22.3 meters cubed have a transient time of 110 seconds. If you take the transient time that they should have taken at steady state natural circulation, it would have gone through in 77 seconds. They took and increased that time, in other words, they made the flow slightly slower because they said this is going to be the start up of natural circulation.

What we are doing as a bounding slug as I said to you before is 28 meters cubed and it goes through in ten seconds as opposed to 110 seconds. So we basically bound that by volume and we bound that by flow rate pretty substantially. It's 11 times faster.

CHAIRMAN WALLIS: Why is it so much faster?

DR. DIMARZO: Because now we are pumping.

CHAIRMAN WALLIS: Now you have the pump running.

DR. DIMARZO: Yes. I mean, in the bounding slug.

CHAIRMAN WALLIS: I thought you weren't running the pump.

DR. DIMARZO: Let me put it this way. We have two cases; one that you see today which is natural circulation and the transient time is 110 seconds. The one that we will do is pumped 28 meters cubed so it's a slightly larger slug going through in ten seconds.

CHAIRMAN WALLIS: Yes.

DR. DIMARZO: Okay.

DR. BANERJEE: What difference does that backmixing in the pump do for you? Does it help at all?

DR. DIMARZO: Yes because the front of the slug is what is most important here. To put it through that volume softens it up enough to make a difference. If you put through the vessel a square wave that is completely different.

DR. BANERJEE: Will you get the Doppler feedback?

DR. DIMARZO: I don't know exactly what the neutronic impact of that is. That's very important what you do at that slug.

DR. BANERJEE: That's the smoothing.

DR. DIMARZO: That's the smoothing there. Right. The tail it doesn't really matter what you do in a way. It's there for completion. Now obviously you could start doing over-speculation of what mixing should occur in vessels, but we are trying to stay out of that at this point.

CHAIRMAN WALLIS: Well, if a pump is what's saving you, I think you may need to be more cautious about your assumption that the pump is well mixed.

DR. DIMARZO: Yes. But I got a substantial amount of data from Maryland that when I passed a lot of slugs through there that tells me that it does do something. That I can use and validate against. The scaling that comes out of it is based on the volume of the pump and the volume of the slug. So it's portable. You don't have to make too much argument of scaling with that type of an assumption.

CHAIRMAN WALLIS: So the down-comer floor is not just one dimensional either.

DR. DIMARZO: No. Since you asked, the down-comer floor is of this kind. We have an experiment. You mentioned about an experiment. I just brought it so that you could get an idea. But that's how misleading a computation could be versus an experiment. For example, this is a CFD of the down-comer done by the owners group in their report. As you can see the slug comes in the cold leg and basically goes straight through down.

CHAIRMAN WALLIS: It makes a -- and goes straight down.

DR. DIMARZO: Yes. That's what they say. These are experiments. They're from Maryland. Here is the first slide where the cold leg is the blue spot.

CHAIRMAN WALLIS: The blue stuff is --

DR. DIMARZO: Where the cold water is going to start to come in. Now the first upper portion of the down-comer has been flooded. As you can see, there is a significant amount of uncirculated region below that cold leg which indicates that the slug is going anywhere but down. Even later in the transient, everything happens except for that thing to go down in that direction. It goes around and down and then even pops up from the bottom up again.

These are obviously just information because you can't scale it to the real thing. But what I'm trying to say here is that to touch the CFD in the vessel is a very complex enterprise.

CHAIRMAN WALLIS: But it may well be that it'll never go pump critical at all.

DR. DIMARZO: Absolutely.

DR. BANERJEE: All you are doing is you're getting a residence time distribution. You could do this without any --

DR. DIMARZO: Yes. But the problem is I could take the experiments in Maryland and say scale them, in other words, get an idea of how much mixed region there is in that. You could translate this into saying for example that if you take the volume of the down-comer and lower head and you imagine that 20 percent of that is fully mixed and run some simple model, get the curve out of there and plot it.

We did all these exercises at Maryland.

That's been put in our reports. The problem is that I don't know how to answer the question what does it mean to prototype. That's basically where I think if you go down that road you have to have a validation of a CFD model against Maryland perhaps and then at that point scale it up with that code once you're convinced that what you see is what you get. That is not a simple enterprise.

DR. BANERJEE: But a level is always below the pump in the pipe --

DR. DIMARZO: The level?

DR. BANERJEE: Of the deborated water.

DR. DIMARZO: When you form the deborated --

DR. BANERJEE: It never reaches into the --

DR. DIMARZO: No. It might come into that pipe. But the problem is that this is a slow process, this formation of the deborated. The deborated is somewhat lighter. Being the same temperature of the borated water that it displaces, it's lighter. So as it enters the vertical portion of the pipe towards the pump it would tend to mix with it. What's in that particular leg is not really deborated. At best, it's some kind of a smooth mixed type thing.

CHAIRMAN WALLIS: Isn't there a slow flow because of the condensation that comes through and keeps washing out that borated?

DR. DIMARZO: Right. Exactly.

CHAIRMAN WALLIS: So you get some dilution before the slug actually gets in.

DR. DIMARZO: Exactly. In the front of the slug, there's not even that chance because of that effect. To that you add the fact that there is some limited amount of HPI injection too which borated the slug as it goes back.

CHAIRMAN WALLIS: I'm saying that the deborated water actually flushes out some of the boron from the pump.

DR. DIMARZO: No. The deborated at best can come to the level of the pump really. It can also trickle through the pump. But you have an HPI injection that you haven't considered here. So it's a wash. In one way, your pump could be more deborated then what I anticipated, yes. But on the other hand, all the water between the water and the steam generator will be far more borated than what I guessed.

CHAIRMAN WALLIS: How do you know about that?

DR. DIMARZO: That's because it mixes.

CHAIRMAN WALLIS: Does it? If you have enough low trickle flow you called it or enough flow of deborated water because of condensation and flow around so that it keeps on flushing out some boron, then you could have less boron.

MR. SCOTT: I think it depends on how long that BCM went on.

DR. DIMARZO: Right.

MR. SCOTT: If it just goes on forever and ever, then it's really clean water.

DR. DIMARZO: Yes. Then you have clean water coming through to your core from that.

CHAIRMAN WALLIS: Right.

DR. DIMARZO: But you would be very slow.

CHAIRMAN WALLIS: Well, very slow. I guess you would have to have an analysis that shows it.

DR. DIMARZO: I mean, by deboration alone you have basically -- If you imagine the condensation process to go on indefinitely and to have the deborate come through the core with that kind of a rate, I don't think we'll get anything.

CHAIRMAN WALLIS: That's not a problem. The problem is if the condensation builds enough deborated water that it actually flushes out the pump then you can't take credit for the boron.

DR. DIMARZO: I can't take credit for the boron in the pump. But the pump remember is a minuscule volume compared to down-comer and lower head.

CHAIRMAN WALLIS: You're assumption is that you get mixing in the pump. If there's no boron left --

DR. DIMARZO: I see your point. The realization here is that's what you take credit for. The practice of the fact is that you are a down-comer and a lower head of which you don't take credit at all which is a tremendously conservative assumption. So I understand your point and it's well taken. The problem is that I'm not taking credit of a potentially mixing volume which is enormous compared to the pump itself.

CHAIRMAN WALLIS: But I'm saying you could be more conservative and not take credit for that boron in the pump because it's being trickled out by condensation.

DR. DIMARZO: Right. I'm not an expert. I'll let Diamond discuss that. I think that the leading edge of that slug is very important in what you're saying too. So if you're saying to a square wave which is virtually impossible considering all the mixing volume, he has a problem with it. The results would change dramatically.

DR. BANERJEE: For a thermal shock situation, what happened in the down-comer? There were a lot of studies done. Weren't there?

DR. DIMARZO: You mean in the PTS.

DR. BANERJEE: Yes.

DR. DIMARZO: We didn't look at that.

DR. BANERJEE: Well mix ups or --

(Inaudible.)

MR. ROSENTHOL: (Away from the microphone.) We had the OSU experiments.

DR. DIMARZO: The down-comer what appears to happen is that there isn't even a plume. In other words, by the time you are five or six diameters of the cold leg down you can't find anything anymore.

DR. BANERJEE: Why wouldn't you expect something like that here?

DR. DIMARZO: Absolutely. But what I'm saying is that I cannot come here and quantify how much mixing occurs in the down-comer. I can simply say there will be a tremendous amount of mixing in the down-comer. But I cannot say exactly how much. In other words, I do not have a scalable transfer function from the flow coming into the down-comer to the entrance of the core. All experiments that have been done do show that there is a significant amount of mixing there.

DR. BANERJEE: There's not been any quantitative experiments.

DR. DIMARZO: Not scalable.

CHAIRMAN WALLIS: Why not scalable?

DR. DIMARZO: In the sense that you have to come here and tell me that I've seen in experiments one through ten how does it relate to prototype. Nobody has ever done that kind of a study in detail. There is the problem of a small item in the geometry which alters tremendously what you see. For example, the enlargement of the down-comer. For example, the equipment that's in the lower head and all of that.

MR. SCOTT: The Germans are trying to do that at Wasendorf (PH) in Dresden. They have a big glass see through type device.

DR. DIMARZO: Right.

DR. BANERJEE: You would think that scale effects can be very important.

DR. DIMARZO: Oh, yes. This is decided on a smaller scale.

DR. BANERJEE: So you cannot quantitate.

DR. DIMARZO: It's not that you cannot. You can definitely do it. The problem is that relative to these issues if you can close it with this very lasting assumption, that's it.

MR. SCOTT: The point that Jack Rosenthol made earlier was the 3-D kinetics thing is sort of washing all these things out. It's so benign.

CHAIRMAN WALLIS: Okay. So you're going to close it with worst assumptions about the flow mechanics.

DR. DIMARZO: Exactly.

CHAIRMAN WALLIS: Otherwise you would think that all of those experiments at University of Maryland must be good for something. They should give you a handle on mixing.

DR. DIMARZO: I mean, we could definitely go down that route. The route would be very simple. You have to take a CFD code and try to duplicate it as an experiment and go from there.

CHAIRMAN WALLIS: That would allow you to continue. You're going to show that even if you make very bad assumptions, the kinetics saves you.

DR. DIMARZO: Right. That's my point.

CHAIRMAN WALLIS: Okay.

MR. ROSENTHOL: And we did use the Maryland because without the Maryland we would have to have square wave. But now we can have what I call diMarzo rounded edges.

CHAIRMAN WALLIS: Well, I was thinking about the diMarzo rounded. It seems to be related to this mixing in the pump.

DR. DIMARZO: No. In the -- what you are saying is that in a real scenario that situation may not occur which is okay. But there is a lot of mixing going on anyway in the real scenario.

CHAIRMAN WALLIS: No. I understand that if you don't have the diMarzo mixing in the pump you get a square wave and you're still in trouble.

DR. DIMARZO: Yes.

CHAIRMAN WALLIS: So you better be pretty clear that the diMarzo mixing in the pump is real and that you don't get flushing out of that.

DR. DIMARZO: Yes. But remember that you're not taking credit for what happens in the down-comer.

CHAIRMAN WALLIS: You're taking the credit.

DR. DIMARZO: No. We are not taking credit for that mixing which is pretty substantial.

DR. BANERJEE: Yes. But you're trying to close the issue. And you either say okay we are not going to consider this mixing but we are sure that there's going to be mixing in the pump.

DR. DIMARZO: Right.

DR. BANERJEE: So I'm not going to do a CDF calculation. I'm just going to do this backmixing in the pump.

DR. DIMARZO: Right.

DR. BANERJEE: And then if the pump itself would be full of deborated water by any stretch of the imagination.

DR. DIMARZO: Full it's not going to be because the rate at which it goes the best you're going to have is a trickle.

CHAIRMAN WALLIS: So you're going to quantify that trickle and do an analysis.

DR. DIMARZO: Yes. We could do that.

CHAIRMAN WALLIS: Yes. I think you have to.

DR. DIMARZO: Yes. It makes sense. Basically that amount is to a reduction in the volume of the pump.

CHAIRMAN WALLIS: I have no idea what you mean by "trickle."

DR. DIMARZO: We know what the power is. We know basically the condensation rate. So we can quantify exactly what the trickle is.

CHAIRMAN WALLIS: The other thing is how long does that trickle take to wash the boron out of the pump. Is it days or months?

DR. DIMARZO: You are bringing up an interface. First of all you have to deborate all the legs. Then you're bringing up an interface of deborated water which can flow out of the pump.

CHAIRMAN WALLIS: If you're going to deborate all that volume down here, why can't I deborate the pump as well?

DR. DIMARZO: In order to pass through the pump, you have to deborate, you have to pass only through the level that sees the exit of the pump. You don't have to go through the whole volume of the pump.

CHAIRMAN WALLIS: See what I mean. If you've created all that deborated water by condensation, you fill all this 1000 cubic feet. Why can't you make a little bit more and deborate the pump as well?

DR. DIMARZO: The whole pump you can't because at some point you start to get out of the pump.

CHAIRMAN WALLIS: Well, I guess --

DR. DIMARZO: But I see your point and we'll make an argument of this type. We compared the volume of the pump with the volume of down-comer and lower head.

DR. BANERJEE: What about the pipe? You are saying that deborated water should rise through borated water. Right?

DR. DIMARZO: It should push borated water ahead of itself. There is a G.I. Taylor paper --

DR. BANERJEE: Taylor and stability.

DR. DIMARZO: Yes.

DR. BANERJEE: So why would the pipe be full of deborated water.

DR. DIMARZO: No. The point initially you're absolutely right. Initially the deborated won't stay together. It would start bubbling through the back. That's fine. We went through that.

DR. BANERJEE: (Inaudible.)

DR. DIMARZO: You well it up in the pump. That's okay. And it will flush out on the other side and drain out. So through all that process what Graham is saying that we fill the whole pipe with deborated completely, flush the pump completely with deborated.

CHAIRMAN WALLIS: It keeps bubbling through the pump as you described it.

DR. DIMARZO: As you completely flush it out. Right. The argument that I would like to make is that the volume of the pump is a certain amount and then compare that to down-comer and lower head volume. Then we can make a claim to that effect.

CHAIRMAN WALLIS: (Away from microphone.)

DR. DIMARZO: Yes. But assuming that you have a mixing volume which is equivalent to the volume of that pump.

CHAIRMAN WALLIS: Yes. But it depends on what's in that pump when you start to move the slug.

DR. DIMARZO: Absolutely.

CHAIRMAN WALLIS: We are not convinced that there is boron left in the water in the pump.

DR. DIMARZO: Right.

CHAIRMAN WALLIS: I think that has to be shown.

DR. DIMARZO: Well, that cannot be shown. What can be shown then we'll still have to go to the vessel at some point.

CHAIRMAN WALLIS: But your whole analysis I thought depended on there being borated water left in the pump.

DR. DIMARZO: Yes. I understand that.

CHAIRMAN WALLIS: We are not convinced that there is borated water left in the pump.

DR. DIMARZO: That's a good point. The point is that in order to show that you have to basically say that the deboration takes place over a very long period of time and so forth.

CHAIRMAN WALLIS: I don't know. How long?

DR. DIMARZO: We can calculate that. It's clear.

DR. BANERJEE: But if it's bubbling through so you're talking about having deborated water bubbling up through up borated water, of course as it bubbles up, it mixes.

DR. DIMARZO: It mixes. There is no way of keeping it --

DR. BANERJEE: This seems to me something which is ameanable to calculation by hand.

DR. DIMARZO: Yes. I'm sure of it. That's fine. There's no question about that.

DR. BANERJEE: I mean, you know the wavelength of the --

DR. DIMARZO: Yes. But I can do another calculation too. I can basically say once finally we start moving the slug by natural circulation the assumption that Graham is putting forward is that the whole system is basically deborated ahead of the slug because of this very extensive --

DR. BANERJEE: It won't flush out. It will mix because it's too --

DR. DIMARZO: Right. That's the point. There is a paper by G.I. Taylor that I didn't touch which basically says that as soon as you move this thing it's going to start mixing within the pipe just because at the wall the water drags.

DR. BANERJEE: Forget that complexity. If you had a straight vertical pipe full of salt water and you put fresh water in it --

DR. DIMARZO: It's going to mix before it gets up there. There's no question about it.

DR. BANERJEE: You can calculate the concentration.

DR. DIMARZO: Yes. There's no question about that. If you keep putting fresh water which is what he suggests, at some point you'll have it all fresh water. That is what he's saying.

DR. BANERJEE: If you put in enough.

DR. DIMARZO: Yes. That's what he's saying. That's the question. How ultimately is ultimately. That's the whole point. So I can push this and resolve it that way. What he's saying is if we sit in that predicament for --

DR. BANERJEE: Days.

DR. DIMARZO: Right. Then eventually you have the square wave.

MR. ROSENTHOL: But the scenario doesn't go like that.

DR. DIMARZO: Right.

MR. ROSENTHOL: Here's a small break LOCA which is going to be over in a couple of hours one way or the other.

DR. DIMARZO: I don't think there is the time to do what is predicating. But I can calculate that. That's the way I'm going to get out of this.

CHAIRMAN WALLIS: I'm not sure you can calculate this flushing out of --

DR. DIMARZO: Yes. You need a certain amount of time and volume of water to do it.

CHAIRMAN WALLIS: The vertical part of this pipe by the bubbling water.

DR. BANERJEE: It's not bubbles.

DR. DIMARZO: It will mix. So that volume becomes like another mixed volume.

CHAIRMAN WALLIS: It depends a lot on how big the entities are that come around the bend and are released. If there's some kind of a oscillation and big hunks of water come through, they probably --

DR. DIMARZO: There aren't any big hunks of water coming through. The condensation process is a very slow process.

CHAIRMAN WALLIS: So it comes oozing across the top of the bend and up the walls.

DR. DIMARZO: Exactly. And it's fully mixed by the time it goes up there.

CHAIRMAN WALLIS: I don't know.

DR. DIMARZO: You're dealing with a very long pipe. But I'll show that.

DR. DIAMOND: It mixes with water that has become more highly borated than before because the --

DR. DIMARZO: Now remember one thing though. The scenario without the pump calls now that the system is refueled. So you are now taking borated water and you fill the pump with borated water. You push the borated back down. You lift the deborated all the way to the top of the steam generator. At that point, natural circulation starts. At that point, you basically have the slug totally in the steam generator.

CHAIRMAN WALLIS: So you say when you fill with borated water you know the level in the pump by which it comes to.

DR. DIMARZO: What I'm saying is this is a two-phased scenario. Scenario part one you generate the slug.

CHAIRMAN WALLIS: Because there is a free surface.

DR. DIMARZO: Yes. Let's imagine the pump by then is totally deborated. Now you have to resume natural circulation. In order to do that somehow HPI flow starts to be larger than break flow so that the system refills. So the bottom of the system now is being filled by HPI water. Right? This is at full system right now. You start putting HPI system in and it trickles over also from the pump side because it fills the system on both sides. At which point everything in that leg is full of HPI water which is borated.

DR. BANERJEE: Where is the HPI coming in exactly on that diagram?

DR. DIMARZO: In the incline portion of the cold leg.

CHAIRMAN WALLIS: Well, I guess it's hard to follow this description which is all verbal.

DR. DIMARZO: I don't have a mic. That makes my life complicated. But initially you are filling this with deborated. (Indicating.) Then imagine the trickle over here and makes this deborated completely. There's no question. There's no problem. Now the water is deborated up to this level. I have to refill the system. HPI comes through here. (Indicating.) So HPI starts to flow on this side.

CHAIRMAN WALLIS: It goes up to the candy cane. Doesn't it? It fills up that pipe there.

DR. DIMARZO: In order to fill up this pipe, it has to fill up also this pipe.

CHAIRMAN WALLIS: But it can't get there.

DR. DIMARZO: The deborated --

CHAIRMAN WALLIS: It has to push the slug back into the steam generator.

DR. DIMARZO: Right. So the slug is all the way up there. (Indicating.) By the time the slug is all the way up there, all these regions are full of HPI water which is deborated.

CHAIRMAN WALLIS: Oh. You have to tell us all that.

(Inaudible.)

DR. DIMARZO: Which is totally borated. When the slug starts to move down, it will go to --

CHAIRMAN WALLIS: You told us about Act I and Act V and missed out Acts II, III, and IV.

MR. ROSENTHOL: Okay. We'll write it up that way for the final.

DR. DIMARZO: The point is this. There is a confusion here between the paper and what you are talking about here as a scenario. So that's probably what the problem is. The issue that you move being a situation of natural circulation is not really there. In the situation where we pump, it could be potentially there.

DR. BANERJEE: You are saying that the HPI will tend to keep the pump full of borated water. Is that it?

DR. DIMARZO: Not really.

DR. BANERJEE: I mean that's --

DR. DIMARZO: (Away from microphone.)

CHAIRMAN WALLIS: Yes.

DR. BANERJEE: The HPI. Where does the HPI come in?

DR. DIMARZO: Right there. (Indicating.)

DR. BANERJEE: Okay. Does it tend to go into the pump?

DR. DIMARZO: It will fill both sides.

DR. BANERJEE: Both sides.

DR. DIMARZO: Correct. So you have now a flush of HPI water in here.

CHAIRMAN WALLIS: It also pushes the green stuff back up.

DR. DIMARZO: Yes.

DR. BANERJEE: Okay. That makes more sense.

CHAIRMAN WALLIS: So when the green stuff comes to the pump, it has borated water in it.

DR. BANERJEE: Okay.

CHAIRMAN WALLIS: That's much more believable. Why didn't you tell us that an hour ago?

DR. DIMARZO: I tried.

CHAIRMAN WALLIS: I think this is the Italian sense of drama. You get the audience totally confused and then tell them the answer.

(Laughter.)

MR. ROSENTHOL: If you make him put his hands in his pockets, he can't talk so much.

DR. DIMARZO: I couldn't stand and just talk.

CHAIRMAN WALLIS: So when this whole thing comes to the full committee, this story is going to be clear.

DR. DIMARZO: Yes.

MR. BOEHNERT: Well, we also have the option of inviting him back in late August at the subcommittee meeting if we think we need to hear this.

DR. DIMARZO: The pump part.

MR. BOEHNERT: This pump part which we may need to do.

CHAIRMAN WALLIS: I think it would be very good that before anything goes to the full committee we make sure that the story is clear.

MR. BOEHNERT: I think so too.

MR. ROSENTHOL: At one time we thought that we would go to the subcommittee and then the full committee a week later. Then we recognized that we needed to satisfy the --

CHAIRMAN WALLIS: So I will tell the full committee in July. I guess I probably have to make some report that we had a presentation which needs to be worked on and we will hear it again before it comes to the full committee.

MR. ROSENTHOL: If you desire.

CHAIRMAN WALLIS: I think it has to be. This was not clear. If you get into this kind of confusion with the full committee, they won't accept it.

MR. BOEHNERT: It will be fatal.

MR. ROSENTHOL: Agreed.

CHAIRMAN WALLIS: I think this

presentation has to have a proper description of the scenario. You have green water and blue water or something. You show where it goes and how it comes back and there's interface here and the worst possible assumption. But it must mix in the pump anyway. Give us a proper story.

DR. DIMARZO: So we need to provide you with a much better description of the scenario which we didn't include this time at all.

CHAIRMAN WALLIS: Right.

DR. DIMARZO: We just simply said this is the slug that gets through.

CHAIRMAN WALLIS: Are we going to hear with this mixing in the pump the neutronics save us, but without the mixing in the pump, they don't? Are we going to hear after the break?

DR. DIAMOND: With or without the mixing in the pump the neutronics are probably going to supply feedback so that it's not a --

CHAIRMAN WALLIS: The calories per gram or whatever the figure of merit is are low enough.

DR. DIMARZO: Even with a square wave.

DR. DIAMOND: But we don't have a square wave.

DR. DIMARZO: With or without mixing in

the pump, you said the neutronics can save you.

DR. DIAMOND: No. You can't have a square wave.

CHAIRMAN WALLIS: A square wave is bad?

DR. DIAMOND: A square wave is bad.

DR. DIMARZO: So you need mixing in this.

CHAIRMAN WALLIS: So you need to have a good argument that there is mixing.

DR. DIMARZO: In the natural circulation scenario.

CHAIRMAN WALLIS: The fact that Marino feels there's mixing in the pump is not good enough.

DR. DIMARZO: No. That's not the correct view. I said this. I have data. I made a model.

CHAIRMAN WALLIS: Show us the data.

DR. DIMARZO: The data is in the paper.

CHAIRMAN WALLIS: Show us the evidence of mixing in the pump. Show us the evidence.

DR. DIMARZO: No. I have data of what the front looks like. Then I said if mixing occurs in this volume I get that.

CHAIRMAN WALLIS: Show that your model for mixing in the pump correlates with the data from the experiment.

DR. DIMARZO: Right. That's what is here.

You have it in front of you.

CHAIRMAN WALLIS: In this?

DR. DIMARZO: Yes.

DR. BANERJEE: Is that a measurement of the pump outlet?

DR. DIMARZO: Yes.

DR. BANERJEE: It's not --

DR. DIMARZO: No. That's the slug.

DR. BANERJEE: I think I would buy the fact that you get backmixing in the pump if the pump was full of borated water.

DR. DIMARZO: Right. That's the argument.

DR. BANERJEE: Deborated water too.

DR. DIMARZO: Absolutely. There's no question. But in this particular scenario it must be full with borated water in the natural circulation part. The question that keeps lingering in my mind is how do I show you that it's full of borated water under the hypothesis that you start the pump. That becomes a more complicated thing to do.

CHAIRMAN WALLIS: It also gets mixed in the region downstream of the veins.

DR. DIMARZO: Yes.

CHAIRMAN WALLIS: The veins that create --

DR. DIMARZO: Yes. What I'm basically

saying is if you consider the volume of the pump as a representation of both you get the data to correlate.

CHAIRMAN WALLIS: That has to be clear too somehow.

DR. DIMARZO: Right. One issue remains open. If I pump, I cannot in any way state that the pump will be full of borated water. You understand that.

DR. BANERJEE: If you start --

CHAIRMAN WALLIS: Because it's already been deborated and you --

DR. DIMARZO: If you presume that, exactly.

