MR. KELLY: Well, we're talking about not inside the drop, we're talking about between the vapor and the drop. And so, quite often, it is close to a conduction limit. If you look at the formulas, the traditional one is Lee and Ryley, but there are more modern versions.

MEMBER KRESS: Yes. I was ignoring the inside of the drop, I was still talking about vapor to the drop.

MR. KELLY: Yes. They all say the Nusselt number is something like two plus a square root -- a constant times the square root of the Reynolds number times the Prandtl number. And, quite often, the value is between two and ten.

MEMBER KRESS: Okay. So it's not just two.

MR. KELLY: It's seldom more than ten, but it's not just two. It depends on the flow condition.

DR. BANERJEE: It depends on the size of the drop. I mean if it's too big, then you get internal circulations.

MEMBER KRESS: Yes. I'm assuming for this size drop that's not a big factor, though.

MR. KELLY: The drops will become distorted, they won't stay spherical.

DR. BANERJEE: They'll oscillate a little bit.

MEMBER KRESS: Well, it could be higher then.

DR. BANERJEE: You can get an analytical solution to this problem as a bounding calculation by just taking a heat sink in your equations and integrating them, and that will at least show you an upper bound.

MR. KELLY: There is an analytical solution out in the literature. There was one done by Jens Andersen, and there was an older one before that but I can't remember the author's name. But Yao at, I think, the University of Pittsburgh has done a lot of work on this.

DR. BANERJEE: Yes, maybe.

MR. KELLY: And I did a numerical solution for laminar flow on this, and that's where I came up with the heat sink factor and the superheat factor. And those results, actually for certain conditions, give you the kind of numbers that you see in the data.

MEMBER KRESS: Well, if this two-phase enhancement factor turns out to be a relatively strong function of the liquid vapor mass loading ratios, which you expect it to be, I worry about only having three values for those.

MR. KELLY: Well, I would like to have more, but if we can only operate the facility for half a year, and they're actually saying it's going to take them two years to do this series of tests --

MEMBER KRESS: Yes. You take what you can get, I guess.

MR. KELLY: Yes.

DR. BANERJEE: Also, if it turns out to be really important, you can probably go back and do that.

MEMBER KRESS: Probably go back and do that, yes.

DR. BANERJEE: If it is.

MR. KELLY: So Steve and I are both very interested in this program and trying to follow it along and also to encourage it and direct it to what we think is important.

MEMBER KRESS: You're going to choose these three liquid vapor mass loading ratios to span what you expect in the real case, I guess, so that you can extrapolate in between them.

MR. KELLY: At least up to the point for the dispersed flow regime.

MEMBER KRESS: Yes, okay.

MR. KELLY: Now, one of the regimes we're going to talk about later, if we get there, is what I call inverted slug, and that's why I'm thinking of more as like a fluidized bed where the volume fractions are on the order of 50 to 90 percent, and you have these liquid drops and fragments going every which way, and the heat transfer can be pretty significantly enhanced. And the loading ratios there get up to about 1,000. And if we were to spray that kind of liquid mass flux in these little droplet injectors, there's no way we wouldn't quench the bundle. We wouldn't be able to do the steady state dispersed flow test. So we'll push it as far as we can, but we'll at least make sure we end up with a good model for disperse flow. And this is how we would use that data that we would get from the facility to generate the model we need. Okay.

Now we're going to back up, because I skipped some slides, and go back to the background and talk about drop diameter, because it's primary role is its effect on vapor superheat, and that's really crucial because that's going to be your sink temperature. But it also affects the grid space-to-drop breakup. This two-phase conductive enhancement factor is going to be a function of a drop diameter.

And also water drop radiation heat transfer is a function of the drop volume fraction and diameter. So it affects all of these.

We don't even know what mechanisms forms these drops. If you look in the literature, there's a lot of speculations. You know, is it aerodynamic breakup of these liquid slugs? Well, maybe and probably at least some of the -- maybe the majority of the drops come from that. You'll see papers where they waive entrainment from that inverted annular core. Now, if you're going to develop waves on it, you can strip drops off of it. Or if you go to a low flooding rate, what you have is actually an annular film down below the quench front. You can develop waves in that film and entrain drops actually before you get to the quench front. But this wouldn't too often happen just because of the heat flux levels below the quench front.

MEMBER KRESS: Aren't you producing vapor at the quench front? And when the vapor breaks to a liquid interface, doesn't it carry liquid with it?

DR. BANERJEE: That's a splattering.

MEMBER KRESS: Is that what you mean by splattering?

MR. KELLY: Yes.

MEMBER KRESS: Oh, okay.

MR. KELLY: It depends on your liquid flow rate and your liquid subcooling. If you're at high flow rates and high subcooling, yes, you generate vapor at the quench front, but you immediately condense a lot of it. So you get your onset of film boiling there, but the eventual -- and that's how you have the liquid inverted annular core downstream of the quench front is because you've condensed the majority of that vapor.

You can also generate droplets by wall-to-drop interactions. As we talked about, if you slam a drop up against this hot wall, it's going to flatten out, you're going to be generating under the drop, instability is -- as you start to push the drop away, you'll have instabilities on that vapor surface, and the drops will tend to break up with some critical wavelength that will be the size of the drop. And I don't remember what the formula is, but that's there.

You also have drops colliding with other drops, with the grids, of course, and sputtering is what happens if, say, for example, you have an actual annular flow, we're talking about low flooding rate cases, so below the quench front it's two-phase and you actually have an annular flow regime near the quench front that then this film trips over the quench front itself where you go from basically a cool wall to red hot and blows the liquid film off, and the name for that is sputtering.

But if you look at the current database, there is some data for drop diameters in reflood from both experiments in tubes and rod bundles. But, typically, the local conditions are not reported. All you get are the droplet diameters. And so what happens, and I guess now I can't use "ad hoc" anymore, I'm going to have to go check that definition. What you'll see in a lot of codes is they'll take a critical value for the Weber number based upon the local conditions, not where the drop was actually created, and they'll tune that critical Weber number so they'll match the PCT for a particular experiment. And you'll end up seeing things like Weber numbers of one or two years.

MEMBER KRESS: That seems backwards to me.

MR. KELLY: But part of it's a limitation that if you don't have some kind of interfacial transport mechanism for the droplets, you have to do it based upon local conditions, because the reality isn't steady state. Normally, you know, you can analytically you can say, "Well, I know where it was," but that doesn't happen in the codes. And this is not an idea, this is what gets done, and that's what we want to improve on.

This gives you an example of what's out there now. You know, I searched, I looked for droplet data, and there's not a whole lot. I've got two set -- ah, my legend went away here. That happens sometimes when you cut and paste things in.

MEMBER KRESS: We have it on ours.

MR. KELLY: So the black triangles are from FLECHT SEASET, and these were done optically, high-speed movie, looking through a window, then you project it on graph paper and your graduate student draws circles around the drops and gets out. So in this case, each one of these triangles represents an individual reflood test. You notice most of them are at 40 psi, one is at 20.

Typically, the number of drops measured range between about 50 and 300. So these populations that -- each of these represents a population, and what this is is the Sauter mean diameter in millimeters, but they're fairly small populations, so you wouldn't really trust the shape of it and even the value. It give you a pretty good idea. But, again, we don't know what the flow conditions were. We know the pressure, but we don't know what the vapor velocity and we don't really know where the drops came from.

MEMBER KRESS: But those size droplets are, for example, too large to get Kelvin Helmholtz stripping off -- you don't get droplets that big, do you?

MR. KELLY: No, and you don't get droplets this big with a Weber number of 12.

MEMBER KRESS: With a Weber number of 12, you get a really small --

MR. KELLY: Well, no, actually, let me back up. You don't get -- these drops are too small for the Kelvin Helmholtz thing if you use the droplet terminal velocity. That's why you need to go to a Weber number of like one or two to get these.

DR. MOODY: Larry Hochreiter showed droplet data. Did he make predictions of those droplet diameters that he measured?

MR. KELLY: No.

DR. MOODY: He just measured them and there they are for --

MR. KELLY: Yes. And I'm going to talk about that in just a minute, about how we're going to use that data. I'll finish with this. These orange diamonds are from the ACHILLES test which were done in Great Britain, and in this case they did two reflood tests. This is the only -- they have more data, but this is the only that I had access to. So there are two different tests, and what you're looking at is each diamond is a value measured for one sub-channel. And I don't remember how these were measured.

And then we have some tube test data, some tests done at the University of Berkeley, I think it was an Inconel tube, I don't remember. And in tests done in Britain by -- I think it was Britain -- by Ardron and Hall, and these are quenching of a quartz tube with a little wire wrapped around it. And so here -- in both cases, they were using optical techniques. Each one of these represents a point in a reflood test, and these are sometimes as many as 1,000 drops in each one of these. Again, this is Sauter mean diameter. And so these were taken at a couple axial elevations in the tube, so at different distances from the quench front. Whereas these were all at the exit of the tube. So we have a very large difference between the two, and one of the questions is why, how can you measure droplets that are --

DR. BANERJEE: It's hard to get a nine millimeter drop.

MEMBER KRESS: Yes.

MR. KELLY: Well, we talked about Kelvin Helmholtz. Let's throw Rayleigh-Taylor into this. These are about as large as a drop can be and remain stable.

DR. BANERJEE: They must be these big chunks. I think Keith Ardron must have been calling those drops, he was English. Anything which has sort of a circular shape is okay.

MR. KELLY: Well, but --

DR. BANERJEE: They're big chunks of liquid, I think.

MR. KELLY: But, you know, that's what they were measuring.

DR. BANERJEE: Yes.

MR. KELLY: That's what was there. And this is actually Sauter mean, so they saw things even bigger, but you can't get much bigger than this. You just can't. You know, a Rayleigh-Taylor limit is about four times over -- which is about ten millimeters at these conditions, so you're not going to get much bigger than that.

So at any rate, if you were to ask me what's a droplet correlation --

DR. BANERJEE: One to two millimeters.

MEMBER KRESS: Yes. That's what I was thinking.

MR. KELLY: Well, except what we're measuring in RBHT, at least the couple of tests I looked at, are about half a millimeter. And that's one of the things we're going to have to look at is what's the difference here.

DR. BANERJEE: But maybe there's a spacer effect.

MR. KELLY: These have spacers too. Egg crate, not mixing vane, but definitely there's a spacer effect. But part of it may be the flow conditions being different, you know, vapor velocities being higher in these tests. Part of it may be the measurement technique. Here we're actually using an automated software to measure the drops. And the laser camera, the digital camera here has a very high resolution, better than what was available back in the 1970s. So if you look in the test report for these, they say that they -- I don't remember the number, but there's a certain diameter drop that they can't see. Anything below that, they can't see. Whereas here we can see some of those very small drops, and, of course, if what you're doing is Sauter mean, you know, ratio of the volume to the area for the population, if you're not counting small drops, it's very easy for you to overestimate the droplet size.

DR. MOODY: I guess in every case the droplets are formed from a bigger body of liquid, whether they're ripped off, stripped off, coaxed off.

MR. KELLY: Somehow. And probably several different mechanisms build a population, and we simply don't know.

DR. MOODY: Isn't that amazing, here we are 100 years later and we still don't know.

MR. KELLY: You know, there's thousands of papers out there on inverted annular or dispersed flow film boiling, and when you have to sit down and put their model for a code, you're scratching your head sometimes, and it's surprising. There's a lot of inconsistency between the papers that are there.

Okay. I talked about this. Okay. This was how are we going to get the interfacial heat transfer between the vapor and the drop. And the point is you can't really. I mean we're not measuring the rate at which droplets are evaporating, but we can get an indication of it by looking at the axial profile of the vapor temperature. So we can use the models that we get -- excuse me, we can use the data that we're going to get, the superheated vapor temperatures, the drop diameter and the vapor-entrained liquid flow rates.

MEMBER KRESS: Does the change in Sauter mean diameter give you any information on that?

MR. KELLY: It's --

DR. BANERJEE: Too small.

MEMBER KRESS: Too small?

MR. KELLY: The uncertainty in what you're measuring is much larger.

DR. BANERJEE: But the superheated vapor temperature is a function of the heat transfer from the wall and a whole lot of stuff going into that.

MR. KELLY: Right. But it can give you -- you can at least use it to help you select which models, and then once you have a set of models in and are doing a comparison, you can then validate their integral effect.

MEMBER KRESS: I would be tempted there to use existing correlations for single drops and swarms. I think some of those exist, don't they?

MR. KELLY: Yes.

MEMBER KRESS: I think I'd be tempted to say, "All right, we'll just put those in for that."

MR. KELLY: Yes. Whenever you think you know something, use it. That's what I'm doing. And so, for example, for the vapor-to-drop interfacial heat transfer, there are experiments where they either put a little sphere and coat it with a liquid film and put it in a wind tunnel and --

MEMBER KRESS: Yes. They've done a lot of that.

MR. KELLY: -- come up with those correlations, so that's what I'll use. The only catch is the multi-particle effect.

MEMBER KRESS: Now, it may be that your loading is so small that these act like single particles, but I don't know that.

MR. KELLY: Well, not quite. We're not at the dense solution where you have to worry about clusters like in fuel ignitors. So we're not having to worry about penetrating clouds of drops. But on the other hand, we have enough drops around that the rate's going to be a little bit more than the single particle. And that's where you might look like and what I've been doing is looking at the correlations for fluidized beds for the vapor-to-particle heat transfer in a fluidized bed.

DR. BANERJEE: Are you talking of the heat transfer coefficient on the vapor side or on the liquid side?

MR. KELLY: Vapor side.

MEMBER KRESS: Yes. I think --

MR. KELLY: Between the vapor and the particle.

MEMBER KRESS: Yes. I think you would generally neglect the liquid side for this size particle.

MR. KELLY: The drops are in saturation and it's high enough because the drops are small.

DR. BANERJEE: But, usually, the liquid side heat transfer can vary, of course, by a factor of two or three.

MR. KELLY: Yes. Here it's so much larger than the vapor side that it's really a no "never mind," and if you just do a conduction on the drop and have a fairly constant number, you're close enough, because it doesn't limit the rate process.

DR. BANERJEE: Well, the flow around the drop is turbulent, correct, by then?

MR. KELLY: But it's fairly -- if you look at the Nusselt number, you get a Nusselt number of about ten or less on the vapor side.

DR. BANERJEE: You see, if you had a very high conduction heat transfer inside the liquid compared to the convective heat transfer outside, you won't get any vaporization.

MR. KELLY: But these drops are saturated.

DR. BANERJEE: They are saturated.

MR. KELLY: By this point, you know, the liquid is broken up and everything, and now you've got little small drops. They're basically saturated.

DR. BANERJEE: If that's the case, then all that heat transfer will just go to vaporization.

MR. KELLY: Right.

DR. BANERJEE: And you don't care what happens.

MR. KELLY: Yes. We don't care what happens on the liquid side. I should have said that at the outset.

Now we're going to talk about drop diameter again. Sorry for the aside in interfacial heat transfer. What I said in the existing database, as you see some drop diameters, is there's a large disparity but you don't have a local fluid conditions, so you can't go and make any judgments. Well, this one set of data by Ardron & Hall they do report at least the exit conditions. So at the end of their tube, they give you the steam velocity. And so if I assume that steam mass flux were constant all the way back to where they made their measurements, I don't have enough data to make any other assumption, but if I assume that, I can do this plot, which is a non-dimensional drop diameter, it's a drop diameter divided by the cost number, so that's the square root of the surface tension over G delta rho, versus a modified Weber number.

It's modified in two ways. It uses the vapor superficial velocity rather than the relative velocity, so I don't know the relative velocity, I only know the vapor superficial. And, actually, you see that in a lot of annular mist things for droplet diameter. The other way it's modified is instead of using the droplet diameter, it uses the LaPlauce number. So that's what meant by modified Weber number here.

And because you're plotting it that way, and I picked this up with some annular mist stuff, you can draw these dashed lines that are straight, and what you'll see in your handout is that it says Weber number equals 12, Weber number equals four. There are two sets of data here. What I'd like for you to look at first are the diamonds. Those are the drop diameters that they measured for locations that were more than I believe it was 0.7 meters away from the quench front -- or maybe it was one meter. It's in your handout. So what you're basically seeing for these Sauter mean diameters is something that you would get for the Weber number criterion based on vapor superficial velocity of about four. Well, you would tend to believe the number of 12, but 12 would give you the maximum size drop. In the Sauter mean, because there's a population, a distribution, it's typically three to four times smaller than the maximum, which brings you right into this value.

Now, if you look at the open orange triangles, those were taken at a distance of a tenth of a meter, only ten centimeters, away from the quench front in these tests. So these drops haven't had much time to accelerate, haven't even had much time to break up, but they tend to be bounded by that Weber number value of 12 and then move down towards this limit. So this is an indication of something you might be able to use as a correlating factor, and that's one of the things I'll be looking at --

MEMBER KRESS: Droplet size versus position along the tube, without consideration of evaporation?

MR. KELLY: Well, actually, I didn't mean that. What I meant as a correlating factor was the vapor superficial velocity or the vapor momentum flux.

Okay?

MEMBER KRESS: Would you use the four or the 12 or the --

MR. KELLY: Well, for the maximum, you would use a 12, for the Sauter mean, a value more like the four. And this is just first order model here.

DR. BANERJEE: Anyway, the vapor velocity is very close to superficial, right? There aren't that many problems.

MR. KELLY: Right. And also -- well, yes. But I'm ignoring the relative velocity here.

MEMBER KRESS: The relative velocity is pretty low.

MR. KELLY: Yes. There's a difference between the vapor superficial and the relative, and what I'll be saying in this model, if I were to use this, is that where the drops are actually created the drops are initially standing still. They haven't accelerated to the terminal velocity up here. So their velocity is basically zero so that that vapor superficial is indicative of the relative, the relative at the top of this, say, fluidized bed before it becomes fully dispersed.

MEMBER KRESS: Even if it wasn't that way, you almost have an empirical factor.

MR. KELLY: Oh, it's going to be empirical.

MEMBER KRESS: Yes. So it wouldn't matter if that was the right interpretation or not would be a good way to look at it.

DR. BANERJEE: It's more or less in line with what you expect.

MEMBER KRESS: Yes.

MR. KELLY: Yes. And the point of showing the 12 and this is to show where some of those very large drops came from. These are drops close to the quench front that haven't had the chance to really accelerate and break up.

MEMBER KRESS: And they're not going to do much, I don't think, are they?

MR. KELLY: They're going to stay down.

MEMBER KRESS: Yes. So we don't know really a whole lot about them.

MR. KELLY: Yes. Eventually, they'll break up and then become important.

MEMBER KRESS: Yes.

DR. BANERJEE: It's a mess down there.

MR. KELLY: Yes. And one that I'm not going to model the details of for a long, long time.

MEMBER KRESS: But it looks like a Weber

number might be a good shot at getting --

MR. KELLY: That's what I'm going to try. And I got this from the annular mist literature, and I'm just adapting it for a different situation. And then I'm going to try to actually get other data to check this, and I'll explain that when I come back and give you the models, okay?

This is what Professor Hochreiter showed you from the RBHT --

MEMBER KRESS: I think we're going to lose one of our members here very shortly.

DR. MOODY: Your audience is shrinking, it's nothing personal.

MR. KELLY: I'll tell you what: Before I lose all my audience, let me go to my last slide. It's not in your handout.

MR. BOEHNERT: Powerpoint poisoning.

(Dilbert Cartoon.)

(Laughter.)

MR. KELLY: Since I'm noted for standing up here for hours on end and boring my audience with hundreds of viewgraphs, I just couldn't resist. This is what I was trying to desperately get to just before Professor Wallis left, because I thought he would enjoy this.

MR. ROSENTHAL: Let me be serious for just a second, and that is we read the consultant's report, and to some extent I think we have to agree that the experimental program and the analytic program wasn't tucked together as tightly as everybody would have liked, just what was funded when and who was on staff when and what not. I mean even we recognize that we could have done better, but I think that we're playing catch up but we're getting better. So I'm sure that you have to -- or would be writing additional consultant's reports, and if in those reports you included your views, having read this presentation, I'd appreciate it.

MEMBER KRESS: I think that may be all you get out of this meeting is a consultant's report, unless Graham wants to write a summary.

MR. ROSENTHAL: I'm not asking for anything more, but what I'm saying is that the prior reports were based on the Hochreiter were fair but negative. So if you have whatever -- if you change your views or have additional views, we'd appreciate seeing what they are.

MEMBER KRESS: Well, the other issue -- I share your concern about losing support for the rod bundle heat transfer test, and I don't know how to convey that concern at the moment, because I don't think we intended to have a letter.

MR. BOEHNERT: Well, you're writing a research report. Maybe you want to think about that, getting some --

MEMBER KRESS: But the research is what were supposed to focus on advance reactors, but I think this is probably --

MR. BOEHNERT: I haven't seen it, so I don't know.

MEMBER KRESS: -- appropriate.

MR. ROSENTHAL: Or even in your lesser reports. If you think that --

MR. BOEHNERT: Well, but the research report would be good because that's going to elevate this right to the top.

MEMBER KRESS: Okay. That's a good point.

MR. BOEHNERT: Yes.

MR. KELLY: And from my perspective, even in a consultant report, you know, you may even see a sentence that says, "This is a pretty interesting test series. We think we're going to get some valuable data." But then there might be 20 different ways in which it could be better, and they may be very true, and maybe we can make the program better, but when couple levels of Management above sees this, they see 20 and one, and they come away with, "Well, this -- my staff doesn't know what we're doing, our experimenters don't know what we're doing, let's just kill the program." So if there's a cover letter that goes with the consultant reports, I mean if you really feel this is a worthwhile program, just make it very clear in the front, and then tell us how to do it better. We don't mind that, because --

MR. BOEHNERT: Let me give some input here, because you have to keep in mind what are the intents of the reports the consultants provide the Subcommittee. It's basically for internal use, and in fact we kind of grapple with, gee, should we give you guys these reports? And I tend to say you ought to see this stuff because I think it's useful, but I always have to get the permission of the Chairman to do that. And he generally says, "Sure, go ahead." So that's why it's -- it's a different audience and that's why they tend to be maybe not as positive as you'd like, but it's basically for internal use.

MR. ROSENTHAL: I think that given the presentations that were made, I think that the reports that came in were fair. And we're all saying we need to do better. Having heard this presentation, if you have additional comments x

DR. BANERJEE: Well, you have to know that that when we listen to the RBHT Program, this program which is going on in parallel wasn't presented.

MR. ROSENTHAL: Right.

DR. BANERJEE: And maybe the right thing would have been to make it one more day at that point and put those two together.

MR. ROSENTHAL: Fair enough.

DR. BANERJEE: That would have made a difference.

