MR. BAJOREK: We have to partition it. It's basically using model by -- and you come up with a partition and then you also have to come up with a model for the condensation in order to --

CHAIRMAN WALLIS: To get back to Professor Schrock's question, I would think that Professor Dhir would have the assignment of develop better understanding of the physics and then tell us how to put this into the code. It looks as if he's got an assignment to understand the physics. And the way in which this is related to what actually has to go into TRAC seems to be a very important part of the problem. Is he doing that?

MR. BAJOREK: No, that's going to be our job.

CHAIRMAN WALLIS: I'm not sure you can. I think he has to do it. I would assign him of making the burdens, because then he knows what he's got to measure and what he's got to model. If he just goes off into an academic world and models everything he's interested in, that's not the same thing as getting an engineering model that goes into TRAC-M.

MR. BAJOREK: No, I don't --

MR. KRESS: You're presupposing that V.J. doesn't know what the code meets?

CHAIRMAN WALLIS: I don't know. I'm just saying it should be part of his environment.

MR. BANERJEE: He may know, but he may not want to do it.

MR. SCHROCK: I'd just like to say amen if I do it.

DR. MOODY: Well, as I read this report, I got knowing a little bit about the way V.J. operates. I got the feeling that you were asking him to do kind of a -- on a bottoms up study that you could incorporate into a top down model. In other words, a microscopic lab study that will give some clue and I thought probably on his data that he presented in correlations, that's what you were going to use to incorporate into the TRAC code.

MR. BAJOREK: Yes.

DR. MOODY: Somehow.

MR. BAJOREK: We need to know the individual mechanisms that dominate that split. It's going to be up to us to make that we can take those things, put in the variables, code those in such a format that it can replicate the model that you might come up with in a lab or, you know, in a more academic setting. And we realize that there are always going to be shortcomings in a two-fluid code that's not going to get us down to a CFD type of modeling of any process. But at some point if we know the physics and if we know models which are mechanistic and can be faithfully used to represent what goes into a rod bundle, whether it's, you know, a GE type or a Westinghouse type over a range of subcoolings, then we're going to have the confidence to put the models in the code and get realistic results.

And I think, you know, in going back to this there may be something physically real that's going on, but we went additional steps in this to go back and note when you had a large blip it was when a ramp was being turned on and off in the subcooled boiling model. So it wasn't just, you know, pointing finger --

MR. RANSOM: Well, I would take issue with that, too. What actually turns out interface drag is very important to this kind of prediction. And if you don't pay attention to that, you know, it doesn't matter what you do in the heat transfer partition, you're not going to get the right answer either. So, this has to be looked at in that global way.

And, as a matter of fact, you know, in the subcooled boiling experiment that we're going to talk about I didn't see any real discussion or consideration of that. And that goes back to how are you going to put this in the code. And I think there are other issues, too, that we have to talk about.

CHAIRMAN WALLIS: Would you go back to your first slide and do it properly, and you could say that in order to predict the average boiling and I have to know how many nucleation cites there are, at what temperature they're activated. I need to know how rapidly those bubble grow attached to the wall. I need to know when do they move away from the wall. Do they grow some more when they leave the wall.

MR. BAJOREK: Right.

CHAIRMAN WALLIS: How do they move away from the wall in a transverse direction. Are they carried along in the axal direction. And then when do they begin to condense and how rapidly do they condense.

And what I see from his book is there's some work on when they start to form and how many nucleations sites are there. And there's some work on isolated bubbles condensing. But where's all the rest of what's going on that you need?

MR. BAJOREK: If we're concentrating on the head transient, we haven't looked so much at the interfacial drag at this point, no.

CHAIRMAN WALLIS: And they've tracked this interfacial drag, which has nothing to do with what I've just talked about, how does it, you know, influencing the result anyway because of the TRAC model?