CHAIRMAN WALLIS: All right.

DR. DIMARZO: That is the part that I cannot show but it's not really part of this scenario.

CHAIRMAN WALLIS: All right.

MR. SCOTT: Some of these pumps you see did have higher borated water.

CHAIRMAN WALLIS: All the way through the pump.

MR. SCOTT: (Away from microphone.) It's not always very deborated --

CHAIRMAN WALLIS: The green is slightly borated.

MR. SCOTT: (Away from microphone.) This one seems to have higher than -- This one's an intermediate. This one has low. This was just before we started the circulation which now you would be injecting this unborated water. This is a PKL experiment.

CHAIRMAN WALLIS: So each LOOP is different too.

MR. SCOTT: It's a PKL.

DR. BANERJEE: But this is a once through scenario.

MR. SCOTT: No.

(Inaudible.)

CHAIRMAN WALLIS: This is a Westinghouse.

MR. ROSENTHOL: That's a Westinghouse full LOOP. PKL is the experiment facility. That's an interpretation of what PKL would be to the Westinghouse four looper.

CHAIRMAN WALLIS: Okay. So we're now going to take a break. At 4:00 p.m., we will hear the end of this story. Thank you. At 4:00 p.m., we will resume. Off the record.

(Whereupon, the foregoing matter went off the record at 3:48 p.m. and went back on the record at 4:03 p.m.)

CHAIRMAN WALLIS: On the record. We will hear the final part of this story of GSI-185.

DR. DIAMOND: All right. I'm going to talk about the consequences in the core of having this diluted slug.

MR. BOEHNERT: Could you introduce yourself, sir?

DR. DIAMOND: Yes, sure. David Diamond from Brookhaven National Laboratory. The background for this is that there was a study done by Framatome. It's been mentioned before. That was supposedly a conservative study.

They estimated the boron concentration as a function of time at the inlet to the core and also at the lower plenum. Then they used a lump thermal-hydraulic/point kinetics model. This was a RELAP5 calculation to assess the consequences. We had looked at that and noted that because of this rather simplistic model which didn't take care of the significant spatial effects that go on during this event that it would be worthwhile to consider the event with a much more rigorous model.

So we said to ourselves what can a three-dimensional coupled neutronic and thermal-hydraulic analysis tell us. One thing is that it can contract the radial and axial distribution of the boron changes. Those are significant as I will demonstrate.

It can also take into account the fact that when this reactor goes critical again the other situation where all of the control rods are inserted and so we have a checkerboard pattern of control rods in the reactor which means that the neutron flux in the reactor is non-uniform. So we know that the radial and axial power distribution are complicated. Therefore, it makes sense to treat this problem using a three-dimensional calculation or at least address the neutronics with a three-dimensional model.

CHAIRMAN WALLIS: Now, you're assuming uniform fuel or do you know something about the burn up patterns?

DR. DIAMOND: Yes. This is a real reactor. So that's one part of the problem that I'm going to address today. I'm going to show you some results which demonstrate the physical phenomenon that takes place in the core and show that the spatial effects are important and what the differences are between the detailed neutronics calculation and the simplistic calculation that Framatome did.

Then of course at the end of the day we're interested in the consequences. So I'm also going to show a result to explain what sort of fuel enthalpy increase one gets during this event. There are essentially two different calculations that I want to leave you with today.

We've discussed this. I don't think that we have to go any further here except to say that of course the reactor is going to go critical because there is a considerable amount of deborated water.

CHAIRMAN WALLIS: How much does the level of deborated water have to rise before it does go clear? How far does it have to go into the core?

DR. DIAMOND: I will show that to you specifically, quantitatively what that looks like. Let me tell you a little bit about the core model that we used. We modeled a BNW reactor, specifically TMI-1. It was a beginning of cycle model because in that case the reactor starts off with a need for boron in the core. Therefore, the deboration has a much larger effect than say an end of cycle.

This is a core with 177 fuel assemblies. It's very much like the core but not exactly equal to the core that the Framatome people used when they did their analysis. There's a starting point for these calculations. I won't get into the details of this. The only reason that I mention this here is because our boron dilution accident will begin at 200 seconds into the transient that I'm going to show.

So we have some sort of starting point. After 200 seconds, we get to reactor condition which emulate the identical conditions that Framatome said would occur after several hours of this small break LOCA scenario when natural circulation has just started again and the boron dilution even can take place. So at that time as I said all banks are inserted. The fuel and the moderator have cooled down considerably or at least a little bit. They're down to 500 Kelvin. In this first case that I will show you the boron ppm is at 1165. The reactivity is at zero.

CHAIRMAN WALLIS: Why has it gone down to that?

DR. DIAMOND: Well, this first case that I'm going to show you is an attempt to make a comparison with the BNW calculation. So we tried to duplicate the reactivity insertion that BNW applied in their calculation. This is a detailed calculation preserving the same reactivity insertion and rate of reactivity insertion as in the BNW calculation. After I explain the physical phenomenon that take place during this event, I'm going to show you a calculation in which we apply our best estimate of the inlet conditions and show you what the consequences are of that particular event.

CHAIRMAN WALLIS: This starting point is the reactor is full of boron at 1165 ppm.

DR. DIAMOND: Yes.

CHAIRMAN WALLIS: It's gone down from 1700 in some way.

DR. DIAMOND: Yes. In this case, artificially.

CHAIRMAN WALLIS: Why hasn't it gone up?

DR. DIAMOND: It has. That's correct. In the actual scenario, it has gone up to 2500 ppm.

MR. BOEHNERT: Are you accounting for the Xenon growth?

DR. DIAMOND: No. We're neglecting that.

MR. BOEHNERT: So that's a conservative assumption.

DR. DIAMOND: Yes.

MR. BOEHNERT: Okay.

MEMBER RANSOM: How does it get down to 1165 ppm?

DR. DIAMOND: The realistic reactor conditions would be at 2500 ppm.

MEMBER RANSOM: So why did you take this

lower number?

DR. DIAMOND: Because we were trying to emulate the Framatome calculation. They did a point kinetics calculation. Well, it was a RELAP5 calculation which uses point kinetics. In that point kinetics calculation, they start from zero reactivity and add three and a half dollars worth of boron positive reactivity. So we wanted to go through the same point in order to emulate that. In reality, you would be starting at 2500 ppm of boron and you would be considerably subcooled. You would have to come up to zero reactivity and then go some.

CHAIRMAN WALLIS: So they're assuming boron ppm in order to make the reactivity zero essentially.

DR. DIAMOND: Yes. No, we are. In their calculations, they don't do a boron transport calculation. They just insert a certain amount of reactivity based on what they would expect in the core.

This first calculation is a little bit contrived. As I say it's to get you to understand that the physical phenomenon that are taking place. Then I'll show you something that's a little bit more realistic.

The layout of the core is shown here. This is 177 fuel assemblies. Because we assume uniform inlet conditions across the core, we can focus on one-eighth of the core. This is that one-eighth of the core. The numbers at the top of the boxes are the top of each fuel assembly just as the number of thermal-hydraulic channel. There are 29 fuel assemblies in this one-eighth core and 29 thermal-hydraulic channels in our model.

The burn up for each fuel assembly is the lower number. We see that there are yellow and white fuel assemblies. The yellow assemblies are assemblies that have a control rod in there because one of the first things that happens is all of the rods are SCRAMed into the core. So you can see this checkerboard pattern. Rod in. Rod out. Rod in. Rod out. If you look at the burn up numbers, you see that these fuel assemblies along here without control rod have the lowest burn up. (Indicating.)

CHAIRMAN WALLIS: They're all new essentially.

DR. DIAMOND: Those are new. Right. These that are shaded here are going to be the assemblies where the fuel enthalpy is going to be the highest in this particular scenario.

To do the calculation, we used PARCS. You heard Joe Kelly mention PARCS a little bit earlier today. It was a code that was originally developed at Purdue and is now incorporated as part of TRAC-M. The code models the neutronics and three-dimensions. It is able to break up the core fuel assembly-by-fuel assembly and axial node-by-axial node. There are 24 axial nodes in a neutronics calculation and actually four neutronic nodes in each assembly in these calculations.

The code takes into account the neutron kinetics. So it takes into account the effect of delayed neutrons. It uses two neutron energy groups. It uses diffusion theory. The diffusion equation is solved based on a nodal method. I think that you're going to learn more about this code when you learn more about the models within TRAC-M because this is a part of TRAC-M.

The code has feedback from the appropriate feedback mechanisms; fuel temperature, moderator density, the boron concentration, the change in position of control rods. Of course, the thermal-hydraulic conditions here need to be calculated from a thermal-hydraulic model. In this particular case, PARCS is coupled with RELAP5. So this is really

PARCS-RELAP5 or RELAP5-PARCS.

The cross sections are generated with a different code. These are the cross sections which enable you to solve the two neutron energy group diffusion theory equations. Those cross sections are obtained for each of the fuel assemblies, again for the TMI-1 reactor's beginning of cycle.

There was one problem with the cross sections. They're not good to below 500 K. That's why our calculations started at 500 K. The actual reactor conditions would ger you down to about 425 or 450 K. Since we were not able to go down that far, we made sure that we preserved the same subcooling as would be expected in the actual plant.

The RELAP5 calculation took advantage of this octant symmetry. As I explained there were 29 channels to represent the 29 fuel assemblies. There's one channel to represent the reflector regions. These of course are parallel channels. There's no mixing.

CHAIRMAN WALLIS: Now, voids are formed in the core.

DR. DIAMOND: Yes.

CHAIRMAN WALLIS: So you need to have some regions for the thermal-hydraulic analysis.

DR. DIAMOND: Yes. But the thermal-hydraulic analysis proceeds as multiple parallel channels rather than with any mixing.

CHAIRMAN WALLIS: It doesn't analyze each channel separately. Does it?

DR. DIAMOND: Yes it does.

CHAIRMAN WALLIS: It does.

DR. BANERJEE: 29 channels.

CHAIRMAN WALLIS: 29 channels.

DR. BANERJEE: And one reflector.

CHAIRMAN WALLIS: All RELAP5. That's quite a lot.

DR. DIAMOND: 29, yes. The reason we're able to do this is again as I explained because of this octant symmetry.

DR. SCHROCK: Is the symmetry really that good?

MR. BOEHNERT: Virgil, use the mic please.

DR. SCHROCK: I asked is the symmetry really that good. You have previously burned bundles mixed with new bundles and so forth. Are the burn ups really that close to preserve this symmetry?

DR. DIAMOND: Yes. They certainly are. I will mention something later where there is a problem in symmetry of course. That is that there is always this question of the flow into the core inlet and how uniform that flow is. But of course we would have to have additional knowledge to really understand.

CHAIRMAN WALLIS: From what we saw, the pictures of the down-come are where it's probably not very uniformed in terms of boron concentration.

DR. DIAMOND: Yes. Okay. So this first calculation that I'm going to show as I said it has about three and a half dollars worth of boron reactivity as the maximum value. That's why I say we can't have a square wave coming in here. That's an awful lot of reactivity to come in instantaneously.

When we talk about the rod ejection accident, generally we're talking about one and two dollars worth of reactivity. So if we have a maximum of three and a half dollars and put it in the square wave, I don't think that anybody would accept that.

DR. SCHROCK: In your previous statements, you said you were trying to replicate the BNW owners group calculation. Their reactivity assertion only goes to one dollar.

DR. DIAMOND: That's the total reactivity. So the total reactivity is of course the boron reactivity less the feedback.

DR. SCHROCK: Oh, yes. I see.

DR. DIAMOND: All right. The mass flow rate at the lower inlet plenum was about three percent. As I said, we had about 200 seconds of simulation to bring the core to the same conditions before the boron dilution accident.

CHAIRMAN WALLIS: Are you going to show us far the boron front goes up before the core goes critical?

DR. DIAMOND: Yes. We can infer that. I won't show that exactly. This just gives you the boron concentration versus time. As I said we're starting really from 200 seconds and going through this particular transient which is a transient from almost 200 to almost 600 ppm of boron concentration in this slug of water.

CHAIRMAN WALLIS: Why doesn't it go to zero?

DR. DIAMOND: This is based on Framatome.

CHAIRMAN WALLIS: Oh, this is Framatome.

DR. DIAMOND: Yes. This is based on the Framatome analysis.

CHAIRMAN WALLIS: I put diMarzo on that fuel.

DR. DIAMOND: Well, we have another curve which is a little bit more severe than this but it still doesn't go to zero.

MR. ROSENTHOL: This is the concentration in the core.

DR. DIAMOND: This is the concentration at the inlet plenum.

CHAIRMAN WALLIS: I thought he had a dilution of 100 percent.

DR. DIMARZO: Graham, what you are looking at is a paper from Maryland. It's contained in the paper from Maryland that the concentration does go to zero. What we're talking about here is a scenario which is defined differently. You don't have zero.

CHAIRMAN WALLIS: What's conservative?

DR. DIMARZO: It's not a question of conservative. It's a question of where the slug is initially. Remember the slug is confined completely in the steam generator before this process starts. Therefore, that slug has to go to the steam generator out of plenum and mix. Then it has to go to the pump and mix. That's the front of the slug.

DR. BANERJEE: This is Framatome.

DR. DIMARZO: Right.

DR. BANERJEE: That's why it's so mild.

DR. DIAMOND: Okay. So that curve shows you that we start to get some dilution around 230 seconds. It's about another 20 seconds of dilution and one sees a large increase in the power. The power goes up to between 70 and 80 percent of nominal power.

Then as it typical in power excursions like this, the power turns over because of Doppler feedback. That's the nice thing about low uranium cores. They have a very strong Doppler feedback. The power turns over but the core is still being diluted. Therefore, there's this pull. There's this positive reactivity being put in. There is this pull from the Doppler trying to hold it back. Then with time, the moderator heats up and you have moderator density feedback.

Another nice thing about a PWR is that it has a negative feedback coefficient from the moderator temperature or the moderator density. So this competition between the boron and the feedback results in the power coming down and then up and then down and then up a little bit and then it settles down as the boron slug moves off. What this means in terms of fuel enthalpy and this is fuel enthalpy at the node in the core that has the highest fuel enthalpy is that the fuel enthalphy starts from about 14 and goes up initially only to about 34. So initially there's only about a 20 calorie increment in fuel enthalpy.

If you look at the peak change in fuel enthalpy, you see that it goes up maybe a total of 37 calories per gram from here to here. (Indicating.) But if there was going to be any fuel failure, it would probably be the result of this initial increase in enthalpy. So that's fairly low.

DR. SCHROCK: So what is the cause of the second peak?

DR. DIAMOND: Again, it's the competition between the positive boron reactivity which is still coming into the core and the feedback effects from Doppler and from the moderator temperature.

CHAIRMAN WALLIS: But it's the second power peak that puts more --

DR. SCHROCK: There's no boiling in this case.

DR. DIAMOND: There is a little bit. I'll show that momentarily. There is some boiling.

MR. BOEHNERT: Localized?

DR. DIAMOND: Yes. Localized. The behavior here will become clearer as we go through a few more of these curves. This curve shows the power versus time but on a logarithmic scale. I just wanted to point out that when we looked over here, we saw that it looks as though the power doesn't increase until close to 250 seconds. (Indicating.) But in reality, the power begins to rise soon after 200 seconds and then goes up to as I say about 80 percent nominal power.

This curve is the curve that Harold Scott showed earlier. This curve shows the boron concentration during the period from 230 to 330 seconds. You can see that the boron concentration is decreasing during this first roughly 50 seconds. So the reactivity change is a result of this positive reactivity insertion due to the boron concentration going down, this is the scale for the boron concentration, and also the negative effects from fuel temperature and moderator temperature feedback. This erratic behavior as a result of the competition between those feedback effects accounts for the corresponding curve of power versus time.

Okay. This gives you an idea of how the front moves through the reactor. This is the relative power along a channel. This is the bottom of the core. This is the top of the core. (Indicating.) If we look at say 240 seconds, we see that initially the power is quite flat. Then if we look at later times, this is 249 seconds, we see that of course the power is no longer flat.

The power is quite peaked at the bottom of the core because that's where the slug has entered. So at the bottom of the core, it's becoming critical and where the power is increasing rather than uniformly through the core. This is another reason why you need a spatial representation in your neutronics model.

If we look now at the radial power distribution, this happens to be at 260 seconds. These numbers are the relative power in each assembly.

DR. BANERJEE: So this is the second peak, not the first.

DR. DIAMOND: Yes. Right. This is at the second peak. It doesn't matter. You would see the same effect at other times. The effect that I wanted to show is that these bundles, these fuel assemblies that have the low burn up are the ones that have the relatively high power. Again, you see the importance of having to have that spatially dependent calculation. You can see how the power is down, up, down, up depending on which --

DR. BANERJEE: What are the units for the power here?

DR. DIAMOND: This is just relative units.

DR. BANERJEE: In terms of, are they twice normal operating power or what does that mean?

DR. DIAMOND: No. The average here is 1.0.

DR. BANERJEE: Okay.

DR. DIAMOND: Here is a graph of void fraction versus axial position at different times. Again, if we look at one particular time here, 289 seconds, we see in this particular channel that we have a little bit of void formation at the bottom of the core. That's the hot spot. If we look at later times, for example 291 seconds, we see that the void has shifted further down and has increased in this particular case. But these void fractions in this case are quite low.

CHAIRMAN WALLIS: But still doesn't that have quite an effect on the neutron balance?

DR. DIAMOND: Yes. It certainly does. It's also the result of the fact that we have a very low flow in the reactor.

DR. BANERJEE: But this is much later than the power peaks.

DR. DIAMOND: Yes.

DR. BANERJEE: So they are just giving you negative reactivity later on, shortly after that.

DR. DIAMOND: Right. But again this is in a very small fraction of the core.

DR. BANERJEE: Did you use the negative void co-efficient here, or is it negative?

DR. DIAMOND: Yes. The void co-efficient is negative. So any void formation is --

DR. BANERJEE: It will shut it down.

DR. DIAMOND: Yes. This shows you the average boron concentration in each of the assemblies.

DR. SCHROCK: It doesn't mean axial average.

DR. DIAMOND: It is averaged axially. So it is for a particular radial position.

CHAIRMAN WALLIS: This is in the liquid phase or it takes care of the voids.

DR. DIAMOND: It's in the liquid phase.

DR. BANERJEE: There is no void at this time.

DR. DIAMOND: Right. There is very little void in this particular case. But what it shows is of course that there is a radial distribution of boron concentration. The reason for that is that if you look for example at these three fuel assemblies here that have the highest power level, we see that it has the lowest boron concentration. What's happening is that where you have more power you're sucking up the diluted water faster. So what you have is an autocatalytic type of reaction here. That tends to feed the power.

CHAIRMAN WALLIS: So if you avoid formation rapid enough, you'd be expelling the boron at the bottom.

DR. DIAMOND: Yes. Well, in this particular case, you don't get void in these assemblies because the flow rate is a little bit higher. You get the void in the assemblies where the flow rate is lowest.

DR. BANERJEE: This is natural circulation.

DR. DIAMOND: Yes. But we imposed a flow rate at the --

DR. BANERJEE: At the boundary conditions.

DR. DIAMOND: At the inlet plenum.

DR. BANERJEE: So this is a distribution effect.

DR. DIAMOND: This is a distribution effect. Okay. So that gives you an idea of the complex physical phenomenon that are taking place there. As I said, this first calculation that I wanted to show you was really to compared the detailed three-dimensional calculation with the lumped point kinetics calculation.

In that calculation, the Framatome calculation and remember this is not apples and apples because they're model was actually Crystal River which was very similar but it's a different core than whatever cycle of TMI we were using. So it's not exactly apples and apples. Anyway, the peak reactivity in their calculation was about $1.2. In our case it was about $1.02. This is a typo here. It should be $1.02.

Peak power in their case was about 83 percent occurring about six seconds after dilution. In our case it was a little bit lower. Similarly, their peak enthalpy was 69 calories per gram. Of course it's difficult to estimate that when you're doing a lumped parameter calculation. When you're treating the entire core as a single unit, it's hard to say what the peak is within the core. Anyway, their estimate was 69. Our calculation was 37. That was the peak enthalpy.

DR. BANERJEE: That's the hottest channel.

DR. DIAMOND: The hottest axial position in the hottest channel.

DR. BANERJEE: Hottest axial.

DR. DIAMOND: Yes. So it's the hottest

node over the entire reactor. Whereas as I said, there are 24 axial nodes and one radial node per fuel assembly.

DR. BANERJEE: What time does that occur actually? 13 seconds is after the dilution starts. Is that right?

DR. DIAMOND: No. That's the peak power. The peak enthalpy occurs much later than that. If you recall that the peak enthalpy occurred at that second enthalpy peak.

DR. BANERJEE: Why does that happen?

CHAIRMAN WALLIS: To integrate.

DR. DIAMOND: Yes. Because enthalphy is an integral. So even though the power came down after the first power pulse, enthalpy is an integral. There is some heat transfer out of the fuel. So it's a question of the energy deposition less the heat transfer out of the pellet. The net result is that it occurs not after the first peak but later in the event.

DR. BANERJEE: So the power pulse is so sharp in the first case that when it is integrated it doesn't --

DR. DIAMOND: Right. Remember that when we examined that curve it was an increase of only about 20 calories per gram after the first peak and then 37 calories per gram after the second peak. Sporadic voids. And here the core return subcritical 45 seconds after prompt. In our case it was 24 seconds after prompt. So the calculation generally with the point kinetics model seem to be more conservative then our calculation.

DR. SCHROCK: You have a small difference in beta shown between those two calculations.

DR. DIAMOND: Yes.

DR. SCHROCK: I presume that's because you've weighted the beta in your -- calculation somehow to reflect some plutonium.

DR. SCHROCK: No. The beta that we calculate is the beta for that beginning of cycle condition at TMI. So it's based on the fuel in that particular reactor.

DR. SCHROCK: Which has some pleutonium.

DR. DIAMOND: Yes. It has a considerable amount of burn up.

DR. SCHROCK: Right.

DR. DIAMOND: The average burn up in that core at beginning of cycle is probably around average.

DR. SCHROCK: If anything it's surprisingly high, that value of beta.

DR. DIAMOND: No. I wouldn't say it's surprisingly high. I'm not surprised.

DR. SCHROCK: Well, if you had much pleutonium.

DR. DIAMOND: Well, if you go back to here, you have a burn up of 30 gigawatt days per ton. So you do have pleutonium here. But here you have essentially fresh fuel. So you have a mix.

DR. SCHROCK: Yes. You have a mix. Somehow you're weighting beta. You get a beta core wide.

DR. DIAMOND: Yes. And it's weighted,

DR. SCHROCK: What's the weighting at joint flux?

DR. DIAMOND: The weighting in this case is a volumetric weighting.

DR. SCHROCK: Volumetric weighting. So I guess we'll get another look at that when we review PARCS. That's a feature of PARCS that's used.

DR. DIAMOND: The PARCS calculation can put in a different beta for each fuel assembly. In this case, we used an average beta. But it can have a different beta for each assembly. That's not a problem.

DR. BANERJEE: So remind me beta is

related to the kinetics.

DR. DIAMOND: Yes. Beta is the delayed neutron fraction. A smaller beta as you get with pleutonium means that you have less delayed neutrons. Therefore, the control is a little bit more sketchy.

DR. BANERJEE: Right.

CHAIRMAN WALLIS: Within a rapid transient I thought it was the -- You have to look at the distribution of the beta among the different precursors. It's a really good answer.

DR. DIAMOND: Well, as I said, PARCS enables you to put in the appropriate beta for each fuel assembly which takes into account the burn up in that fuel assembly and therefore the distribution of material.

CHAIRMAN WALLIS: What I'm saying is today neutron fraction is an average over a lot of different precursors each with a different time.

DR. DIAMOND: Yes.

CHAIRMAN WALLIS: There's a rapid transient. It's the ones with the long time that matter most to something. You don't just take the average. Do you? I'm trying to remember how this works.

DR. DIAMOND: There are actually six

groups of delayed neutrons. The beta that we show there is actually the sum of those six groups of delayed neutrons.

CHAIRMAN WALLIS: Rapid transient, it's the slowest group or something. It eventually ends up dominating. Doesn't it?

DR. DIAMOND: Well, in addition to the delayed neutron fraction you have to specify the delay time for the delayed neutron to come out.

CHAIRMAN WALLIS: That's right.

DR. DIAMOND: Of course those with the shortest delay times are most important for fast transients, and those with the longest delay time are more important when you're looking at a LOCA for example.

CHAIRMAN WALLIS: Yes.

DR. DIAMOND: Okay. So this is now the second type of transient that I want to present to you. This is a calculation based on our best estimate of what the inlet plenum boron concentration would be based on Professor diMarzo's model of mixing.

CHAIRMAN WALLIS: Why doesn't it go to zero?

DR. BANERJEE: The front meets that back.

DR. DIMARZO: No. Because the regional

slug here proposed by Framatome which generates those two curves, it doesn't go to zero.

CHAIRMAN WALLIS: I'm just saying that in your spiel you talked about percent dilution 100 percent, you had this pure water --

DR. DIMARZO: Okay. In the Maryland experiment, we go to zero.

CHAIRMAN WALLIS: Why?

DR. DIMARZO: The Framatome experiment does not go to zero. I have an overhead here.

CHAIRMAN WALLIS: Okay. I guess I'm confusing the two. There has been mixing in the real phase.

DR. DIMARZO: Yes. Framatome gives you an initial slug in the steam generator.

CHAIRMAN WALLIS: Okay.

DR. DIMARZO: Then they proceed to mix it that way. I proceeded to mix it my way along that model.

DR. BANERJEE: But you have only two mixing mechanisms. One is at the front and one is at the back. Right?

DR. DIMARZO: The mixing depends on --

DR. BANERJEE: How does it not go to zero? Otherwise you get some smoothing.

CHAIRMAN WALLIS: I think it never was there or anywhere except in Maryland.

DR. DIMARZO: (Away from microphone.) This is what the initial slug looks like.

CHAIRMAN WALLIS: It never went to zero.