MR. ROSENTHAL: A little bit of a history, by the way, if we go back like six months to a year, we would come in and have these like summary presentations, you know, a one-day or two-day marathon. And Professor Wallis said it would be more useful if we came in instead of with these big overview presentations where you got into no detail on anything is if you can have more detailed ones on specific topics. So Steve brought Vijay Dhir, Hochreiter, et cetera, and I guess we're losing something in maybe we're being too fragmentary. So I'm just saying some combination.

DR. BANERJEE: Yes. In fact, if there was even an hour presentation by Joe or Steve or something to put this in some context, yes, that would have been different.

MR. ROSENTHAL: Fair enough. Fair enough.

DR. BANERJEE: The only thing that still bothers me, to some extent, and I think it's a crucial issue, is this maybe we need to see something of what Steve and Joe have done in terms of sensitivity of these temperatures to the sort of modeling assumptions you were saying that you had made. Because we are sort of getting conflicting information on this, and I can see how it's coming about, because there are people who want to get S-RELAP or whatever the next code applicable for their fuel reload analysis or whatever they're doing, and so they're going to present a case that nothing needs improvement in these codes, we can do everything with it, right? I mean even if you --

MR. ROSENTHAL: I think you're still bleeding from yesterday.

DR. BANERJEE: Yes. If you take that at face value, then there's no program needed of any sort whatsoever. We know that's not true. But there is something there which is sort of in the middle ground I think that they've been maintaining that a lot of the dispersed flow, heat transfer flow, the nuances and so on, don't matter. What we've got is good enough to give us PCT, which I disagree with personally, because I think the work should be done. But we need to have some evidence presented to us that we can make the case stronger, because I believe this is a good program too.

MR. ROSENTHAL: We've had a lot of discussion, by the way, and you've heard a little bit from Joe, a little bit from Steve about developing metric again. The one thing that I think we're all convinced of is that PCT should not be the only metric.

MR. ROSENTHAL: Right.

MR. BAJOREK: When we did the best estimate methodology for the Westinghouse model, that was our original attack was to, hey, if we can get the PCT correct, everything might be all right. And that was thrown out and rightfully so, because when we did take a look at what the code was doing, we did start to find compensating errors. You're getting the right reason but for the wrong -- you're getting the right answer but for the wrong reasons. Where that comes back to haunt you is in a full-scale PWR analysis where if you might be correct for a test, which runs either at steady state or over a short time scale, now you think you have an answer that's got a good bias, small uncertainty. But it becomes very important if you take that uncertainty and propagate it over time. So if you think your answer is good and you do it only on PCT, you may be missing the fact that your heat transfer coefficient may be off by ten, 20 percent. And when you propagate that in a code that goes for several hundred seconds, then you could be mispredicting your PCT by hundreds of degrees.

MR. ROSENTHAL: And along that line, we're trying to -- you know, this idea, you heard the expression, large-break LOCA center, and that is that if on probability you dismiss the double-ended guillotine break, I don't think that you'll ever dismiss breaks that depressurize the plant, you know like surge line. Then people will immediately take the margin that they've gained by that, you'll be up against new limits, and then you have to ask is your code capable of these other issues? So for all these --

DR. BANERJEE: Well, one of the points I made in my last report was that NRC, now I don't know which appropriate branch of NRC it should be, should develop more than just the PCT criteria for evaluating a code. Maybe it should have -- this is up to NRC to decide what is the most important factors, but say time to PCT could be important too or there could be a number of other things which I can think of, and I'm sure you can, which are sort of would give more credibility to these calculations, which have been presented by all the vendors and people like that in licensing their codes. And there should be a short list of four or five things that they have to get right, more or less, before we sign off on these things. Because PCT is -- you know, they adjust stuff and they finally get the PCT and they say, "Well, we've assessed 59 experiments now" or whatever the number is, "and we're fine."

MR. BAJOREK: If you'd like, I'll give you part of a presentation we made December last year, and we covered exactly some of those concerns where we said quantification of code performance it's conservative, you compare the PCT, and we basically said that's unacceptable. For reflood heat transfer, we would look at more of a list of parameters which would go from steam cooling heat transfer coefficient, dispersed flow heat transfer coefficient, inverted annular heat transfer coefficient. Minimum film boiling temperature has a very big effect in your blowdown cooling, a carryover fraction. We haven't said anything on that yet, but if you remember watching that movie from RBHT, we were still well above the minimum film boiling point, but we saw lots of water in this, very high carryover fractions. We need to get that correct and level swell to make sure that you aren't frothing up your quench front to a higher elevation than it should be.

So I can give you this, and that's when it comes to assessment and in our model development we're not going to use PCT except as a --

DR. BANERJEE: But somehow it has to get through to NRR, and they have to say, "Okay, these are five or six variables that we look at."

MEMBER KRESS: You've got to change the rule.

MR. BOEHNERT: You have to change the rule.

MEMBER KRESS: That might be a problem. I guess given the hour and the time, I want to thank you guys for a very interesting, productive meeting, and I think at this point I'll declare the meeting adjourned.

(Whereupon, at 1:20 p.m., the ACRS meeting was concluded.)

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, MD

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.

Rebecca Davis

Rebecca Davis
Official Reporter
Neal R. Gross & Co., Inc.

United States Nuclear Regulatory Commission

TRAC-M
Code Consolidation and Development

Presented to ACRS Thermal-Hydraulic Subcommittee

J.M. Kelly

Office of Nuclear Regulatory Research

December 12, 2002

1

TRAC-M: Code Consolidation and Development

- CONTENTS
  - TRAC-M Release Schedule
  - Development Objectives & Status
  - Legacy Input Models
  - Current & Short Term Activities
  - Long Term Development Plan

2

TRAC-M: Code Consolidation Status

- Code Release Schedule
  - Release α version to internal users: 12/31/02
    - Run input decks from RELAP5, TRAC-B & TRAC-P
    - Documentation
      - User Guide: first draft, may be missing RELAP5 translation guide.
      - Theory Manual: first draft, will not include BWR models and sections on new physical models (e.g., reflood).
      - Developmental Assessment: not available.
  - Release β version: Spring CAMP meeting 2003
    - Documentation
      - User Guide: final form.
      - Theory Manual: complete draft version
      - Developmental Assessment: partial first draft.
  - Official release: 12/31/03
    - Meets success metrics & documentation in draft form.

→ Potential that documentation and some assessment may be delayed due to AP-1000 & ESBWR efforts.

3

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

4

TRAC-M: Code Consolidation Status

- TRAC-M Development Objectives
  - Architecture — **Status**
    - Ease of Development — complete
    - Extensibility (ECI) — complete
      - REMIX & CONTAIN (preliminary)
    - Reduce maintenance — continuing effort
      - Modularity & readability
  - Consolidation
    - Coupled Kinetics & T/H (Ramona) — complete
    - BWR Transient & LOCA (TRAC-B) — complete
    - PWR SBLOCA (RELAP-5) — late 2002
    - PWR LBLOCA (TRAC-P) — late 2002

5

TRAC-M: Code Consolidation Status

- TRAC-M Development Objectives
  - Ease of Use — **Status**
    - Graphical User Interface
      - Construct new input models with drag/drop — complete
      - Display, edit and run existing RELAP5 , TRAC-B and TRAC-P input models — late 2002
      - Post-processing plotting & playback — late 2002
      - Interactive display with user feedback — future
    - Automatic mapping to 3-D kinetics — complete
    - Platform independent graphics and restart file — complete
    - Documentation — continuing effort

6

TRAC-M: Code Consolidation Status

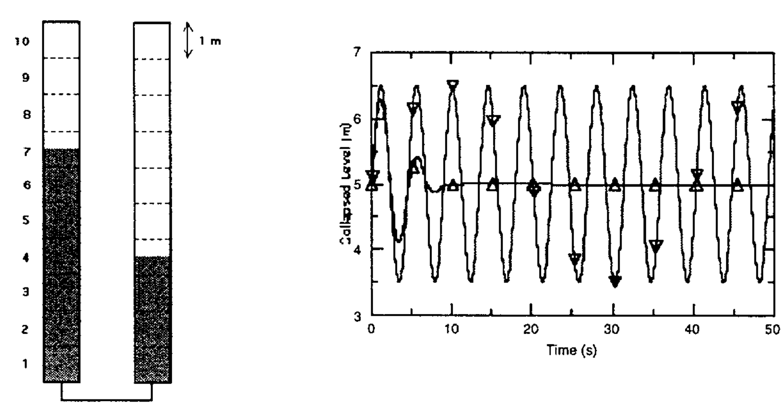
- TRAC-M Development Objectives

	Status
• Accuracy	
◆ Physical Models	beginning
◆ Advanced 2Φ Model	2003-2005
◆ Quantification of Accuracy	
• Numerics	
◆ Robustness	continuing effort
◆ Computational Efficiency	2004-2005
◆ Parallel Processing (coarse grain)	completed
◆ Accuracy:	
» Higher order differencing (e.g., thermal fronts).	2003-2004
» Level tracking (1-D & 3-D).	completed
» Semi-implicit scheme (stability).	completed

7

TRAC-M: Code Consolidation Status

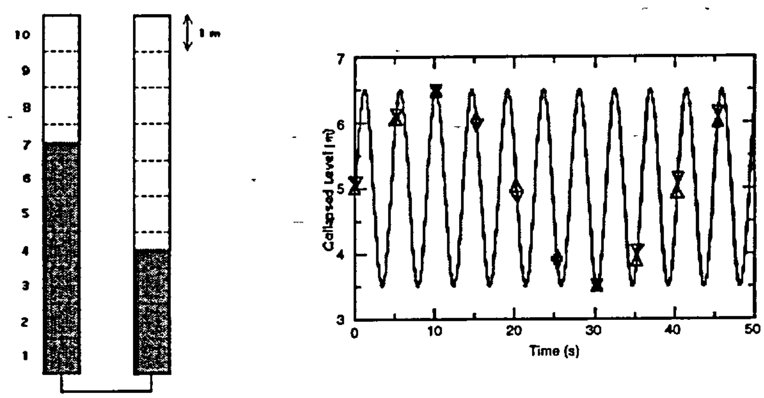
- Oscillating Manometer Test Problem
  - TRAC-M without Level Tracking:



8

TRAC-M: Code Consolidation Status

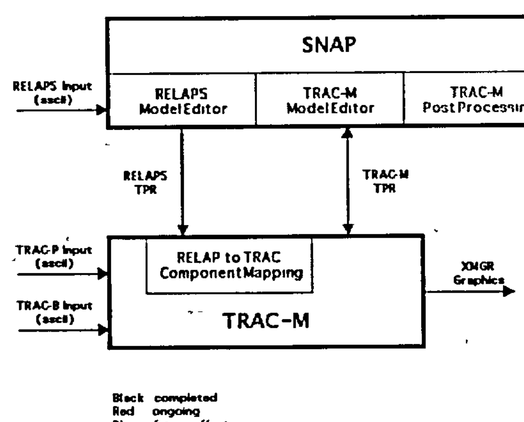
- Oscillating Manometer Test Problem
  - TRAC-M with Level Tracking:



9

TRAC-M: Code Consolidation and Development

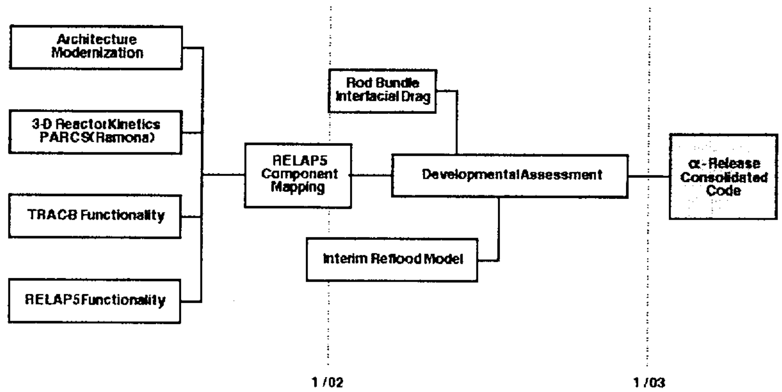
- Legacy Input Models



10

TRAC-M: Code Consolidation Plan & Status

- Calendar Year 2002 Activities:



11

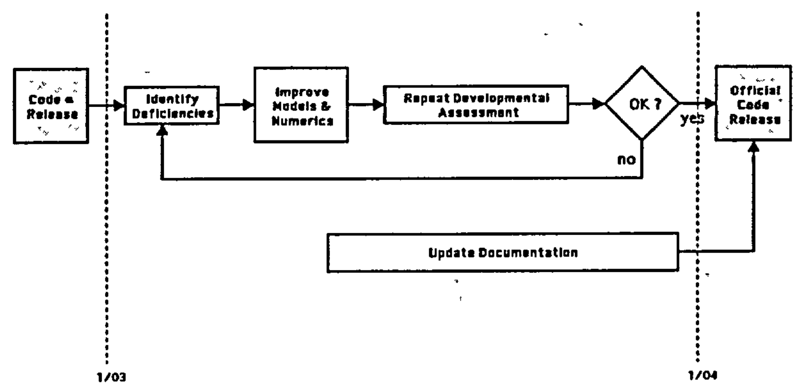
TRAC-M Current Model Development

- 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.
- 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.
      - Fine Mesh: phase I (correct implementation)
      - Physical Models
      - Fine Mesh: phase II (improve adaptive grid criteria)

12

TRAC-M: Code Consolidation Plan & Status

- Calendar Year 2003 Activities:



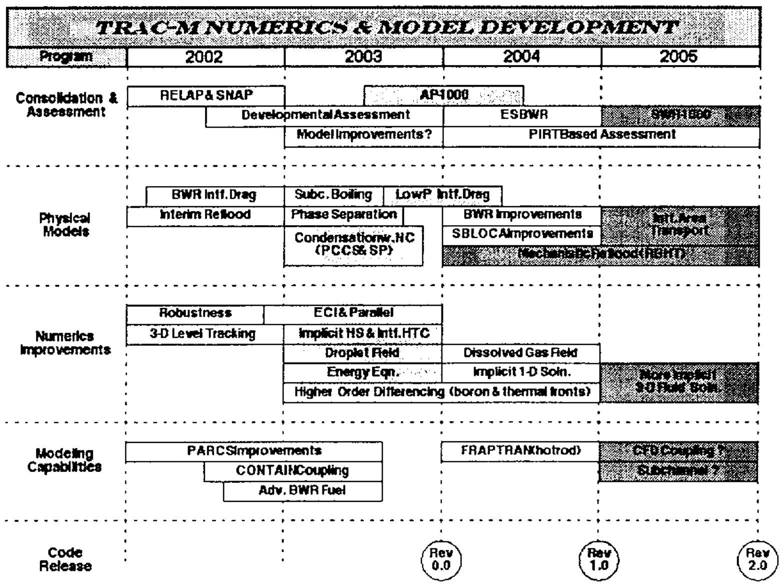
13

TRAC-M: Code Consolidation Assessment Plan

- Developmental Assessment Matrix (example):

Test	Code: RS	Code: T-B	Code: T P	Code: T M	Priority	Comments
Reflood Heat Transfer						
FLECHT SEASET - Test 31504 (1"/s) - Test 31701 (6"/s) - Test 3400 (0.6"/s)		X	X	X	H	Basic reflood modeling capability Test 33436 dropped due to gravity reflood
SCTF Core III - Run 719		.	X	X	H	Large scale gravity reflood with steep power
GOTA Reflood. - Test 42		X		X	H	Combined top and bottom flooding
Post-CHF Heat Transfer						
THTF Transient - Test 3.03 6AR - Test 3.06 6B - Test 3.08 6C		X		X	H	Transient upflow film boiling at high pressure mass flux & heat flux conditions
THTF Steady Test 3.07 9B - Test 3.07 9H Test 3.07 9N Test 3.07 9W	X	X		X	H	Steady upflow film boiling at high pressure, and moderate mass flux & heat flux conditions
GOTA Radiation Test 27		X		X	H	

14



15

TRAC-M Long-Term Development

- Anticipated BWR model improvement needs:
  - Core spray model.
  - Boiling transition:
    - Better default model.
    - Provide “user defined routine” to easily incorporate proprietary model for auditing calculation ?
  - Modern fuel designs:
    - Radiation view factors (part length rods, water channels)
      - This effort is underway.
  - Reflood model.
  - Top-down rewet:
    - Channel box
    - Fuel rods

16

TRAC-M Long-Term Development

- Anticipated PWR SBLOCA model improvement needs:
  - Loop seal clearing.
  - Hot leg stratified 2Φ flow and CCFL.
  - Critical flow (SGTR).
  - Reflux condensation with non-condensable gas.
  - Recirculation in parallel loops (2x4 plants).
  - Core level swell
    - High pressure: operating plants
    - Low pressure AP-1000
  - Thermal stratification:
    - Vertical components (e g pressurizer & CMT)
    - Horizontal loops
  - Phase separation in tees:
    - Hot leg to ADS carryover (e g AP-1000)

17

TRAC-M Long-Term Development

- Anticipated PWR LBLOCA model improvement needs:
  - Reflood model.
    - Interim model for AP-1000.
    - More mechanistic model based on RBHT data.
  - Blowdown heat transfer & rewet.
  - Upper plenum de-entrainment => hot leg carry over.
  - Downcomer interfacial drag => ECC bypass.
  - Downcomer & cold leg condensation:
    - ECC bypass
    - Downcomer boiling
  - Steam generator heat transfer => steam binding.
  - Core interfacial drag.
    - Normal flow regimes at low pressure.

18

TRAC-M Long-Term Development

- Incorporation of Experimental Results
  - UCLA Subcooled Boiling
    - Targeted to known code deficiency, implementation in 2003.
  - 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 & 2007.
      - Steam cooling/drop injection tests in 2004-2006.
      - Data analysis & model development to begin in 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.

19

TRAC-M: Code Consolidation and Development

- Summary
  - Code development associated with consolidation will be completed by the end of 2002.
  - Developmental assessment initiated in the second half of 2002 and will be completed in 2003.
  - 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 β-release to CAMP members at Spring 2003 meeting.
  - 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.

20

TRAC-M DEVELOPMENTAL ASSESSMENT

Stephen M. Bajorek
Office of Nuclear Regulatory Research
Ph.: (301) 415-7574 / e-mail: smb4@nrc.gov

Meeting of the Advisory Committee on Reactor Safeguards
Subcommittee on Thermal-Hydraulic Phenomena

December 12, 2002

INTRODUCTION

- Summarize and present and typical results from "Code Consolidation" related Developmental Assessment
- Work in Progress
- Summarize Developmental Assessment planned for 2003

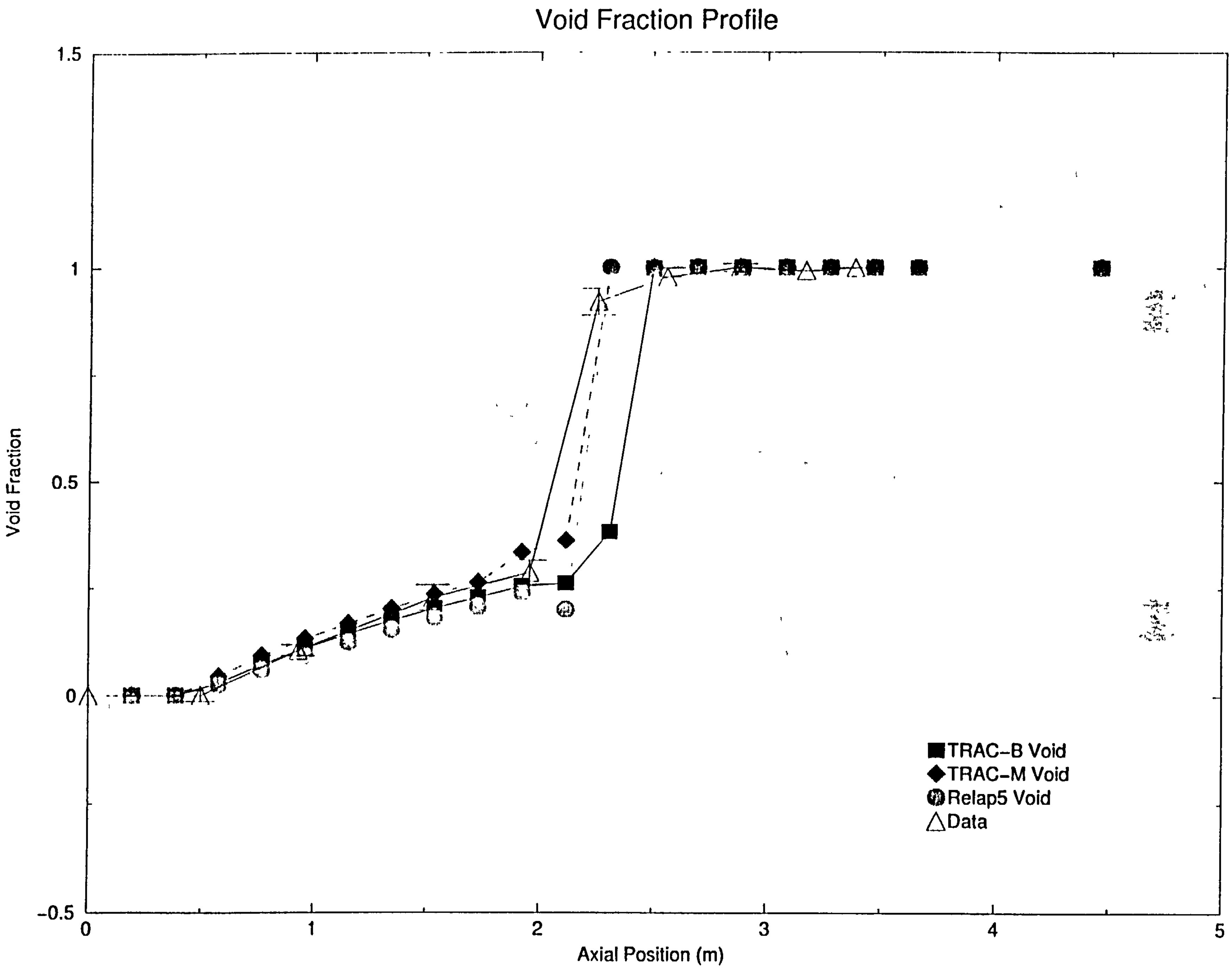
Code Consolidation DA

- Purpose of the "Code Consolidation" DA is to demonstrate that TRAC-M produces results similar to TRAC-P, TRAC-B, and RELAP5.
- Most efforts to date have been on small scale separate effects tests.