MR. BANERJEE: Well, interfacial drag will surely influence the condensation rate. Because in a way that's Reynold's analogy, right. So you have to have an effect of the drag on the --

CHAIRMAN WALLIS: Well, it would probably accelerate the bubbles to the same speed as the fluid and there won't be any Reynolds --

MR. RANSOM: Well, in fact the nestled number is the function of the relative Reynolds number. The Reynolds number is based on relative loss--

MR. BANERJEE: I guess the main point here, Steve, that there should be framework laid out to receive these results. And what is not clear is what that framework is.

MR. BAJOREK: Okay.

MR. BANERJEE: So we don't have a set of equation saying this is what's lacking in these equations or this is where we need more information. These the TRAC equations. These are the numbers that we're going to get out of -- whether that interfacial area or whatever, heat transfer --

MR. BAJOREK: Yes.

MR. BANERJEE: It's not clear how that data is getting fixed into TRAC. And that might not be trivial to do. That's really the issue. It's sort of difficult because you've got -- if you put distribution coefficients in for the temperature or something so you have subcooling at the wall, something like that, you might get somewhere into that regime. But it's not trivial to phrase this in, at least I don't see it as trivial. You did this job.

CHAIRMAN WALLIS: You have to go to a microphone. You have to say who you are.

MR. DHIR: I'm V. J. Dhir from UCLA.

The key difficulty when we started this work was with the cores that they could not -- they did not know what the repagination date was. What was the source -- fraction. When you give a source term you've got to give number density of bubbles, size of bubbles and rate at which they're being injected into the boil. So that information we're trying to provide.

Then they also need to know what is the local liquid temperature. That is effected not only by the heat transfer from the wall the liquid, but also by condensation. So you need to know what rate the bubbles will be condensing. So that's the problem that we have looked at.

MR. RANSOM: In fact, that brings up an interesting issue. It's not the local temperature that you need to know in these codes, it's the bulk temperature that you reference to. It's the bulk liquid temperature which in the heat transfer coefficient between the bubble and the bulk of the liquid you must use.

And I know in a paper that I was reading it went to great pains to measure the temperature at the bubble, which of course is not the code variable.

MR. DHIR: Right. But if you look at it it really depends on how much resolution you want to have in the code. If there's only cell over the whole -- you could have some average temperature. But what you look at it, or we looked at it, there is a thermal boundary layer which is, you know, temperature changes very rapidly in that region. Beyond that it's like bulk temperature.

MR. RANSOM: And that's quite a different model than the model that you use in these one dimensional codes. Maybe there needs to be some coming together.

MR. BAJOREK: Okay. I mean we aren't finished with this. I mean, we still have to get these models, understand them better, find a way to put them in the code. But, you know, our looking at what is in TRAC-M right now and similar codes leads us to believe that the models and the way they're treated now aren't acceptable. You do your best with the available data to look --

MR. RANSOM: Steve, let me ask you a question along that lines. There's quite a database out there for subcooled boiling and internal geometries. And did you ever -- and I'm sure that was utilized in the development of these models. So what is the explanation between, you know, those separate effects assessment in all the models, then not giving you good results in this case?

MR. BAJOREK: What is it? I'm sorry. I couldn't hear you.

MR. RANSOM: I can't speak for the TRAC-M, I guess, but I can speak for the RELAP-5 part. They did use very -- they used Christian, they used St. Pierre you, his experiments to validate the subcooled boiling models. And you got reasonable results in most cases. So I'm wondering why -- there should be some explanation, I guess, for why this --

MR. BAJOREK: Why? If that model's so good, why couldn't it get things like bubble diameters or interfacial drag in a newer test like McMasters?

MR. RANSOM: Well, the guess that I would have is that's simply a critical number that's used to decide the bubble size and --

MR. BANERJEE: Maybe I should interrupt here. Because I think, you know, Dick Lahey did an interpolation between Unal's experiments and some other stuff. And he never actually broke it into interfacial and heat transfer coefficient. He just call it product of them.

MR. RANSOM: Yes, the multiplier.

MR. BANERJEE: Yes. And in fact what you guys put into RELAP was Lahey's thing.