DR. DIMARZO: (Away from microphone.) It never went to zero, no. Framatome mixed it somehow and got this dashed line. If you take this slug considering what it is in the scenario and you move it appropriately to the steam generator upper plenum and through the pump according to where it is you get this. (Indicating.)

DR. BANERJEE: So that time is actually space. The distribution of the slug in space. Moving at some velocity. Right?

DR. DIMARZO: Exactly. This is the original slug in space.

DR. BANERJEE: So why is that sloped to begin with?

DR. DIMARZO: That's because the scenario prepares the slug in a certain way that results in that.

DR. BANERJEE: How does the scenario prepare it?

DR. DIMARZO: It's very complicated.

That's the part that we didn't present here.

DR. BANERJEE: I see. So you are already assuming part of it is mixed and so on.

DR. DIMARZO: Yes.

DR. BANERJEE: What part of it is mixed already in front? Is that in the pipe rising up?

DR. DIMARZO: That is the pipe rising up to the pump. The steam generator upper plenum is -- around here and then all this is in the steam generator. That's the slug that you can see there.

DR. BANERJEE: It would be interesting to see how you arrive at that.

CHAIRMAN WALLIS: It would be interesting to see how certain you are about that.

DR. DIMARZO: (Away from microphone.) And the pump is totally borated in this particular -- So now you remove this from the pump and move all this through the steam generator upper plenum and the pump.

CHAIRMAN WALLIS: It's really suspicious to me that it has all these sharp corners.

DR. DIMARZO: The sharp corners are --

DR. BANERJEE: Component changes.

DR. DIMARZO: (Away from microphone.) That's the way -- drops initially. That scenario we did not -- It's the result of hours of operation but we didn't do that scenario. We could simply find it and say we have a slug in the steam generator.

CHAIRMAN WALLIS: Right. You wouldn't like that.

DR. BANERJEE: Right. It seems that there's already a lot of credit taken for various things in generating that.

DR. DIMARZO: (Away from microphone.) One case that we can easily do and that we don't have any problem is to start with causing a LOOP like this. That's not a very major difference --

DR. BANERJEE: The reactor would probably go back.

DR. DIAMOND: No. He means start that in the steam generator. You can't have that in the core. You're correct.

DR. DIMARZO: Exactly. Absolutely. But we should take a square wave in the steam generator and move it along. You could probably take the one that you have there without the Marino diMarzo thing and because the front end is sloped that would probably help you. Wouldn't it?

DR. BANERJEE: But you --

DR. DIAMOND: Yes.

CHAIRMAN WALLIS: Well, I guess when you

do the whole story you're going to have to say where this curve came from and why.

DR. BANERJEE: The critical part is that front slope I guess.

DR. DIAMOND: Yes.

DR. DIMARZO: And since you have established by now that in the natural circulation the pump isn't deborated if we passed a step through the pump --

DR. BANERJEE: Well, even if we don't take credit for the pump, what's happening is you've already got a slope there. That would be interesting to know.

DR. DIMARZO: Yes. Because this slug is sitting. There's a little bit of -- that vertical leg like we discussed before.

DR. BANERJEE: So you've already taken credit for that.

DR. DIMARZO: That's what he said. I didn't take credit for it. That's what we were given.

DR. BANERJEE: Who gave you that?

DR. DIMARZO: This is the owners group.

CHAIRMAN WALLIS: Well, you ought to do it yourself.

DR. BANERJEE: Are you going believe the

owners group?

DR. DIMARZO: That's the point. We could do a curved slug which I was just thinking about --

CHAIRMAN WALLIS: I think you should.

DR. DIMARZO: To the steam generator and pass it through. The question is this. If I go for a scenario of a square slug in a natural circulation scenario, it would have to be pushed up into the steam generator before I start.

CHAIRMAN WALLIS: Yes.

DR. DIMARZO: That slug will go through the steam generator upper plenum and through the pump before reaching. That's no problem.

DR. BANERJEE: Whatever it takes.

DR. DIMARZO: It will look more like probably going much slower in here and then going up again like that. (Indicating.) It would be --

CHAIRMAN WALLIS: But for regulatory purposes, you might want to make some conservative assumptions about that slug. That might lead you to conclusions that you didn't particularly like.

DR. DIMARZO: I was just trying to make that case.

CHAIRMAN WALLIS: Well, I think that when you make a presentation eventually to the full committee you're going to see what was the origin of that curve you just showed us and how secure it is, that one with the shape of the slug, the distribution of boron in the slug.

DR. DIMARZO: I think for simplicity it would be much more practical to start with the square slug.

CHAIRMAN WALLIS: Well, then that might not be tolerable though in terms of the transient.

DR. BANERJEE: No. He's saying it would be if you allowed him mixing in the plenum and in the pump.

CHAIRMAN WALLIS: In the steam generator pump.

DR. DIMARZO: Yes.

CHAIRMAN WALLIS: Okay. Well, maybe you need to do that too.

DR. DIMARZO: That would be more like another case bounding this.

CHAIRMAN WALLIS: Okay. So you have some more work to do.

DR. SCHROCK: Could I bring up one point here? The power distribution in the core is quite interesting. Could you compare it to the power distribution in the steady state operating condition?

DR. DIAMOND: You're talking about this particular curve.

DR. SCHROCK: Yes.

DR. DIAMOND: Let's see.

DR. BANERJEE: Is it a factor due to less boron in those channels that you get such high powers?

DR. DIAMOND: First of all, let me explain that this is the axial average.

DR. SCHROCK: Yes. You said that before.

DR. DIAMOND: So this number may be higher at some particular axial position. This is higher than one would expect during normal operation. But it's not a crazy number.

DR. SCHROCK: No, no.

DR. DIAMOND: It's only three times the average.

DR. SCHROCK: I'm not saying it's crazy at all. I'm just interested in seeing how much distortion spatially occurs in the power distribution as a result of this kind of transient. It's pretty large.

DR. DIAMOND: But this core already has a power distribution distortion because of the presence of control rods. Look at this. 0.246. I mean that's only because there's a control rod there. Even in the center of the core, 0.51 is a distortion.

DR. SCHROCK: Well, it's on the edge of the core too.

DR. DIAMOND: No. Even at the edge it's much too low.

DR. SCHROCK: It's too low. I agree.

DR. DIAMOND: So this entire core is already distorted by virtue of the control rods.

DR. SCHROCK: Down here you have one that's near the edge that's 2.1.

DR. DIAMOND: That's right.

DR. SCHROCK: What would that be in the operating steady state?

DR. DIAMOND: In the steady state, it might be 1.5. But in the steady state you wouldn't have 1.5 here and 0.2 here. You wouldn't have such a severe gradients.

DR. SCHROCK: But when you're looking for potential core damage, are you looking at that element or are you looking at some average?

DR. DIAMOND: You're looking at all of the axial positions within this fuel assembly.

DR. SCHROCK: That particular fuel assembly.

DR. DIAMOND: As it turns out, yes, this

assembly and this assembly. I don't know which of these two assemblies and which axial level has the highest pellet temperature and therefore enthalpy. But it's somewhere at the bottom of the core, maybe about a foot above the bottom of the core and it's in one of these two assemblies.

But that's what this calculation does for you. It looks throughout the core at where you have the hottest fuel rod. I should also say --

DR. SCHROCK: And it's important that it gives you something quite different than the picture you would have if you made the assumption that the power distribution in the transient is the same as the power distribution in the operating study state.

DR. DIAMOND: Correct.

DR. SCHROCK: It might be much worse.

DR. DIAMOND: Yes. Primarily by virtue of the axial distortion but also because of the radial distortion.

DR. SCHROCK: Yes. Thank you.

DR. DIAMOND: Okay. So this next calculation that I wanted to show was again with our diMarzo curve which we're saying is our best estimate at the moment of what the boron concentration would look like based on a restart of natural circulation.

In this particular calculation that I'm going to show, the dilution starts at 100 seconds rather than 200 seconds. As you can see the change in boron concentration is from about 2500 to below 500 ppm. It's a dramatic change in boron concentration, an enormous change.

But in this particular case, we're starting from whatever the shut down condition of the reactor is. We're not starting from zero reactivity as I described for the previous calculation. In this particular case, the power peak is between 300 and 350 percent. In the previous case if you remember the power peak was down here at about 70 or 80 percent. So that initial power spike now is quite a bit larger. It's also narrower. But it's quite a bit higher.

DR. BANERJEE: That's also because you started from a much lower, I mean, the thing is completely shut down and you have to bring it back up. Right?

DR. DIAMOND: Yes.

DR. BANERJEE: If you start from zero reactivity this would just go.

DR. DIAMOND: Well, starting from zero that would be different.

DR. BANERJEE: That would be a big bang.

DR. DIAMOND: That would be different. The point is that this is now our best estimate calculation.

DR. BANERJEE: So the conditions are different between the two rods.

DR. DIAMOND: Yes. But this is meant to be the more realistic condition now, starting from the shut down condition and using the diMarzo curve.

DR. BANERJEE: What was the logic for the other one, zero reactivity?

DR. DIAMOND: Because the other one we wanted to see the differences between the Framatome point kinetics calculation and a spatially dependent calculation.

DR. BANERJEE: What was their logic to start from zero?

DR. DIAMOND: Because when you're using point kinetics that's how you're going to, the code easily starts from zero reactivity.

DR. BANERJEE: I see. It was a matter of convenience.

DR. DIAMOND: Yes. A matter of convenience, right.

MR. SCOTT: This is what I mentioned. When BNW got 90 calories per gram, that was in a range where there was some concern particularly for a high burn up fuel. So we wanted to see for a very similar case what we would get with 3-D PARCS.

DR. DIAMOND: So this is the power trace. Again, here we're starting from very low power. This is what it looks like on a logarithmic scale. Now, if we focus on a shortened time scale from 130 to 190 seconds, this is the power pulse here. (Indicating.) It actually goes up to about 330 percent and oscillates. This is what the peak fuel enthalpy looks like.

Again, we have a situation where the enthalpy rises due to that initial power pulse. It goes from about 14 to 37. It's about a 23 or 25 calorie per gram increment during this initial time. Then eventually it goes to its peak value of about 70 calories per gram.

DR. BANERJEE: And that's because your power pulse is so sharp. That's really the reason because you're not getting much enthalpy in the power pulse.

DR. DIAMOND: That's right. The pulse is very sharp.

DR. SCHROCK: The second peak is not has high but it's a broad peak.

DR. DIAMOND: Yes. It's a broad peak. This initial increment here is the integral of that power trace essentially. Of course there is heat transfer because this is taking place over about a second. If you want to look at fractions of a second you can look at --

DR. BANERJEE: How much credit does that heat transfer out at that point? Suppose your gap conductors were wrong or something. What would happen? Is there 150 percent of the heat being lost or ten percent or one percent? What's the number?

DR. DIAMOND: That's a good question.

MR. ROSENTHOL: Your fuel rod time constant is eight, nine, ten seconds.

DR. DIAMOND: There is. In other words, if we assumed an -- reaction would this be 40 or would it be 50?

DR. BANERJEE: Right.

DR. DIAMOND: And I think that it would be closer to 40 here. There is some heat transfer but since the time constant for heat transfer is on the order of a couple of seconds it isn't that much.

Okay. So if we're looking at this first peak as I say it's an increment of about 25 calories per gram. This really shows the consequences that we're interested in.

DR. BANERJEE: So because there are so full power seconds in the pulse that you're getting away with this very low amount of energy deposition.

DR. DIAMOND: Yes. This is the basic physics of a light water reactor. That is when you give it a jolt, you get the Doppler that pulls it back. In this case, you're not only giving it a jolt, you're still pulling on it because the boron concentration is continuing to go down during this period here but you have not only the fuel temperature contributing to the negative feedback but also the moderator temperature and density.

DR. BANERJEE: And the void.

DR. DIAMOND: Yes.

MR. ROSENTHOL: Let me just add that when you did ejected rod calculations over the decades you again saw that it wasn't the initial pulse turned around by Doppler that gave you the enthalpy rise. It contributed to it. But it was the tail of the distribution that when added up gave you the enthalpy. So I'm not surprised at all by that.

DR. DIAMOND: Yes. That's right. This is still sensible power over here. (Indicating.) So after that initial rise the fuel temperature is still increasing, so the enthalpy is still increasing.

This is the maximum local void fraction in this particular event. So in this particular event we get some higher void fractions. But again it's only in very isolated parts of the reactor where the flow is particularly low and it is not sustainable. But it contributes to the overall --

DR. BANERJEE: Now, in that power pulse there must be very high local temperatures within the fuel. Right? I mean, if you get 1000 percent power pulse, it's going to vaporize some piece of the fuel somewhere.

DR. DIAMOND: There is a distribution of temperature within the fuel. We know that the distribution is skewed toward the outside of the fuel. As you burn up the fuel, it becomes skewed even more towards the outside of the fuel because there are more and more plutonium builds up at the rim of the fuel.

DR. BANERJEE: So you're taking the fact that there is a flux depression within the fuel in itself.

DR. DIAMOND: The fuel enthalpy numbers that I show you are average. In regulatory space, we always talk about the pellet average fuel enthalpy.

DR. BANERJEE: What's the highest

temperatures the fuel gets to?

DR. DIAMOND: Well, the average temperature here is still not that high.

DR. BANERJEE: The average temperature. But local.

MR. SCOTT: In the report, there are some numbers. This scenario is not in the report that we gave you because these are just new results. The number I was going to say was at high burn up the calories per gram that would cause some melting at the edge of the fuel pellet is 170 calories per gram, maybe 160 calories per gram. It's way up there. I don't know that the temperature here is --

DR. DIAMOND: Yes. But we're not talking about peaking factors that would get you up to those high fuel enthalpies. Certainly not in this case.

DR. SCHROCK: So, how expensive an effort is this? What is the cost of doing this for the calculation?

DR. DIAMOND: For doing this calculation? Well, the incremental costs. Harold has just given me a curve of inlet boron concentration versus time which includes assumptions about the one pump starting. I have a post-doc working with me who's name is on the cover page. I would say if he's around tomorrow he'll probably give me the results on Friday.

DR. SCHROCK: So, it's not a terribly expensive proposition to do this these days.

DR. DIAMOND: That's the incremental cost is not expensive. To get set up and have a beginning of cycle model --

DR. SCHROCK: That doesn't include cross section evaluation preparation and all that.

DR. DIAMOND: Right. That's another matter.

CHAIRMAN WALLIS: You've run a whole lot of scenarios. If Marino came up with different slugs and so on, you could run a whole lot more.

DR. DIAMOND: Not a problem, no.

CHAIRMAN WALLIS: You might think about what you need to do to complete the story.

DR. DIAMOND: As I say these are coupled RELAP calculations. I mean, even with the RELAP --

CHAIRMAN WALLIS: Are you going to complete the story or is everyone going to say that risk analysis makes it not a problem?

DR. DIAMOND: Well --

MR. ROSENTHOL: I would say we're trying to run the scenario that corresponded to the BNW postulate transient. In the preparation for doing that we said events that involve let's say cold shutdown really have nothing to do with GSI-185. We thought that inadvertently starting with pumps was so close to the transient at interest it's just one more operator error that we ought to include.

So then Marino and I are whispering at each other well should we run the pump start or we should do some square wave that is even a little bit worse than that or maybe we'll run both. Yes. The promise is that we'll do the one, two, three more mechanistic calculations to bring back to you.

DR. BANERJEE: What's the physical reason that you get such a change between the point kinetics and the distributed calculation?

DR. DIAMOND: Well, there are so many spatial effects here that are not taken into account in the point kinetics calculation. Point kinetics calculation assumes a certain average boron concentration versus time in the core. Whereas in the spatial calculation we're assuming that the boron slug moves in and the bottom of the core feels that effect of the diluted water first. Then the whole thing evolves.

DR. BANERJEE: So that's the reason.

DR. DIAMOND: Yes.

DR. BANERJEE: It smooths it.

DR. DIAMOND: Right.

DR. BANERJEE: The transient time of the boron. It's going to start going and then it just --

DR. DIAMOND: Right. The point kinetics calculation is meant to be somehow bounding. At least in the best of all worlds you would justify the point kinetics calculation by saying that it's bounding or conservative in some fashion. I think Framatome's rationale was that they claimed that their inlet boron concentration versus time was already bounding. Therefore, they could just apply that in the core and assume that the results for power and enthalpy would be bounding. But it's not only the axial effect as I explained. The core is so radially non-uniform that it's important to take into account that variation as well.

DR. SCHROCK: Does the RELAP5 calculation beta of 0.0065 come because that's the default number in RELAP5?

DR. DIAMOND: I have no idea where that came from.

DR. SCHROCK: I'll bet that's where it is.

DR. DIAMOND: It could be.

DR. SCHROCK: You get your 35 numbers.

DR. DIAMOND: Yes it is. You're right. I know what you're saying. All right. Let me just analyze this presentation. I said that 3-D analysis gives a lower energy deposition relative to the point kinetics. It's very important to observe that here the evolution of the energy deposition is much slower than in a rod ejection accident. In a rod ejection accident, the reactivity is inserted in 100 milliseconds, essentially the square wave which we're avoiding in this scenario.

Thermal-hydraulic feedback limits the fuel enthalpy during the boron dilution accident. The calculation that I showed shows an initial enthalpy increase of less than 25 calories per gram. There is some void formation sporadic. We haven't looked at the possibility of DNB. It may be possible in more severe cases however. That's not really the problem here. This core has already boiled. What we're really concerned about here is energy deposition.

I should also mention that we have some preliminary comparisons with a completely different code system. It's called BARS/RELAP5 which is Russian. Well, the BARS part anyway is a Russian code, totally different methodology. It models the entire reactor on a pin-by-pin basis. I didn't show any comparisons. It's one example of what we have done to try and understand the validity of our model. We've done a lot more than that. I think as you learn more about TRAC-M, you'll be learning more about the validity of the three-dimensional neutron kinetics within it.

A couple of items where when I generated this slide I thought there could be additional refinement and extension. One is mixing in the core. I think someone already mentioned that we don't have that of course. I think that would tend to smooth things out and make things less severe.

The non-uniform boron concentration at the inlet would be nice to have but of course that's a difficult problem. When I put this on the slide here "the effect of turning on pump" I didn't realize that I would be making a commitment to have a result by Friday.

CHAIRMAN WALLIS: I think this non-uniform boron concentration would be worth while to try something on it. Try half of it here. Instead of putting uniform, try some sort of a distribution because you've already shown that there's a lot of variation between challenges. If you have much less boron in some place, you know that's a much more reactive place.

DR. DIAMOND: Right.

CHAIRMAN WALLIS: The critical reactor is here and the rest of it is like a reflector or something. There's a certain region which is -- So if you have a certain region that has much less boron than other regions, you know that's a critical thing. I would suspect that non-uniform boron concentration would give you higher powers. And there will be deposition in that particular area which might make things look worse. The question is what the regulators do with that assuming uniform boron concentration may be non-conservative.

DR. DIAMOND: Well, certainly with the pump on.

CHAIRMAN WALLIS: That may reunify things.

DR. DIAMOND: Then one could argue that it's conservative.

CHAIRMAN WALLIS: We showed from Maryland that there's a lot of variation in the down-comer in the boron concentration. So I would think that you could just run a calculation and instead of taking uniform concentration take an extreme case where half of it is zero and the other half is the rest or something.

DR. DIAMOND: Okay. Then I have to change my answer to the question asked of me before of how easy is it to do these calculations. In order to do that calculation, then I would have to represent half of the core rather than an octant so that I could have half of it at zero.

CHAIRMAN WALLIS: Okay. So there's a problem.

DR. DIAMOND: If that's the change.

CHAIRMAN WALLIS: Maybe what you can do is a symmetrical non-uniform distribution.

MR. ROSENTHOL: Let's think about it.

(Inaudible.)

MR. ROSENTHOL: We also know that there's very effective mixing in the lower plenum. Right?

DR. DIAMOND: Yes.

MR. ROSENTHOL: Surely very effective when the -- this would be a natural circulation case. There's supposed to be very good mixing in the lower plenum by design. It's one thing to do a variant and another one a --

CHAIRMAN WALLIS: It would be how sensitive your results are to the mixing in the lower plenum. So think about how you might do it and don't just not do this because it might give you an answer you might not want to see.

MR. ROSENTHOL: No. But we should do something that's reasonable.

MR. SCOTT: But, Jack, is Froude going to give me money to spend on ten to the minus six accidents?

MR. ROSENTHOL: Yes.

DR. BANERJEE: Is it a ten to the minus six accident?

MR. ROSENTHOL: It was estimated that the scenario that we're talking about is of the order of ten to the minus five.

MR. SCOTT: But that was for all small breaks. If we get it down to the small breaks that can produce these kind of boron slugs, it's going to be lower. If you turn on the pump, it's going to be lower.

CHAIRMAN WALLIS: You're going to make the whole thing go away by means of risk analysis.

DR. BANERJEE: This break is not too big so it's much more likely than a large break.

MR. ROSENTHOL: Yes.

MR. SCOTT: But I think Vander Molen already assumed he knew what the percentage of S-2 size breaks were. That's part of the risk numbers to see the core damage function frequency.

DR. BANERJEE: Ten to the minus five is the number that comes out of this.

MR. SCOTT: Yes. Assuming that size break, yes.

MR. ROSENTHOL: Well, the way I see it is we've been guided to do a modest amount of additional sensitivity studies that could put this to bed deterministically and somehow would be more satisfying than appealing to risk numbers. I think that we're close enough to it that we need to do some more work.

MR. MYER: This is Ralph Myer from NRC Research. I just wanted to comment on what you would need to do to the fuel to start getting into trouble. You're going to have to roughly triple that fuel enthalpy number and get that fuel enthalpy in within 20 milliseconds before you're going to have a situation where you crack the cladding and disburse any fuel. So if you can't get 60 or 100 calories per gram in there in under about 20 milliseconds, you'll have benign fuel damage.

CHAIRMAN WALLIS: So, you're not concerned about the eventual peak. You're only concerned about the initial rise right in the beginning there.

MR. MYER: That's correct. The eventual

peak may in fact cause the cladding to crack. But unless you can insert energy quickly in high burn up fuel, it won't even happen at all in low burn up fuel, you need the energy in there quickly so that the fission gas bubbles on the grain boundaries will blow the fuel out the crack.

DR. DIAMOND: Steady state fuel enthalpy on average for the reactor is about 45.

DR. BANERJEE: This is based on ppm.

MR. MYER: No. It's based on test data from CABRI in France and NSRR in Japan, both of them.

MR. BOEHNERT: Did you say 200 milliseconds? What was the time?

MR. MYER: 20.

MR. BOEHNERT: 20?

MR. MYER: 20.

MR. BOEHNERT: Thank you.

CHAIRMAN WALLIS: So you have a huge margin it looks like.

MR. MYER: Right.

MR. ROSENTHOL: Well, that was the reason that I wanted to make the comment because with small changes you're not going to get that.

CHAIRMAN WALLIS: I think if you assume something about very poor mixing in the lower plenum and you actually allowed it to be a very diluted piece of slug as a constant part of the course. You might be able to get a much more extreme initial rise.

MR. ROSENTHOL: Right.

DR. DIMARZO: If I may make a comment. The reason why we didn't go to the extent of making square slugs and so forth was because our understanding was exactly of that nature, in other words, whether we tweak that scenario a little bit isn't going to make that kind of a change.

CHAIRMAN WALLIS: I don't think we were just talking about tweaking it.

DR. DIMARZO: If you start making a front that's very sharp, yes.

CHAIRMAN WALLIS: Then I think you may well get into trouble. You should. You should go there and then figure out why that's not a good assumption or something. You should go there. You shouldn't just not go there because you might get an answer you don't want.

DR. DIAMOND: Actually a square wave at the bottom is really not a square wave to the core. It's a square wave to the first node.

CHAIRMAN WALLIS: Right.

DR. BANERJEE: There's a smearing effect.

DR. DIAMOND: Yes.

DR. BANERJEE: There's always going to be some smearing effect because it's not like a rod ejection which was a bang.

DR. DIAMOND: That's right.

CHAIRMAN WALLIS: Well, Jack, do you have enough to know where you're going from here and what you should come back with in a month or two?

MR. ROSENTHOL: Yes. Thank you for hearing the side on the subcommittee level because it will help us when we come back to you again. Then we will go to the committee.

CHAIRMAN WALLIS: I expect you'll get the usual comments from the consultants too which should be helpful.

MR. ROSENTHOL: Right. But what I'm also hearing and actually it was Marino's idea again and that is that rather than suffering through years of thermal-hydraulic analysis the idea was let's do something fancier on the physics side and see where we stand. It looks like we have a fair amount of margin. I mean, whatever the answer is I think we've done good work. What you're saying is (1) we ought to do some more pessimistic cases to make sure that we've bounded this situation and (2) when we come in to tell the story we should tell the story of the scenario, the evolution and tell the story better.

CHAIRMAN WALLIS: Yes.

MR. ROSENTHOL: But conceptually if it all bares out, it seems like a satisfactory way to go to you. Yes?

CHAIRMAN WALLIS: Yes.

MR. BOEHNERT: Yes. I think so.

CHAIRMAN WALLIS: So are we ready to adjourn? Does anyone have a burning desire to --

MR. BOEHNERT: I was just going to say you're going to report to the committee about this issue.

CHAIRMAN WALLIS: It will be pretty short.

MR. BOEHNERT: Pretty short, yes.

CHAIRMAN WALLIS: Okay. Thank you. Off the record.

(Whereupon, the above-entitled matter concluded at 5:23 p.m.)

CERTIFICATE

This is to certify that the attached proceedings before the United States Nuclear Regulatory Commission in the matter of:

Name of Proceeding: Advisory Committee on Reactor Safeguards Thermal-Hydraulic Phenomena Subcommittee

Docket Number: N/A

Location: Rockville, Maryland

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.

/s/ Jorge Besa /s/ Debra Wilensky

Jorge Besa/Debra Wilensky
Official Reporter
Neal R. Gross & Co., Inc.