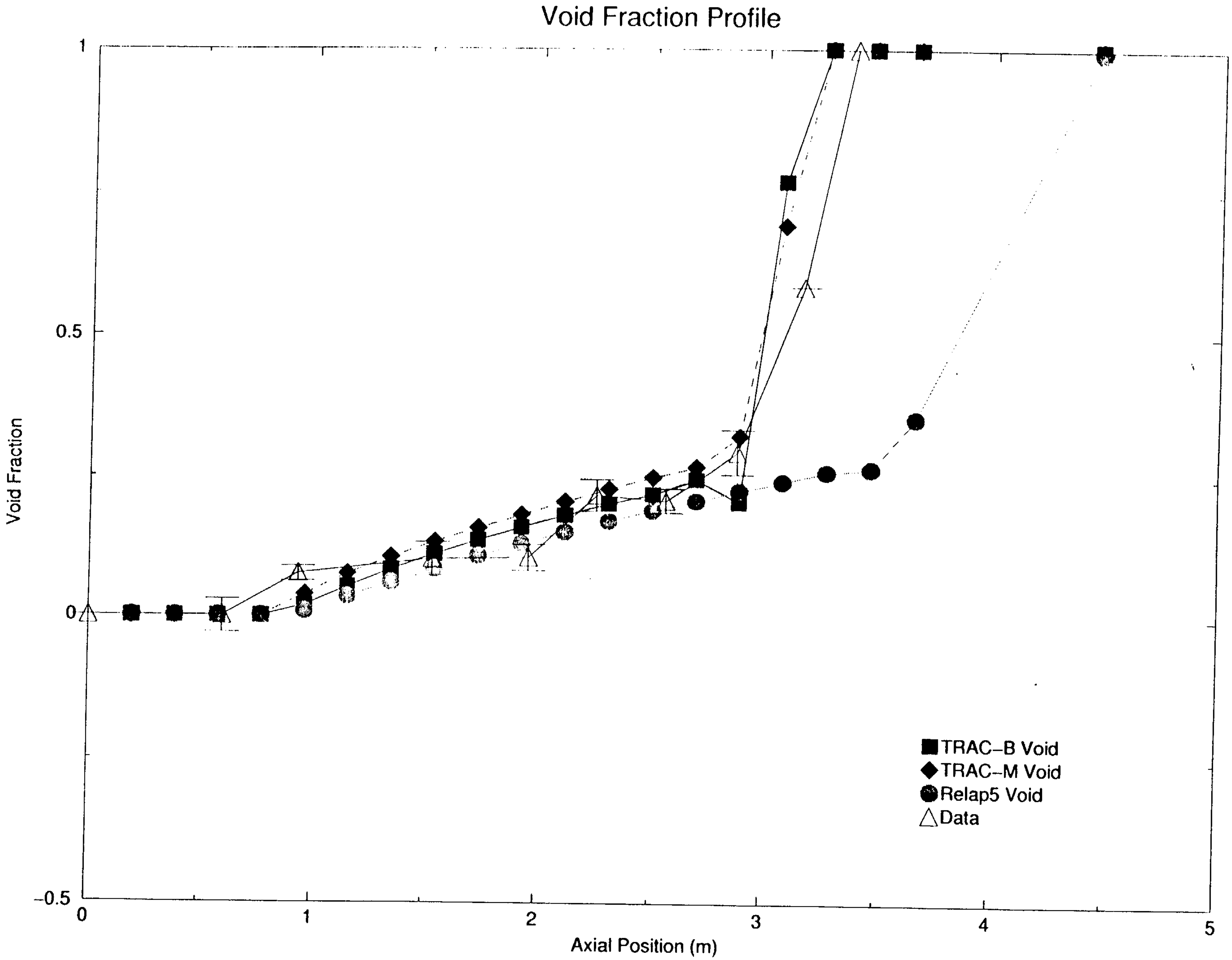
Assessment Performed in 2002

- ORNL THTF Steady State Blowdown
- ORNL THTF Transient Blowdown
- FRIGG Subcooled Boiling
- CISE
- ORNL THTF Level Swell Tests
- THETIS Boil-Off Tests
- Marviken and Moby Dick Critical Flow Tests
- UPTF Test 6
- SCTF Test 719

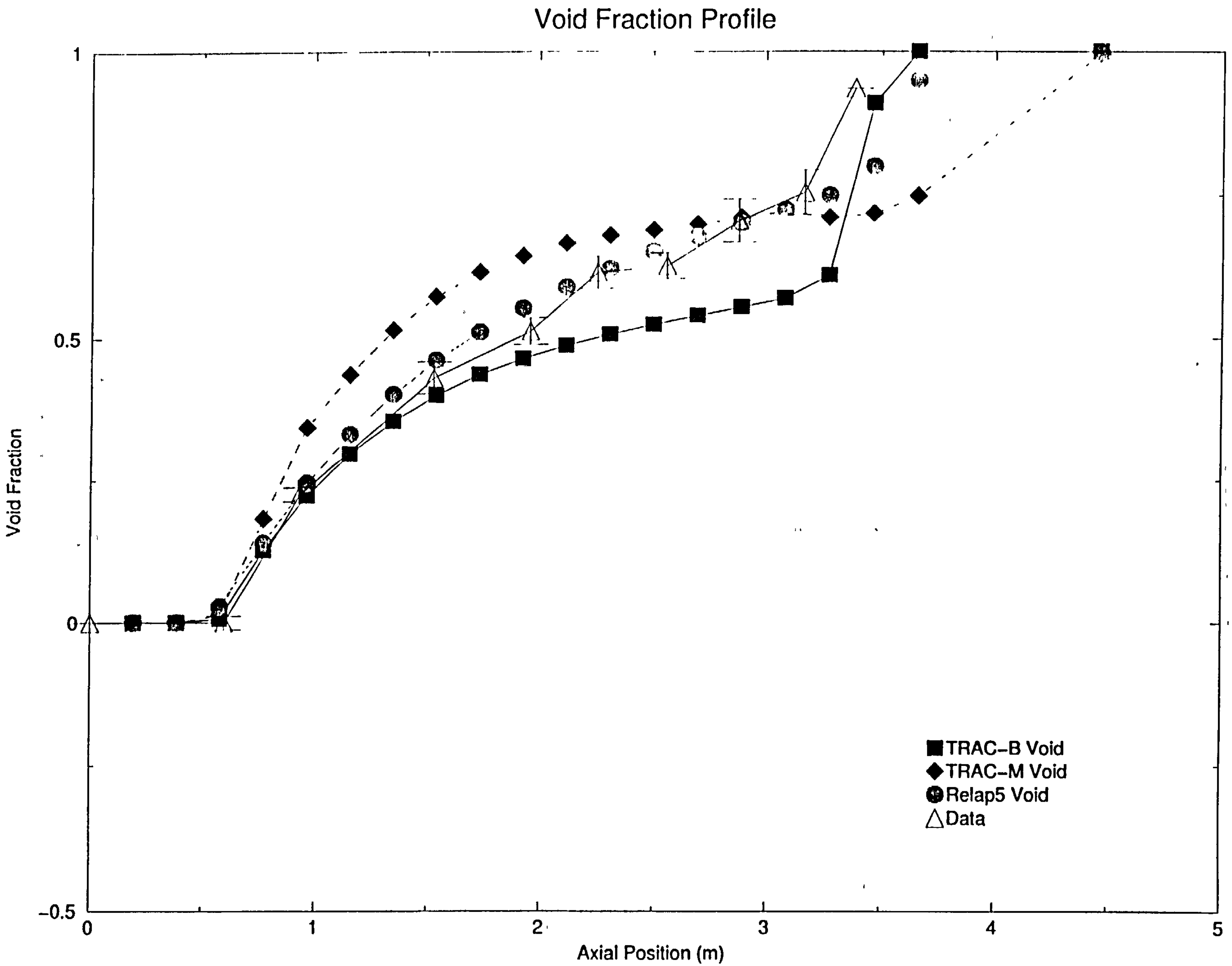
Task 14: THTF 3.09.10.n



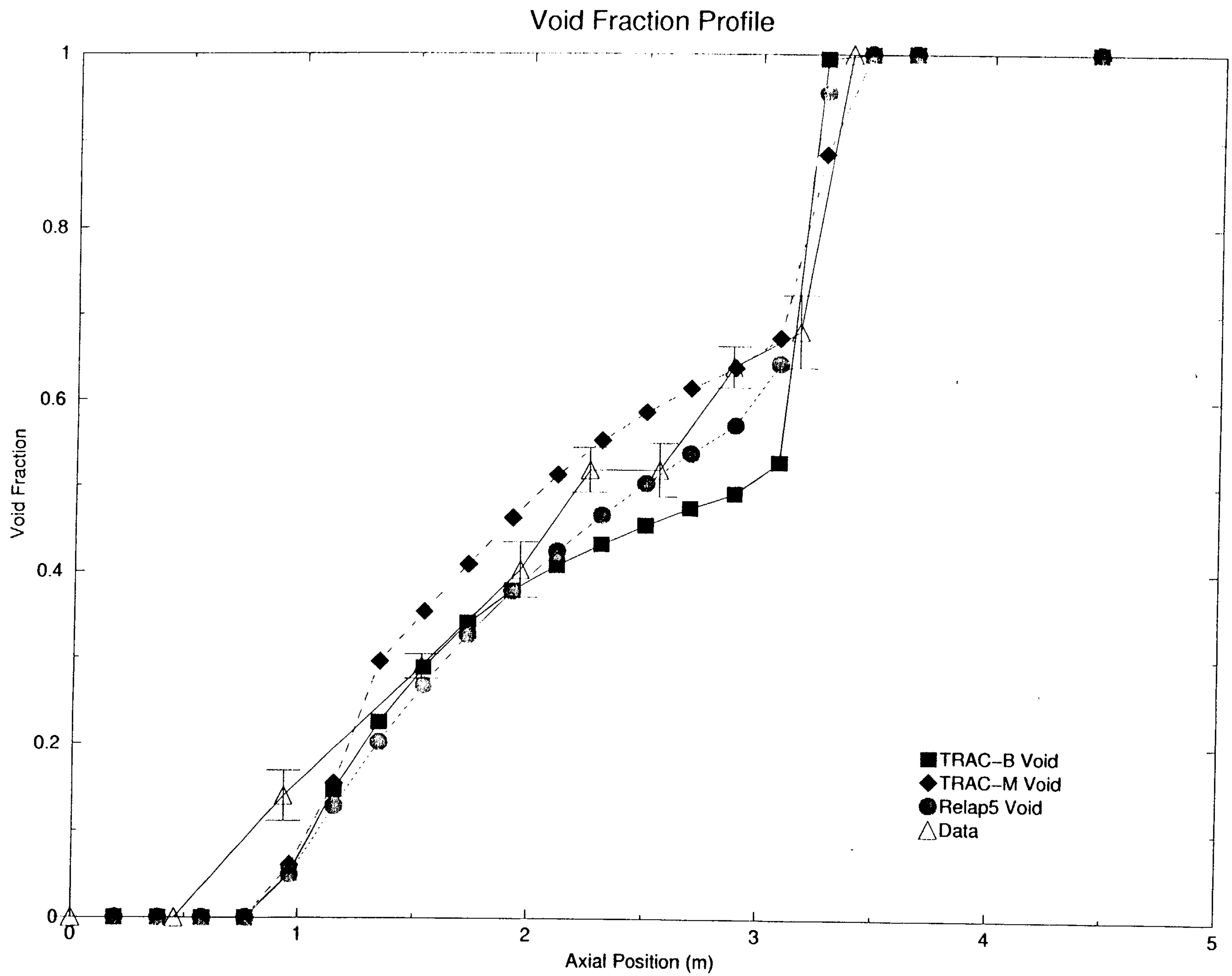
Task 14: THTF 3.09.10.ff



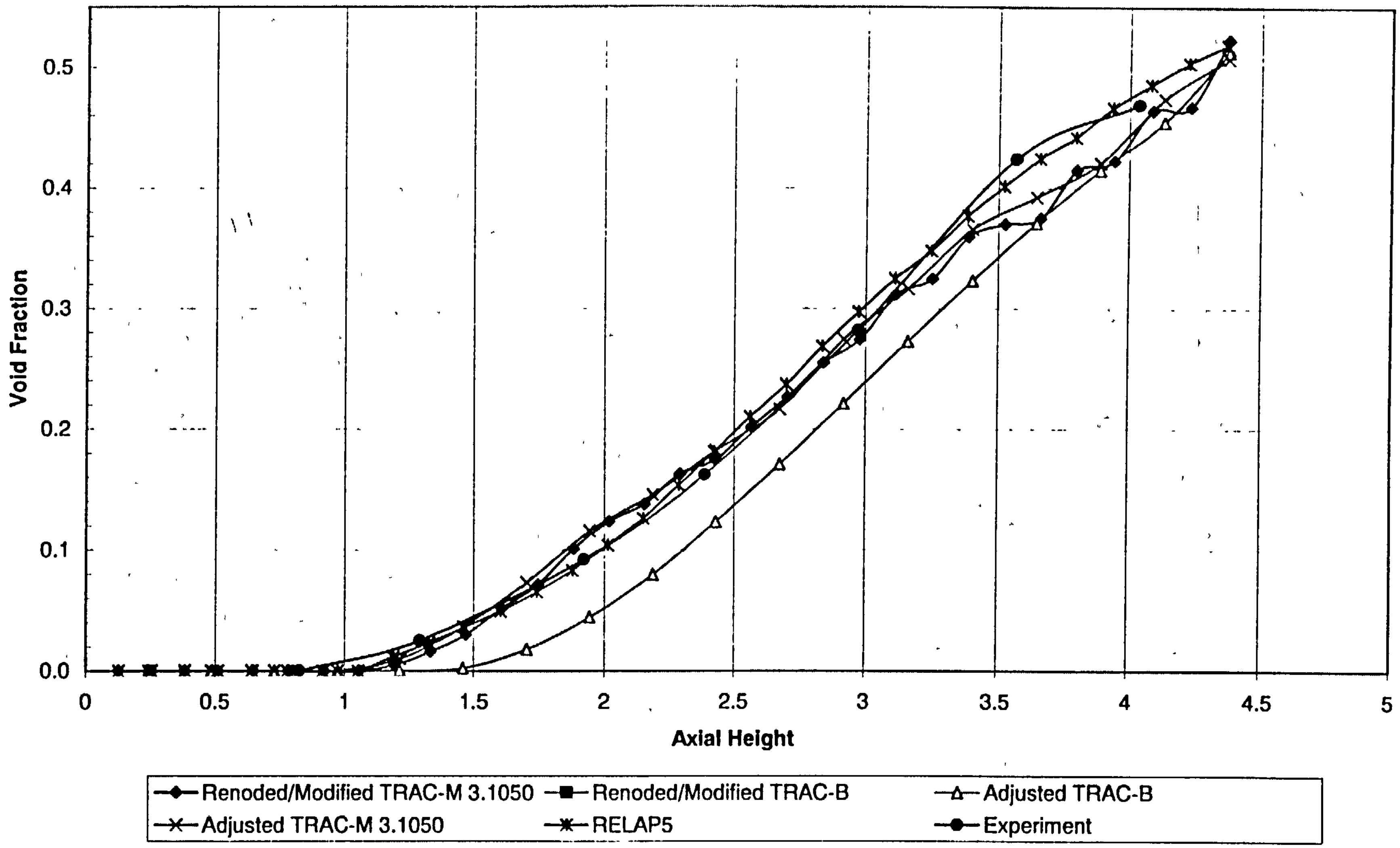
Task 14: THTF 3.09.10.aa



Task 14: THTF 3.09.10.dd



Void vs. Axial Height
FRIGG ft-36a test 313-016



Work in Progress

- Priority given to BWR related assessment, in order to support anticipated ESBWR review.
- For small and intermediate break LOCA:
  - FIX-II Test 3025 (ISP 15)
  - ROSA-III Test 912
  - FIST Test 6SB1
  - LOFT L3-7
- For large break LOCA:
  - LOFT Tests L2-5, L2-6, LB-1

Simulations for 2003

- Depending on available resources:
  - UPTF Test 6, Test 7, Test 21, Test 25, MIDAS
  - SPES small break LOCA tests
  - APEX-AP600 small break LOCA and LTC tests
  - APEX-AP600 BDBA tests and "No reserve" tests
  - ROSA-IV AP600 small break LOCA tests
- On completion of interim reflood model:
  - FLECHT-SEASET, FLECHT-Skewed, RBHT
  - CCTF and SCTF

Summary

- A significant number of the "Code Consolidation" DA cases are in progress. Progress has been hampered due to delays and difficulties in completing SNAP and the interim reflood model.
- Next step is to quantify code accuracy in terms of bias & uncertainty for major parameters and models.
- In 2003, assessment will continue with focus on integral effects tests and simulations that examine reflood heat transfer.

Additional Assessment

- ATLATS
  - **Model of facility being set up for both TRAC-M and RELAP. Objectives are to simulate ATLATS tests with existing and new correlations for onset of entrainment and phase separation.**
- UCLA Subcooled Boiling Tests
  - **Subroutines of new subcooled boiling model being developed. Intent is to perform assessments using existing and new correlations using UCLA rod bundle data and FRIGG.**

United States Nuclear Regulatory Commission

TRAC-M Modeling Needs and the Rod Bundle Heat Transfer Program

Presented to ACRS Thermal-Hydraulic Subcommittee

J.M. Kelly

Office of Nuclear Regulatory Research

CONTENTS

- Background: Program Rationale
- TRAC-PF1/MOD2 Reflood Model
- Sample of TRAC Reflood Results
- Reflood Model Development Needs
  - Role of the RBHT program in providing data for model development, selection, or validation.
- Summary

Rod Bundle Heat Transfer Program

Background

- What is the Rod Bundle Heat Transfer Program ?
- Why is this research needed ?
- What are the products of this research ?
- What is the technical approach ?
- What is unique about the experimental program ?
- What is the schedule ?

Rod Bundle Heat Transfer Program

What is the Rod Bundle Heat Transfer Program ?

- Model Improvement Effort:
  - Improve accuracy of LBLOCA modeling for the consolidated code to minimize uncertainty in best-estimate calculations.
  - Make extensive use of current data base augmented with new more detailed measurements.
  - Principal investigator: J.M. Kelly (USNRC)
- Experimental Program:
  - Small-Scale Reflood/Blowdown rod bundle heat transfer test facility.
    - Instrumentation & testing guided by needs of best-estimate model development NOT demonstration of Appendix K margin.
  - Contract awarded through competitive bid: November 1997.
  - Located at the Pennsylvania State University.
  - Principal investigator: Prof. L.E. Hochreiter (PSU)

Rod Bundle Heat Transfer Program
What is the Rod Bundle Heat Transfer Program ?

- **Types of Tests:**
  - Bundle Characterization:
    - steady-state flow => bundle & grid spacer pressure drop
    - steady-state two-phase => low pressure / low flow void fraction
      were not performed as part of bundle characterization.
    - bundle heat loss => boundary condition for other tests
    - radiation tests with evacuated bundle => rod-housing etc.
  - Steam & Mist Cooling:
    - single-phase steam cooling
      turbulent & mixed convection vapor htc.
      single-phase grid spacer enhancement
    - steam cooling with injected drops (fixed drop mass flux & size)
      two-phase enhancement of convective heat transfer
      interfacial heat transfer => vapor superheat
      two-phase grid spacer enhancement

Rod Bundle Heat Transfer Program

What is the Rod Bundle Heat Transfer Program ?

- **Types of Tests (cont):**
  - Forced Reflood Tests:
    - froth region parametric study: (P, G, ΔT_{sub})
      - void fraction & heat transfer
      - break-up & entrainment
    - dispersed flow film boiling parametric study: (P, G, α_{qf})
      - drop size & entrainment rate
    - guide tube and/or grid parametric study
  - Gravity Reflood Tests:
    - forced reflood overlap:
      - effect of oscillations on entrainment & heat transfer
    - outlet resistance parametric study

- **NOTE: cost of facility construction and operation together with funding reductions make "grayed out" tests now unlikely.**

Rod Bundle Heat Transfer Program

Why is this research needed ?

- **LBLOCA CSAU study quantified uncertainty for TRAC-PF1/MOD1:**
  - demonstrated methodology for best-estimate plus uncertainty
  - illustrated existence of large safety margin for LBLOCA:

    ~350 deg K for Westinghouse 4-Loop with peak LHGR of 9.35 (kW/ft).

- **To improve nuclear reactor performance and economics, licensees are beginning to use best-estimate analysis methods:**
  - Longer fuel cycles, increased core power levels, higher peaking factors, etc.

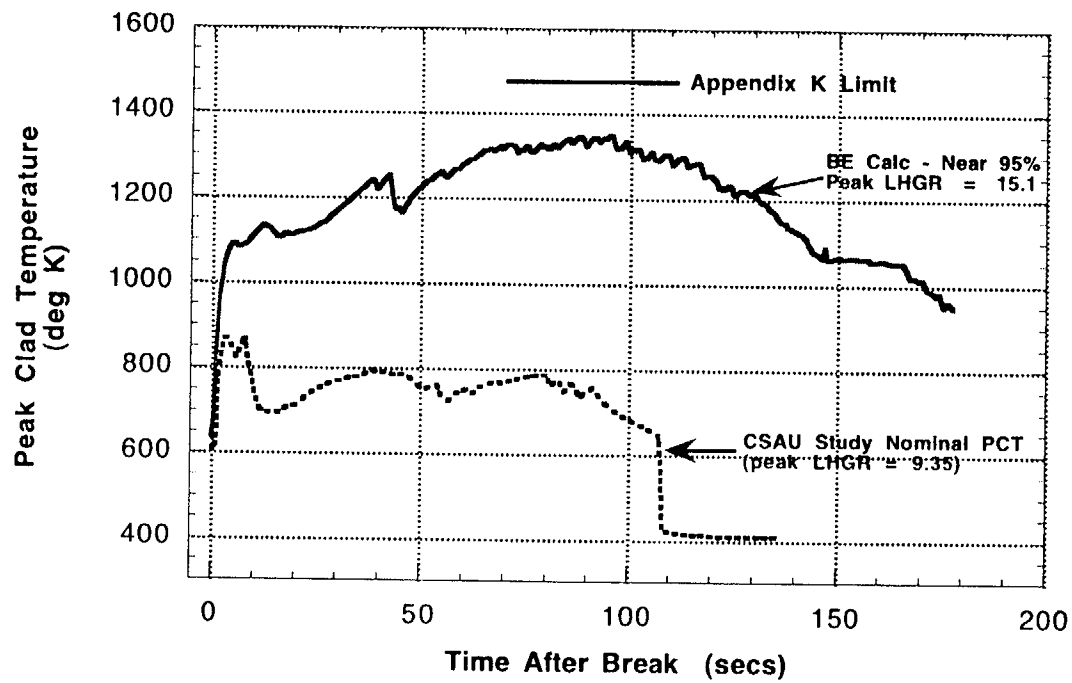
    recent calculations are using peak LHGR ~ 15 (kW/ft).
  - Result: peak clad temperatures (95th percentile) are calculated to occur during reflood and are similar to Appendix K values (see plot on next slide).

- **Risk Informed Regulation:**
  - NRC needs LBLOCA analysis tool that can be applied with a high degree of confidence to assure public safety without unduly penalizing licensees.