Now, what happens here this is -- Dave, I don't know how they've separated it into bubble diameter, but it looks like the -- in my opinion, the interfacial area in that was roughly right. They got the heat transfer coefficient completely wrong. So it's the opposite problem to what you're seeing here. So because of the getting the heat coefficient completely wrong, they got the void fraction completely wrong because --

MR. RANSOM: In this case you mean?

MR. BANERJEE: In this case.

MR. RANSOM: Well, this is the Chen correlation for the overall --

MR. BANERJEE: No, no. This is the McMasters experiment where there were bubbles condensing in a subcooled liquid. So the bubble diameter was followed. This was not attached to the wall.

MR. RANSOM: I see.

MR. BANERJEE: These were just steam bubbles. So it's a condensation experiment basically.

MR. RANSOM: Who did that?

MR. BANERJEE: This was an old friend of mine, a guy name Shukri or something.

And what happened was in these experiments that they could measure of the diameter of the bubbles as well as the rate of condensation. If remember right, though, the reason these experiments are so wrong compared to RELAP-5 is not the interfacial area. It's the heat transfer coefficient.

MR. RANSOM: Between the bubble and the bulk of the --

MR. BANERJEE: Yes, between the bulk. And there's a very nice graph in the report by Joe Kelley which actually shows the incorrectness in the heat transfer coefficient. So the problem has not been-- Lahey's coefficient was basically an interpolation.

MR. RANSOM: Well, Lahey's correlation does not tell you what the heat transfer between the bubble and the bulk is. It only divides between the sensible heat and the heat of vaporization. So it tells you how much vapor is being produced.

MR. DHIR: That's Lahey's model, but it doesn't work.

MR. BANERJEE: It doesn't work.

MR. RANSOM: Well, it works rather well in the codes of --

MR. BANERJEE: It works in certain regime, but doesn't work.

MR. BAJOREK: That's the rollover term that's in there.

MR. SCHROCK: These data are steam injected into flowing subcooled liquid.

MR. BANERJEE: Yes, single bubbles. Well, this area of bubbles.

MR. RANSOM: Oh, this is the McMasters -- I see.

MR. SCHROCK: Doesn't that depend on what the diameter of the bubbles injection.

MR. BANERJEE: Well, it was larger. It went up, it condensed and they were followed with a camera.

MR. SCHROCK: But single bubbles going up the core --

MR. BANERJEE: Yes, single or multiple, but they were in tubes. In fact, you get a very good correlation of the heat transfer coefficient with the interfacial drag which you can estimate very easily in this problem. So when you correct the heat transfer coefficient with a Reynolds analogy here, you get almost a perfect correlation. That was the heat transfer coefficient, you get that.

MR. SCHROCK: It seems to me that the situation in the subcooled flow boiling channel is different from that in the sense that there's a radial distribution of liquid temperature which you don't know.

MR. BANERJEE: No.

MR. SCHROCK: But it exists. And the amount of vapor that's formed at the wall is in part dependent upon that. So the amount that detaches from the wall and is then part of the flow process is different than in this kind of experiment.

MR. BANERJEE: It's a pure condensation

experiment.

MR. SCHROCK: Both the growth and the condensation occurred in the subcooled boiling flow situation, but only condensation occurs here.

MR. BANERJEE: Correct.

MR. SCHROCK: And so you can't get the right void fraction in subcooled boiling, shouldn't expect to bring those two things into reconciliation--

MR. BANERJEE: Yes, we shouldn't give too much credence to this other than knowing that the condensation rate is wrong.

MR. BAJOREK: What's in TRAC-M right now could have been used to compare to FRIGG, some other experiments. Some comparisons look good, others don't. It's based on the Saha-Zuber model. It's shown graphically over here in Saha-Zuber to get that total heat transfer where things are thermally dominated. Assume it's a Nussett number of 455 when it's hydrodynamically dominated, it comes to a constant Stanton number of .0065. That's what was used, that's what was in the --

CHAIRMAN WALLIS: How do you know if it's .0065 and 01065. There are two different statements there.