INTRODUCTORY STATEMENT BY THE CHAIRMAN OF THE SUBCOMMITTEE ON THERMAL-HYDRAULIC PHENOMENA
11545 ROCKVILLE PIKE, ROOM T-2B3
ROCKVILLE, MARYLAND
JUNE 26, 2002

The meeting will now come to order. This is a meeting of the ACRS Subcommittee on Thermal-Hydraulic Phenomena. I am Graham Wallis, Chairman of the Subcommittee. The other ACRS Member in attendance is Victor Ransom. ACRS Consultants in attendance are Sanjoy Banerjee and Virgil Schrock.

For today's meeting, the Subcommittee will review portions of the Office of Nuclear Regulatory Research's Thermal-Hydraulic Research Program. Specific topics to be discussed include: (1) the phase separation test program being conducted in the Air-Water Test Loop for Advanced Thermal-Hydraulic Studies experimental facility located at Oregon State University; (2) the status of the TRAC-M code consolidation and documentation effort; and (3) the Rod Bundle Heat Transfer test program being conducted at the Pennsylvania State University. The Subcommittee will also review the proposed resolution of Generic Safety Issue 185: "Control of Reactivity Following Small-Break Loss-of-Coolant Accidents in Pressurized Water Reactors". The Subcommittee will gather information, analyze relevant issues and facts, and formulate proposed positions and actions, as appropriate, for deliberation by the full Committee. Mr. Paul Boehnert is the Cognizant ACRS Staff Engineer for this meeting.

The rules for participation in today's meeting have been announced as part of the notice of this meeting previously published in the *Federal Register* on June 11, 2002.

A transcript of this meeting is being kept, and the transcript will be made available as stated in the Federal Register Notice. It is requested that speakers first identify themselves and speak with sufficient clarity and volume so that they can be readily heard.

We have received no written comments or requests for time to make oral statements from members of the public.

(Chairman's Comments-if any)

We will now proceed with the meeting and I call upon Mr. J. Rosenthal, from the NRC's Office of Nuclear Regulatory Research, to begin.

Rod Bundle Heat Transfer (RBHT) Program Status

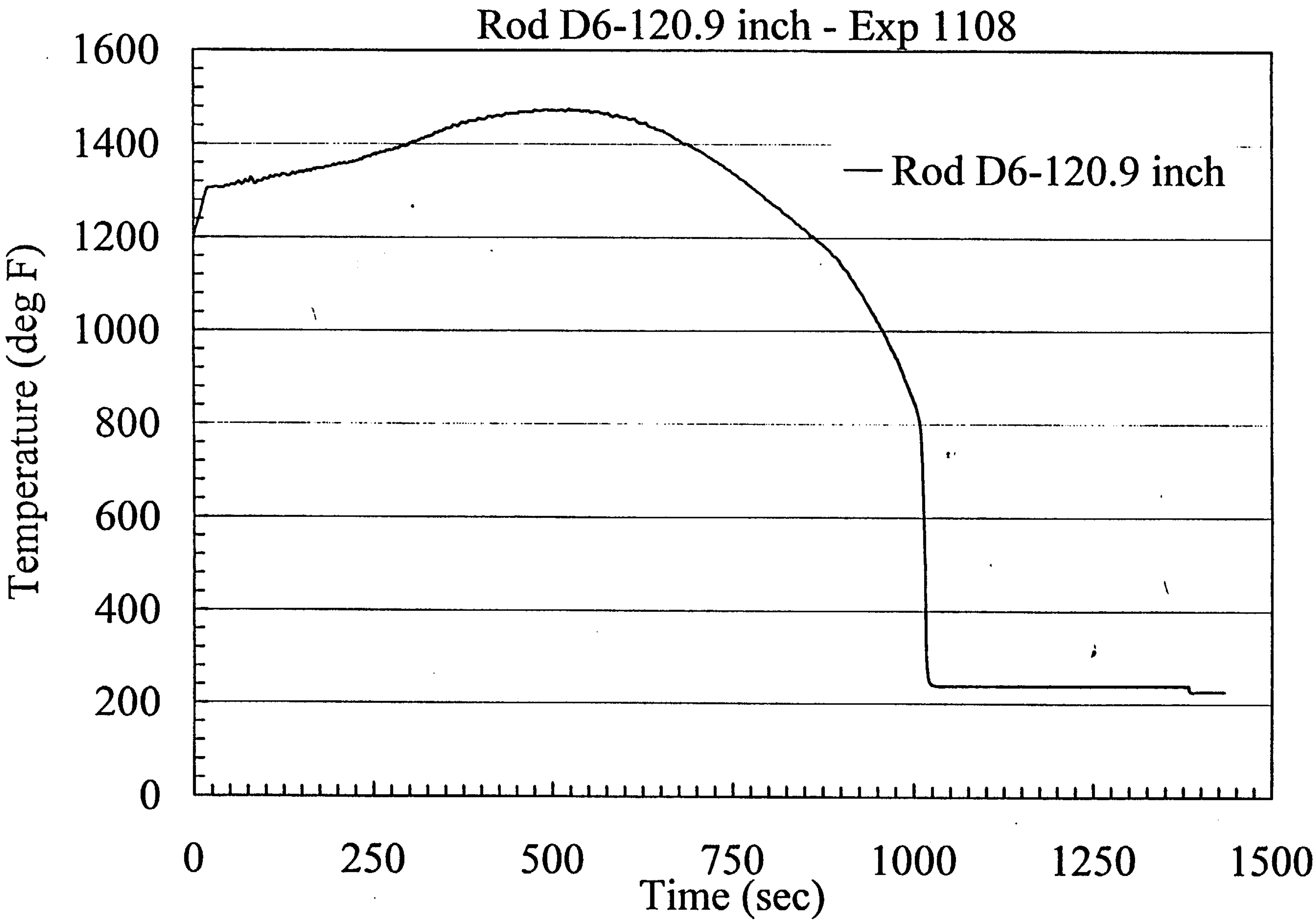
Presentation to the ACRS Subcommittees on Thermal-Hydraulic Phenomena

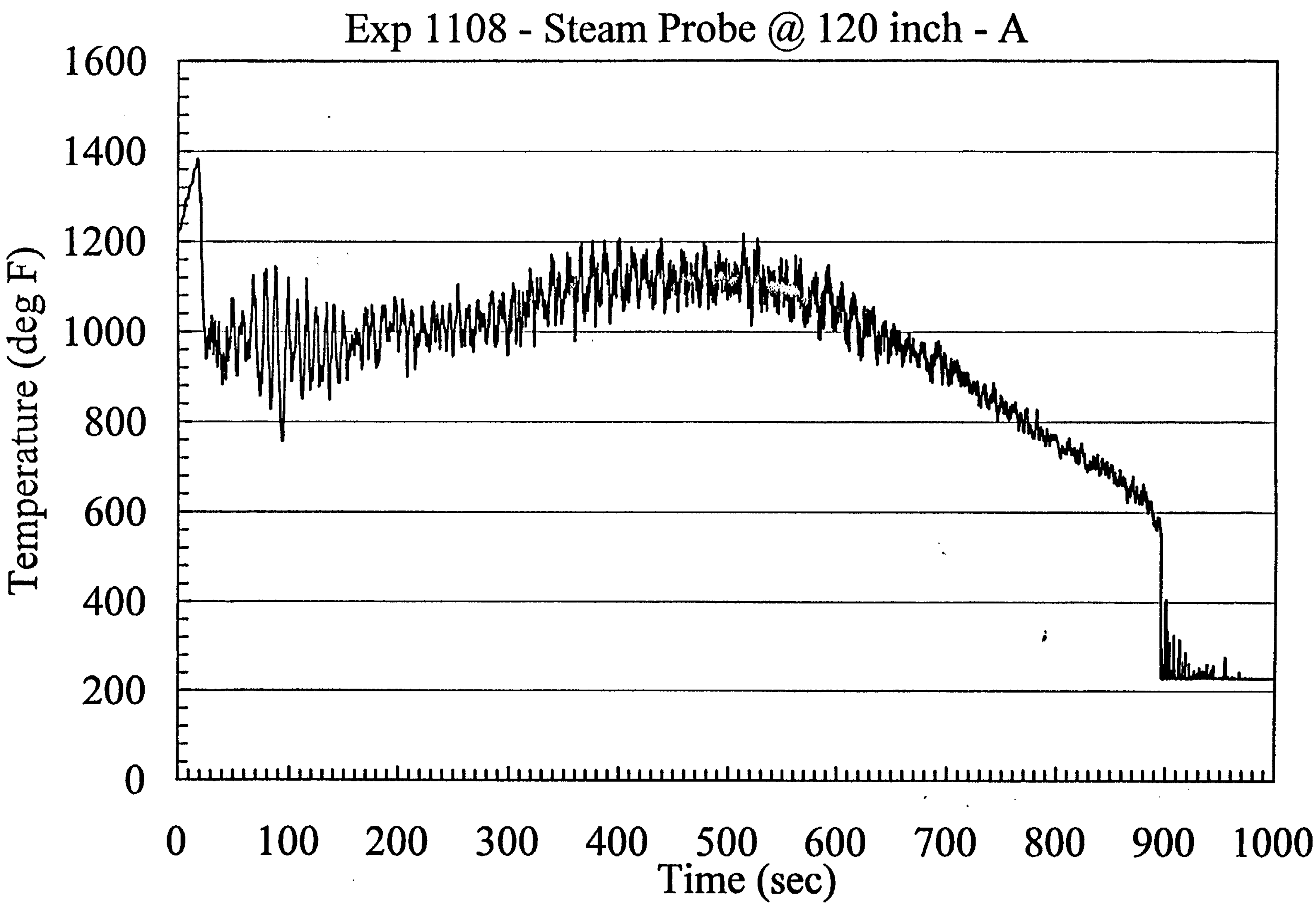
June 26, 2002

Stephen M. Bajorek
Safety Margins and Systems Analysis Branch
Division of Systems Analysis and Regulatory Effectiveness
Office of Nuclear Regulatory Research

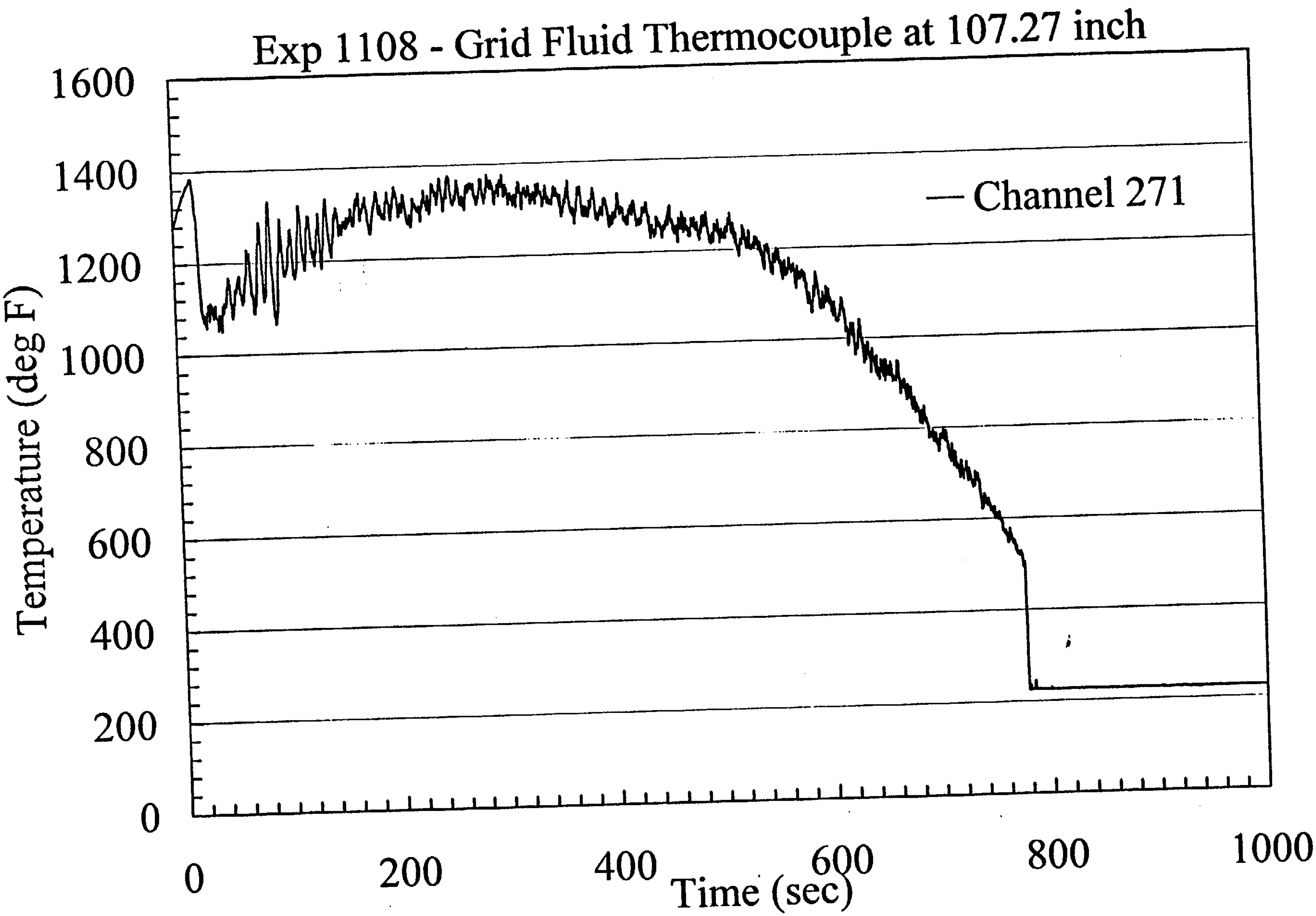
Rod Bundle Heat Transfer (RBHT) Project

- The RBHT project is designed to provide detailed experimental information on reflood thermal-hydraulics including:
  - axial void distribution near quench front
  - droplet size
  - bundle carryover fraction
  - grid spacer effects
  - steam temperatures
  - cladding temperatures
- Long term objective is to develop mechanistic models for reflood heat transfer, entrainment, interfacial drag.

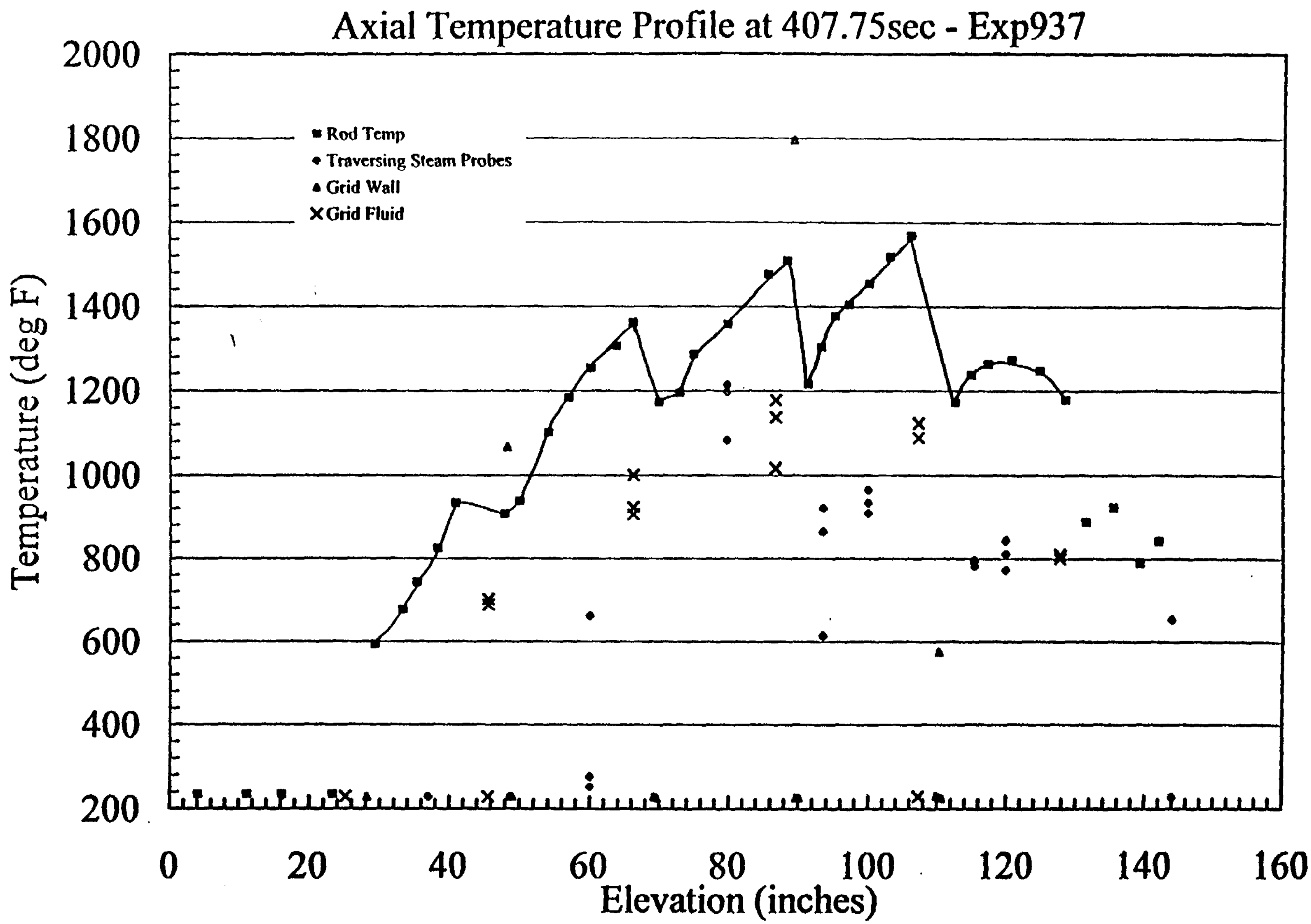

Rod D6-120.9 inch - Exp 1108
Temperature (deg F)
Time (sec)
Rod D6-120.9 inch
0
200
400
600
800
1000
1200
1400
1600
250
500
750
1000
1250
1500



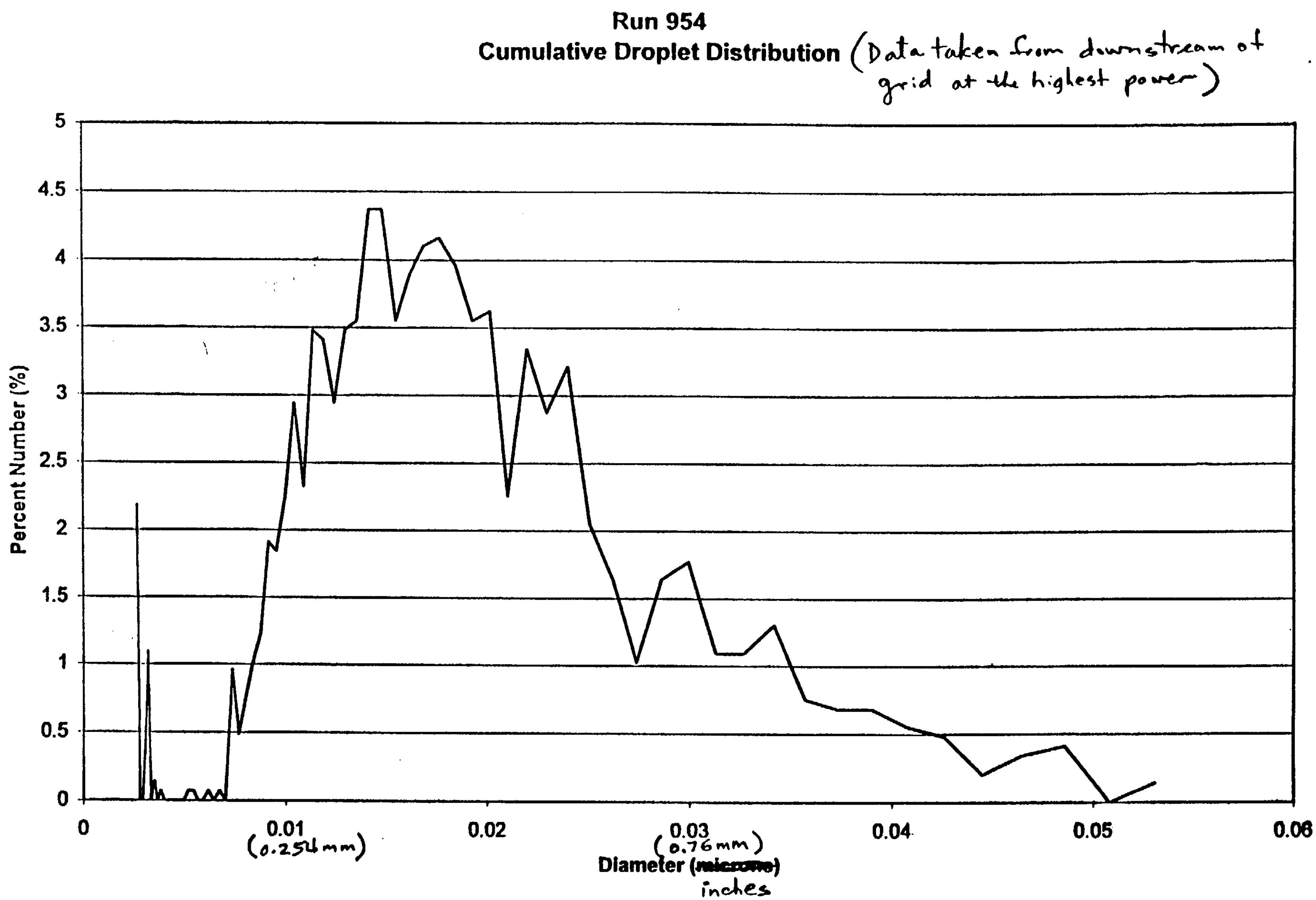
Exp 1108 - Steam Probe @ 120 inch - A
Temperature (deg F)
1600
1400
1200
1000
800
600
400
200
0
0
100
200
300
400
500
600
700
800
900
1000
Time (sec)



Exp 1108 - Grid Fluid Thermocouple at 107.27 inch
1600
1400
1200
1000
800
600
400
200
0
Temperature (deg F)
— Channel 271
0
200
400
600
800
1000
Time (sec)

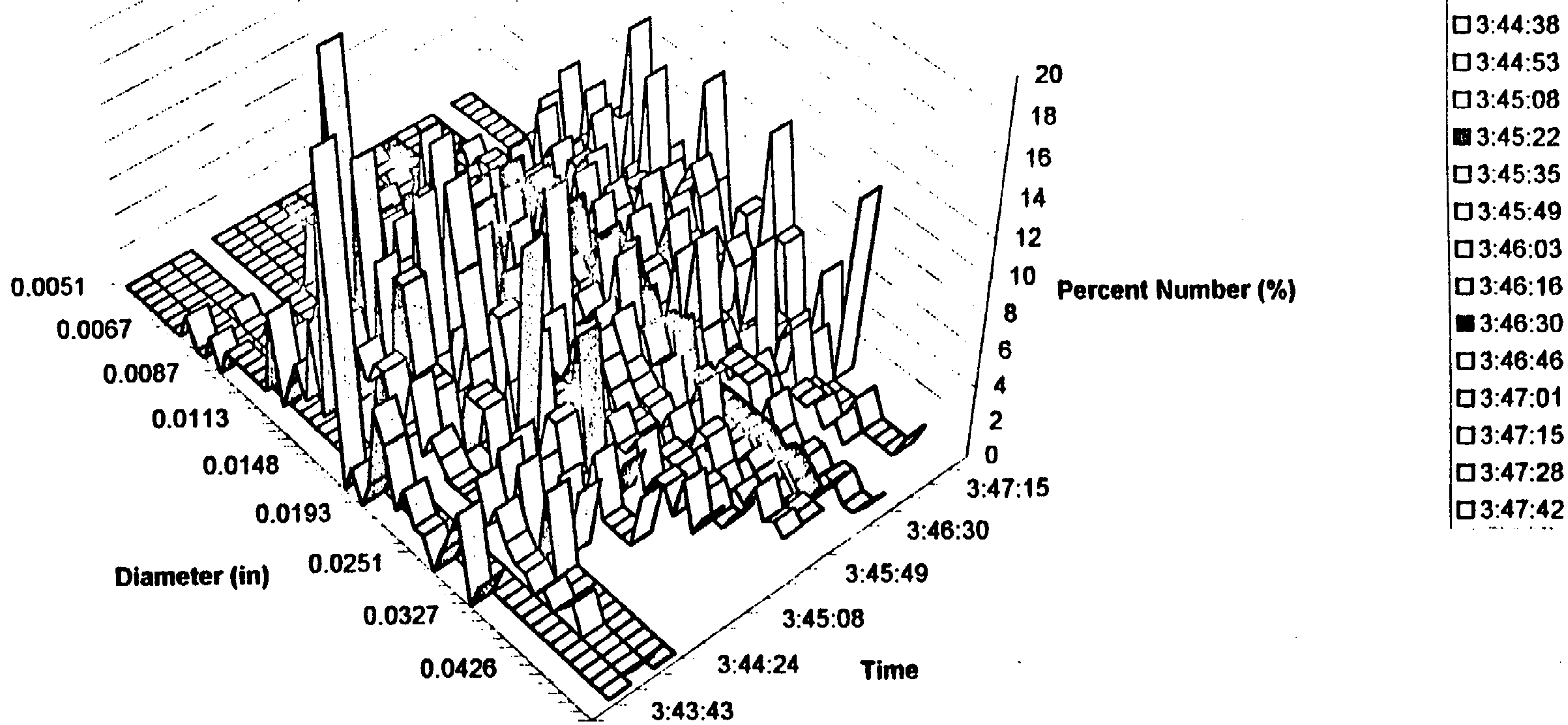


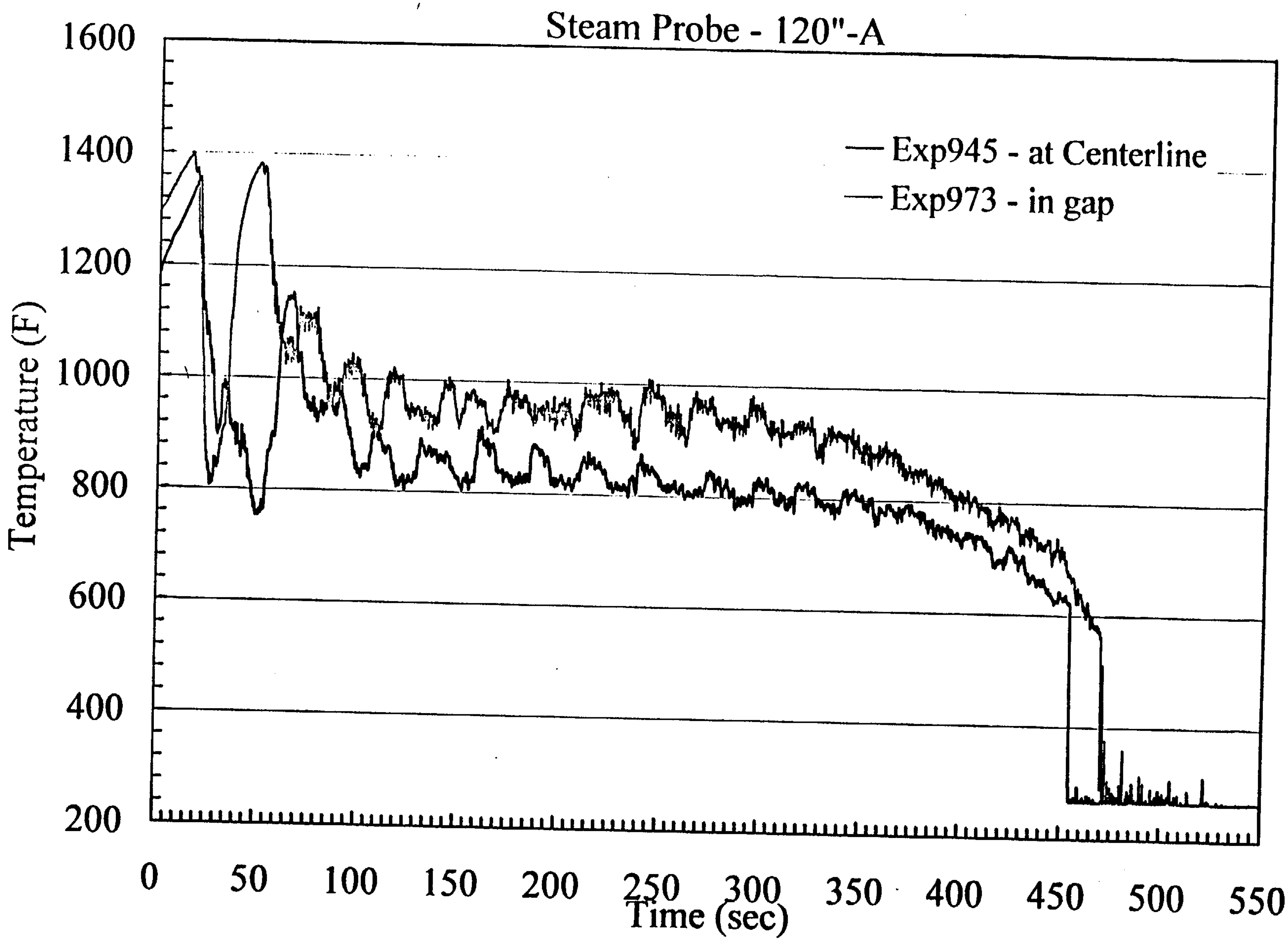
Axial Temperature Profile at 407.75sec - Exp937
Rod Temp
Traversing Steam Probes
Grid Wall
Grid Fluid
Temperature (deg F)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
20
40
60
80
100
120
140
160
Elevation (inches)