Rod Bundle Heat Transfer Program

Why is this research needed ?

- **Sample Best-Estimate Calculation:**
  - Peak LHGR = 15.1 (kW/ft)
    - ➡ Peak Clad Temperature is representative of 95^{th} percentile value



Rod Bundle Heat Transfer Program

Why is this research needed ?

- **Is the NRC's LBLOCA analysis tool "good enough" ?**
  - CSAU study quantified uncertainty for TRAC-PF1/MOD1:
    - ➨ identified areas of TRAC modeling deficiency & high uncertainty
      - ...potential for significantly larger margin than that demonstrated in CSAU study
  - TRAC constitutive models extensively modified => MOD2.
    - ➨ completely new "mechanistic" reflood model based primarily on experimental data for tubes (e.g., Winfrith "hot patch" tests).
    - ➨ minimal assessment against rod bundle data.
    - ➨ pedigree of MOD1 does not apply to MOD2 version.
  - Initial SET assessment results for TRAC-PF1/MOD2:
    - ➨ calculations for low flooding rate are unrealistically conservative
    - ➨ calculations exhibit large oscillations (even with fixed inlet flow rate)
  - ➨ **Significant model improvement is needed before uncertainty quantification is pursued.**

Rod Bundle Heat Transfer Program

Why is this research needed ?

- **What needs to be done to make the model "good enough" ?**
  - TRAC Reflood modeling capability needs improvement:
    - current model is overly complicated, a simpler approach is needed
      - reduce oscillatory behavior, and
      - improve accuracy of predictions
  - Old Approach:
    - try different correlations, tune coefficients, increase smoothing...
    - overly complicated model with compensating errors
      - no assurance answer is "right for the right reason" !
  - Current Program:
    - experimental program to provide detailed data for model development
    - models are selected/developed based on "fundamental assessment"
      - right local fluid conditions <=> right heat transfer
    - compatability with numerical representation considered from outset

Rod Bundle Heat Transfer Program

What are the products of this research ?

- **Improved code models to support the Agency in implementation of Risk Informed Regulation:**
  - **minimize uncertainties to provide true best-estimate analysis capability for auditing of licensee submittals**

- LBLOCA Analysis Capability:
  model that is more accurate, credible, and robust
- T/H Data Base:
  ensure existing reflood data base is archived & useable
  expand data base with detailed measurements targeted to code modeling issues
- Assessment Library:
  comprehensive assessment matrix => automated DA system
- Experimental Facility:
  provide NRC with a flexible rod bundle separate effects test facility
- University/Student Support:
  provide learning opportunities for next generation of T/H engineers

Rod Bundle Heat Transfer Program

- **What is the Technical Approach ?**

  - Analysis of Existing Data Base
    - ➡ Perform detailed analysis of separate effects tests for reflood and blowdown heat transfer phenomena.
      - assess data needs => testing needed ?
      - provide informed guidance on instrumentation, test matrix & procedure
      - provide data base for model assessment and/or improvement

  - Small-Scale Experimentation
    - ➡ Use well-instrumented facility to provide detailed data under carefully controlled conditions.
      - allows "fundamental assessment" of the underlying physical parameters upon which code constitutive models are based
      - provides detailed data base targeted at two-fluid code modeling needs

Rod Bundle Heat Transfer Program

Technical Approach: (cont.)

- Model Development (when necessary)
  - **Accuracy:**
    improve by detailed experimentation, better use of current data base, component specific relations, and development within two-fluid framework.
  - **Consistency:**
    treatment of flow regimes and constitutive models should be consistent
    - (e.g.) interfacial friction & heat transfer should use same flow regime.

    level of detail in numerical model should be consistent with that of the experimental data base => eliminate use of "ad hoc" models.
  - **Numerical Characteristics:**
    remove unphysical discontinuities, base correlations on "integral variables", build-in physical time scales when possible, and make sure model is appropriate for discretization used in system calculations.

Rod Bundle Heat Transfer Program

What is unique about the experiment ?

- Purpose of program => provide data for model development
  - NOT a demonstration of design adequacy vs. Appendix K limits
- Series of well defined experiments to separate and evaluate the individual phenomena which together constitute “Reflood Heat Transfer”
  - provide consistency between level of detail in code model and in data base
- Takes advantage of instrumentation improvements to provide more accurate detailed information than is currently available, for example:
  - froth region: axial profile of void fraction just downstream of the quench front
  - froth => dispersed transition: laser enhanced imaging of regime transition
  - dispersed flow: drop size, entrainment rate & 2Φ enhancement
- Close collaboration between experimental & modeling efforts.
  - NRC staff is responsible for performing code development, and provided input to instrumentation needs and test matrix.

Rod Bundle Heat Transfer Program

What is unique about the experiment ? (cont.)

- Power Profile
  - Top skew axial power profile:
    - Provides limiting case.
    - Extends length of dispersed flow film boiling region by minimizing region of reversed heat transfer at top of bundle.
    - Constant rod power extends reflood transient providing longer periods of film boiling with conditions that are changing less rapidly.
      - » facilitates data analysis to infer local fluid conditions for model development.
- Test Matrices:
  - "Inverted Annular Film Boiling" parametric study (subcooling at QF)
  - "Dispersed Flow Film Boiling" parametric study (void fraction at QF)
  - Droplet Injection Tests: two-phase convective enhancement

Rod Bundle Heat Transfer Program

What is the Schedule ?

- Experimental Program (proposed, based on reduced budget)
  - Interfacial Drag Tests: 2003 to mid-2004
  - Steam Cooling Test: mid-2004 to mid-2005
  - Droplet Injection Tests: mid-2005 to 2006
  - Higher PCT Reflood Tests: 2007
  - Variable Flow Reflood Tests: 2007
- Model Development Effort
  - Interim reflood model: mid-2003
  - Implementation of droplet field: 2003
  - Reflood model based on RBHT: 2004 to 2005
- NOTE: model development effort has been delayed due to potential submittal of ESBWR.

Rod Bundle Heat Transfer Program

- **Background Summary:**
  - Anticipated trend in industry: increasingly utilize margin to pursue operation at ever higher linear heat rates and peaking factors:
    - Plants can be LBLOCA limited with best-estimate peak clad temperatures approaching those of Appendix K.
  - CSAU study identified significant modeling deficiencies and uncertainties in MOD1 so that CSAU result was conservative.
  - MOD2 has not undergone uncertainty quantification and recent experience indicates that model improvement is needed before uncertainty quantification is pursued.
  - Rod Bundle Heat Transfer Program has goal of reducing uncertainty and biases due to CSAU identified modeling deficiencies.

TRAC-PF1/MOD2 Reflood Model

- **MOD2 vs. MOD1:**
  - Changes to Constitutive Packages:
    - Interfacial Friction & Heat transfer correlations (other than reflood) changed considerably.

      (e.g.) use of "Blasius" correlation for interfacial shear in the downcomer
    - Blowdown heat transfer: Forslund-Rohsenow removed (now as option)
    - Interface sharpener removed.
    - Wall shear changed, consistent between 1-D and 3-D components.
    - New subcooled boiling model for partitioning wall heat transfer between vapor generation and sensible heat transfer.
    - "Relaxation Limiter" method employed universally to damp changes in constitutive models.
    - **New reflood model implemented:**

      completely new set of correlations for interfacial friction and heat transfer, and wall heat transfer based on fundamental tube experiments

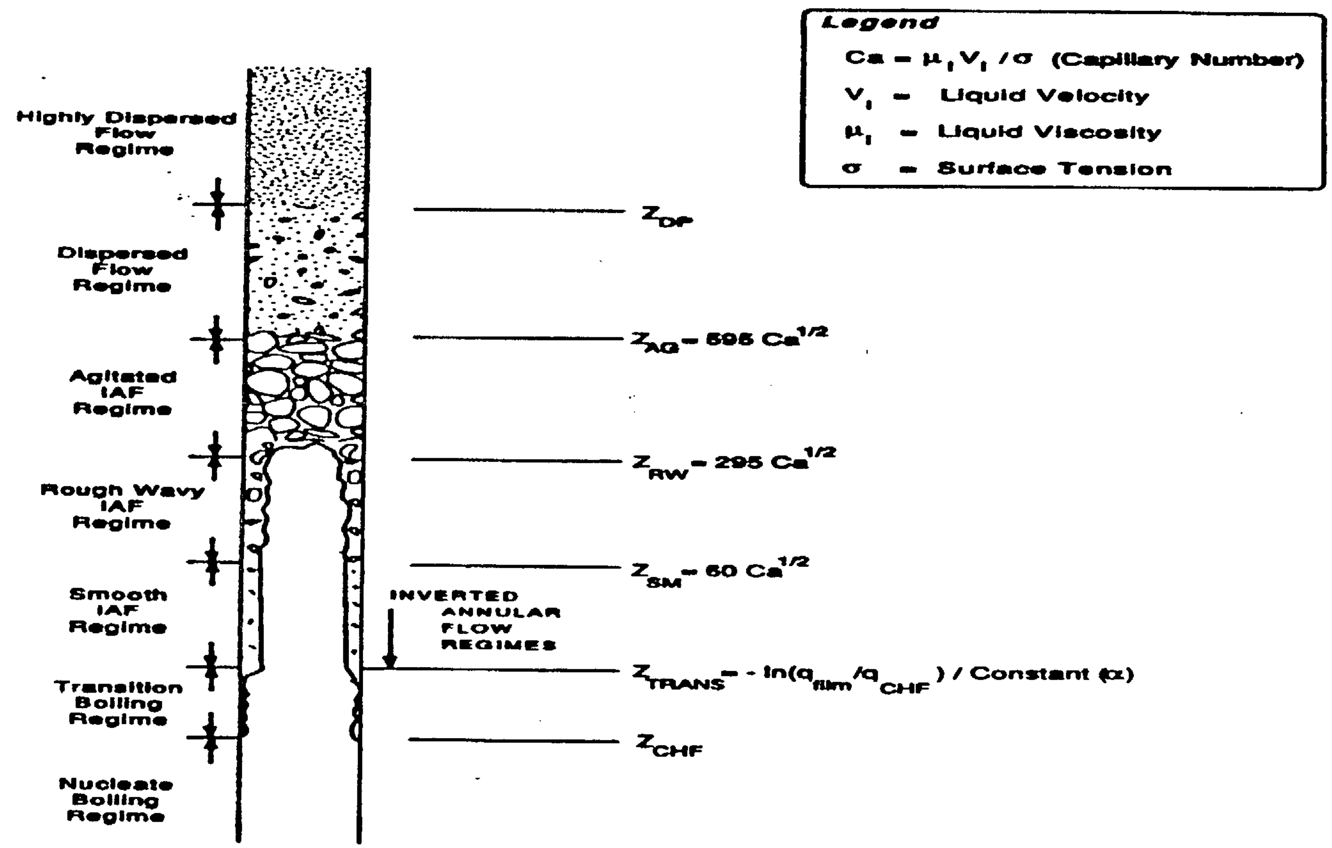
      requires user intervention (setting a trip) to activate during transient

TRAC-PF1/MOD2 Reflood Model

- **MOD2 Reflood Model Development:**
  - "Well-Intentioned"
    - Used data from fundamental experiments performed in tubes
      (e.g.) Ishii & DeJarlais experiments on jet breakup
    - Consistent treatment of flow regimes for interfacial shear, interfacial heat transfer & wall heat transfer:
      position dependent inverted annular flow map (distance from quench front)
  - But...
    - Very complicated, level of detail not supported by experimental evidence and not consistent with system discretization.
      contains 48 adjustable coefficients to be optimized
      contains multiple "smoothing" functions (what is really being used ?)
    - Ignores differences between rod bundles & tubes.
    - Appears susceptible to numerical oscillations.
    - Requires user intervention to switch from blowdown to reflood heat transfer packages.

TRAC-PF1/MOD2 Reflood Model

- **Reflood Flow Regimes:**



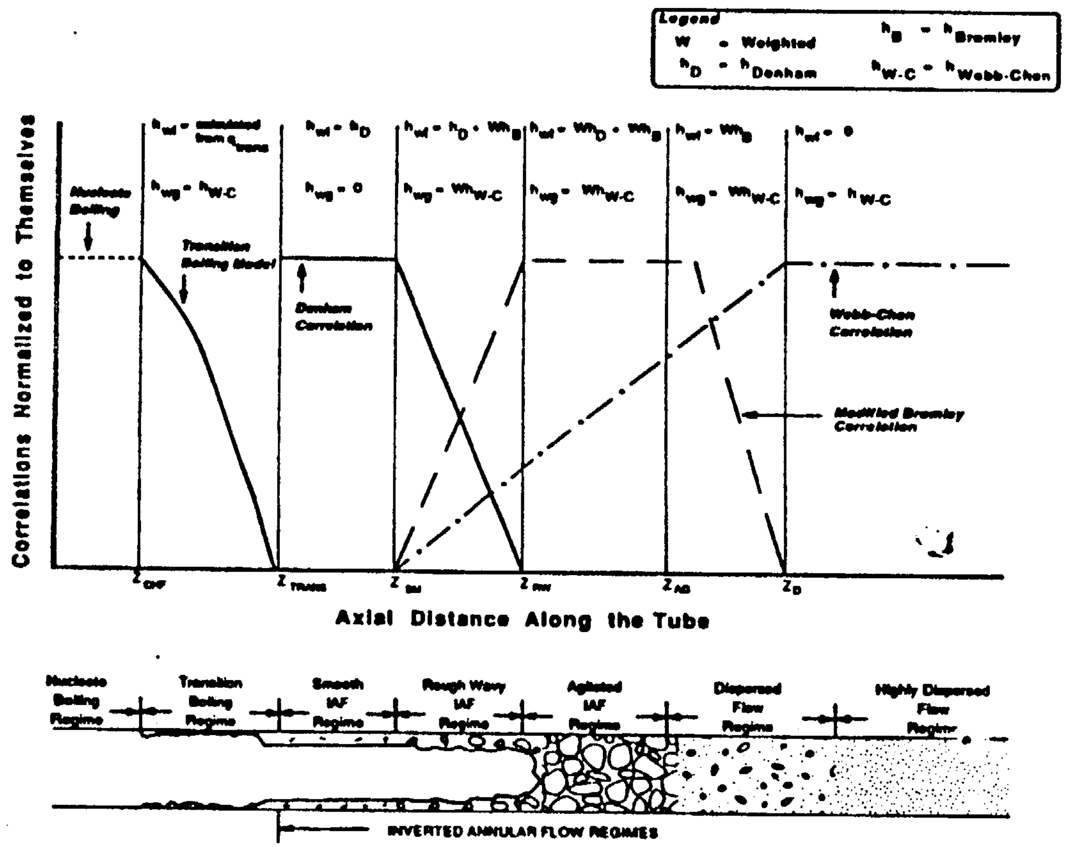
TRAC-PF1/MOD2 Reflood Model

- **MOD2 Reflood Flow Regimes:**

Regime	$Z_{QF} = fn\{Ca\}$	$V_{in} = 2.54$ (cm/s)	$V_{in} = 15.2$ (cm/s)
Transition Boiling	$= fn\ (q_{film}/q_{CHF})$	-	-
Inverted Annular Smooth	$= 60\ Ca^{1/2}$	0.83 (cm)	2.04
Inverted Annular Rough	$= 295\ Ca^{1/2}$	4.10	10.05
Inverted Annular Agitated	$= 595 Ca^{1/2}$	8.28	20.28
Highly Dispersed Flow	$\alpha > 0.98$	-	-

TRAC-PF1/MOD2 Reflood Model

- **Reflood Heat Transfer Coefficient Logic:**
  - ➡ weighted sum of contributions from each regime



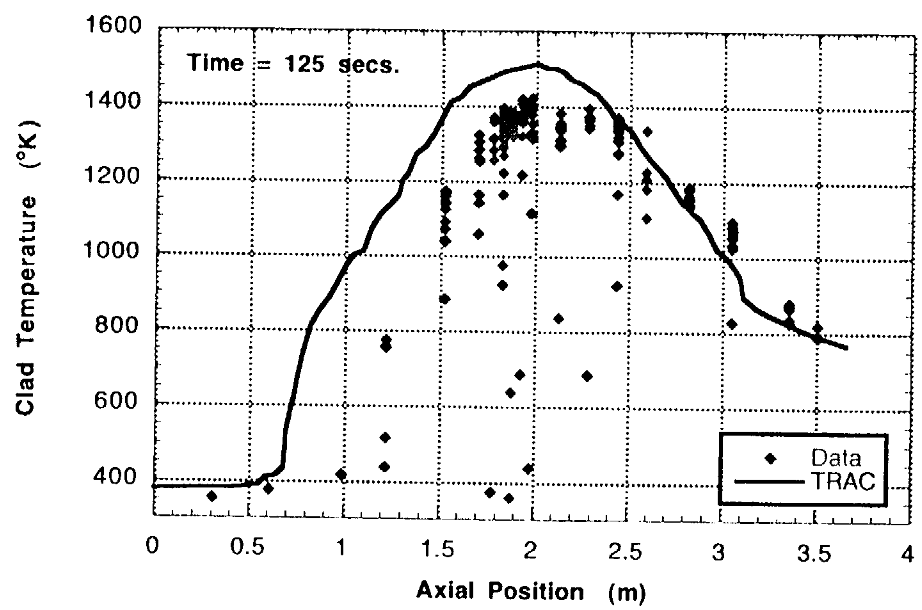
Sample of TRAC/Mod2 Reflood Results

- **FLECHT - SEASET Test #31504**
  - Geometry:
    - 17 x 17 bundle geometry
    - 161 heated rods & 16 thimbles
    - 8 egg-crate grid spacers
    - full heated length (3.66 m)
    - chopped cosine axial power profile (peak/avg. = 1.66)
    - uniform radial power profile
  - Test Conditions:
    - Pressure = 2.76 (bar)
    - Inlet Subcooling = 80 (deg C)
    - Nominal Heat Flux = 4.64 (W/cm^2)
    - Inlet Mass Flux = 23.7 (kg/m^2-s)
    - Constant Flooding Rate = 24 (mm/s)

Sample of TRAC/Mod2 Reflood Results

- **FLECHT - SEASET Test #31504**
  - Axial Profile of Clad Temperature (at time of peak clad temperature for data)
    - ➡ TRAC QF lags data by over 0.5 (m).
    - ➡ TRAC over-predicts peak temperature at this time by 85 (deg C)

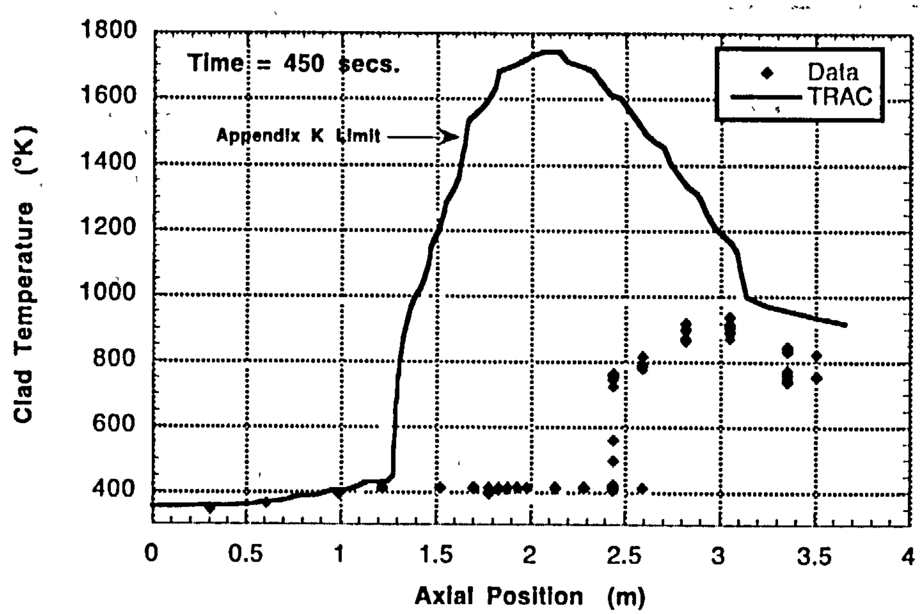
      evidence of compensating error: too hot at mid-plane, too cold at upper levels.



Sample of TRAC/Mod2 Reflood Results

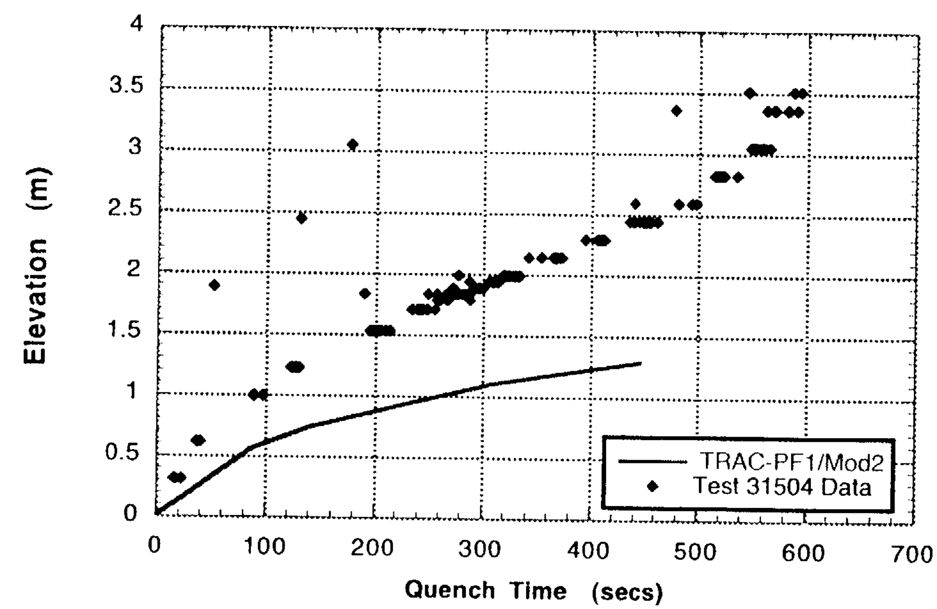
FLECHT - SEASET Test #31504

- Axial Profile of Clad Temperature (at time of peak clad temperature for TRAC)
  - TRAC QF lags data by over 1.1 (m).
  - TRAC over-predicts peak temperature by 320 (deg C)



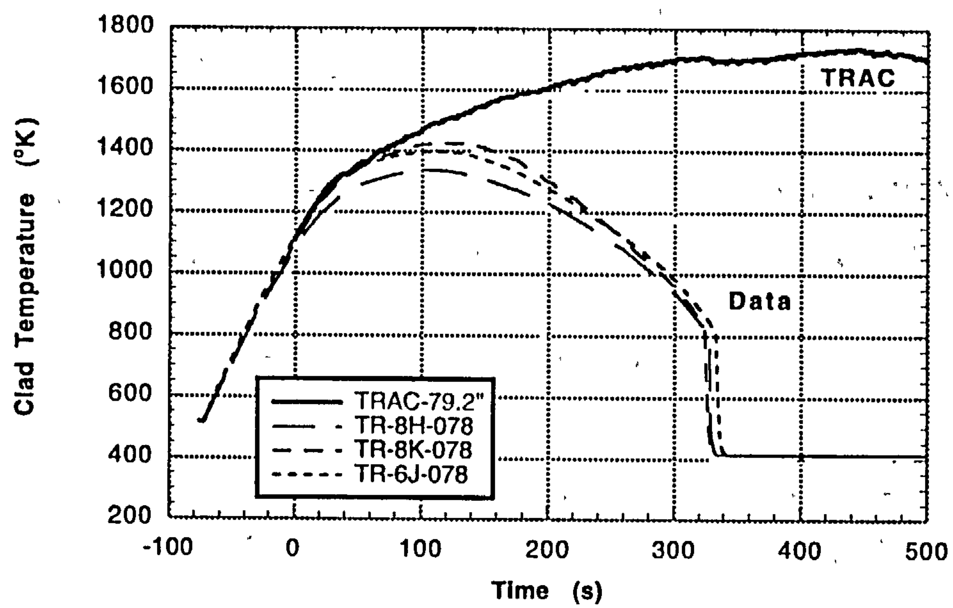
Sample of TRAC/Mod2 Reflood Results

- **FLECHT - SEASET Test #31504**
  - Quench Front Propagation:
    - TRAC significantly under-predicts quenching rate.