MR. BAJOREK: That's part of my point.

This is what was used to correlate various water and freon data in the original. That's not within TRAC-M, which in some cases get good agreement, some cases doesn't. Based on some work that was done at Savannah River in a single tube and down flow, at some point those were adjusted so that in a thermally dominated region, which they defined as being a Peclet number less than 7,000, not a Peclet number of 70,000 in the original model. They say let it be a Nussett number of 74.55. When you get to bubble liftoff, make it a Stanton number of .0165.

I've taken this and plotted this versus Saha-Zuber, which in the TRAC-M documentation is being claimed as the basis, the foundation, for the subcooled boiling model.

MR. SCHROCK: Where did the TRAC-M modification come from?

MR. BAJOREK: It claims to have been based on some Savannah River work that had been done for looking at single tube flows and downflow. This is what --

MR. SCHROCK: Another unnecessary complication thrown into this. We're not interested in downflow here.

MR. BAJOREK: Well, that's the point. I

mean, if you have a good model, you should have been able to match that subcooled data as well as this.

MR. SCHROCK: Why?

MR. BAJOREK: If your model is truly mechanistic and you're getting the bubble size, the condensation rates.

MR. RANSOM: Steve, a little further comment. The results you show are using TRAC or RELAP-5 and yet the correlation you're talking about is TRAC-M. And so I'm wondering what is the connection, you know, between the two

MR. BAJOREK: The connection is both of those are attempting to base their models on something that looks like the Saha-Zuber model.

MR. RANSOM: Well, do you have some TRAC-M calculations that show that they don't behave correctly then:?

MR. BAJOREK: Not today, but next time we get together I'll try to get those.

MR. RANSOM: Well, you're blaming on this correlation. And what I'm wondering was the basis for criticizing the correlation if you have not actually utilized it.

MR. BAJOREK: What is in TRAC-M is many ways very similar to what is in RELAP.

MR. RANSOM: I agree with -- well, RELAP uses the 70,000 transition point.

MR. BAJOREK: Right. But it's using the same -- overall the same type of scheme to come up and do the splitting. Our bottom line is when we look at those models and how either one of them as compared to data, we're not comfortable with either one of those models as an eventual subcooled boiling model in TRAC-M. So the fact that we had oscillations in RELAP which was the code that we needed to use for the AP600, we weren't satisfied with what had been pointed to as the subcooled boiling model there. When we look at what had been put into TRAC-M, however it got there, that's what's in there right now.

MR. RANSOM: And they used the Lahey model for partitioning the energy between --

MR. BAJOREK: It's close. It's not the same thing. I don't see the roe over roe term.

MR. SCHROCK: Who is "they"? Could I ask it in this case?

MR. BAJOREK: They being -- I think this was -- this was Los Alamos that had redone the heat transfer several years ago.

MR. RANSOM: This TRAC-M modification was done several years ago?

MR. BAJOREK: Yes.

MR. RANSOM: As a part of the TRAC-M thing or --

MR. BAJOREK: I don't know for sure.

MR. RANSOM: I mean, TRAC-M has been going on for more than 4 years, but --

MR. BAJOREK: I don't know if this was specifically put into TRAC-M to be TRAC-M or was something that had been in one of the TRAC-P or TRAC-B that had been grandfathered over into TRAC-M. I could find that out, but I don't know.

MR. RANSOM: Okay.

CHAIRMAN WALLIS: You have a new slide now?

MR. BAJOREK: Yes. This is a new slide to show you what is in TRAC-M, not by way of saying this is what we think is the right way of doing it, but to show you that what TRAC-M does in a way of getting at this partition is to put on a subcooled weighting factor and another evaporation factor that it claims goes back to Lahey to adjust the heat transfer coefficient that you get out of this modified Saha-Zubar.

Now, if you go to other codes they're doing something similar, okay. Or they'll change this and they'll use a different model for this ramping, and they'll change something over here with the vaporization in order to try to get this split. In some cases it works against the data. It other it falls flat. And our argument is that the model no longer has a basis, okay. If the one in TRAC-M has been changed, some data, that we may not even care about for reactor safety applications.