Run 954
Cumulative Droplet Distribution (Data taken from downstream of grid at the highest power)
Percent Number (%)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0.01
(0.254mm)
0.02
0.03
(0.76mm)
0.04
0.05
0.06
Diameter (~~microns~~) inches

Droplet Distributions - 5/15/02

(Data taken downstream of grid at the highest power)





Steam Probe - 120"-A
Exp945 - at Centerline
Exp973 - in gap
Temperature (F)
Time (sec)
1600
1400
1200
1000
800
600
400
200
0
50
100
150
200
250
300
350
400
450
500
550

- **Testing began in May 2002. Initial tests and preliminary data have been reviewed & test matrix revised accordingly.**

- **Initial observations:**

  - **Spacer grids are a first order effect**
  - **Relatively uniform planar rod temperature profile**
  - **Traversing steam probes show lateral profile, subchannel effects**
  - **Reasonable drop size distribution / rapid processing**
  - **Acceptable mass balance & facility heat loss**

- **Reflood testing to continue through September 2002**

GSI - 185 Recriticality

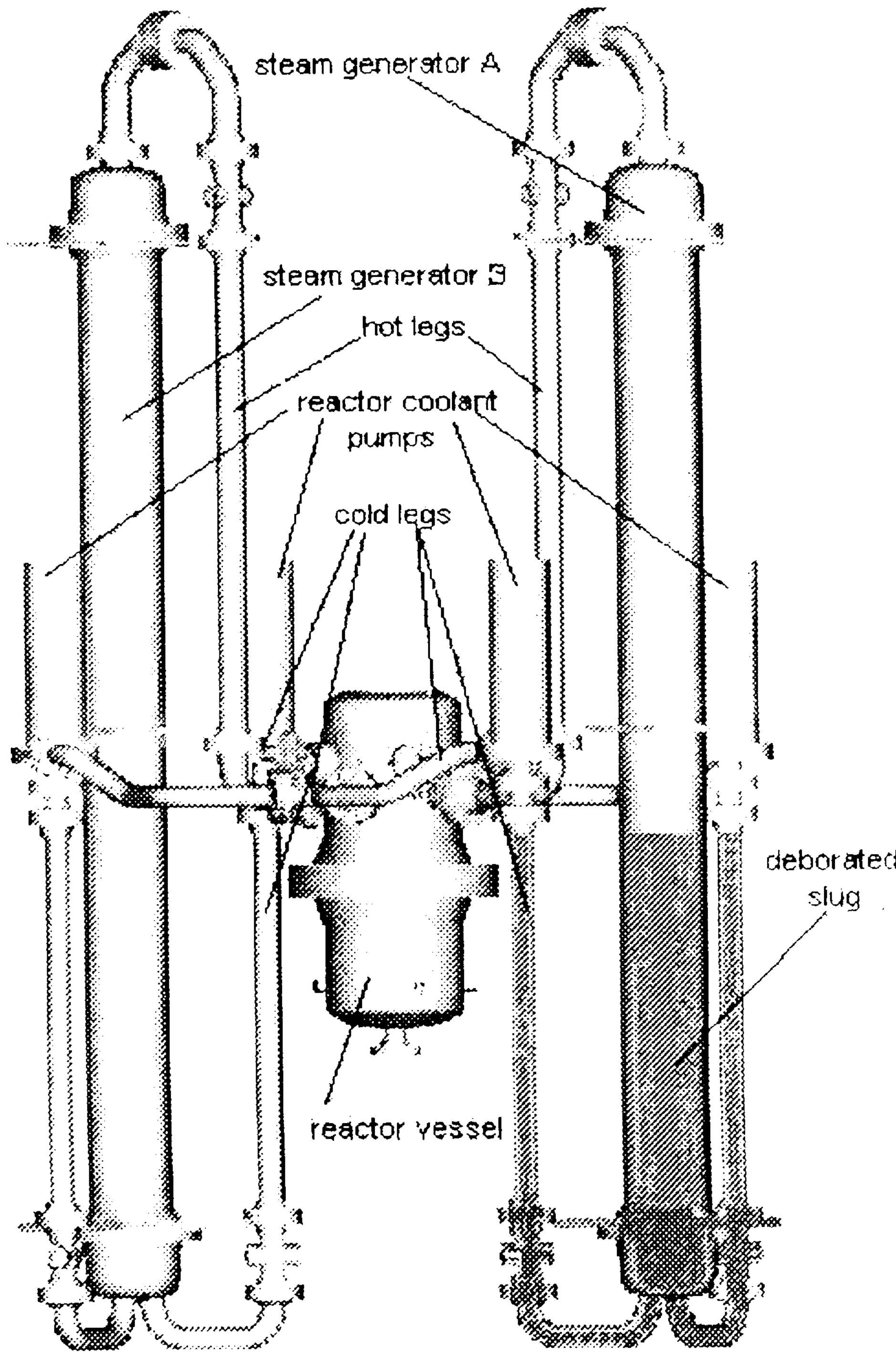
Via Boron Dilution during SBLOCA in PWRs

Harold Scott Marino diMarzo David Diamond

June 26, 2002

- Overview of GSI-185 Harold Scott
- Thermal Hydraulic Analyses Marino diMarzo
- Neutronics Analyses David Diamond

Generic Safety Issue (GSI) 185 addresses those SBLOCA scenarios in PWRs that involve steam generation in the core and condensation in the steam generators, causing deborated water to accumulate in part of the RCS. Restart of RCS circulation may cause a recriticality event (reactivity excursion) by moving this deborated water into the core.


steam generator A
steam generator B
hot legs
reactor coolant
pumps
cold legs
deborated
slug
reactor vessel

BNL FINDING TO DATE

The boron dilution transient caused fuel to:

go above prompt-critical

reach peak reactivity as high as \$1.02

reach 80% of nominal power

undergo peak fuel enthalpy change of 37 cal/g.

Thus do not expect fuel damage for this case.

OTHER SCENARIOS

GSI-22 Inadvertent boron dilution

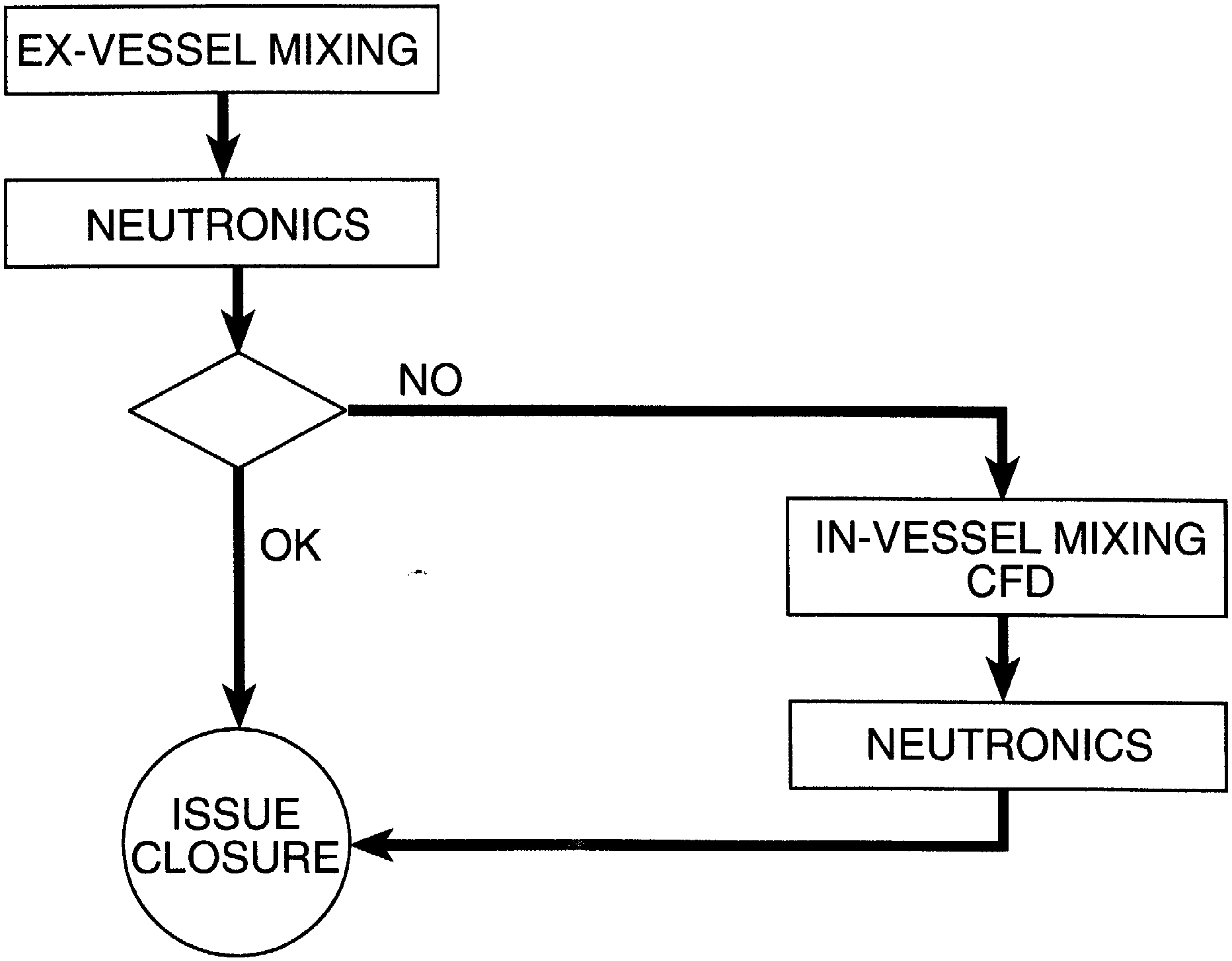
Reactor startup with LOOP ["French" Scenario]

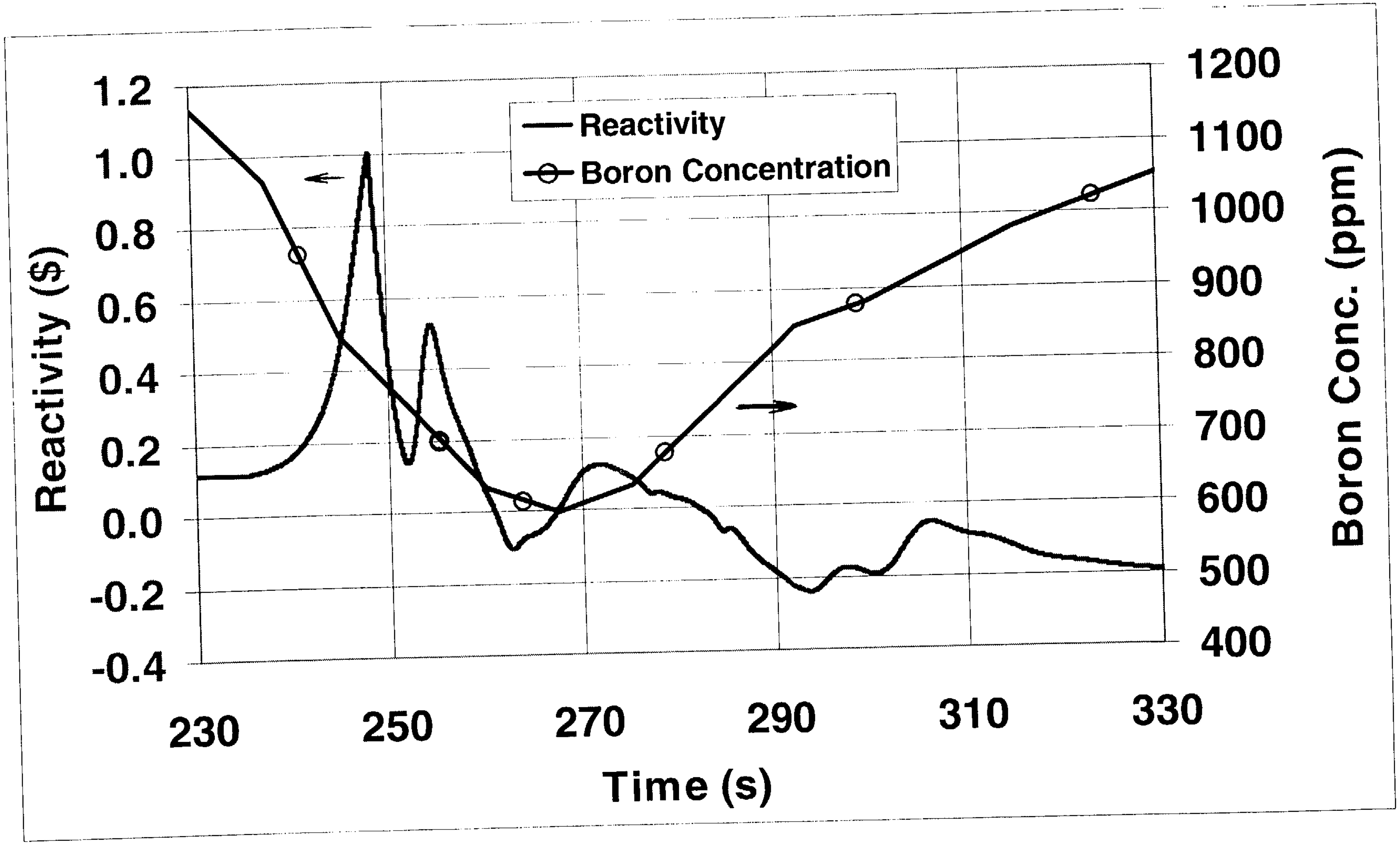
Leakage of secondary water via SG tube leak followed by RCP start ["Swedish" scenario]

GSI-185 SBLOCAs with reflux or boiling - condensation resulting in boron dilution

During shutdown with loss of decay heat removal and consequent reflux or boiling -condensation resulting in boron dilution and subsequent pump restart

GSI - 185


EX-VESSEL MIXING
NEUTRONICS
NO
OK
IN-VESSEL MIXING CFD
NEUTRONICS
ISSUE CLOSURE



Reactivity
Boron Concentration
Reactivity ($)
Boron Conc. (ppm)
Time (s)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
1200
1100
1000
900
800
700
600
500
400
230
250
270
290
310
330

CLOSING THE GENERIC SAFETY ISSUE

An additional calculation assuming RCP bump

Preparation of RES report

Review of RES report and BNL analyses by NRR

Review by full ACRS

Closeout Memo to EDO

PUBLIC AVAILABILITY OF DOCUMENTS

- B&W Owner Group Report January 2000 — ML003686545
- Prioritization Report July 2000 — ML003730563
- Brookhaven Report February 2002 — ML021700591

STATUS AND PLANS FOR TRAC-M DOCUMENTATION

FRANK ODAR

ACRS T&H SUBCOMMITTEE MEETING

JUNE 26, 2002

EXISTING DOCUMENTATION

- TRAC-M/FORTRAN 90 (VERSION 3.0) THEORY MANUAL, NUREG/CR-6724, JULY 2001
- TRAC-M/FORTRAN 90 (VERSION 3.0) USER'S MANUAL, NUREG/CR-6722, MAY 2002
- TRAC-M/F77, VERSION 5.5, DEVELOPMENTAL ASSESSMENT MANUAL, NUREG/CR-6730, JULY 2001
- TRAC-M/FORTRAN 90 (VERSION 3.0) PROGRAMMER'S MANUAL, NUREG/CR-6725, MAY 2001
- ASSESSMENT OF MODERNIZATION AND INTEGRATION OF BWR COMPONENTS AND SPACIAL KINETICS IN THE TRAC-M, VERSION 3690, CODE, NUREG-1752, DECEMBER 2001
- ASSESSMENT OF TRAC-M CODES USING FLECHT-SEASET REFLOOD AND STEAM COOLING DATA, NUREG-1744, MAY 2001
- SOFTWARE QUALITY ASSURANCE PROCEDURES FOR NRC THERMAL HYDRAULIC CODES, NUREG 1737, DECEMBER 2000

PLANNED DOCUMENTATION

- TRAC-M, (VERSION ____), USER'S GUIDE-DRAFT(1) (TARGET DATE: 12/31/02)
- TRAC-M, (VERSION ____), THEORY MANUAL-DRAFT(1) (TARGET DATE: 12/31/02)
- TRAC-M, (VERSION ____), USER'S GUIDE- DRAFT(2) (TARGET DATE: 03/31/03)
- TRAC-M, (VERSION ____), THEORY MANUAL-DRAFT(2) (TARGET DATE: 03/31/03)
- TRAC-M, (VERSION ____), DEVELOPMENTAL ASSESSMENT MANUAL-DRAFT(1) (TARGET DATE: 03/31/03)
- TRAC-M, (VERSION ____), USER'S GUIDE (TARGET DATE: 12/31/03)
- TRAC-M, (VERSION ____), THEORY MANUAL (TARGET DATE: 12/31/03)
- TRAC-M, (VERSION ____), DEVELOPMENTAL ASSESSMENT MANUAL (TARGET DATE: 12/31/03)
- TRAC-M, (VERSION ____), PROGRAMMER'S MANUAL (TARGET DATE: 12/31/04)
- ASSESSMENT REPORTS ON INDIVIDUAL TEST CASES (REPORTS TO BE PUBLISHED AS WORK IS COMPLETE)

United States Nuclear Regulatory Commission

TRAC-M
Code Consolidation and Development

Presented to the ACRS Thermal-Hydraulic and Severe Accident Subcommittee

by

Joseph M. Kelly

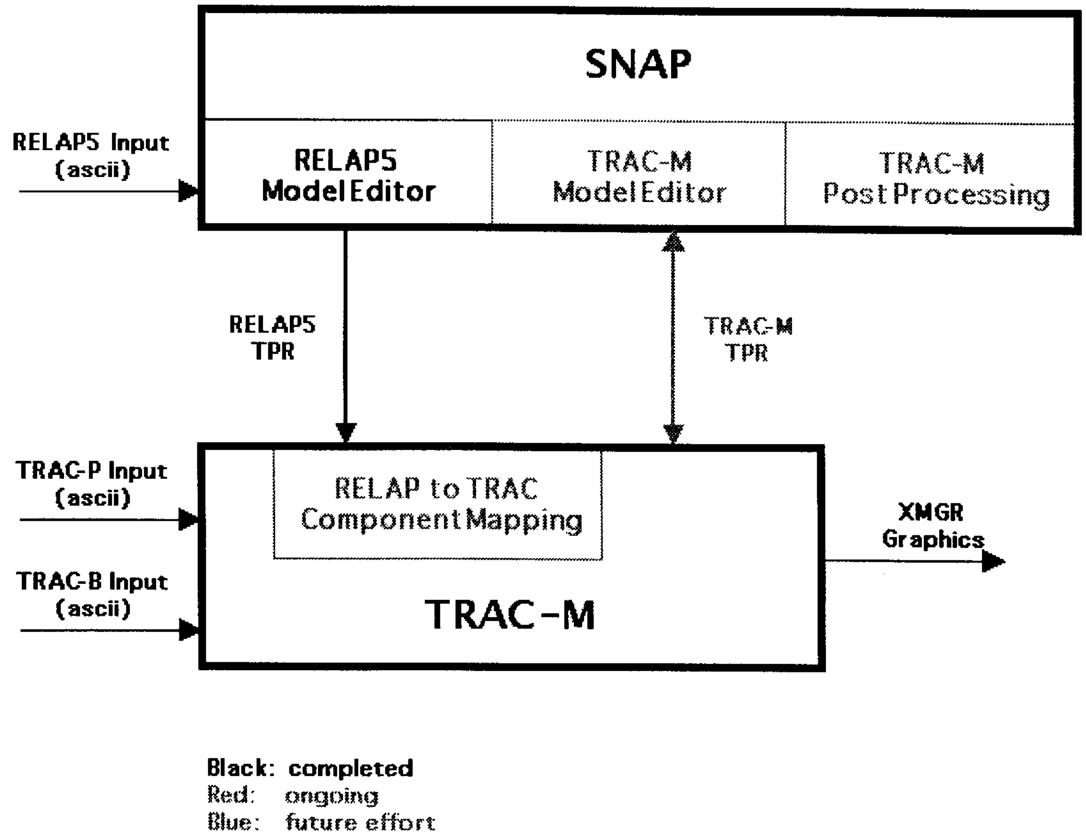
June 26, 2002

TRAC-M: Code Consolidation and Development

- TRAC-M Development Objectives
  - Modern Architecture
  - Code Consolidation:
    - Recover modeling capabilities of predecessor codes (Ramona,TRAC-P, TRAC-B, RELAP5), and
    - Retain investment in legacy input models (RELAP5 & TRAC-B).
    - ➡ Success Metric: simulation fidelity must be equal to or better than that of predecessor codes for their targeted application.
  - Ease of Use
  - Accuracy
  - Numerics