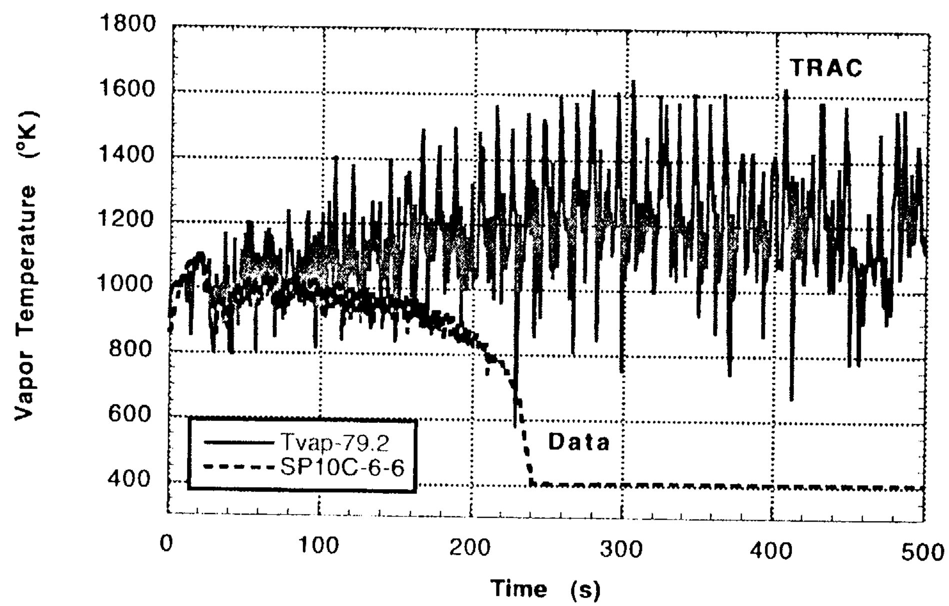
Sample of TRAC/Mod2 Reflood Results

- **FLECHT - SEASET Test #31504**
  - Clad Temperature vs. Time (just above core mid-plane)



Sample of TRAC/Mod2 Reflood Results

- **FLECHT - SEASET Test #31504**
  - Vapor Temperature vs. Time (just above core mid-plane)
    - ➡ TRAC calculation exhibits large oscillations (400-800 °K)

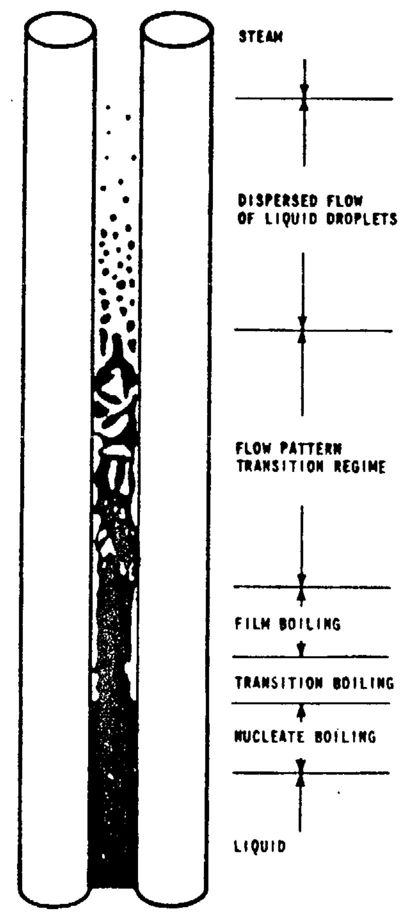


Sample of TRAC/Mod2 Reflood Results

- **FLECHT - SEASET Test #31504**
  - **Summary:**
    - ➡ TRAC-PF1/Mod2 drastically over-predicts the peak clad temperature (320 deg C) for this low reflood rate test.
    - ➡ TRAC-PF1/Mod2 calculation exhibits very large oscillations:
      vapor temperature, void fraction, vapor & liquid flow rates
    - ➡ TRAC-PF1/Mod2 greatly under-predicts quench front progression.
      oscillations throw too much liquid out of bundle
    - ➡ Improvement is needed:
      reduce oscillatory behavior, and
      improve accuracy of prediction
    - ➡ **Use a simpler modeling approach based on rod bundle data.**

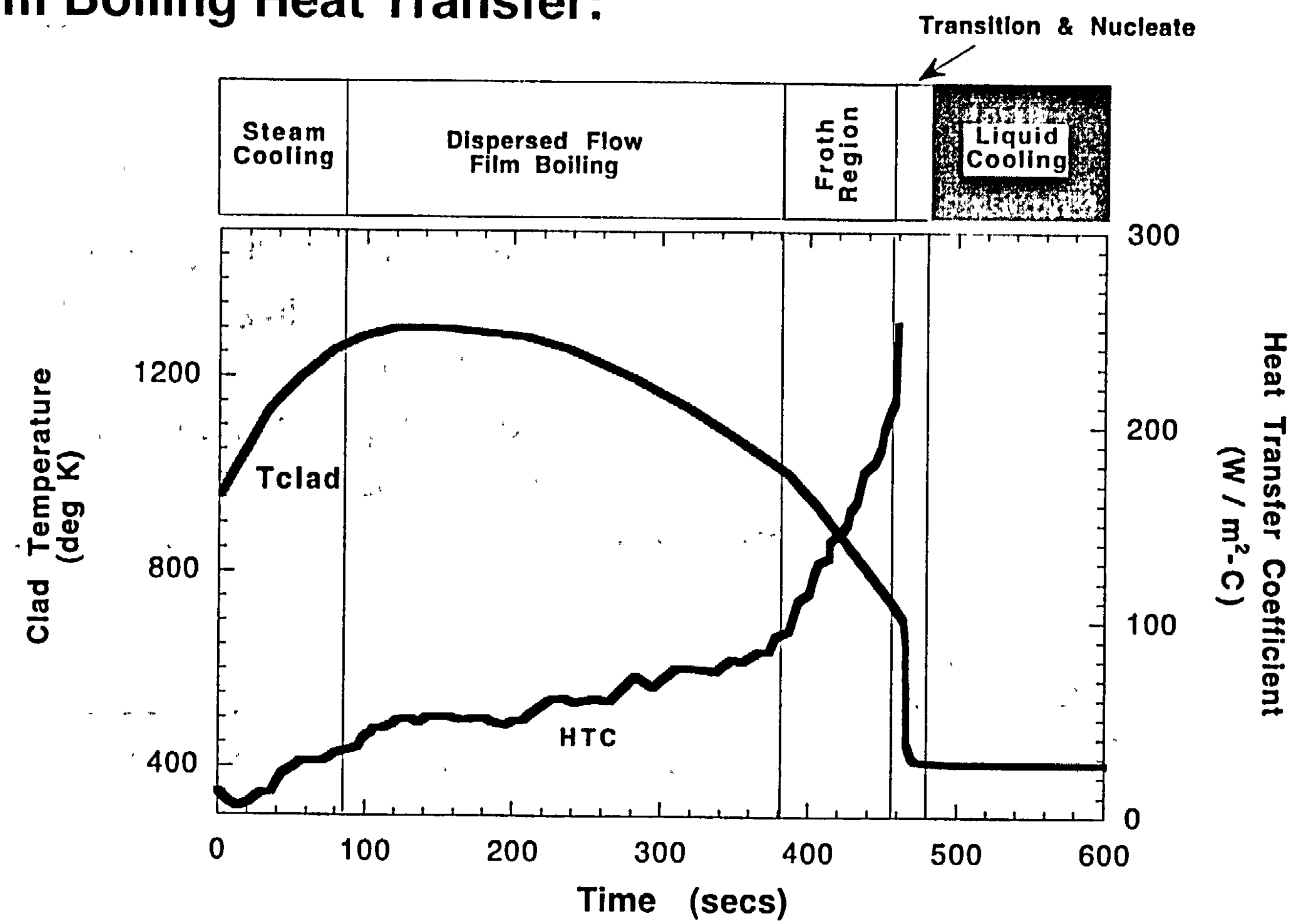
Reflood Model Development Needs

- **Reflood Regimes**
  - Transition Boiling:
    - ➡ at quench front, ~ 1-2 cm long.
  - Film Boiling:
    - ➡ a.k.a. inverted annular film boiling
    - ➡ occurs for high flow & subcooled conditions.
  - Transition Regime:
    - ➡ a.k.a. inverted slug, agitated inverted annular, or froth.
    - ➡ mixture of liquid fragments & droplets
    - ➡ occurs when inverted core disintegrates or when 2Φ mixture exists below quench front.
  - Dispersed Flow:
    - ➡ a.k.a. dispersed flow film boiling.
    - ➡ superheated steam & droplets with Sauter mean diameter ~ 1 mm.



Reflood Model Development Needs

- **Film Boiling Heat Transfer:**



Reflood Model Development Needs

- **Discuss modeling needs for each regime:**
  - Inverted Annular Film Boiling
  - Dispersed Flow Film Boiling
  - Inverted Slug Film Boiling
  - Transition Boiling
  - Normal 2Φ Interfacial Drag
- **For each regime:**
  - Importance
  - Background
  - Constitutive models needed
  - How RBHT data will be used

Reflood Model Development Needs
Inverted Annular Film Boiling

- **Importance:**
  - Heat transfer in this regime is largely responsible for the rate of quench front propagation (cools rods to the quench temperature).
  - The vapor generation from the combined film boiling and quench front heat release provides the inlet condition (m_d, G_v, T_v) to the dispersed flow region where the peak clad temperature occurs.
- **Background:**
  - Quasi-steady analysis of PERICLES reflood tests
    - Rod bundle with 368 heater rods
    - Most important effect is the void fraction just downstream of the quench front.
  - Steady-state low-quality film boiling data of Fung
    - Tube with hot patch (to freeze quench front) and gamma-densitometer
    - Subcooling is also highly important (interface-liquid heat transfer).

Reflood Model Development Needs
Inverted Annular Film Boiling

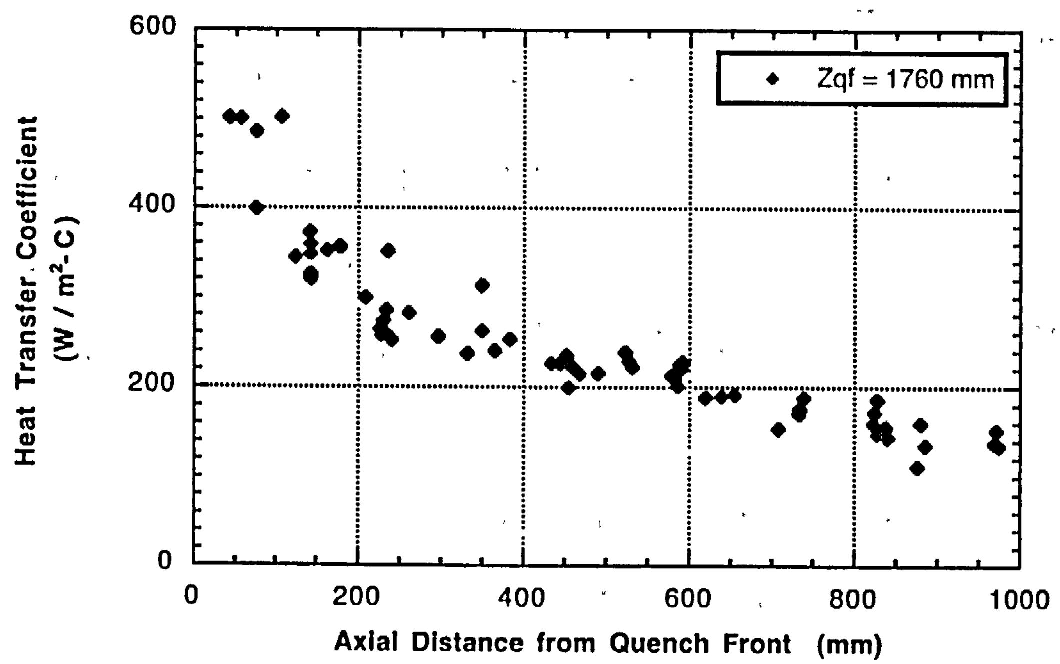
- **Background: PERICLES Cylindrical Reflood Tests**
  - Geometry:
    - 17 x 17 bundle geometry
    - 368 heated rods & 25 guide tubes
    - 8 mixing vane grids
    - full heated length (3.66 m)
    - chopped cosine axial power profile (peak/avg. = 1.6)
    - uniform radial power profile
  - Test Conditions:
    - Pressure = 3 (bar)
    - Inlet Subcooling = 60 (C)
    - Nominal Heat Flux = 3.35 (W/cm^2)
    - Inlet Mass Flux = 10 - 190 (kg/s-m^2)
  - Instrumentation:
    - Rod thermocouples and delta-P cells (~0.5 m)

Reflood Model Development Needs
Inverted Annular Film Boiling

- **Background: PERICLES Cylindrical Reflood Tests**
  - Frozen Quench Front: example of results

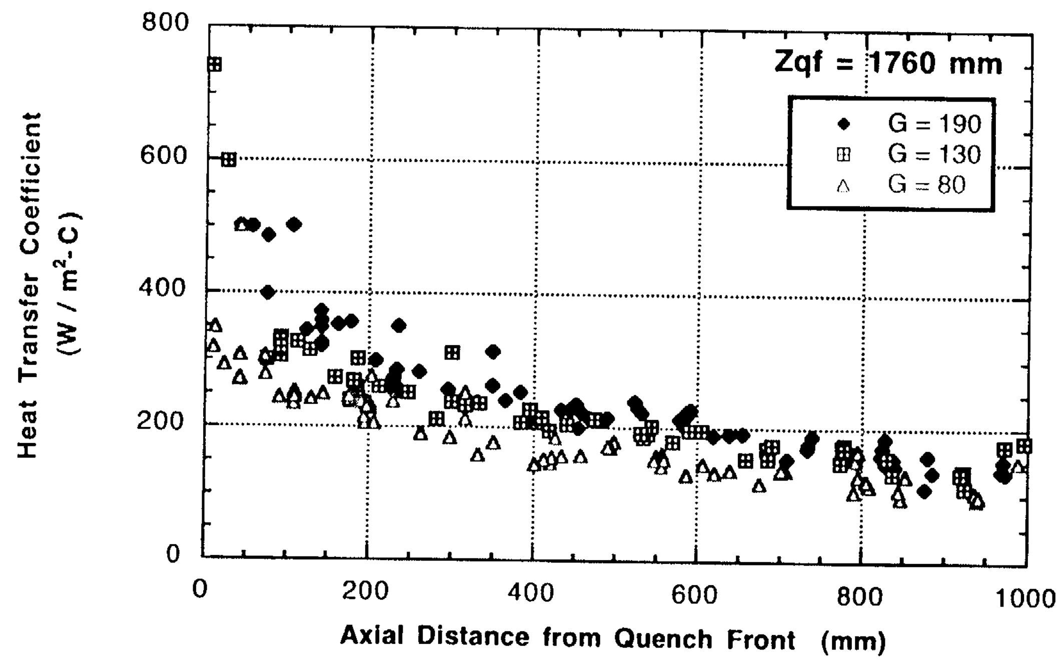
    heat transfer coefficient referenced to saturation temperature

    large value near quench front with axial decay



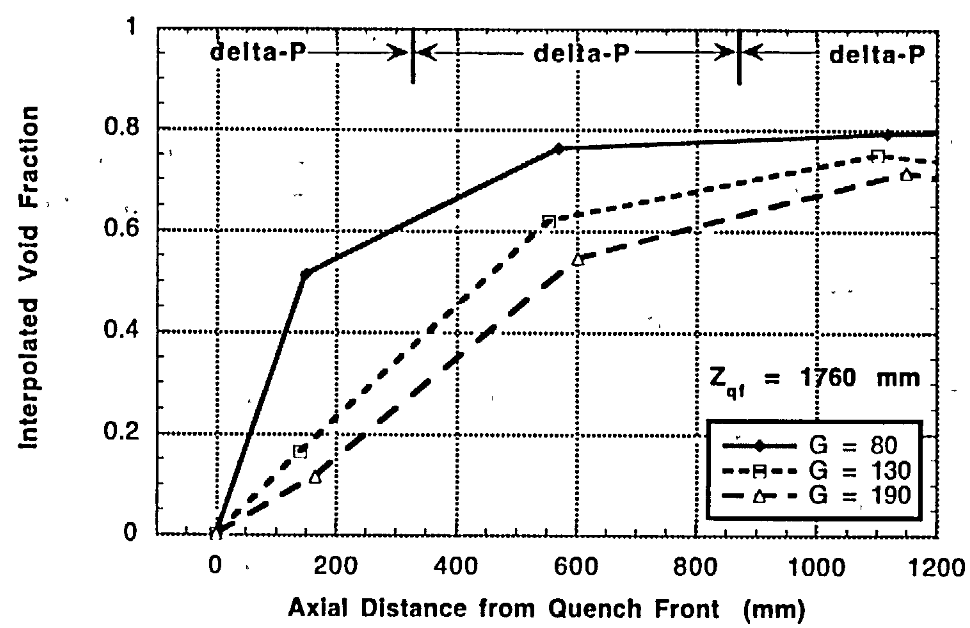
Reflood Model Development Needs
Inverted Annular Film Boiling

- **Background: PERICLES Cylindrical Reflood Tests**
  - Liquid Mass Flux Effect:
    - ➡ Heat transfer coefficient increases with mass flux.



Reflood Model Development Needs
Inverted Annular Film Boiling

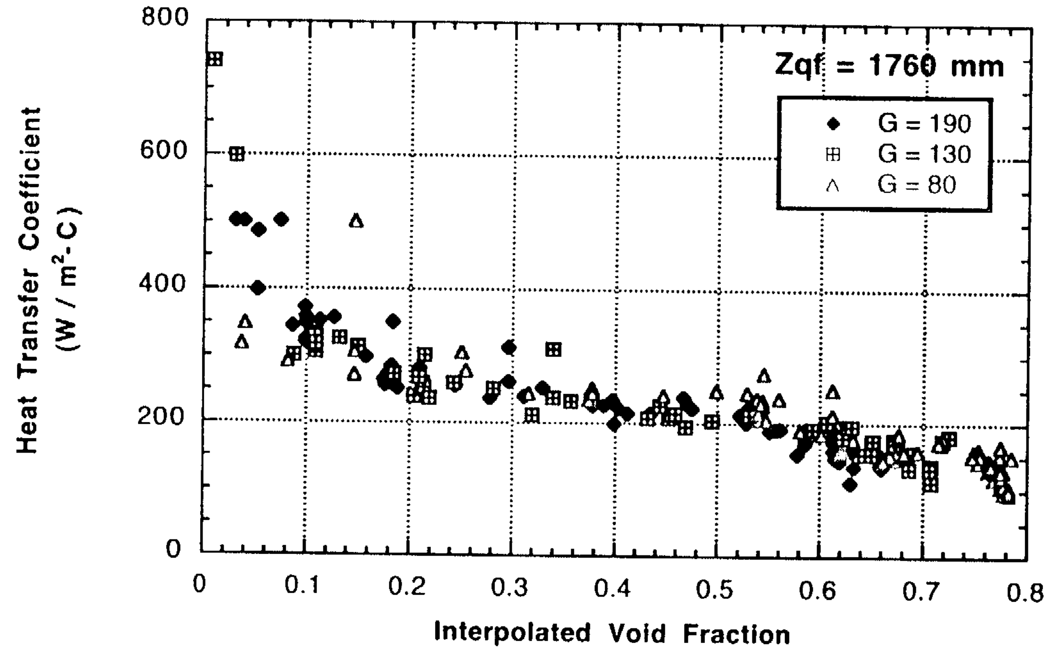
- **Background: PERICLES Cylindrical Reflood Tests**
  - Liquid Mass Flux Effect:
    - Void Fraction Profile:
      interpolated from ΔP cell data (no friction correction).



Reflood Model Development Needs
Inverted Annular Film Boiling

- **Background: PERICLES Cylindrical Reflood Tests**
  - Heat Transfer Coefficient vs. Void Fraction

Mass flux effect appears due to the void fraction profile.