CHAIRMAN WALLIS: Professor Dhir is going to come with a better alternative, you know, to this.

MR. BAJOREK: Yes.

CHAIRMAN WALLIS: He's going to have --

MR. BOEHNERT: He said that's right.

CHAIRMAN WALLIS: He's going to have a different -- or whatever.

MR. BAJOREK: No. We're going to get away from this taking a overall heat transfer coefficient and slapping on a couple of ramps and at the very least split this up into the individual mechanisms. And if we understand those individual mechanisms, now we an come up with better models that we could somehow eventually put in the code and get the overall net vapor generation that's going into the cell.

CHAIRMAN WALLIS: You mean the amount which is formed by bubble growth minus bubble collapse?

MR. BAJOREK: Yes.

MR. BANERJEE: But it must depend on the size of the cell, right?

MR. BAJOREK: Size of the cell --

MR. SCHROCK: I've got a question about your equation 3 on the last slide.

CHAIRMAN WALLIS: Well, since it's going to be replaced anyway.

MR. BAJOREK: Well, go ahead.

MR. SCHROCK: So what is H subscript WL?

MR. BAJOREK: That's the total heat transfer -- that's the heat transfer or the total heat transfer from the wall. And you get that out of the Nussett number from the Saha-Zuber.

CHAIRMAN WALLIS: Which itself has more correlating perimeters in it.

MR. BAJOREK: Yes.

MR. SCHROCK: But see, WSB is a pure number and FE is a pure number.

MR. BAJOREK: That's a pure number. That's dimensionless. Yes, those two are dimensionless.

MR. SCHROCK: And so the dimensions of H gamma and WL are the same, those are the ordinary dimensions of a heat transfer coefficient?

MR. BAJOREK: Yes. And when you put it all in here with B cell, which is the cell volume and -- it does work out to be -- it's actually a volumetric vapor generation.

MR. SCHROCK: So it's in the definitions of these W and F that there's some physical sense to this H gamma, is it?

CHAIRMAN WALLIS: We should move on. I think we'll move on.

MR. RANSOM: Quickly, is this written up in the TRAC-M manual?

MR. BAJOREK: Yes, it is. Appendix G.

MR. RANSOM: The new one that we got?

MR. BAJOREK: Yes. July 2000 I think is the most recent one.

Okay. So just to quickly conclude. We don't think what we see in there has an adequate database. We don't have an adequate basis for it and the ramps are essentially ad hoc. We wouldn't expect that model to work over --

CHAIRMAN WALLIS: But you're going to release this code before Professor Dhir is finished.

MR. BAJOREK: The beta version.

CHAIRMAN WALLIS: You going to leave it the way it is?

MR. BAJOREK: For the first release it's probably going to have to be that way. But later releases we hope we can change that.

And that's all I have.

CHAIRMAN WALLIS: Thank you.

MR. BAJOREK: Thank you.

CHAIRMAN WALLIS: Very reassuring computation.

MR. ROSENTHAL: While V.J. is going up, we had -- you know, at least from perspective we had some separate effects experimental programs going on and we had some code development programs going on. And I didn't have some key staff, which I now have.

And we're working very hard now to play catchup to glue the experimental programs and the code development far better together.

Steve's been with us for about a year. Joe Kelley has returned to the staff. And now we have the staff to do it. And these guys are starting what ideally would have taken place over the years.

MR. DHIR: Good afternoon.

You know, about 4½ years ago we started on this project of subcooled flow boiling at low pressures, so that was the specific topic. And there we wanted to investigate subcooled boiling through experiments and model development. With me there is one student, one post-doctorate fellow working and they did most of the work.

In the last 4 years we have made several presentations to NRC with respect to the progress we have made. We have published some of the work in various journals and present to conferences. And today I think I appreciate the opportunity to discuss with you what we have done and look forward to your critique.