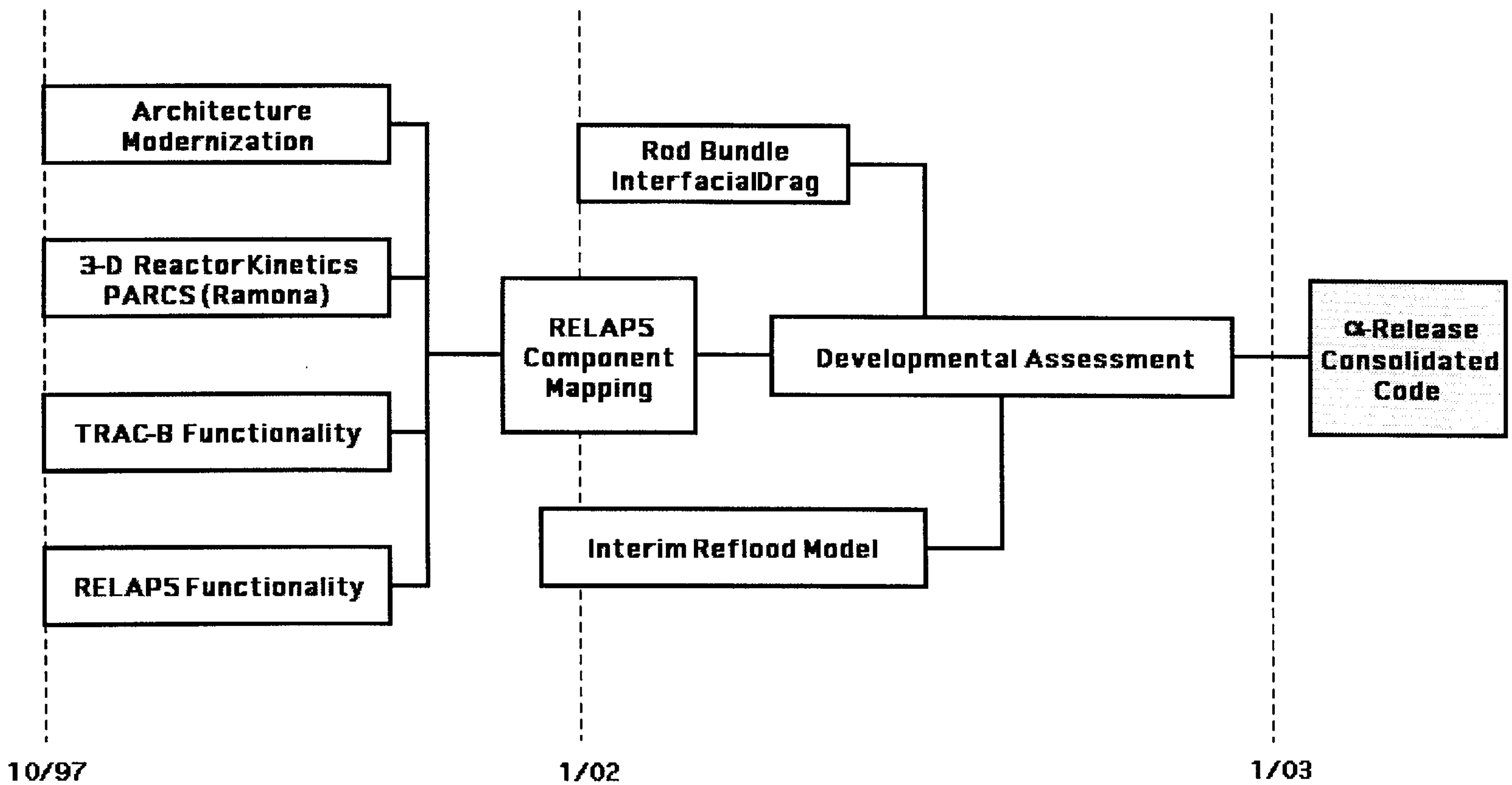
TRAC-M: Code Consolidation and Development

- Legacy Input Models



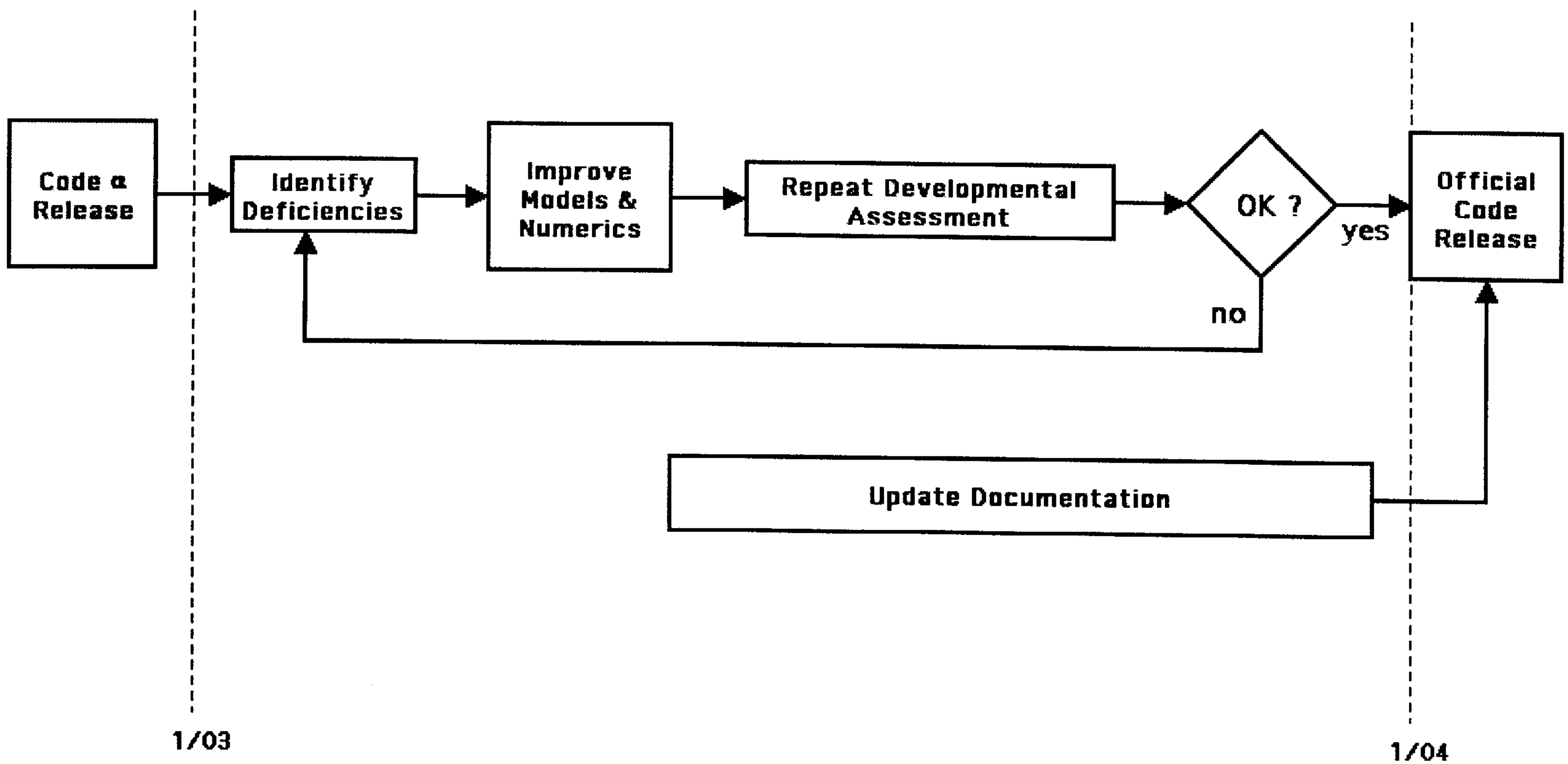
TRAC-M: Code Consolidation Plan & Status

- Calendar Year 2002 Activities:



TRAC-M: Code Consolidation Plan & Status

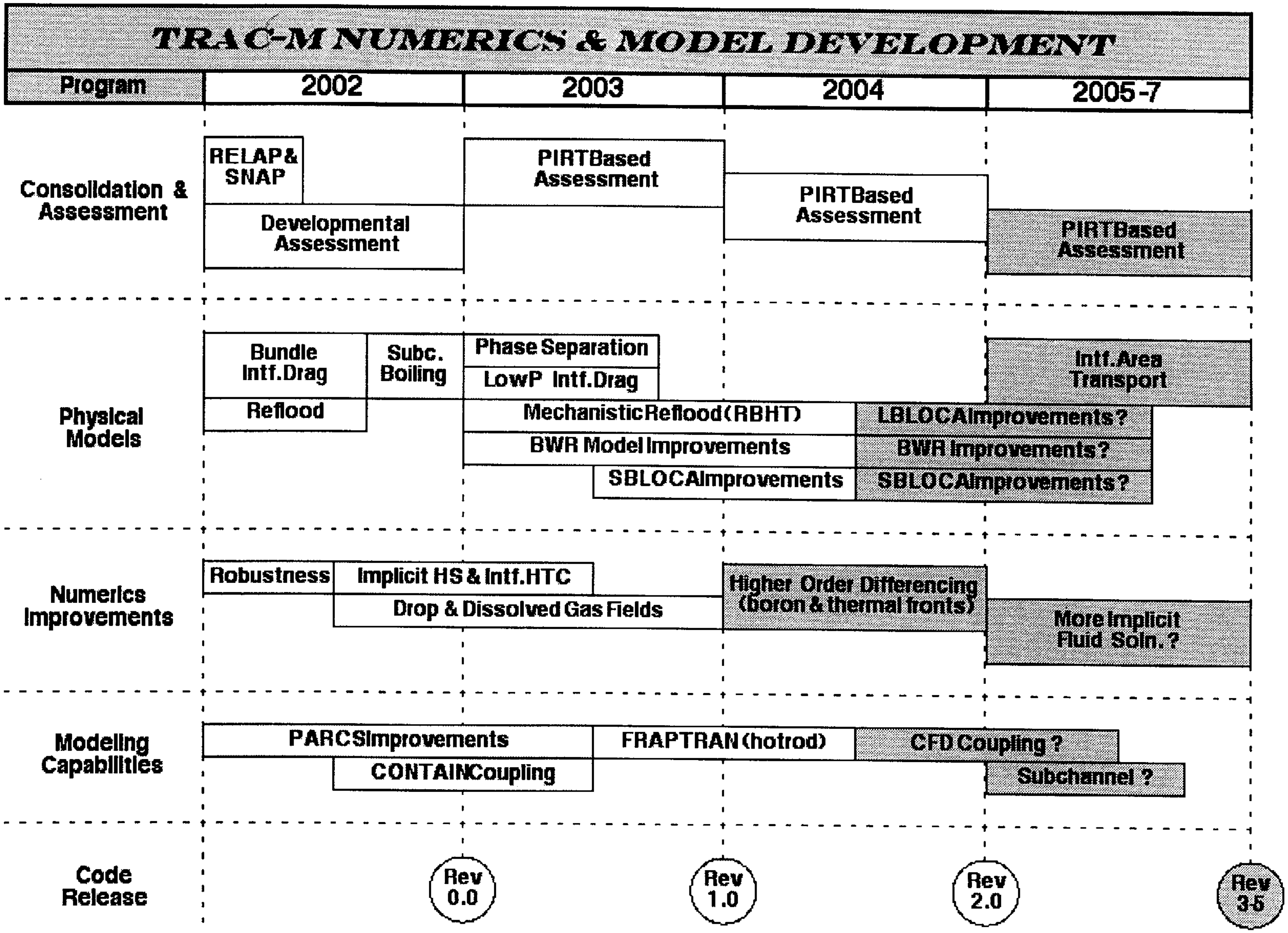
- Calendar Year 2003 Activities:



TRAC-M Current Model Development

- Bundle Interfacial Drag:
  - Necessary for Peach Bottom Turbine Trip benchmark.
    - Implement TRAC-B interfacial drag and heat transfer models.
      - Apply to CHAN component (BWR fuel assembly).
      - Apply to 3-D Vessel core region.
    - Implement low-level modularization of interfacial drag package.
    - In-house effort: Joe Staudenmeier & Tony Ullses

- Reflood Model (interim)
  - Necessary for realistic auditing calculations of AP-1000.
      - Current model has unacceptably large oscillations and is highly conservative for separate effects tests.
    - Physical models and fine-mesh rezoning numerical scheme.
    - In-house effort: Weidong Wang & Joe Kelly



TRAC-M NUMERICS & MODEL DEVELOPMENT
Program
2002
2003
2004
2005-7
Consolidation & Assessment
RELAP& SNAP
Developmental Assessment
PIRTBased Assessment
PIRTBased Assessment
PIRTBased Assessment
Physical Models
Bundle Intf.Drag
Subc. Boiling
Reflood
Phase Separation
LowP Intf.Drag
MechanisticReflood(RBHT)
BWR Model Improvements
SBLOCAImprovements
Intf.Area Transport
LBLOCAImprovements?
BWR Improvements?
SBLOCAImprovements?
Numerics Improvements
Robustness
Implicit HS & Intf.HTC
Drop & Dissolved Gas Fields
Higher Order Differencing (boron & thermal fronts)
More Implicit Fluid Soln.?
Modeling Capabilities
PARCSImprovements
CONTAINCoupling
FRAPTRAN(hotrod)
CFD Coupling ?
Subchannel ?
Code Release
Rev 0.0
Rev 1.0
Rev 2.0
Rev 3-5

TRAC-M Long-Term Development

- Incorporation of Experimental Results
  - UCLA Subcooled Boiling
    - Targeted to known code deficiency, implementation in late 2002.
  - OSU Phase Separation
    - Extension of data base to larger off-take diameter ratio and non-stratified regimes.
    - Targeted to known code deficiency, implementation in 2003
  - PSU Rod Bundle Heat Transfer
    - Designed to provide detailed measurements for model development.
      - Reflood tests to be conducted in 2002-2003.
      - Steam cooling/drop injection tests in 2003.
      - Data analysis & model development in 2003-2004.
  - Purdue/UW Interfacial Area Transport
    - Exploratory research program with the potential for a revolutionary improvement in two-phase flow modeling capability.
      - Implementation to begin in 2005, data can be used for model assessment.

  - Code assessment results => future experimental programs.

TRAC-M: Code Consolidation and Development

- Summary
  - Code development associated with consolidation will be completed by the end of summer 2002.
  - Developmental assessment will be conducted in the second half of 2002.
  - Both interfacial drag and reflood models will be improved for inclusion in the consolidated code.
  - Initial α-release of the consolidated code at end of 2002.
  - Initial public release of the consolidated code at end of 2003.
  - Long-term code development and experimental programs to be driven by assessment results and user needs.

Thermal-Hydraulic Test Programs at OSU for Code Development & Validation

Presentation to the ACRS Subcommittees on Thermal-Hydraulic Phenomena

June 26, 2002

Stephen M. Bajorek
Safety Margins and Systems Analysis Branch
Division of Systems Analysis and Regulatory Effectiveness
Office of Nuclear Regulatory Research

OBJECTIVES

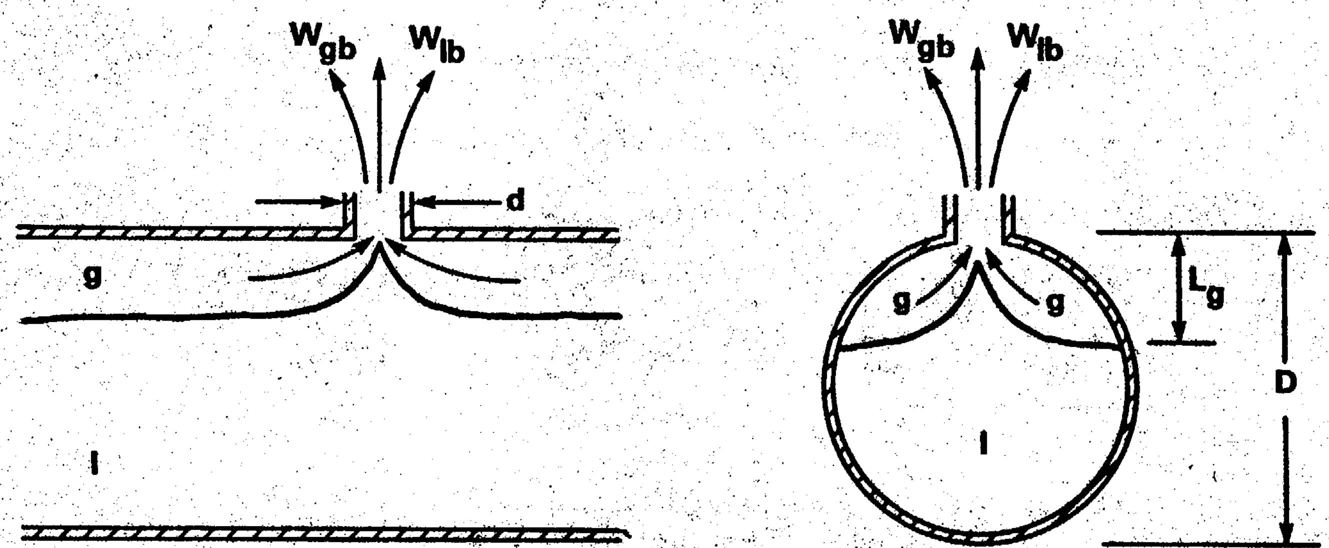
1. Update the Subcommittee on efforts to develop improved models & correlations characterizing entrainment in a horizontal pipe with upward oriented branch line.

2. Outline confirmatory experimental work being planned for OSU facilities (APEX and ATLATS) to address entrainment phenomena.

3. Obtain comments from the Subcommittee on value of the test programs, and suggestions on model development.

Background

- The ATLATS facility was constructed in 1999 and was designed to investigate phase separation at the tee formed by a large diameter pipe and a "small" branch line.



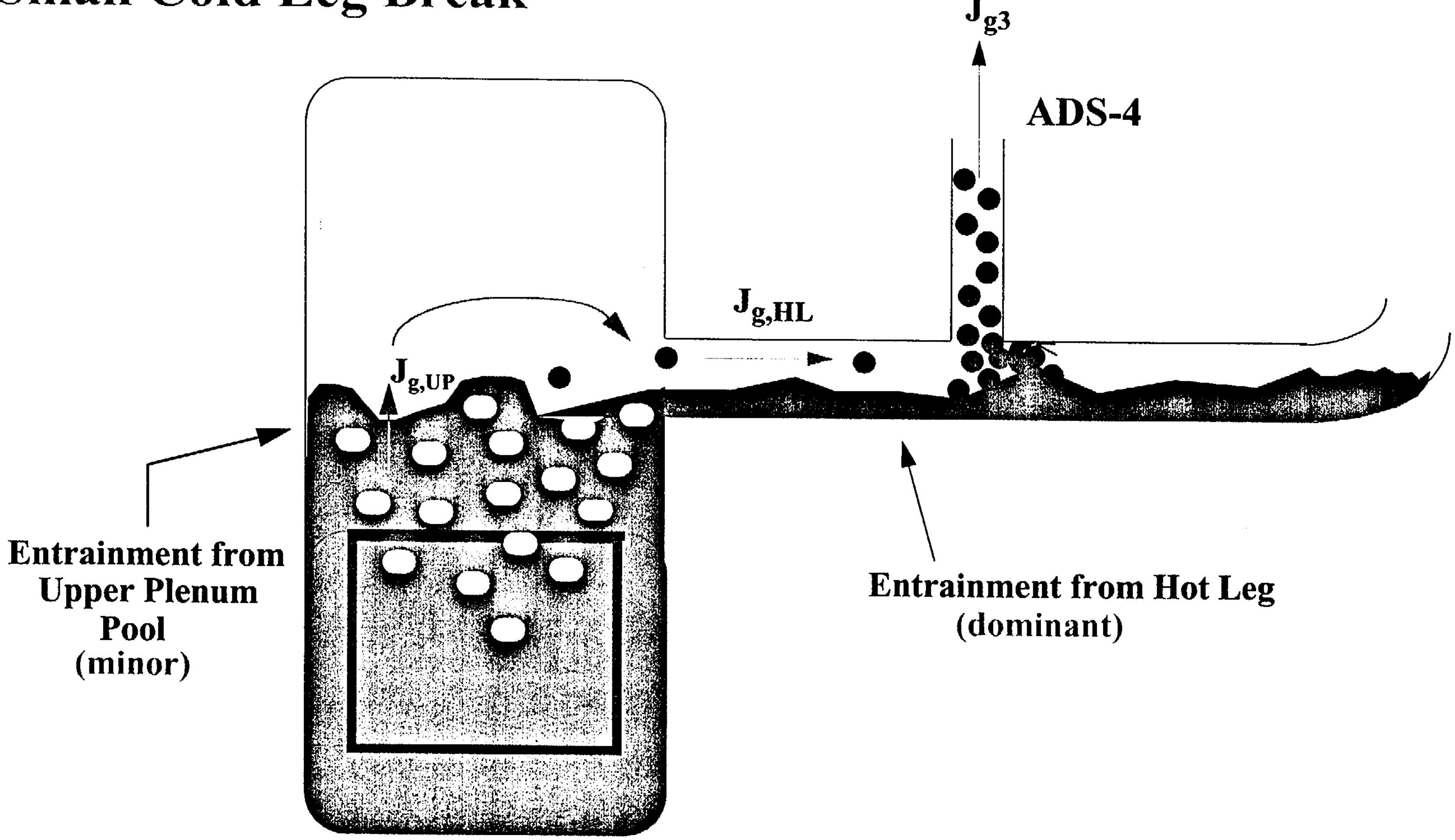
- Initial tests examined geometry applicable to AP600 due to concerns on predicting phase separation in the hot leg at the ADS-4 branch line junction.

AP1000 Scaling & Database Issues

- **Entrainment in the hot leg & carryover to the ADS-4 remains an open issue in AP1000:**
  - **Higher Jg in AP1000 hot leg expected to result in earlier onset, and higher entrainment rates**
  - **Value of $\left.\frac{d}{D_{HL}}\right|_{AP1000}$ is larger than ratio is AP600 or in test facilites used previously to develop phase separation models & correlations.**
- **Upper plenum pool entrainment & carryover**

Hot Leg Entrainment

Small Cold Leg Break



Summary of Main Issues from July 2001 Meeting

- **Literature Review:** Not focussed on upward oriented branchline, and prior work improperly referenced.

- **Flow Patterns:** The flow patterns observed in the hot leg were highly oscillatory. Typical flow pattern descriptions from co-current horizontal flows do not apply.

- **Model Development:** Models were preliminary. Based primarily on horizontal-stratified flow assumptions even though the flow was oscillatory.

Program Re-Direction

1. Revise & reduce the literature survey and corresponding database. Focus only on prior work for upward oriented branch line.

2. Modeling efforts should assume a physical situation similar to that observed in ATLATS and expected to occur in APEX and AP600/AP1000: Flow patterns and entrainment dominated by a coherent "oscillating plug" between branch line and SG inlet plenum.

3. Objective is to develop models to predict the onset of entrainment, and the net "global" entrainment rate.

Phase Separation at an Upward Oriented Vertical Branch in a Horizontal Pipe

Q. Wu, K.B. Welter, Y. Yao, J.N. Reyes
Advanced Thermal Hydraulics Research Laboratory

Presentation to the ACRS of NRC
June 26, 2002

Progress Since Last ACRS Review Meeting on July 17, 2001

- Database Review Update
- ATLATS Test Facility
  - Liquid Level Probe Sampling Rate Evaluation
- Entrainment Onset Study
  - Tests (air injection from the vessel top)
  - Entrainment Onset Correlation Development
- Entrainment Rate Study
  - Tests
  - Entrainment Rate Model Development

Nuclear Engineering & Radiation Health Physics
Oregon State University
OREGON STATE UNIVERSITY
Open minds. Open doors.

Database Review Update

Nuclear Engineering & Radiation Health Physics

Oregon State University

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Database Review Update

- Focus on liquid entrainment at an upward oriented vertical branch in a horizontal pipe
- Database includes:
  - Description of each test facility
  - Test conditions
  - Instrumentation
  - Model Development
  - Cross Comparison

Nuclear Engineering & Radiation Health Physics

Oregon State University

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Database Review Update

Date Published	Authors and Institution	Experiment		Correlations
		Fluids	D/d*	
1980	Zuber (NRC)	N/A	N/A	Scaling, correlations
1981	Crowley and Rothe (Creare Inc.)	Air-water	12	Entrainment Onset
1984	Reimann, Khan and Smoglie (KfK)	Air-water	34, 26, 17, 10	Entrainment Onset Entrainment Rate
1986	Schrock, Revenkar, and Mannheimer (Berkeley)	Air-water Steam-water	31, 25, 17, 10	Entrainment Onset Entrainment Rate
1989	Maciaszek and Micaelli (CEA)	Steam-water	6.8	Entrainment Onset Entrainment Rate
1991	Yonomoto and Tasaka (JAERI)	Air-water	~19, 8.5	Entrainment Rate

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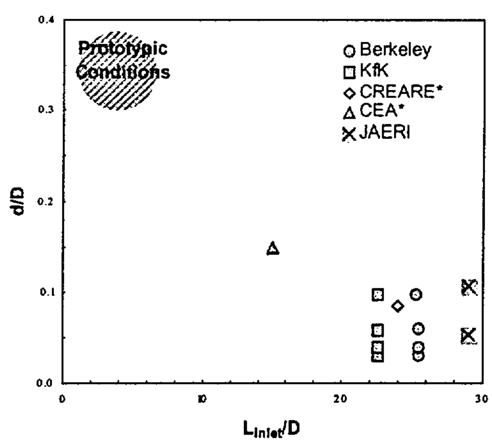
Nuclear Engineering & Radiation Health Physics
Oregon State University

Database Review Update
(Summary of Geometric Conditions)



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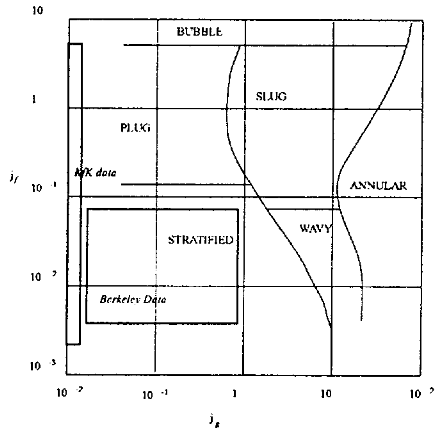
Database Review Update

(Range of the Entrainment-Rate Test Data)



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Oregon State University

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Database Review Update

- For advanced plants, d/D_{AP1000}=0.47 and d/D_{AP600}=0.34, significantly greater than those of previous investigations
- The gas superficial velocity range in previous tests is much lower than that in the advanced plant (>1 m/s)
- Previous experimental investigations were applicable to co-current stratified flow. Traditional flow regime map may not be adequate for this investigation.