Reflood Model Development Needs
Inverted Annular Film Boiling

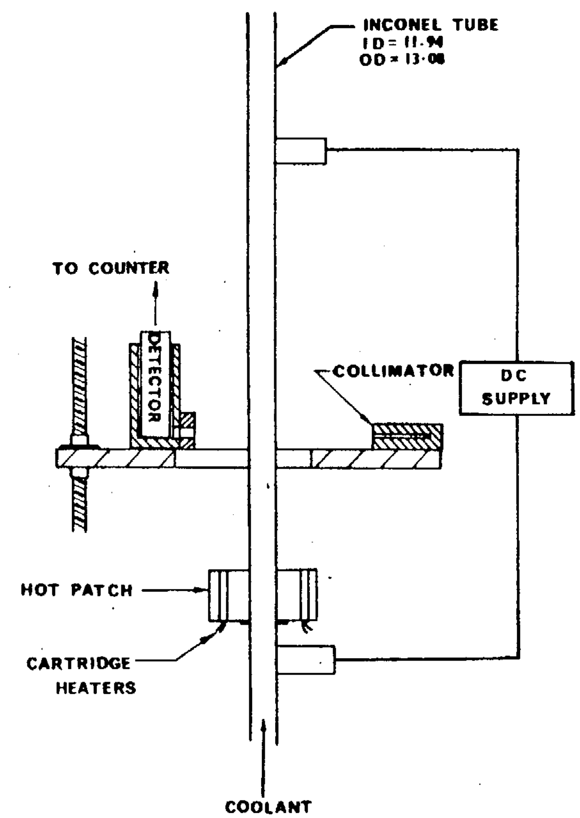
- **Background: PERICLES Cylindrical Reflood Tests**
  - **Summary:**
    - ➜ Both the "mass flux" and "quench front proximity" effects appear to primarily be functions of the axial profile of the void fraction downstream of the quench front.
    - ➜ **NEED TO PREDICT VOID FRACTION CORRECTLY !**

      correct void fraction => correct heat transfer coefficient

      other effects appear to have secondary importance and should only be treated after the void fraction
    - ➜ the rod bundle heat transfer experiment will be instrumented to provide more detailed void fraction data in froth region:
      - ➜ 11 delta-P cells located between 109 - 216 cm ($\Delta z \sim$ 8-12 cm)
      - ➜ investigated use of low energy gamma densitometer

Reflood Model Development Needs
Inverted Annular Film Boiling

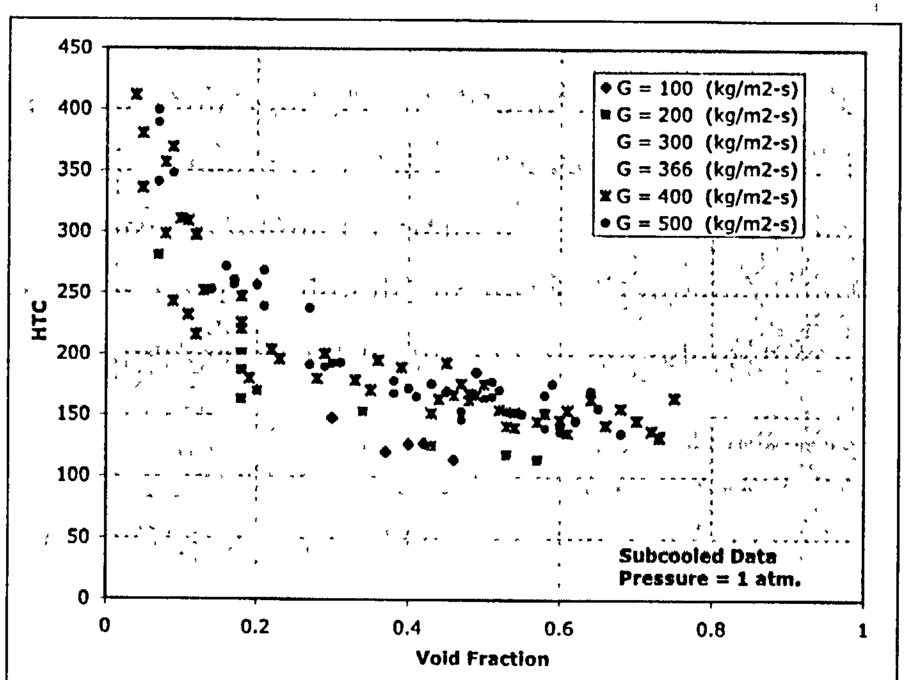
- **Background: Fung Low-Quality Film Boiling Experiment**
  - "Hot Patch" to freeze quench front.
  - Instrumentation:
    - 10 wall thermocouples
    - Gamma densitometer => void fraction at 5 elevations
  - Test Conditions:
    - Atmospheric pressure
    - Mass Flux = 100 - 500 (kg/m2-s)
    - Inlet Subcooling = 1 - 20 (C)



Reflood Model Development Needs
Inverted Annular Film Boiling

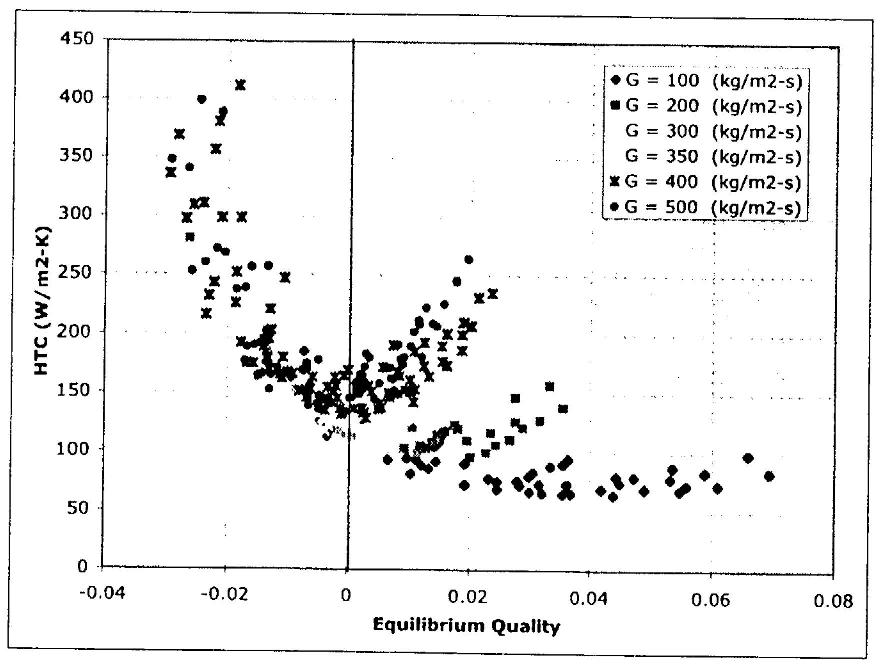
- **Background: Fung Low-Quality Film Boiling**
  - Void fraction dependence is similar to that of PERICLES reflood tests:
    - Mass flux effect may be present but is of secondary importance.

Note: void fraction can be ~70% even though liquid is subcooled!



Reflood Model Development Needs
Inverted Annular Film Boiling

- **Background: Fung Low-Quality Film Boiling**
  - Film boiling heat transfer coefficient is primarily a function of equilibrium quality, i.e., the liquid subcooling.
    - ➡ Interfacial heat transfer (interface-liquid) must be modeled accurately.
    - ➡ Test matrix designed to use subcooling at the quench front as a parameter.



Reflood Model Development Needs
Inverted Annular Film Boiling

Background

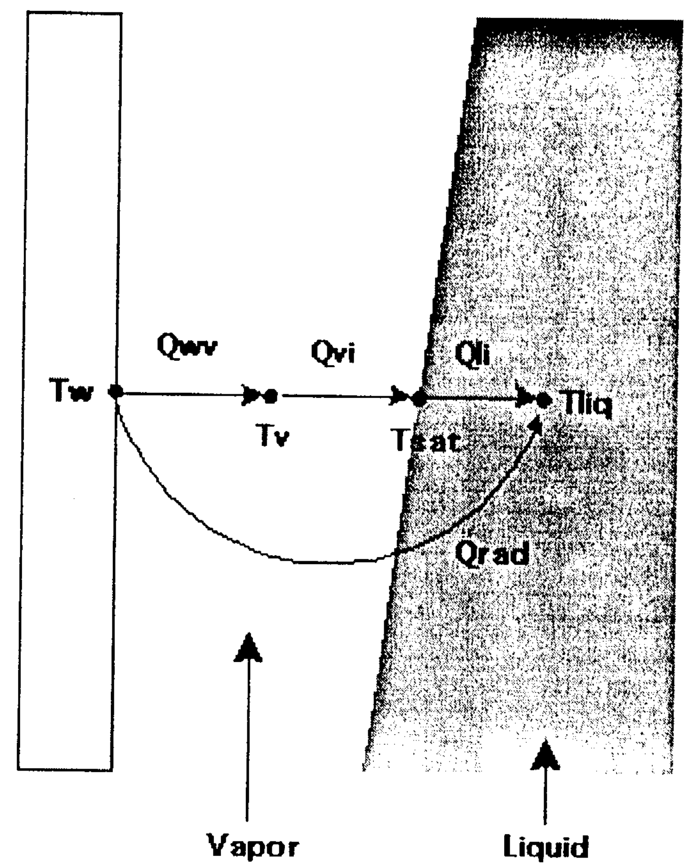
- Proposed RBHT Test Matrix for IAFB Conditions:

Case	Pressure (psia)	Flooding Rate (in/s)	Peak Power (kW/ft)	Inlet Subcooling (deg F)	Initial Temp. (deg F)	QF. Quality[1]	QF. Void Fraction	Comments
5	20	6.0	0.7	150	1600	-0.1146	-	- laser above 90" grid.
6	40	6 0	0.7	150	1600	-0.1181	-	- laser above 90" grid.
7	60	6.0	0.7	150	1600	-0.1208	-	- laser above 90" grid.
8	40	6.0	0.7	96	1600	-0.0596	-	- laser above 90" grid.
9	40	6.0	0.7	42	1600	-0 0005	-	- laser above 90" grid.
10	40	6 0	0.7	20	1600	-	0.554	- laser above 90" grid.
11	20	6.0	0.7	42	1600	-0.0009	-	- laser above 90" grid.
12	60	6.0	0.7	42	1600	-0.0003	-	- laser above 90" grid.
13	40	3 0	0.7	136	1600	-0.0595	-	- laser above 90" grid.
14	40	3.0	0.7	82	1600	-0 0000	-	- laser above 90" grid.
15	40	3.0	0.7	41	1600	-	0.556	- laser above 90" grid.
16	40	10 0	0.7	134	1700	-0.1183	-	- laser above 90" grid.
17	40	10.0	0.7	80	1700	-0.0599	-	- laser above 90" grid.
18	40	10 0	0.7	25	1700	.00006	0 003	- laser above 90" grid.

[1] For quench front at 53 inch elevation, which is the beginning of the span of fine delta-P cells.

Reflood Model Development Needs
Inverted Annular Film Boiling

- **Constitutive Models Needed**
  - Primary wall heat transfer mode is convection to vapor film, ultimate heat sink is the subcooled liquid.
  - Models needed are:
    - ➡ Wall-Vapor heat transfer
    - ➡ Vapor- Interface heat transfer
    - ➡ Liquid-Interface heat transfer
    - ➡ Wall-Liquid radiation heat transfer
    - ➡ Interfacial drag
    - ➡ Criteria for regime transition (liquid core breakup)
  - ➡ Note: the wall heat transfer is enhanced above laminar convection due to waviness of liquid core, as is the interfacial drag.



Reflood Model Development Needs

Inverted Annular Film Boiling

Usage of RBHT Data

- Available Data:
  - Wall temperature & heat flux
  - Liquid mass flux (inferred)
  - Void fraction (for a 8 cm interval)
  - Liquid temperature (maybe)
- RBHT data provides enough detail to validate the combined performance of the wall heat transfer, interfacial drag and interfacial heat transfer models.
- RBHT data can be used as part of model selection process:
  - Wall heat transfer coefficient and void fraction => model for convective heat transfer from wall-interface.
  - If subcooled liquid temperature measurements are accurate enough, can provide guidance for liquid-interface heat transfer model.

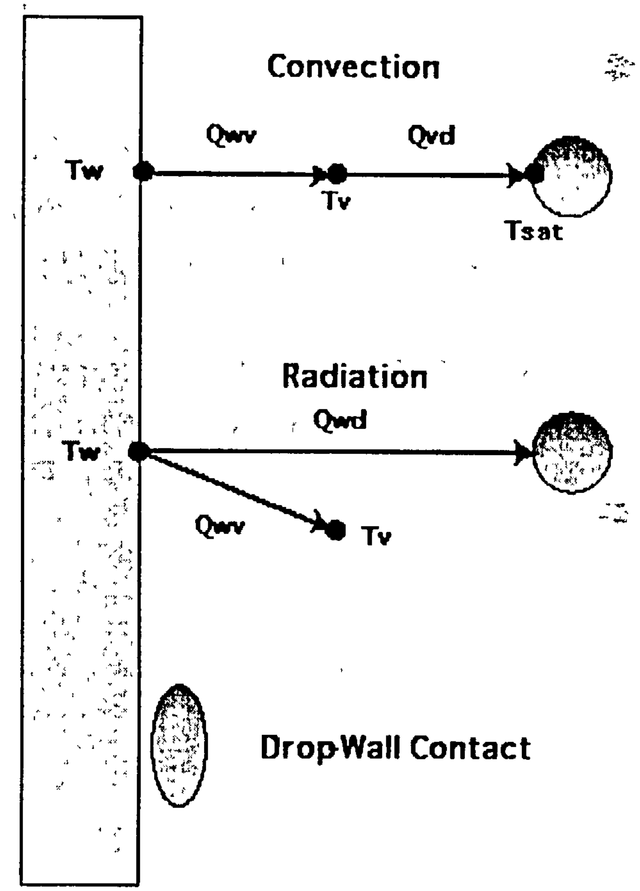
Reflood Model Development Needs
Dispersed Flow Film Boiling

- **Importance:**
  - Peak clad temperature occurs in this regime.

- **Background:**
  - Large over-predictions of heat transfer when drop-wall contact (Forslund-Rohsenow) was included in TRAC-PF1/Mod1.
  - DFFB data indicate large enhancement of convective heat transfer to vapor due to presence of dispersed droplet phase.
  - RBHT, FLECHT-SEASET and FEBA data indicate large heat transfer enhancement due to grid spacers.
    - ➔ Rod temperature decreases of as much as 200 C observed for prototypic mixing vane grids in RBHT facility.

Reflood Model Development Needs
Dispersed Flow Film Boiling

- **Background**
  - Traditional DFFB Model
    - ➧ Superposition of vapor convection, radiation and drop-wall contact.
    - ➧ Primary mode of wall heat transfer is convection to superheated vapor:
      - Prediction of vapor superheat is paramount.
    - ➧ Radiation is small, but wall-drop is non-negligible (~5-30%).
    - ➧ Radiation to structures should be considered for small bundles (BWR or RBHT) and maybe for PWR guide tube effect.
    - ➧ For Twall > Tmin, wall-drop contact heat transfer is less than uncertainty in vapor convective component.
      - Assume negligible.



Reflood Model Development Needs
Dispersed Flow Film Boiling

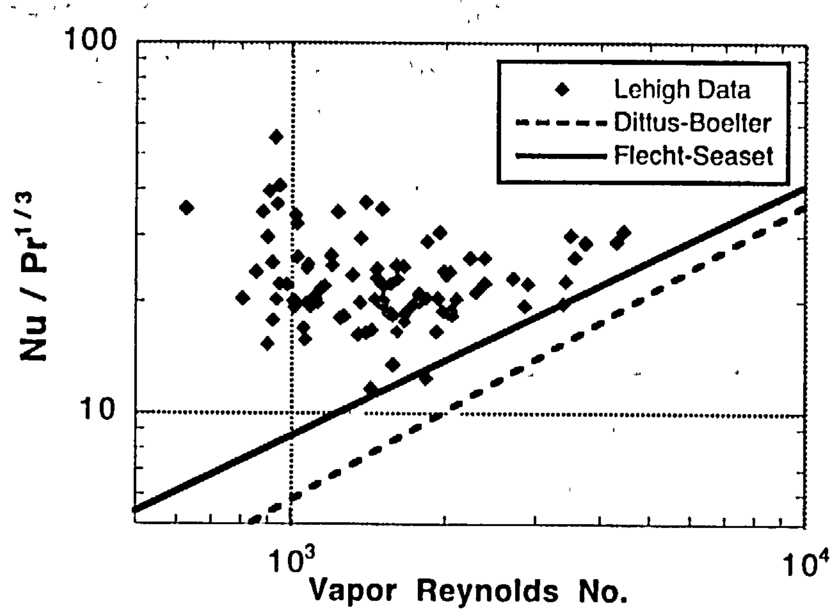
- **Background: 2Ø Enhancement**
  - Preliminary investigation indicates large enhancement of convective heat transfer to vapor due to presence of dispersed droplet phase:
    - ➨ Enhancement ranges from 20% to more than 100% over the single phase forced convection value.
  - Current models under-predict the convective HTC and compensate by calculating cooler than actual superheated vapor temperatures:
    - ➨ Cannot predict rod temperature histories both at centerline and upper elevations of the bundle.
  - Unclear whether enhancement is due to:
    - ➨ enhancement of turbulence (interfacial drag), or
    - ➨ effect of distributed heat sinks on vapor temperature profile

  ➨ Vapor convective HTC is not just a function of vapor Reynolds No. and fluid properties.

Reflood Model Development Needs
Dispersed Flow Film Boiling

- **Background: example of 2Ø enhancement**
  - Lehigh 3x3 Rod Bundle Results:

Pressure:	1.05 to 1.2 (bar)
Mass Flux:	0.1 to .26 (kg/m2-s)
Heat Flux:	5 to 43 (kW/m2)
Inlet Quality:	subcooled to 40%

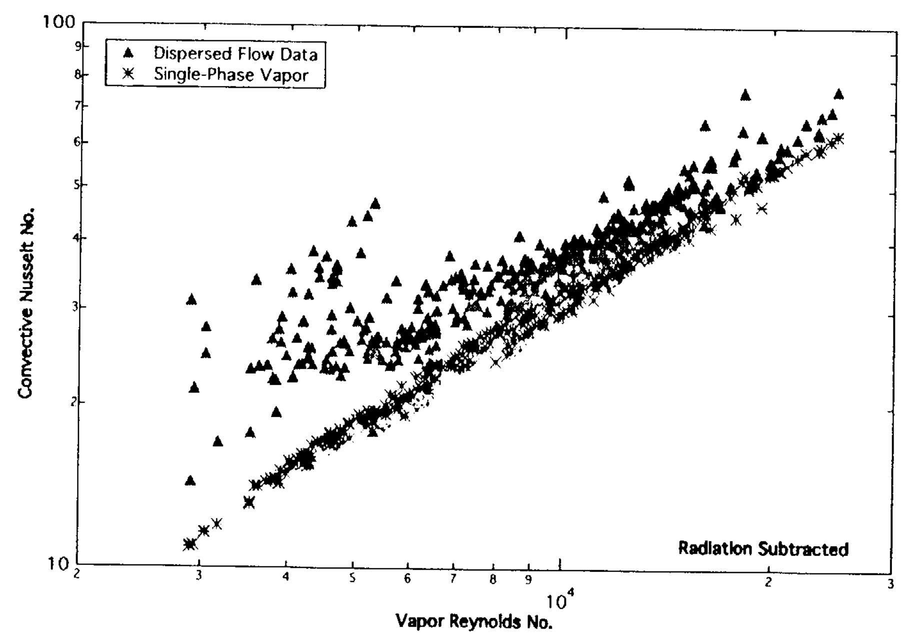


Reflood Model Development Needs

Dispersed Flow Film Boiling

- **Background: example of 2Ø enhancement**
  - Lehigh Tube Film Boiling Test Results:

Pressure:	2.4 to 5.7 (bar)
Mass Flux:	13 to 85 (kg/m2-s)
Heat Flux:	18 to 57 (kW/m2)
Inlet Quality:	subcooled to 70%



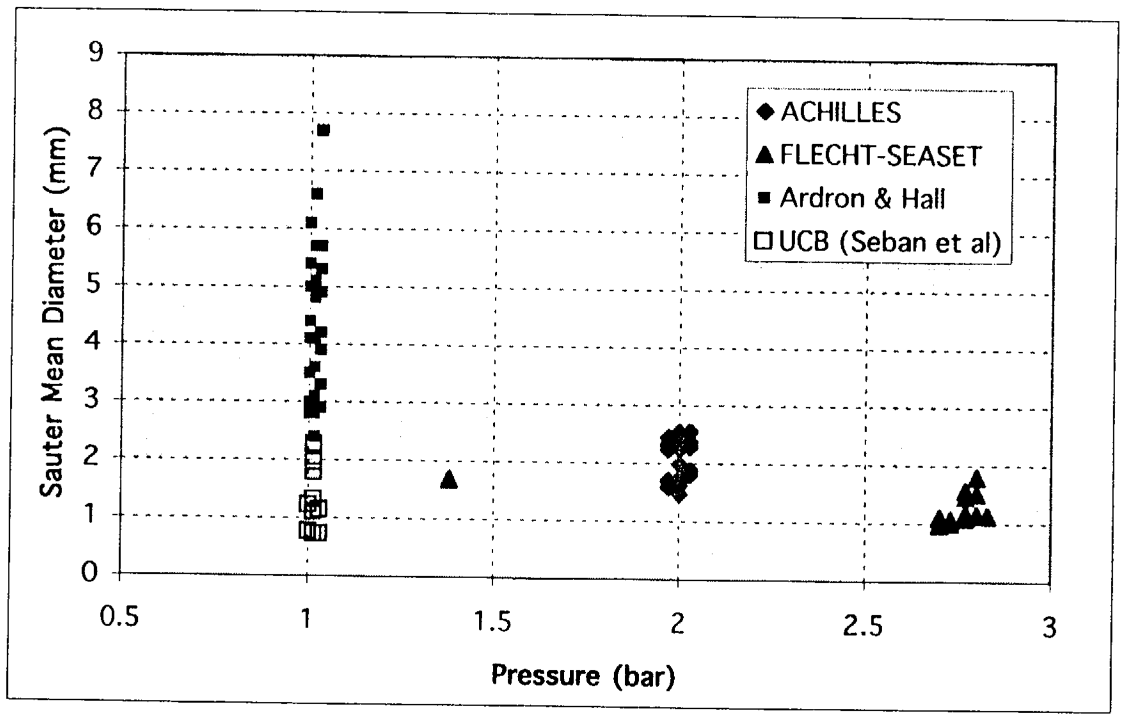
Reflood Model Development Needs
Dispersed Flow Film Boiling

Background: Drop Diameter

- Primary role is its effect on vapor superheat.
  - Also effects:
    - Grid spacer drop breakup.
    - Two-phase convective enhancement.
    - Wall-drop radiation heat transfer.
  - Drop formation mechanism not known:
    - Aerodynamic breakup of liquid slugs, or inverted annular core ?
    - Wave entrainment either from IA core or annular film (low flooding rate) ?
    - Wall-drop interactions, collisions or sputtering ?
  - Current data base:
    - Some drop diameter data is available for reflood experiments in tubes and rod bundles, but
    - Local fluid conditions are not reported, so dependencies are unknown and code models are somewhat ad hoc.
      - » e.g., critical value for Weber no. tuned so pct matched for one reflood test.

Reflood Model Development Needs
Dispersed Flow Film Boiling

- **Background: Drop Diameter**
  - Current reflood data base
    - ➜ Local flow conditions not reported.