And it's also kind of interesting to stand here rather than sit there.

The key objectives of this work were to develop a mechanistic basis for subcooled boiling, heat transfer for incorporation in advanced reactor codes. And we had to support this development through laboratory scale experiments on a 9-rod bundle, although before going to 9-rod bundle, we did experiments on a flat plate heater. That provides good geometry for visualization and to do some detailed studies.

A range of parameters of interests were pressures from 1 to 5 bar, mass velocities from 100 to 1000 kilogram per meter square per second, and liquid subcooling, that inlet from zero to 50 degrees celsius. That was the understanding we had when we started the work.

The whole effort was divided into seven tasks.

MR. SCHROCK: Does the at low pressures imply that the interest in the model is just at low pressure or is --

MR. DHIR: Low pressure. Okay. Our main objective was to develop these models at low pressure and validate them, but evidently I think that's doing half the job. We got to extend these models to high pressure and see if we can describe the whole pressure regime. So what we are doing now while validating the models, we are looking at high pressure data as well. Hopefully, to describe the boiling process, if we understand correctly for all pressure.

MR. SCHROCK: Okay.

MR. DHIR: So this total activity was divided into seven tasks. The first task was to conduct the literature search and see what was out there, whether that was sufficient to develop models or we needed more data as the development proceeded.

And from this literature review we developed the database, and then the forming on task was that we now have already what's out there, what we wanted to develop the test plan for the experiments. And that first pre-task almost took the first year of activity.

Thereafter we designed and fabricated a test loop, and that test loop we used first a flat plate geometry for the heater and subsequently we used a 9-rod bundle.

And then the task 6 was to develop a preliminary model.

And last task is to validate the model with subcooled flow boiling heat transfer data at low pressures and then eventually all pressures.

And currently we are in the last stages of task 7. We are told that there's a sunset rule, so in the next 3 or 4 months this activity will be stopped and something new will start.

MR. BANERJEE: What's the sunset rule?

MR. DHIR: Namely the 5 year limit on these activities. So 5 years will be over, I guess, in a few months.

MR. BANERJEE: So at that point you can go on to incorporating these into the codes, right?

MR. DHIR: I don't know.

MR. ROSENTHAL: We just have contracts, commercial contracts that go five years and we'll be renewing contracts. There's no -- do the work as long as you have to do it. But, of course, you like to start work and conclude work which frees up monies so you can do other work. But there's no rule.

MR. DHIR: Okay. I give you a little more details of the tasks as we go along.

So we did a thorough search of the open literature and found that there was a number of models had lots of empiricism built into them and these models were very often were inconsistent at subprocess level.

MR. RANSOM: This may be a nitpick, but in your literature review I didn't find any reference to the current models that are used in the code or any discussion of the deficiencies in those.

MR. DHIR: We looked at only mostly published literature. We did not look at the code themselves.

MR. RANSOM: Well, I think a lot of this is in the published literature. You know, the experiments which have been used for validation of the models. I believe Lahey's work is in the literature. The Saha-Zuber work is in the literature.

MR. DHIR: Yes.

MR. RANSOM: Why weren't they discussed?

MR. DHIR: What do you mean discussed?

MR. RANSOM: Well, there was no reference or discussion of the existing models.

MR. DHIR: Saha-Zuber --

MR. RANSOM: Is that to say that existing models are inadequate, I guess.

MR. DHIR: Right. But in the report Saha-Zuber was discussed.

MR. RANSOM: I don't believe it was. I never found any mention of it.

MR. DHIR: Okay. But I think you will see that I would mention to Saha-Zuber.

MR. RANSOM: In these two papers that we received.

MR. DHIR: Okay. But we submitted the reports, and it should be in the reports.

MR. RANSOM: You have delivered a report?

MR. DHIR: But I don't have it here.

MR. RANSOM: But it was given to the NRC?

MR. DHIR: Yes.

MR. RANSOM: Yes.

MR. SCHROCK: So there's a NUREG report that has additional detail?