Nuclear Engineering & Radiation Health Physics

Oregon State University

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Database Review Update

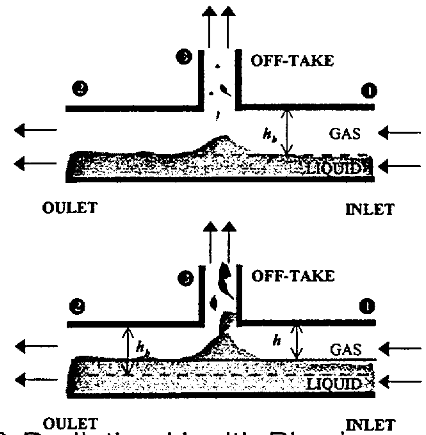
Existing Correlations

Onset of Entrainment

$$\left(\frac{h_b}{d}\right) \sim \left(\frac{V_{g3}^2}{gd}\right)\left(\frac{\rho_{g1}}{\Delta\rho}\right)$$

Steady-State Entrainment

$$x_3 \sim \left(h / h_b\right)$$



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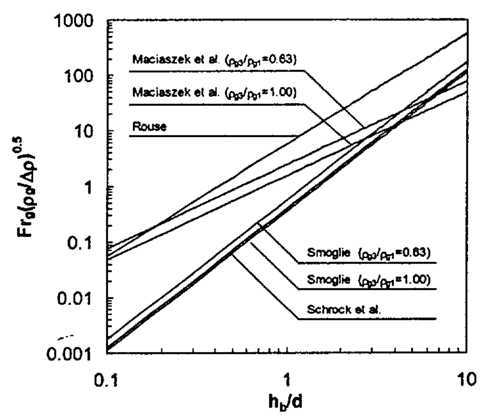
Database Review Update

Existing Entrainment Onset Correlation



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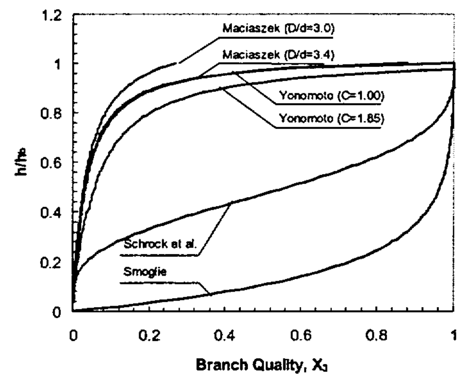
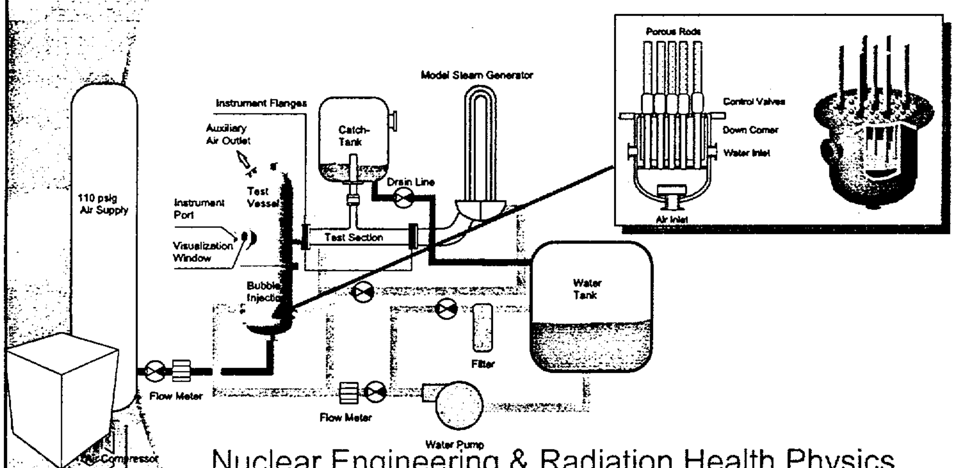
Database Review Update

Entrainment Rate Correlation Cross Comparison



ATLATS Test Facility

ATLATS Test Facility



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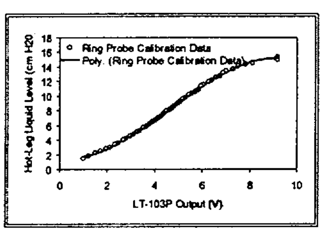
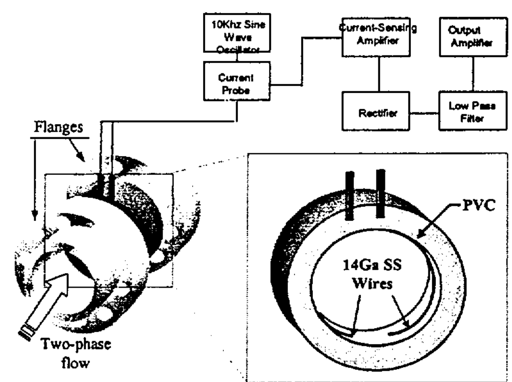
Liquid Level Probe Sampling Rate Evaluation

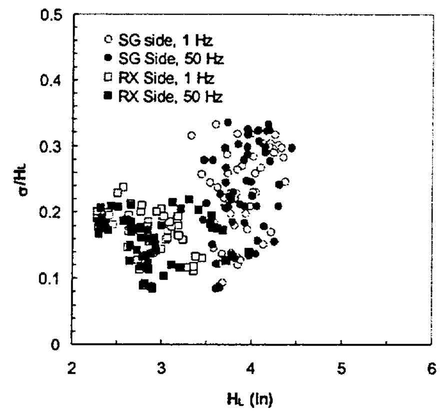




Liquid Level Probe Sampling rate Evaluation in Entrainment Rate Tests

(4 minute Duration)

- The scattering is due to actual liquid level fluctuations
- 1 Hz vs. 50 Hz sampling rate, similar scattering range:
  - SG side, 10% ~ 34%
  - RX side, 10% ~ 24%
- H_L (SG) > H_L (RX)



Entrainment Onset Studies

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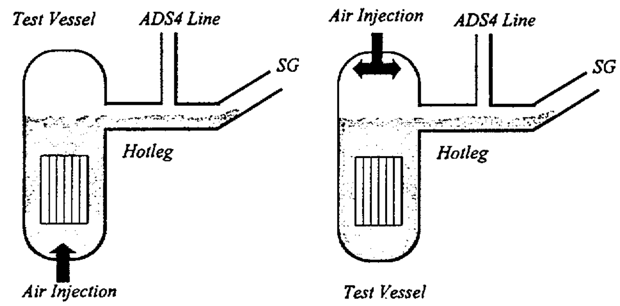
Entrainment Onset Test
with Air Injection from the Vessel Top



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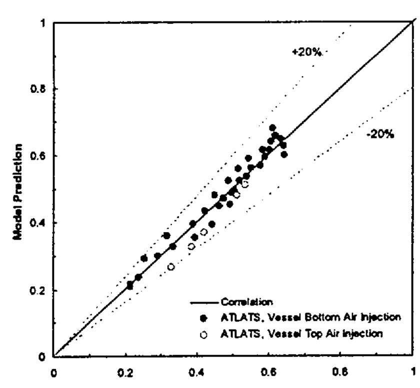
Entrainment Onset Test
with Air Injection from the Vessel Top



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Entrainment Onset Criterion Development

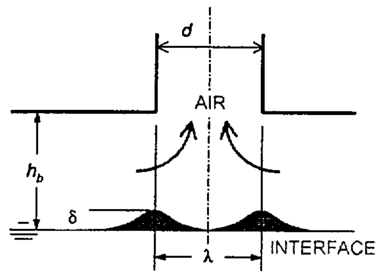
- Original Approach

$$\rho_1 V_1 \pi \lambda (h_b - \delta) = \rho_z V_3 \pi d^2 = w_{3g}$$

$$\Delta P = \Delta \rho g \delta = \frac{1}{2} \rho_1 V_1^2$$

$$\lambda^2 \delta (h_b - \delta)^2 = \frac{1}{2\pi} \frac{w_{3g}^2}{\rho_1 \Delta \rho g}$$

$\delta = 1/3\ h_b$.

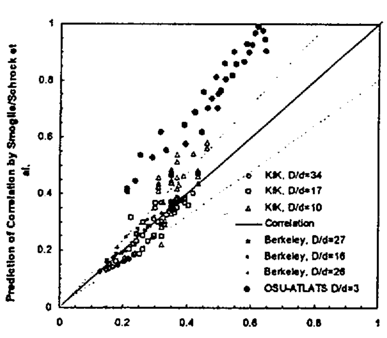


Maciaszek/Bharathan et al. approach:

$$h_b = \frac{3}{2\pi^{2/3}} \left(\frac{w_{3g}^2}{\rho_g \Delta \rho g} \right)^{1/3}$$

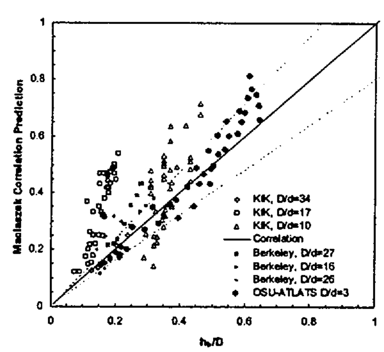
Entrainment Onset Criterion Development

KfK/Berkeley Correlation



Correlation for small d/D ratio

CEA Correlation

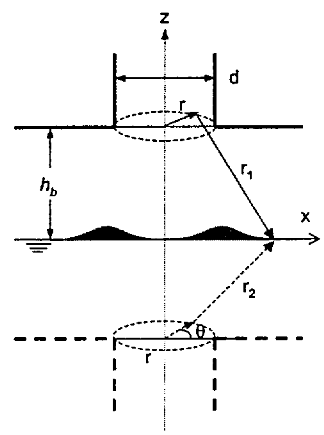


Correlation for large d/D ratio

Entrainment Onset Criterion Development

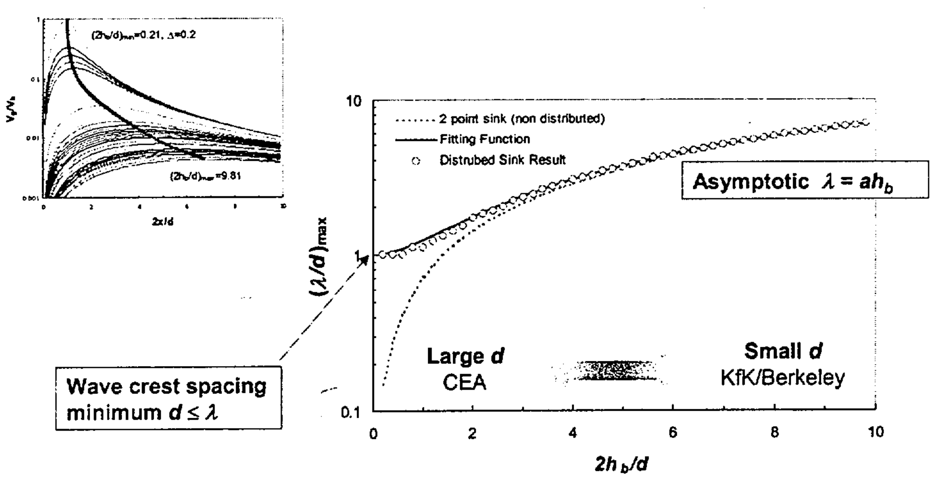
- Modification

  To find λ, potential flow of 2 distributed mirror sinks is considered.

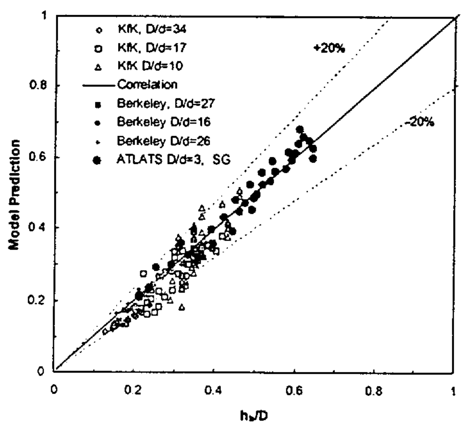


$$V_x = \left(\frac{4w_{3g}}{\pi^2 \rho_g d^2}\right) \int_0^{d/2} \int_0^{2\pi} \frac{(x - r\cos\theta)}{\left[h_b^2 + (r\sin\theta)^2 + (x - r\cos\theta)^2\right]^{3/2}} r\,d\theta\,dr$$

Entrainment Onset Criterion Development



Entrainment Onset Criterion Development



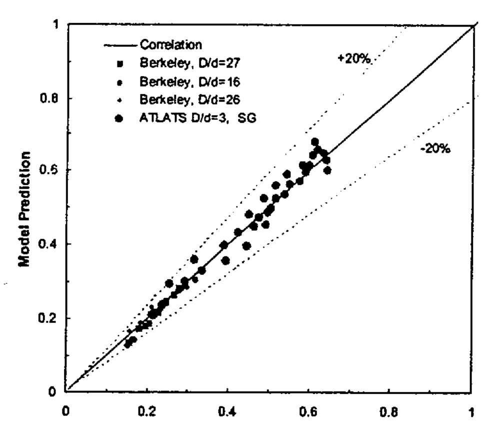
$$\Delta P = \Delta\rho g\delta = \frac{1}{2}\rho_1\left(V_{1,crest}^2 - V_1^2\right)$$

λ/d

$$\left(w_{3g}^2\right)^* = K\left(\frac{h_b}{d}\right)^3\left[a\left(\frac{h_b}{d}\right)+1\right]^2\left[1-\left(\frac{h_b}{D}\right)^2\right]^{-1}$$

$$\left(w_{3g}^2\right)^* \equiv \frac{w_{3g}^2}{d^5\rho_g\Delta\rho g}$$

Entrainment Onset Criterion Development



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Entrainment Rate Studies

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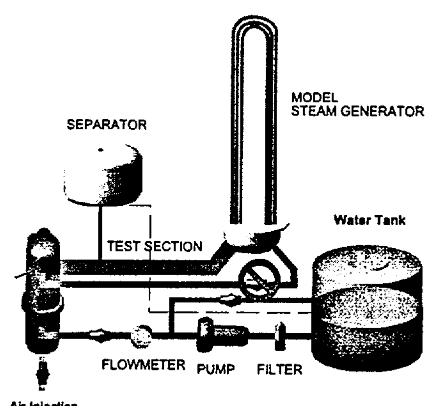
Entrainment Rate Tests



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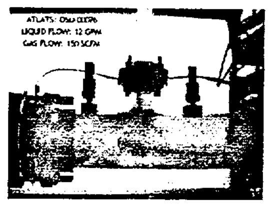
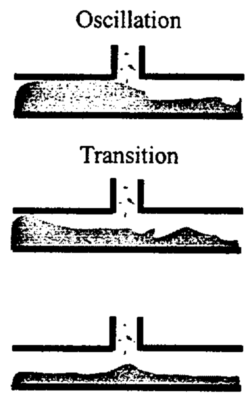
Flow Patterns





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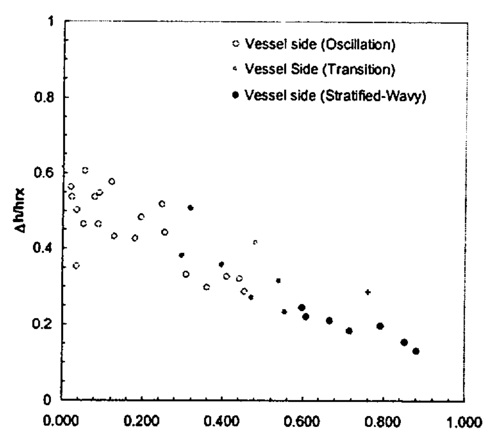
Flow Patterns



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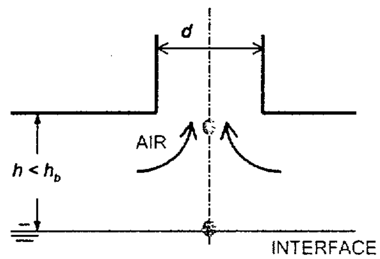
Entrainment Rate Model Development

When $h < h_b$, liquid entrainment occurs



$$\frac{\rho_f V_{f3}^2}{2} \propto \left(\frac{\rho_{g1} V_{g1}^2}{2}\right) - C\Delta\rho g h$$

$$w_{f3} \propto (1-\alpha_3)A_3\sqrt{2\Delta\rho\rho_f g h}\sqrt{\frac{C'}{2h(\alpha_1 A_1)^2}\left(\frac{w_{g3}^2}{\Delta\rho\rho_g g}\right)-1}$$

$$C' = 2(\alpha_{1b}A_1)^2 h_b \frac{\Delta\rho\rho_g g}{w_{g3}^2}$$

Entrainment Rate Model Development

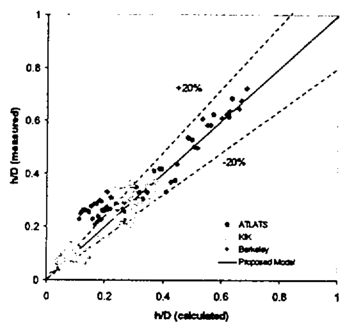
$$x_3 = \frac{1}{1 + w_{f3}/w_{g3}}$$

$$\frac{w_{f3}}{w_{g3}} = C_1 \frac{\left(1-\left(\frac{h}{h_b}\right)\right)\sqrt{\left(\frac{\rho_f}{\rho_g}\right)\left(\frac{h}{h_b}\right)\left(1-\left(\frac{h_b}{D}\right)^2\right)\left[\left(\frac{h_b}{h}\right)\left(\frac{\alpha_{1b}}{\alpha_1}\right)^2-1\right]}}{\left(\frac{h_b}{d}\right)\left(a\frac{h_b}{d}+1\right)}$$

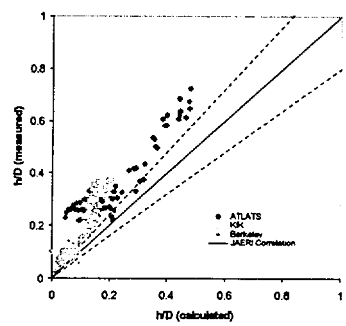
- Function of D, h_b, h, d, and ρ_f/ρ_g
- Relies on accurate estimation of h_b at the given gas flow rate

Entrainment Rate Model Development

Present Model

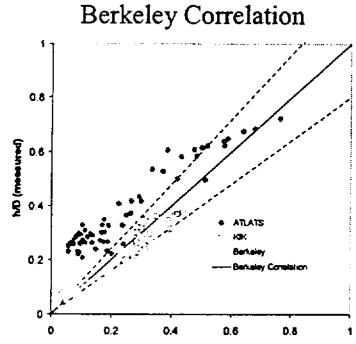


JAERI Correlation

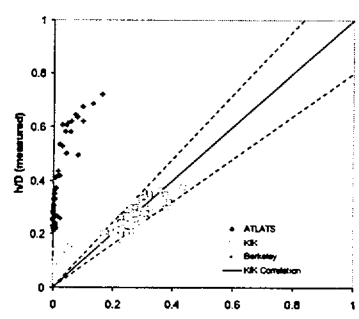


Entrainment Rate Model Development

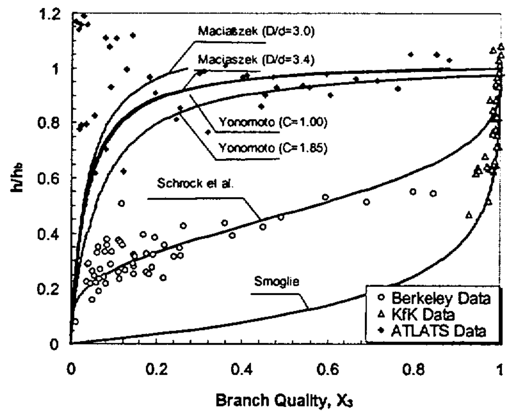
Berkeley Correlation



KfK Correlation



Entrainment Rate Model Development



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Summary

- Database Improvement
  - The new Database focuses solely on previous investigations of liquid entrainment in an upward oriented vertical branch of a horizontal pipe.
- Entrainment Onset Experiments
  - Air injection from the vessel top did not have much affect on the entrainment onset condition (<10%)
  - Data sampling rate for the liquid level probe was appropriate for a duration of ~4 min

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Summary (continued)

- Entrainment Onset Model Development
  - Simplified formulation
  - Considered gas velocity effects in the main pipe
  - The new model agreed with available test data of different geometry, scale and fluid properties (±20% of accuracy)
- Entrainment Rate Experiments
  - Entrainment rate tests were focused on cases with steam generator (oscillatory, transition and stratified-wavy flows)

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Summary (continued)

- Entrainment Rate Model Development
  - Proposed a model based on a mechanical energy balance approach
  - The mechanistic model predicted the trends of different data sets with a reasonable accuracy (an improvement compared to other correlations)

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Related & Future Activities

■ Integration and Validation with TRAC-M

- ◆ Model development & data analysis to continue. Need to establish conditions for hot leg flow pattern transitions in ATLATS, APEX and AP600/AP1000.

- ◆ RELAP model of ATLATS developed. Future efforts will impliment and validate new models by TRAC-M simulations of ATLATS and APEX.

■ Confirmatory Intergal Effects Testing

- ◆ Cooperated with DOE defining DOE-NERI test matrix for advanced plant studies at OSU using the APEX facility.

- ◆ DOE-NERI test matrix to include several tests useful for investigating upper plenum entrainment processes.

- ◆ NRC Confirmatory Test Matrix assumes DOE/NERI tests performed. Focus of NRC tests on Beyond-Design-Basis conditions and to assist in NRC code development & analysis activities.

Table 1: Tentative DOE - NERI Test Matrix

	Comment
1	**Double-ended guillotine break of direct vessel injection line with ADS-4 valve**: Design basis DEDVI with single ADS-4 failure.
2	**2-inch break in bottom of cold leg 3 (CMT side) with 3/4 ADS-4**: Design basis 2-inch break case.
3	**Double-ended DVI break with failure of intact side accumulator**: Beyond design basis case.
4	**Primary Loop Characterization Single-Phase Natural Circulation**: Provides assessment of loop pressure drop.
5	**"No Reserve" Test**. Using AP1000 expected initial conditions for ADS blowdown.
6	**"No Reserve" Test**. Using AP1000 expected initial conditions for ADS blowdown.
7	**SS Entrainment Test**: 3 open ADS-4 valves, 0 psig containment back pressure, UP internals in.
8	**SS Entrainment Test**: 3 open ADS-4 valves, 25 psig containment back pressure, UP internals in.
9	**SS Entrainment Test**: 4 open ADS-4 valves, 0 psig containment back pressure, UP internals in.
10	**SS Entrainment Test**: 2 open ADS-4 valves (both on one side), 0 psig containment back pressure, UP internals in.
11	**SS Entrainment Test:** 4 open ADS-4 valves, 0 psig containment back pressure, UP internals out.

Upper Plenum Entrainment

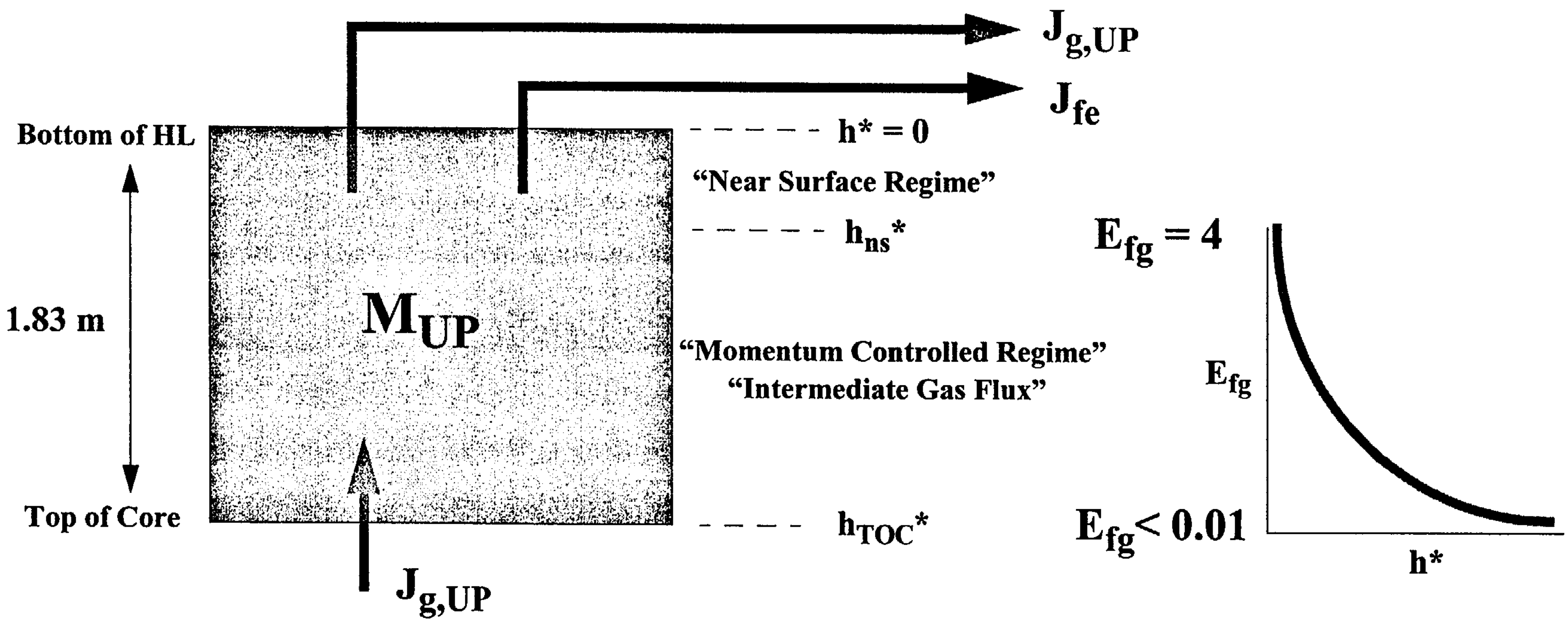

Table 2: Proposed NRC Confirmatory Test Matrix

Test ID	Priority	Comments
NRC-AP1000-1	M	**Double-ended guillotine break of direct vessel injection line with failure of ADS-1/2/3**: DEDVI with failure of ADS-1/2/3, forcing ADS-4 to provide blowdown.
NRC-AP1000-2	H	**Mode 5 (Cold Shutdown) Operation with Loss of RNS Cooling:** Determines if RCS would repressurize sufficiently to prevent IRWST injection and if CCFL prevented pressurizer drainage. (Note: New surge line being added to APEX-AP1000 facility.)
NRC-AP1000-3	M	**Double-ended guillotine break of direct vessel injection line with failure of PRHR, 50% of ADS4-2**: Beyond design basis test.
NRC-AP1000-4	H	**1-inch cold leg break with degraded sump:** Similar test for AP600 used to showed level at which liquid in sump was no longer able to support recirculation.
NRC-AP1000-5	M	**Double-ended guillotine break of non-pressurizer loop direct vessel injection line with failure 50% of ADS4-2**: Beyond design basis test with variation of break location.
NRC-AP1000-6	H	**2-inch DVI break with single ADS-4 valve failure**: Design basis type case not previously considered. Provides effect of break size.
NRC-AP1000-7	M	**Station Blackout**. Addresses PRA, and may also provide information on PRHR performance.
NRC-AP1000-8	H	**SS Entrainment Test**: 2 open ADS-4 valves (both on one side), 60 psig containment back pressure (or max.allowable, UP internals in.
NRC-AP1000-9	H	**SS Entrainment Test**: 2 open ADS-4 valves (both on one side), 60 psig containment back pressure (or max. allowable pressure), UP internals out.
NRC-AP1000-10	H	**SS Entrainment Test**: 2 open ADS-4 valves (both on one side), 0 psig containment back pressure, UP internals out. Comparison to one of the DOE-NERI tests provides low pressure de-entrainment sensitivity.
NRC-AP1000-11	H	**"No Reserve" Test**. Initial pressure = 100 psia, containment backpressure = 25 psia and with core power = 1000 kW. Corresponds to NRC-6425.