Reflood Model Development Needs
Dispersed Flow Film Boiling

- **Constitutive Models Needed**
  - DFFB will be modeled as superposition of convection to vapor and radiation (primarily to droplets):

$$q''_w = (1+\Psi_{2\Phi}) \cdot h_{fc} \cdot (T_w - T_v) + q''_{rad}$$

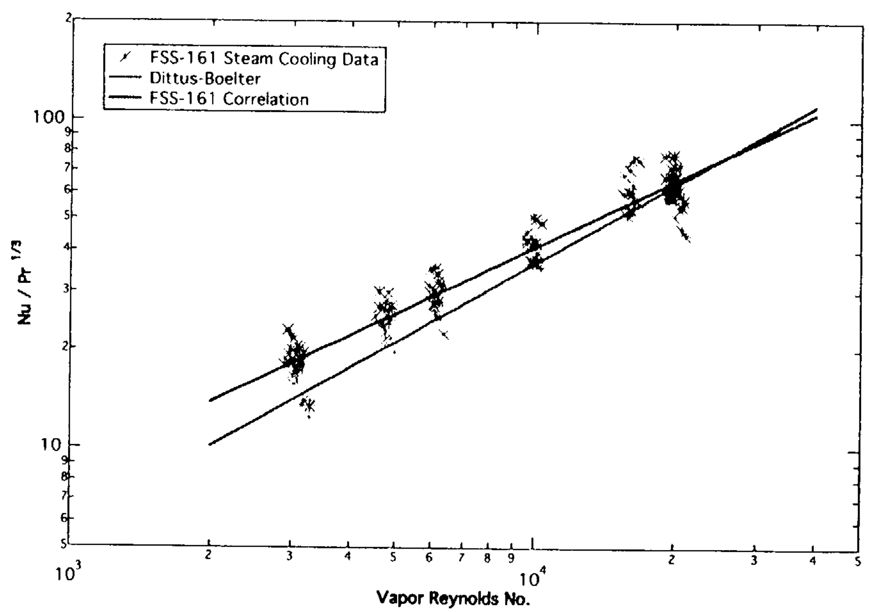
  - Models needed are:
    - ➧ Wall-Vapor convective heat transfer.
      Include effects of two-phase enhancement.
    - ➧ Vapor-Drop interfacial heat transfer.
      Drop diameter and entrainment rate.
    - ➧ Wall-Fluid thermal radiation.
      Wall-vapor is negligible except at high pressure.
    - ➧ Wall-Structure thermal radiation.
      For housing in experiments, BWR channel box, and PWR guide tube.
    - ➧ Grid Spacer Effects:
      Enhancement of convective heat transfer, grid rewet, and drop shattering.

Reflood Model Development Needs
Dispersed Flow Film Boiling

- **Usage of RBHT Data**
  - Wall-Vapor convective heat transfer.
    - ➨ Steam cooling tests will provide data for model selection or development.

      Include effects of bundle geometry, mixed convection, and lower Reynolds no.

      NOTE: major assumption is that single-phase convection heat transfer coefficient can be applied to dispersed flow.



Reflood Model Development Needs

Dispersed Flow Film Boiling

- **Usage of RBHT Data**
  - Wall-Vapor convective heat transfer.
    - Steam cooling tests will provide baseline for two-phase enhancement.

      16 tests: 2 pressures & 8 Reynolds nos.

      Tentative schedule: mid-2004 to mid-2005.
    - Droplet injection tests to provide data for model selection or development.

      48 tests: 2 pressures, 8 Reynolds nos. & 3 liquid/vapor mass loading ratios, possibility of using two different size drop injectors.

      Tentative schedule: mid-2005 to 2006.

      Available data:
      - Rod heat flux and temperature
      - Liquid and vapor flow rates
      - Superheated vapor temperature
      - Drop diameter

      Allows direct evaluation (and correlation) of two-phase enhancement with only assumption being that of the radiative heat transfer component.

$$\Psi_{2\Phi} = \frac{\left(q''_w - q''_{rad}\right)}{h_{fc} \cdot \left(T_w - T_v\right)} - 1$$

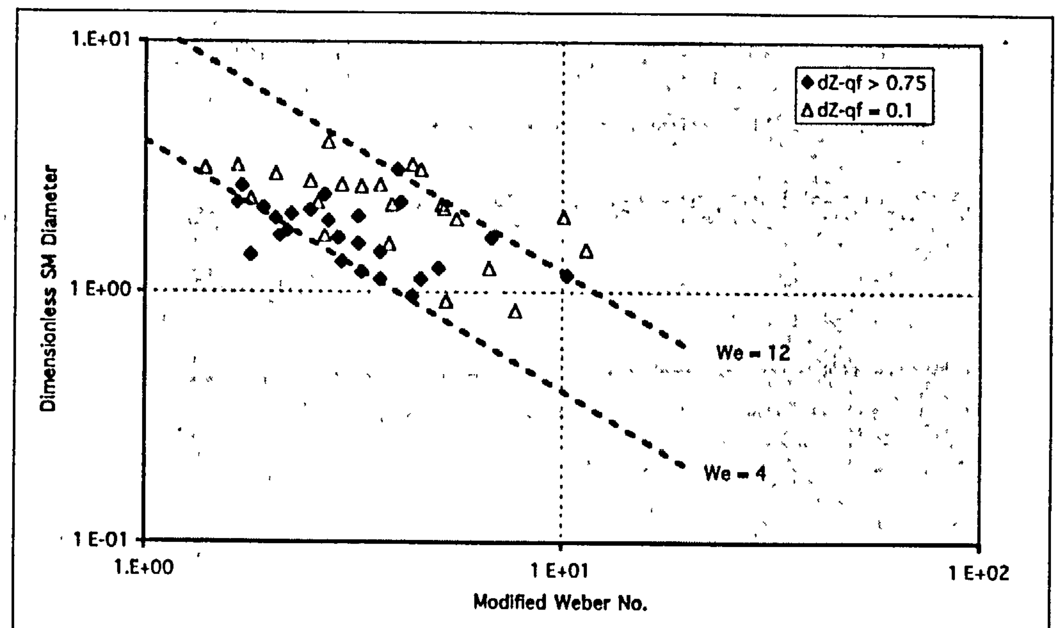
Reflood Model Development Needs
Dispersed Flow Film Boiling

- **Usage of RBHT Data**
  - Vapor-Drop interfacial heat transfer.
    - Modeling needs:
      - Vapor-drop interfacial heat transfer coefficient
        - needs to include multi-particle effect
      - Droplet diameter
      - Droplet volume fraction
    - Available data: reflood test conditions
      - Superheated vapor temperature
      - Droplet diameter
      - Vapor and entrained liquid flow rates (exit measurement)
    - RBHT data should be sufficient to:
      - Develop models for drop diameter and reflood entrainment rate.
      - Perform validation for predictive capability of combined models.

Reflood Model Development Needs
Dispersed Flow Film Boiling

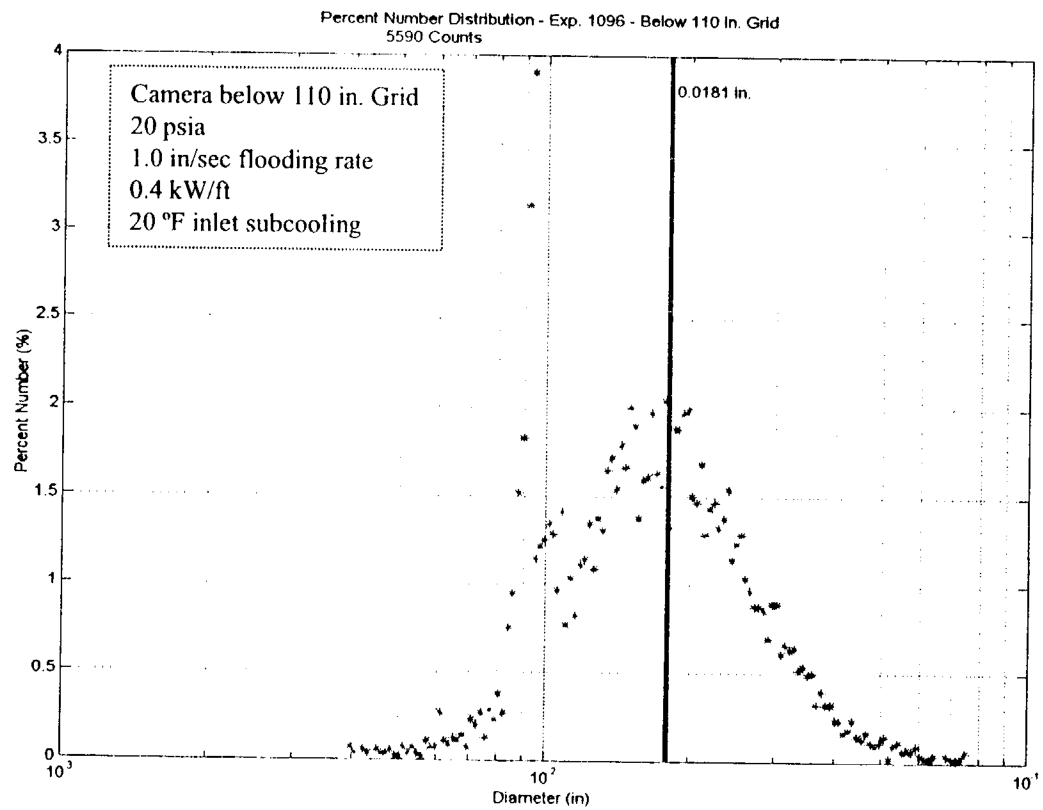
- **Usage of RBHT Data**
  - Reflood Drop Diameter: example of dependence on vapor velocity
    - ➔ Difference between Ardron & Hall data and UCB data may be explained by differing flow conditions.

      Ardron & Hall reported exit steam velocities:



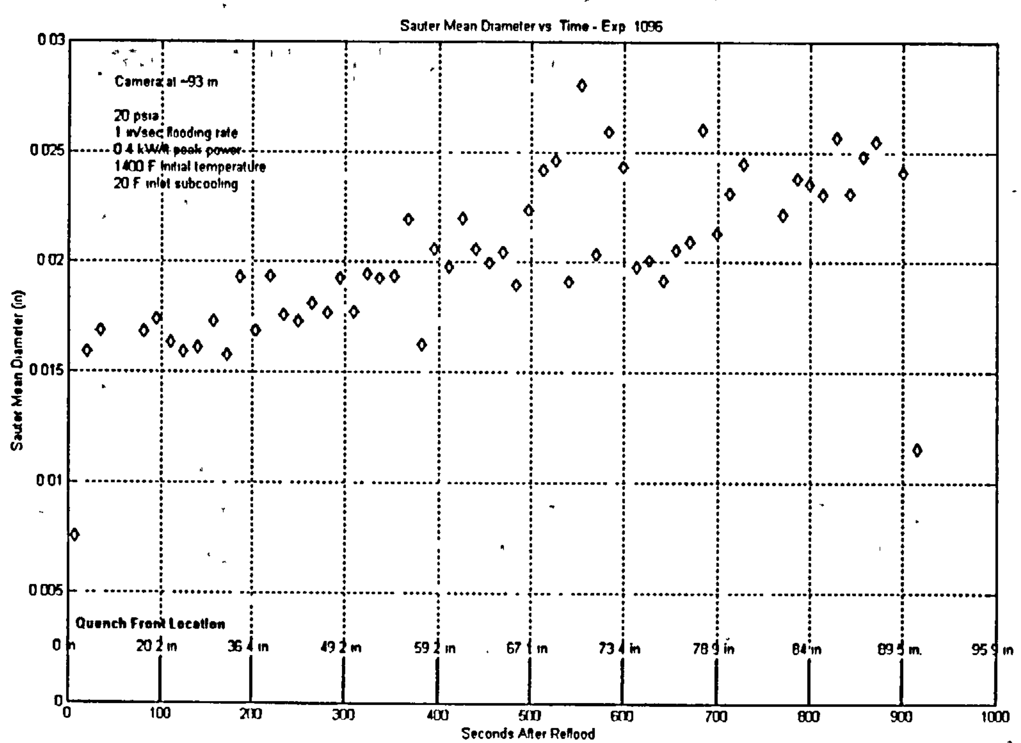
Reflood Model Development Needs
Dispersed Flow Film Boiling

- **Usage of RBHT Data**
  - Drop diameter: distributions based on large populations:



Reflood Model Development Needs
Dispersed Flow Film Boiling

- **Usage of RBHT Data**
  - Drop diameter:
    - Evolution of diameter vs. time provides potential for correlation versus flow conditions.

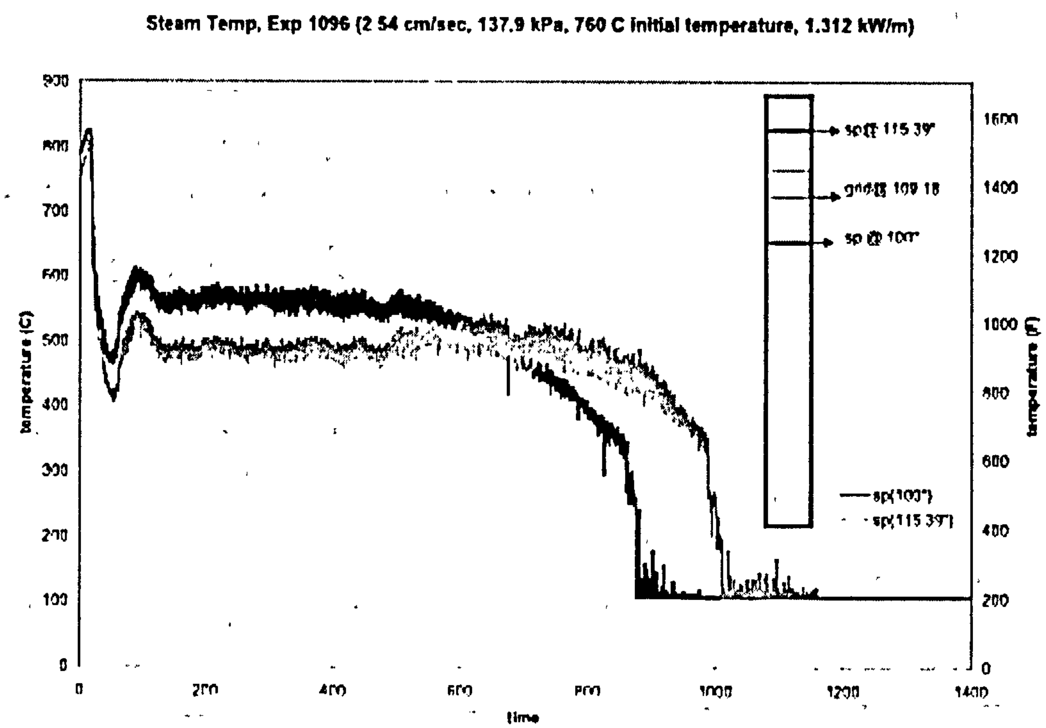


Reflood Model Development Needs
Dispersed Flow Film Boiling

- **Usage of RBHT Data**
  - Wall-Fluid thermal radiation
    - RBHT provides no direct data, only validation for predictive capcbility of combined models.
  - Wall-Structure thermal radiation
    - RBHT data from heatup experiments will allow assessment of CHAN component radiation model.
  - Grid Spacer Effects
    - Steam cooling tests will provide data base for model selection or development for single-phase enhancement downstream of spacers.
      - Prototypic mixing vane grid spacers.
      - Fine array of rod thermocouples downstream of grids.
      - Tests at 8 different flow conditions.

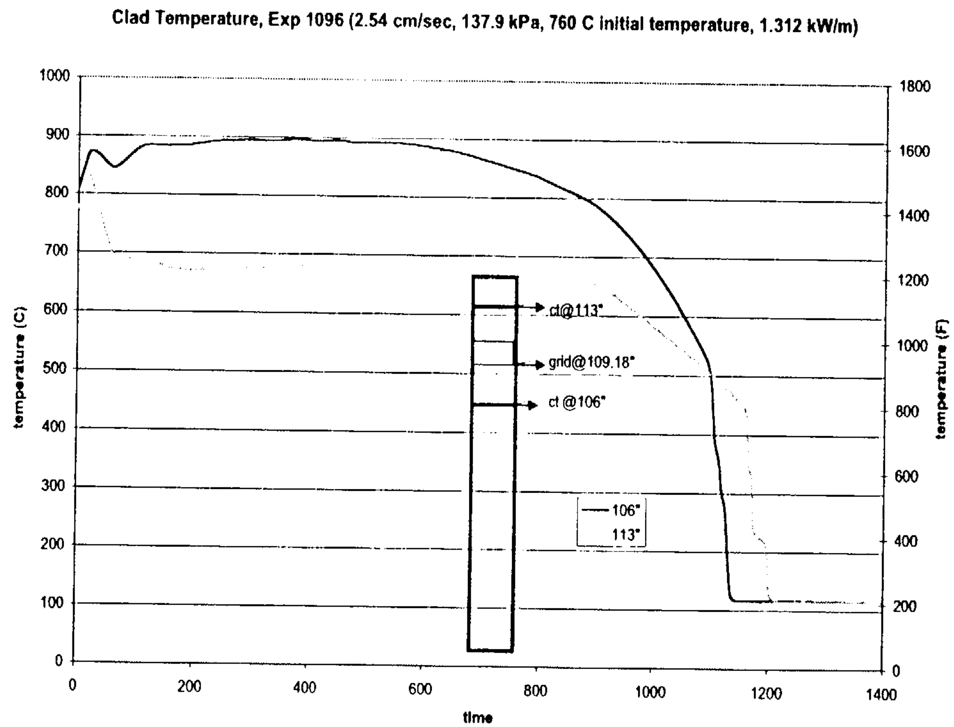
Reflood Model Development Needs
Dispersed Flow Film Boiling

- **Usage of RBHT Data**
  - Grid Spacer Effects (cont.)
    - Two-Phase enhancement is result of vapor desuperheating caused either by grid rewet or droplet shattering.



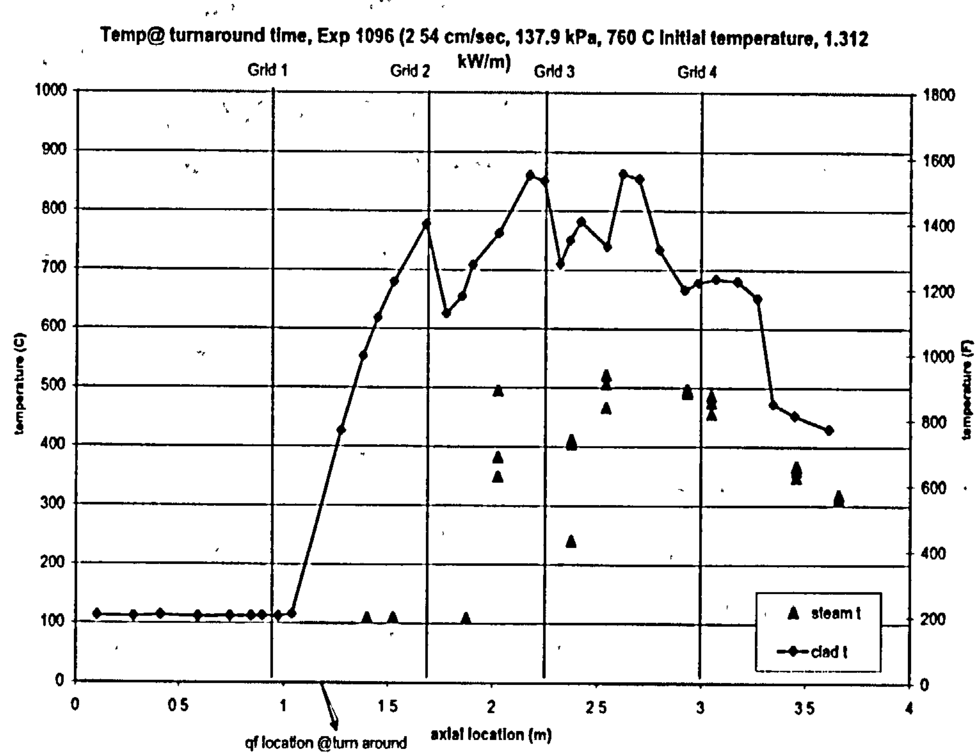
Reflood Model Development Needs
Dispersed Flow Film Boiling

- **Usage of RBHT Data**
  - Grid Spacer Effects (cont.)
    - ➡ Large effect upon clad temperature in upper regions of the bundle for low reflood rate tests.



Reflood Model Development Needs
Dispersed Flow Film Boiling

- **Usage of RBHT Data**
  - Grid Spacer Effects (cont.)
    - RBHT data provides axial evolution of rod and vapor temperatures that can be used for model validation and/or selection.



Reflood Model Development Needs
Dispersed Flow Film Boiling

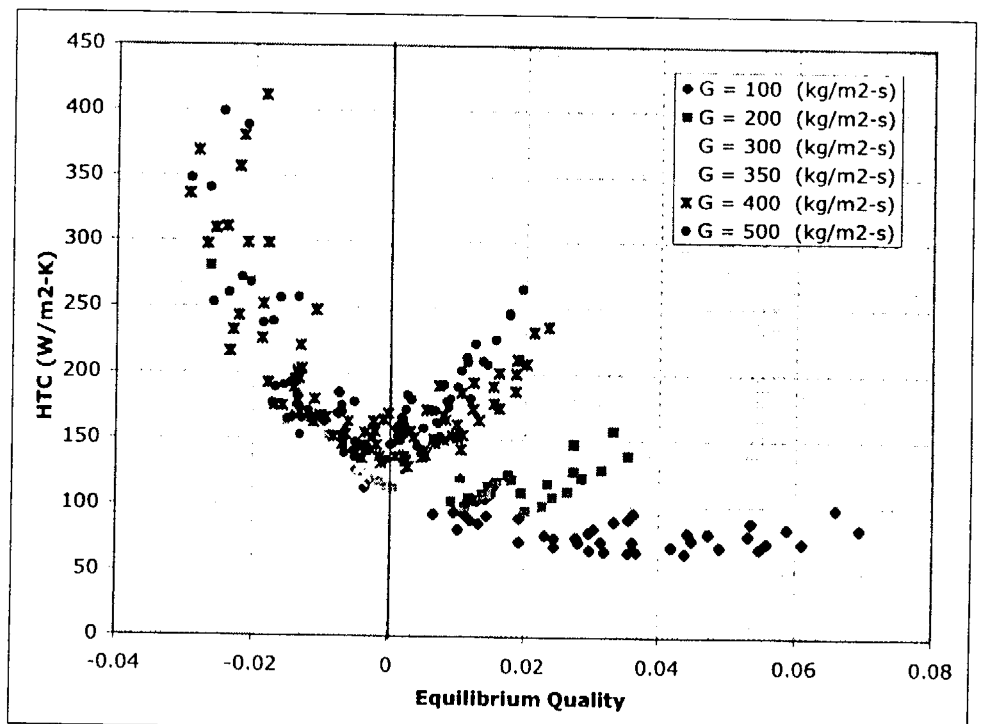
- **Usage of RBHT Data**
  - Grid Spacer Effects (cont.)
    - Droplet injection and reflood tests will provide data base for model validation and possibly for development.
      Available data:
      - Grid condition (dry or wet)
      - Droplet flow rate and diameter (upstream & downstream of grids)
      - Droplet velocity (maybe)
      - Vapor flow rate and temperature
      - Rod heat flux and temperature (fine array downstream of grids)
    - High temperature reflood tests may be needed to distinguish between effects of droplet shattering and wet grids.
      Because of modest clad temperatures (< 1000 K), grids rewet early in first series of RBHT tests, not prototypic for 95th percentile PCTs.
      Criteria needed for grid rewet.