MR. DHIR: I don't think it's a NUREG report. It was UCLA report which we submitted periodically to NRC.

MR. BAJOREK: We have a couple of progress reports, but in preparation for this meeting we thought a more concise way of looking at the models were the technical papers.

CHAIRMAN WALLIS: It looks as if you're going to cover a lot more than was sent to us.

MR. DHIR: Right. I have submitted viewgraph. So that shows what was mostly summary of what --

MR. BANERJEE: Wear us out, huh?

MR. DHIR: Right.

CHAIRMAN WALLIS: He's going to surprise us.

MR. DHIR: So we found that application of these models to low pressures are suspect. We did a number of studies which have shown that. And there was very limited low pressure experimental data available. Most of the data were at high pressures.

So we compile all of the database, also the experiment to conditions, test setup and so forth. And that report which are titled Experimental and Analytical Studies in Subcooled Flow Boiling and just containing database was submitted to NRC.

Now, let's look quickly at what we are

interested in. As you all know that initially in the heated channel as subcooled liquid enters in and this is first phase, first heat is removed by single phase -- forced convection and if there's resulting flow -- then you have a resulting boundary layer so the heat transfer coefficient will be -- in the actual direction.

At some point on the heated surface you see the nucleation start to occur, and that location we call ONB, onset of nucleate boiling. If one is to predict the complete physics of the processes downstream, one should be first able to determine where nucleation occurs.

This is followed a region where the bubbles are detached to the surface, they're just sitting there, vapor is produced and is condensed on the surface but bubbles do not lift off from the wall and migrate into the bulk liquid. And as we move further downstream, downstream at some location the bubbles start to leave the heater surface. Where this process begins we call OSV, onset of significant voids.

And beyond this point we are producing at the wall some condensation is occurring as the bubbles are attached to the wall or slide along the wall, thereafter the bubbles depart the heated surface and move on to the bulk. Okay.

So the key items we need to discuss as we're looking at the wall region, the physics of the process, is that how the wall heat flux partitions.

CHAIRMAN WALLIS: What does that mean?

MR. DHIR: Partitioning means first just as the wall, how the heat is transfer to, let's say, the liquid. Separate the liquid. Then beyond that how much of that energy goes into production of vapor that goes into the bulk and how much is going on condensation as the bubbles surface, and how much goes directly into the liquid.

Q Is this very different from a model for partitioning that may be in TRAC? Because TRAC doesn't look at all these phenomena. Does the meaning of all heat flux partitioning is something else in the code.

MR. DHIR: No, code need -- what is your-- let's say I have a heat flux of -- what fraction of that energy is going into the bulk as vapor, that's what the core needs.

MR. RANSOM: Into the bulk or into --

MR. BANERJEE: Into just generating --

MR. DHIR: Into the liquid. What fraction is going into the liquid as vapor.

CHAIRMAN WALLIS: I don't understand.

MR. BANERJEE: The code is interested in predicting the void fraction.

MR. DHIR: Correct. Right.

MR. BANERJEE: So there is partitioning-- used by Solbrig if I remember it correctly, of partitioning this -- it was a fix at that time. Was say how much went into generating vapor right at the wall, which means to an attached model. That's where it really --

MR. DHIR: That's a different concept. I'm not going to talk about it. I'm just saying this.

MR. RANSOM: Well, let's say the Lahey model is the same, it's how much energy goes into producing vapor. So you can assume that energy is divided by -- and produces vapor.

MR. DHIR: Right.

MR. RANSOM: The other part goes into the bulk heating for the liquid. And I think that's the same thing.

MR. DHIR: No. You will see that. Mine are different. Okay. What I'm trying to say is this, say you -- again, I will repeat myself.

You have a certain imposed heat flux on

the wall.

MR. RANSOM: Right.

MR. DHIR: I draw an artificial boundary here, okay. And I say how much of this energy from the wall is going into this liquid as vapor.

MR. RANSOM: Right.