EX-VESSEL MIXING

Consider two extreme idealized conditions [1]:

- plug flow
- backmixed flow

The ex-vessel mixing is evaluated with the following assumptions [2]:

1. In the primary system we identify two backmixed volumes
    - steam generator outlet plenum
    - reactor coolant pump

2. The cold legs are considered plug flow volumes

This model is validated against UM data

[1] Levenspiel, O., 1962. Chemical Reaction Engineering, Wiley
[2] diMarzo, M., 2001. Ex-vessel transport and mixing of a deborated slug in a PWR primary geometry, NED 210, pp.169-175

MODEL

Slug transit time:

$$\tau = V_{SLUG} / \dot{V}$$

Non-dimensional variables:

$$\theta = t / \tau \quad N = V_{SLUG} / V_{COMPONENT}$$

Backmixed volume transfer function:

$$C(\theta) = N \int_0^{\theta} \left[C(\lambda) - C_0 \right] e^{N(\lambda - \theta)} d\lambda + C_0$$

VALIDATION

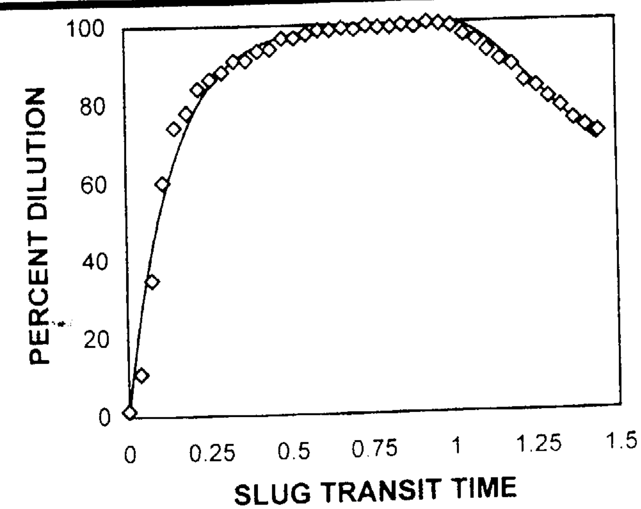

Fig. 5. Comparison of the calculated and measured concentrations at the entrance into the reactor vessel as a function of the transit time [2]

FUEL ENTHALPY DURING A RAPID BORON DILUTION EVENT IN A PWR

Presented to

The NRC Advisory Committee on Reactor Safeguards
Subcommittee on Thermal-Hydraulic Phenomena

Work performed by

D.J. Diamond, B.P. Bromley, and A.L. Aronson
Brookhaven National Laboratory
Energy Sciences and Technology Department

June 26, 2002

Brookhaven Science Associates
U.S. Department of Energy

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INTRODUCTION

- Boron Dilution Accident (BDA) an NRC Generic Safety Issue (185)
- Previous "conservative" study of BDA by Framatome
  - Estimate of boron concentration as a function of time
  - Lumped thermal-hydraulic/point-kinetics model
  - Lacked significant spatial effects, including boron transport
- What can a 3-D coupled neutronic/thermal-hydraulic analysis tell us?
  - Radial and axial distribution of boron changes significantly
  - Checkerboard pattern of control rods inserted
  - Radial and axial power distribution also complicated
- What are the fuel enthalpy increases?
- Calculations done as part of reactor core analysis project at BNL

Slide 2

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BORON DILUTION EVENT

- Small Break Loss of Coolant Accident (SBLOCA)
  - Boiling in core
  - Natural circulation ends
  - Deborated steam condenses in steam generator
- Cooling system refills and natural circulation starts
- Slug of diluted water is pushed into core
- Even with all control rods in, reactor can go critical
- Positive Reactivity Insertion ⇒ Power Pulse ⇒ Energy Deposition

Slide 3

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PWR CORE MODEL FOR BDA ANALYSIS

- TMI-1 Core Model at Beginning-of-Cycle
  - Babcock & Wilcox design, 177 15x15 FAs, 2772 MW_{th}
- Starting point for calculations
  - Hot zero power (2772 W, 1.0E-6 of full power)
  - Fuel, Moderator at 551 K; 1700 ppm boron
  - Banks 5-7 inserted (checkerboard pattern)
  - Equilibrium Xe from hot full power
- Starting point for BDA
  - All banks inserted (control, and shutdown)
  - Fuel, Moderator at 500 K, 1165 ppm boron
  - Reactivity ~ 0.0

Slide 4

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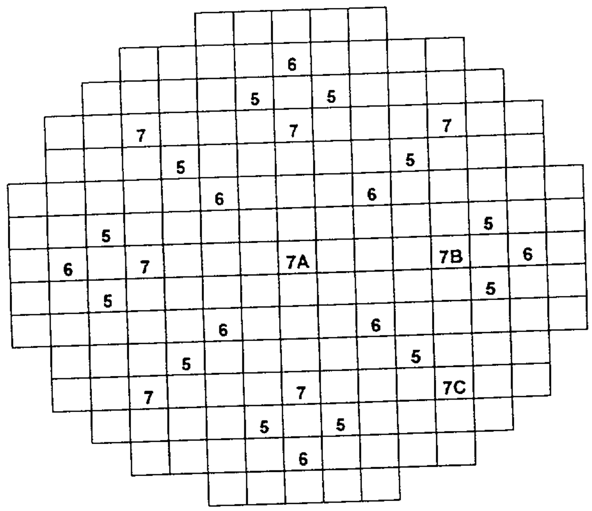
TMI-1 CORE LAYOUT WITH CONTROL BANKS



Slide 5

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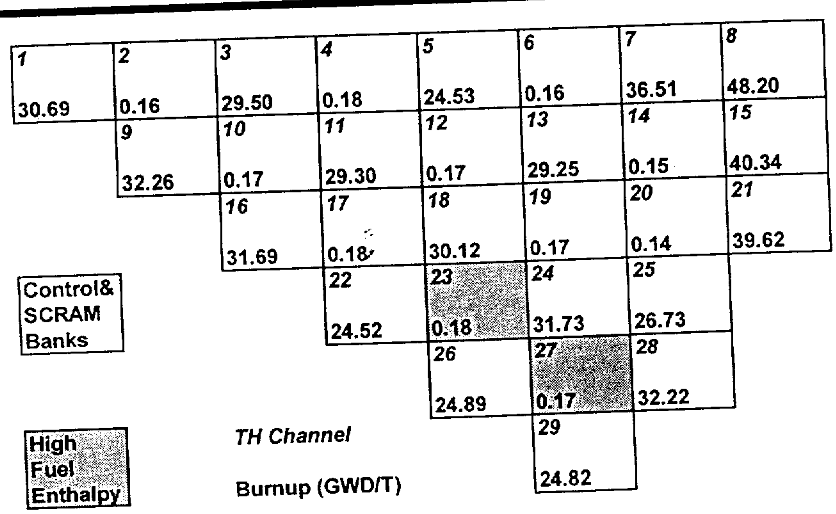
FUEL ASSEMBLY AVERAGE BURNUP AT BOC



Slide 6

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3-D NEUTRONICS ANALYSIS

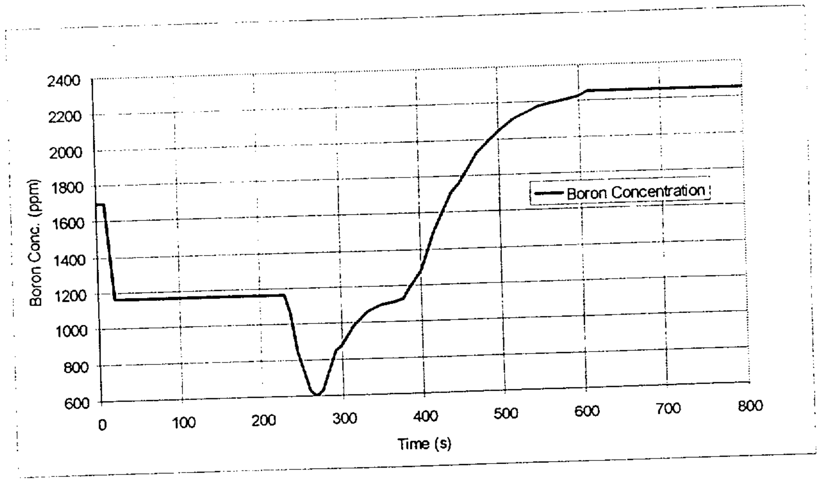
- PARCS (Purdue Advanced Reactor Core Simulator)
- Three-dimensional neutron kinetics via nodal method
- Two neutron energy group diffusion theory
- Feedback from fuel , moderator, boron ppm, control rod movement
- CASMO-3 ⇒ Homogenized FA cross section data for TMI-1 at BOC
- Cross Section Data not reliable below 500 K (limitation)

EVENT ANALYSIS

- RELAP5
  - Octant symmetry (177 + 64) ⇒ (29 + 1) parallel channels
  - Lower inlet and upper exit plena connect channels
  - Inlet flow and temperature fixed; exit pressure fixed

- Boron Dilution Transient
  - Adapted from previous analysis for 6.5 cm^2 SBLOCA
  - $3.44 maximum boron reactivity insertion over 40 s
  - 3% mass flow rate at lower inlet plenum
  - 200 s simulation to bring TMI-1 core to conditions before BDA at ~1 hr into SBLOCA

LOWER INLET PLENUM BORON DILUTION CURVE
(Adapted from Framatome Analysis of 6.5-cm² SBLOCA)



Slide 9

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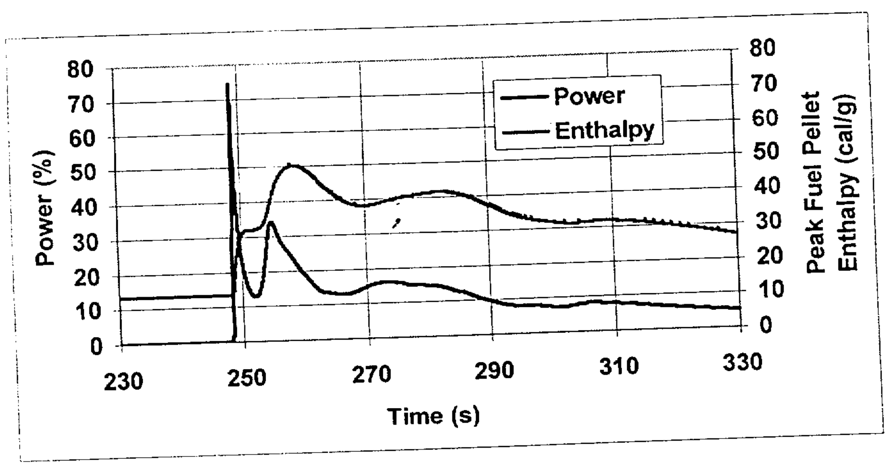
POWER AND PEAK FUEL PELLET ENTHALPY



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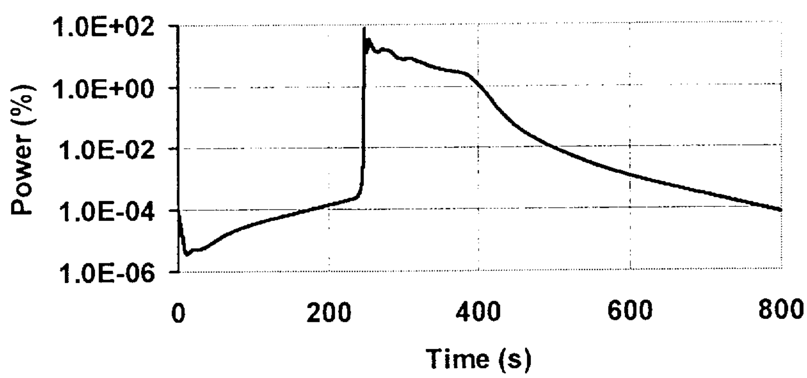
POWER VS TIME



Slide 11

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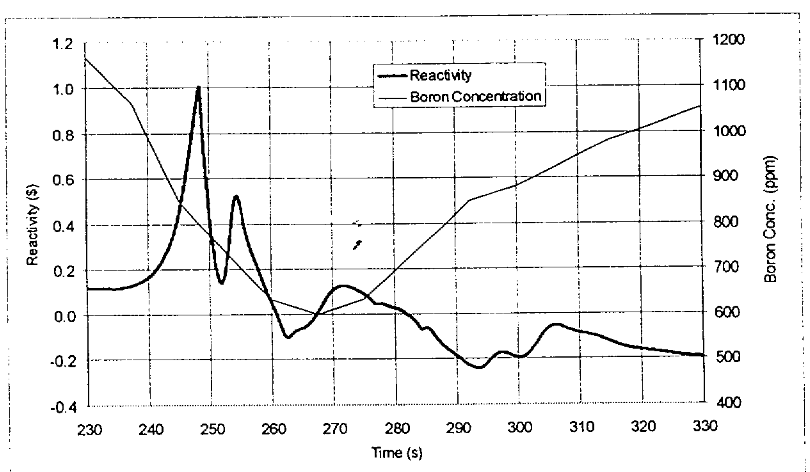
REACTIVITY AND BORON CONCENTRATION



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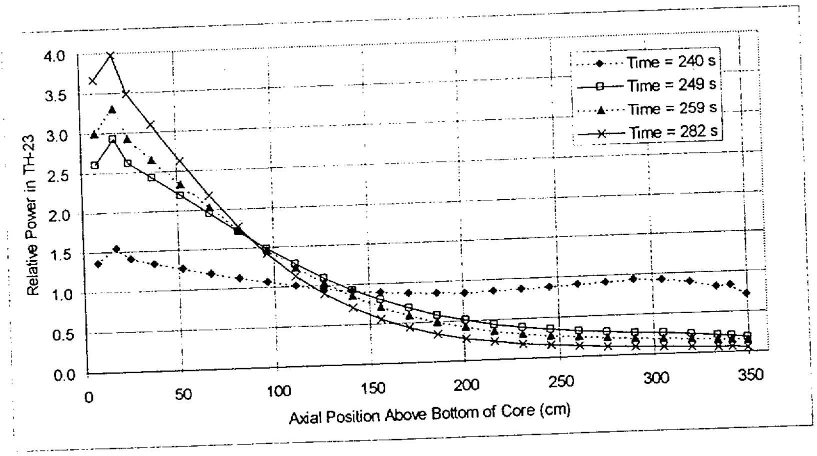
POWER PEAKING NEAR BOTTOM OF CORE



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RADIAL POWER DISTRIBUTION AT ~ 260 s

0.510	0.896	0.670	1.197	0.807	1.031	0.436	0.201
	0.616	1.122	0.881	1.415	0.773	0.822	0.246
		0.879	**1.607**	1.555	1.329	0.494	0.183
			1.210	**1.925**	0.986	0.645	
				1.460	**2.119**	0.663	
					1.191		

High Power FA's

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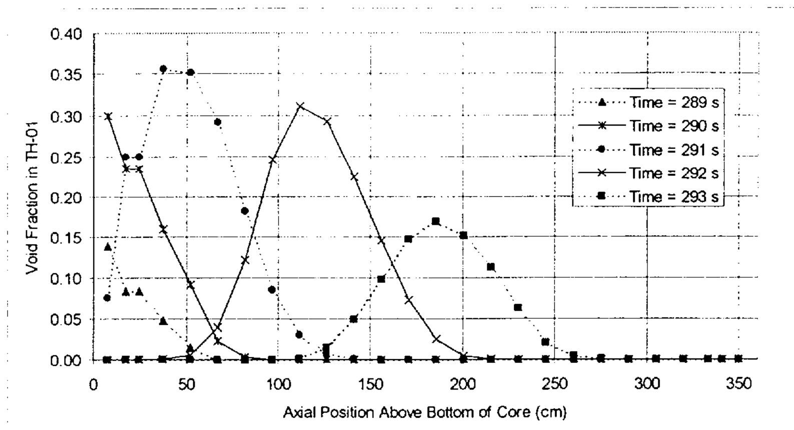
SPORADIC VOID FORMATION



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AVERAGE BORON CONCENTRATION AT ~ 260 s

1147	967	1049	894	1024	931	1150	1151
	1107	907	985	868	1037	1006	1151
		992	**859**	861	874	1148	1151
High Power FA's			893	**852**	933	1107	
				862	**851**	1086	
					885		

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COMPARISON: 3-D VS LUMPED POINT-KINETICS

- LUMPED POINT KINETICS
  - Peak reactivity ~ $1.2 (β~0.0065)
  - Peak power ~ 83%, 6 seconds after dilution starts
  - Peak enthalpy increase ~ 69 cal/g
  - Sporadic voids every 5 s, peak void 26%
  - Core returns sub-critical 45 s after prompt
- 3-D PARCS/RELAP5 - TMI-1
  - Peak reactivity ~ $1.002 (β=0.006323)
  - Peak power ~ 74%, 13 seconds after dilution starts
  - Peak enthalpy increase ~ 37 cal/g
  - Sporadic voids every 5 s, peak void 41%
  - Core returns sub-critical 24 s after prompt

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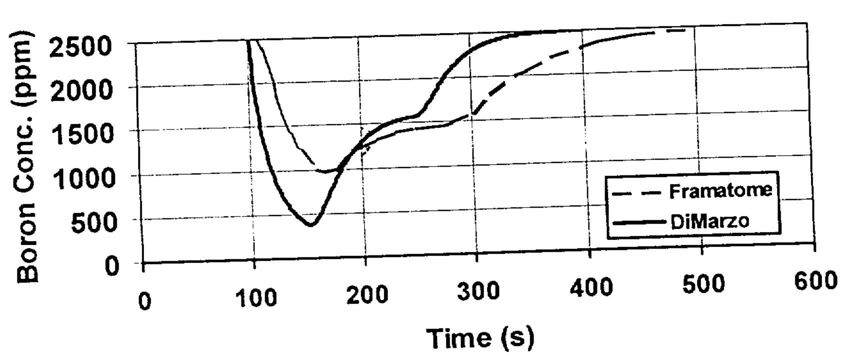
INLET PLENUM BORON CONCENTRATION



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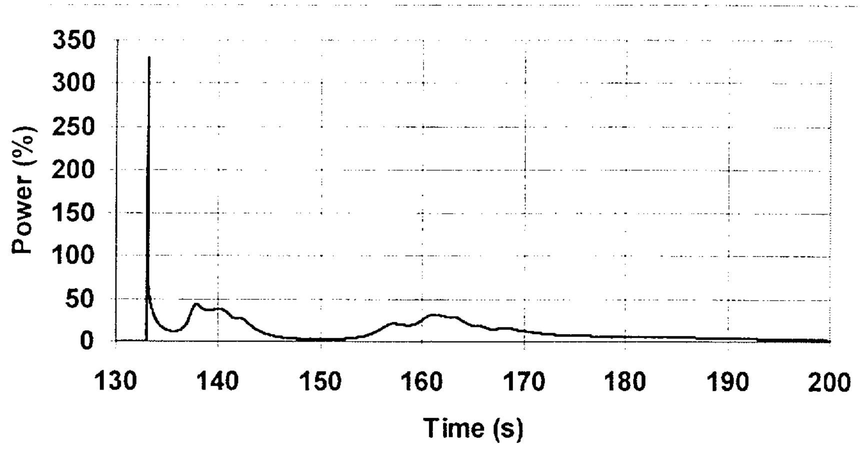
POWER VS TIME (DIMARZO CURVE)



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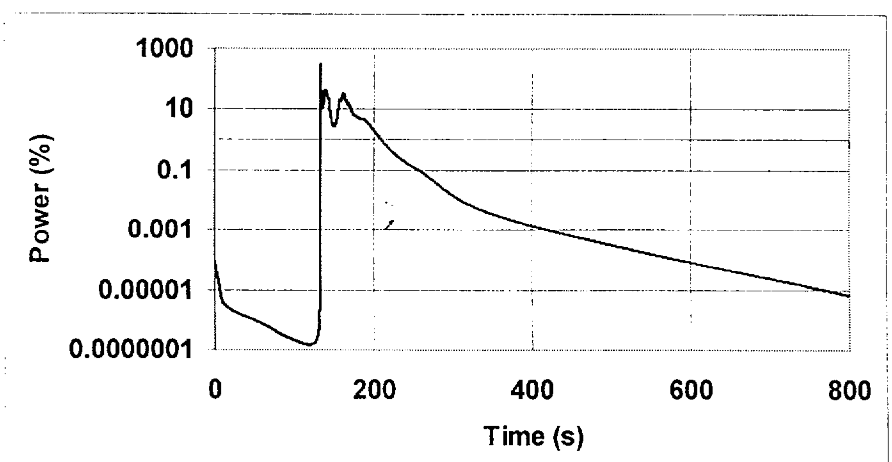
POWER (WITH DIMARZO CURVE)



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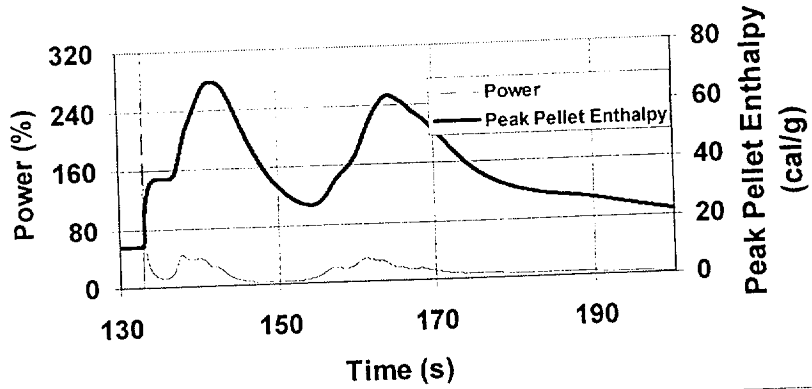
POWER AND ENTHALPY (WITH DIMARZO CURVE)



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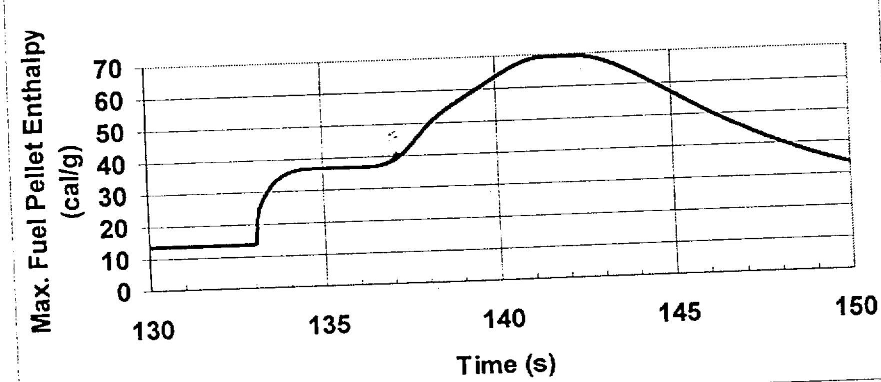
FUEL ENTHALPY DURING FIRST 20 S



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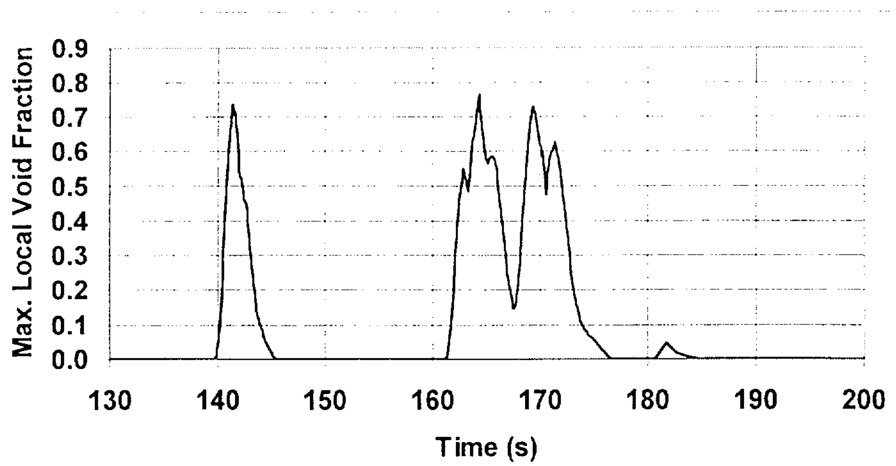
MAXIMUM LOCAL VOID FRACTION (DIMARZO CURVE)



CONCLUSIONS AND RECOMMENDATIONS

- 3-D analysis gives lower energy deposition relative to point kinetics
- Evolution of energy deposition slower than an REA
- Thermal-hydraulic feedback limits fuel enthalpy during BDA
  - Initial enthalpy increase < 25 cal/g for cases considered
- Void formation sporadic, but DNB may be possible in more severe cases
- Preliminary comparisons with BARS/RELAP5 good (not shown)
- Results could use refinement/extension
  - Mixing in core
  - Radial/azimuthal non-uniform boron concentration at inlet
  - Effect of turning on pump