Reflood Model Development Needs
Inverted Slug Film Boiling

- **Importance**
  - For normal reflood conditions, this regime is more extensive than the inverted annular film boiling regime, and
    - The vapor generation from the combined film boiling and quench front heat release provides the inlet condition (m_d, G_v, T_v) to the dispersed flow region where the peak clad temperature occurs.
    - The flow conditions probably govern the droplet diameter.
- **Background:**
  - Unable to find a heat transfer model for this regime.
  - Most codes view it as a transition regime and interpolate between their models for inverted annular and dispersed flow.
  - Codes tend to under-predict heat transfer for low-quality medium-high flow rate conditions, do not have correct trend with mass flux.

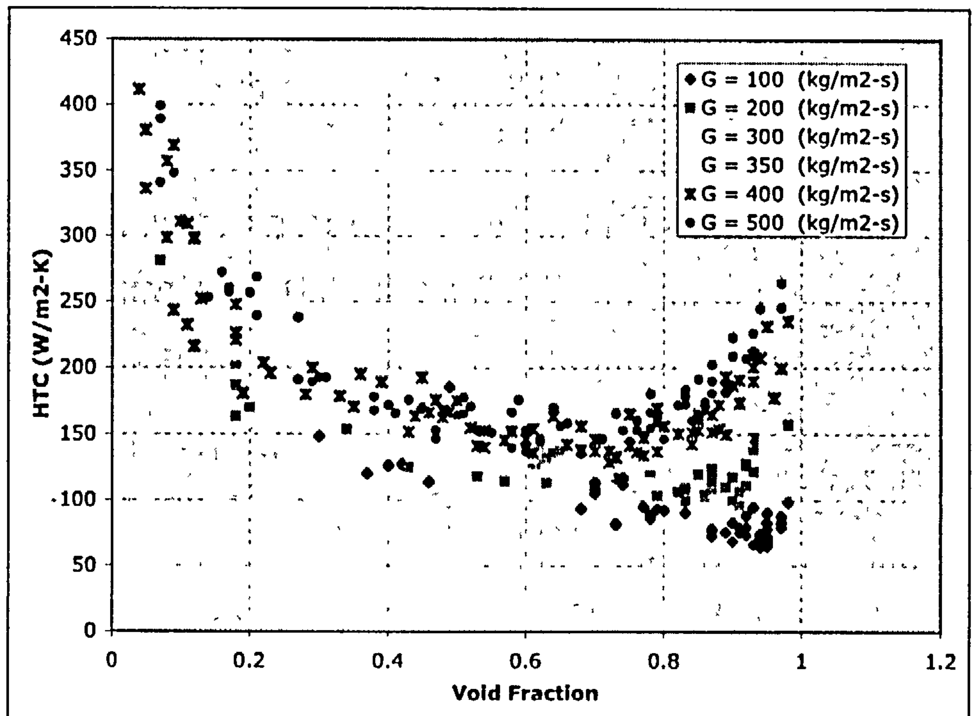
Reflood Model Development Needs
Inverted Slug Film Boiling

- **Background**
  - Fung low-quality film boiling data
    - HTC for positive quality increases as the quality increases, indicating that the primary heat transfer mode is convection to vapor.



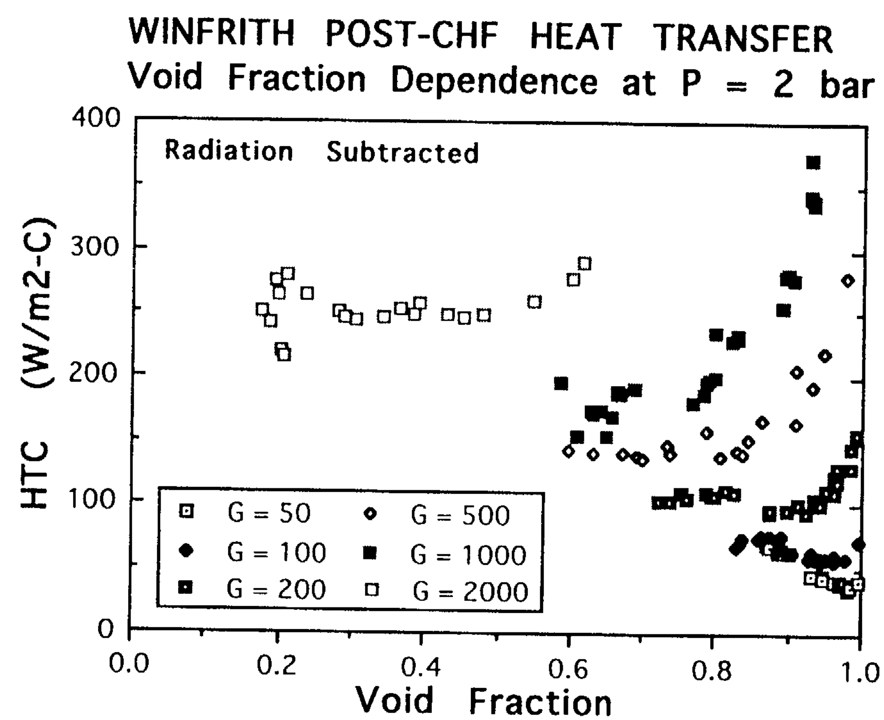
Reflood Model Development Needs
Inverted Slug Film Boiling

- **Background**
  - Fung low-quality film boiling data
    - ➜ HTC for positive quality increases as the void fraction increases, helping to confirm that the primary heat transfer mode is convection to vapor.



Reflood Model Development Needs
Inverted Slug Film Boiling

- **Background**
  - Winfrith “hot patch” film boiling data
    - ➡ Displays same basic trends as the Fung data.



Reflood Model Development Needs

Inverted Slug Film Boiling

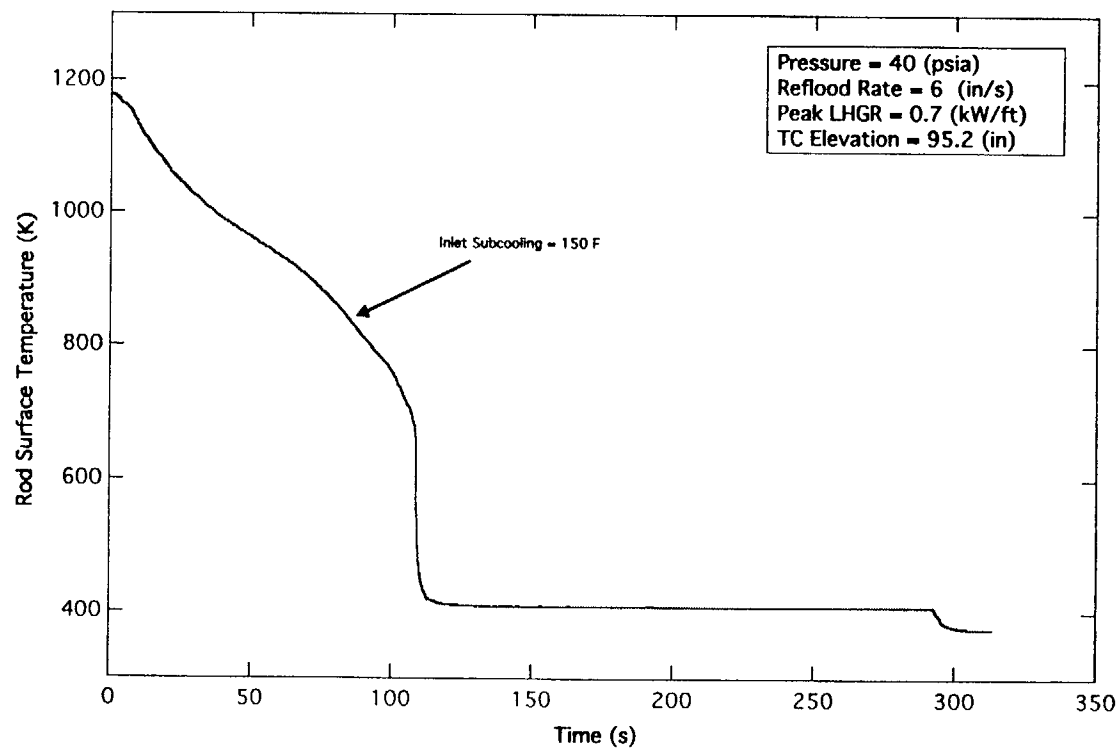
- **Background**
  - RBHT "IAFB" test matrix was designed to investigate this regime by using quench front subcooling as a parameter in addition to mass flux.

Case	Pressure (psia)	Flooding Rate (in/s)	Peak Power (kW/ft)	Inlet Subcooling (deg F)	Initial Temp. (deg F)	QF. Quality[1]	QF. Void Fraction	Comments
5	20	6 0	0.7	150	1600	-0.1146	-	- laser above 90" grid.
6	40	6 0	0.7	150	1600	-0.1181	-	- laser above 90" grid.
7	60	6.0	0.7	150	1600	-0 1208	-	- laser above 90" grid.
8	40	6 0	0.7	96	1600	-0.0596	-	- laser above 90" grid.
9	40	6.0	0.7	42	1600	-0 0005	-	- laser above 90" grid.
10	40	6 0	0.7	20	1600	-	0 554	- laser above 90" grid.
11	20	6.0	0 7	42	1600	-0 0009	-	- laser above 90" grid.
12	60	6 0	0.7	42	1600	-0 0003	-	- laser above 90" grid.
13	40	3 0	0.7	136	1600	-0 0595	-	- laser above 90" grid.
14	40	3.0	0 7	82	1600	-0 0000	-	- laser above 90" grid
15	40	3.0	0.7	41	1600	-	0.556	- laser above 90" grid.
16	40	10 0	0 7	134	1700	-0.1183	-	- laser above 90" grid.
17	40	10 0	0 7	80	1700	-0 0599	-	- laser above 90" grid
18	40	10 0	0.7	25	1700	.00006	0 003	- laser above 90" grid.

[1] For quench front at 53 inch elevation, which is the beginning of the span of fine delta-P cells.

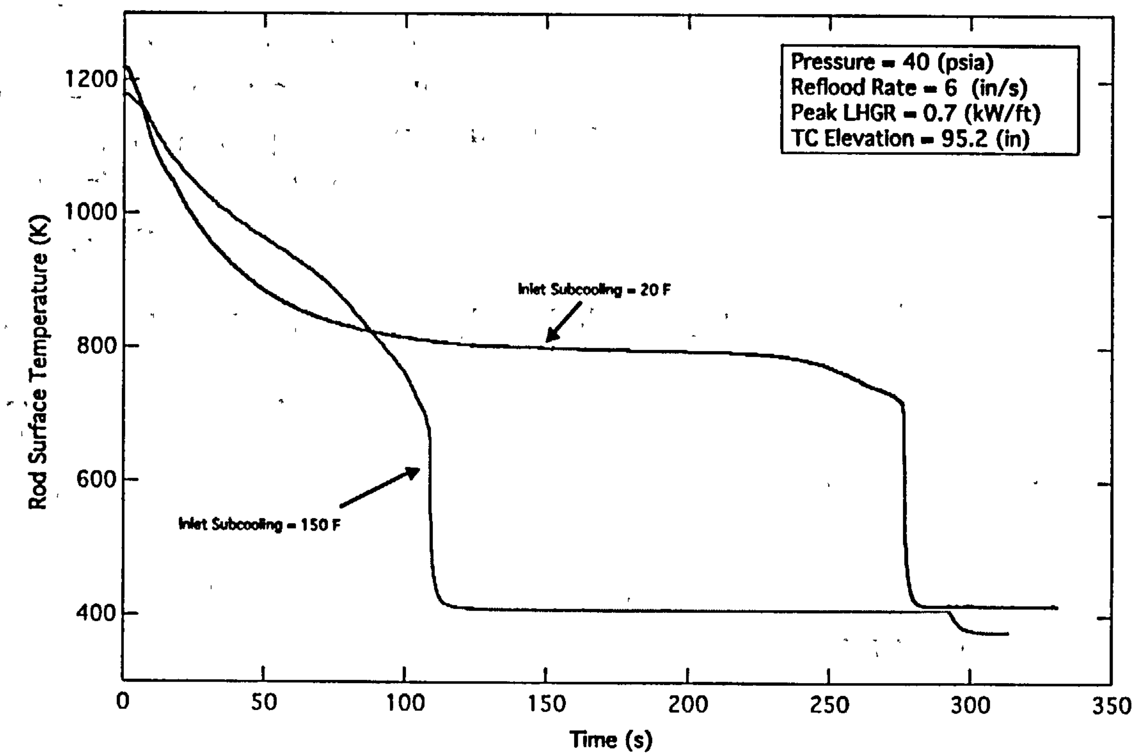
Reflood Model Development Needs
Inverted Slug Film Boiling

- **Background**
  - RBHT results for high inlet subcooling display similar heat transfer behavior to FLECHT-SEASET tests.



Reflood Model Development Needs
Inverted Slug Film Boiling

- **Background**
  - RBHT results for low inlet subcooling display markedly different heat transfer behavior than that observed in FLECHT-SEASET.



Reflood Model Development Needs
Inverted Slug Film Boiling

- **Constitutive Models Needed**
  - Primary wall heat transfer mode is convection to vapor .
  - Models needed are:
    - Wall-Vapor heat transfer
      includes two-phase enhancement effect.
    - Vapor- Interface heat transfer
    - Wall-Liquid radiation heat transfer
    - Interfacial drag
    - Effective drop diameter (liquid fragments)
  - Note: both the interfacial heat transfer and the interfacial drag are expected to be substantially enhanced above normal droplet models due to distortion and multi-particle effects.
- **Usage of RBHT Data**
  - Only validation of combined model can be performed, comparing predicted heat transfer coefficient and void fraction to data.

Reflood Model Development Needs
Transition Boiling

Importance

- Initiation of transition boiling largely governs the quench front velocity.
  - ➔ i.e., the time necessary to cool the surface to the quench temperature
- Quench front heat release can be a major component of the vapor generation rate which provides the boundary condition for the dispersed flow film boiling region.

Background

- The value of "Tmin", the criterion for onset of transition boiling, has a large impact on fraction of core quenched during blow down.
- The "maximum heat flux" during quench is usually modeled as the CHF, its magnitude has little impact as long as it is sufficiently large.
  - ➔ Griffith modification of Zuber CHF can adversely affect quench front propagation by substantially under-predicting this maximum.
- Code oscillations have been traced to the poor behavior of transition boiling heat transfer correlations.

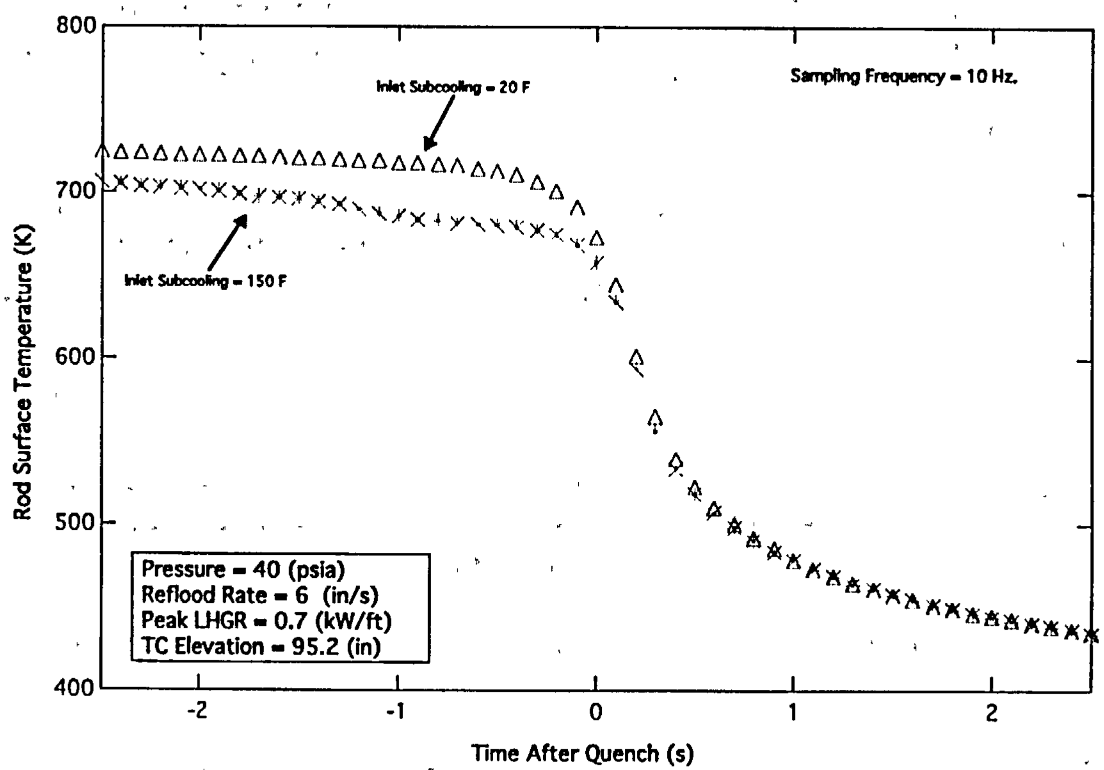
Reflood Model Development Needs
Transition Boiling

- **Constitutive Models Needed**
  - Minimum Film Boiling Temperature: "Tmin"
    - ➡ Should include material property effects for oxidized fuel rods.
  - Maximum Heat Flux
    - ➡ Needed for both bottom reflood and falling-film quench fronts.
    - ➡ Expected to have dependence upon pressure, mass flux, and subcooling or void fraction.
    - ➡ Is not necessarily the same as the critical heat flux due to burnout or annular film dryout.
  - Transition Boiling Heat Transfer Coefficient
    - ➡ Needs to be consistent with the maximum heat flux point and Tmin.
    - ➡ Must have good numerical behavior, that is, not the initiator of large oscillations.

Reflood Model Development Needs
Transition Boiling

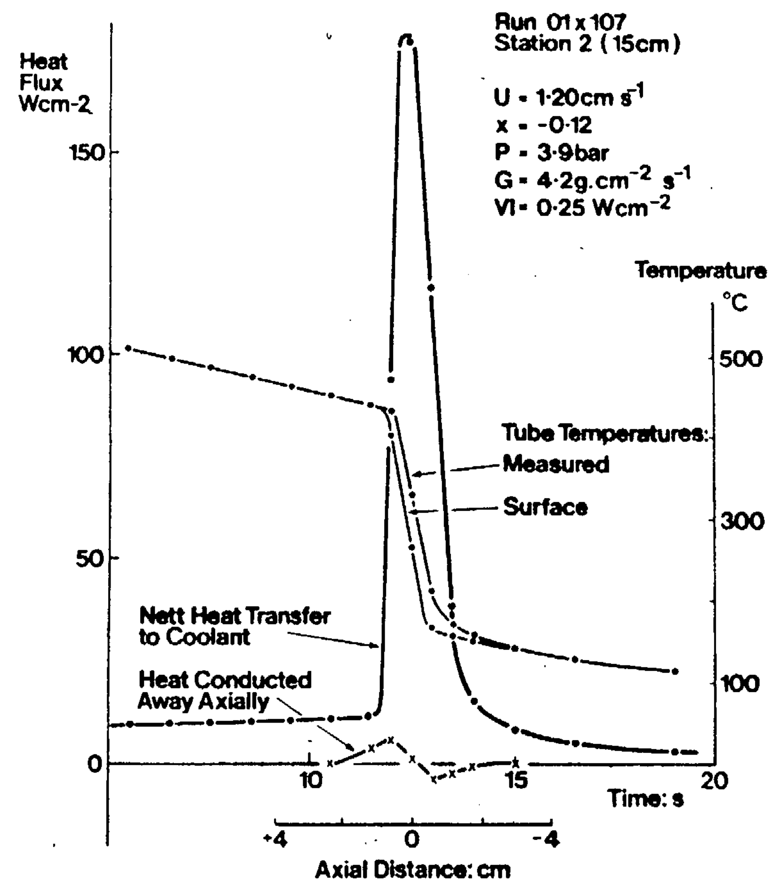
Usage of RBHT Data

- Rod temperature sampling rate increased to 10 Hz so that wall heat flux can be inferred by 2-D inverse conduction.



Reflood Model Development Needs
Transition Boiling

- **Usage of RBHT Data**
  - Maximum Heat Flux
    - Example of maximum heat flux during quenching inferred by 2-D inverse conduction for Reflex reflood tests.
    - Provide data base for model selection for both the maximum heat flux and transition boiling heat transfer coefficient.
  - Minimum Film Boiling Temperature
    - Can be inferred for Inconel-600 from RBHT data without using interpolation scheme needed for FLECHT-SEASET.
    - Need other data (e.g., ANL quench tests) for zirc with oxide.



Reflood Model Development Needs

Normal 2Φ Interfacial Drag

- **Importance**
  - Reflood rate is determined by a balance between buoyancy and frictional losses, the void fraction below the quench front can be an important contributor to the driving force.
  - Highly important for passive plants during depressurization and long term cooling phases of SBLOCA.
- **Background**
  - During AP-600 assessment, RELAP5 was shown to over-predict void fraction in rod bundles for low pressure conditions.
  - Available void fraction data for low pressure conditions in rod bundles is limited.
- **RBHT Data**
  - Series of 75 interfacial drag tests planned for 2003-2004.
    - ➡ 3 pressures, 5 liquid mass fluxes, 5 power levels.

Rod Bundle Heat Transfer Program

- **SUMMARY:**
  - It is anticipated that best-estimate analyses will be increasingly used by licensees to request power & peaking factor upgrades.
    - NRC needs a best-estimate analysis tool for LBLOCA that has minimized uncertainty and can be used with confidence to confirm operating plant limits.
  - TRAC-PF1/MOD2 reflood model is overly complicated and vulnerable to numerical oscillations:
    - a simpler model based on rod bundle data is needed.
  - Existing rod bundle reflood & blowdown data will be analyzed to provide local conditions for model assessment & development.
  - RBHT experimental program is providing detailed data for model selection or development and "fundamental assessment".
    - Provides data not available from FLECHT-SEASET or other reflood tests.