MR. DHIR: Okay. So that is that fraction. How much went into the liquid either because these bubbles moved or the liquid removed some heat from the wall, plus how much came in through condensation which occurred when the bubbles-- beyond their boundary and that heat also went as a sensible heat to the liquid. So the liquid got energy either through condensation or directly from the wall, and the vapor was added from the wall. So now you have number density of these bubbles, the size of these bubbles, so that gives you source term and it also gives you what the LOCA and -- of the liquid is.

CHAIRMAN WALLIS: The void fraction is also made it of the ones attached to the wall, which you don't have in that description you just gave.

MR. DHIR: The void fraction of the wall?

CHAIRMAN WALLIS: Yes, that's a separate model as the void fraction --

MR. DHIR: We could put it, but we have

not addressed that. Yes.

MR. SCHROCK: I think there are two points that need clarification on this description.

MR. DHIR: Okay.

MR. SCHROCK: And one is does the code description include vapor generation in this first region of attached bubbles? Bubbles grow and collapse in that region, but don't detach from the wall. There is no two phase flow problem in the sense that the vapor is moving in the axal direction.

In the second region --

MR. DHIR: Right, in this region, that's what we talk about.

MR. SCHROCK: No, the last comment referred to the first region.

MR. DHIR: Right.

MR. SCHROCK: The lowest region.

MR. DHIR: Right.

MR. SCHROCK: Now in the upper region there still is need to sharpen that description in terms of whether this gamma vapor includes the volume of bubbles growing at the wall before they detach or does it account only for vapor which is detached and moving with the stream.

MR. DHIR: I don't -- again, I'm not doing the code. But I think if I were to advise them, they would not include this. They would be just looking at what is leaving the wall.

MR. SCHROCK: Well, there's probably a significant difference in the meaning.

MR. DHIR: Right. Yes.

MR. SCHROCK: I think there has to be a convergence of what you're describing and what they're trying to describe in the code.

But this implies that the void in the attached bubble zone is insignificant.

MR. DHIR: No.

MR. SCHROCK: Yes, how do you find it then?

MR. DHIR: What do you mean how do I find it? Why do I need to know it?

MR. SCHROCK: There is no gamma --

MR. DHIR: Again, see, you're going --

MR. SCHROCK: There is no gamma vapor in the attached region.

MR. DHIR: That's right. In this region.

MR. SCHROCK: Right.

MR. DHIR: Yes. There's no gamma vapor.

CHAIRMAN WALLIS: Well, how do the bubbles get there?

MR. DHIR: There's such a thing on the wall.

CHAIRMAN WALLIS: Is there nucleate on the wall?

MR. DHIR: They're -- on the wall.

CHAIRMAN WALLIS: They're just attached to the wall in residence, they grow and collapse.

MR. DHIR: Beg pardon?

MR. BANERJEE: Those bubbles even before detachment --

MR. DHIR: Right.

MR. BANERJEE: -- have a significant void fraction.

MR. DHIR: Right. They have -- I don't know how significant you call it, but it's maybe --

MR. BANERJEE: It depends on the size of the channel.

MR. DHIR: Yes, right. But it's a -- it's very low density bubble population on the surface.

MR. SCHROCK: Well, they're small compared to the ground stream region.

MR. DHIR: Very small, yes.

MR. SCHROCK: But I'm just looking for some more rigor in definition of terms linking the experimental observation with the code. That's what

I'm looking for.

MR. DHIR: Right. Again, we have not done that part. Okay. We can speculate on it.

MR. SCHROCK: Well, that's a mistaken, V.J. It's not your fault, but it's a mistake.

MR. BANERJEE: Bad boy.

MR. DHIR: What?

MR. BANERJEE: Bad boy.

MR. SCHROCK: Well, in the codes, for example --

MR. DHIR: And that's why I came here to listen to that.

MR. RANSOM: It terms of clarifying it a little, there are no bubbles attached to the wall in the code models, you know. So they sort of only begin at OSV or somewhere around there.

MR. DHIR: Right. Exactly. They don't look at this part. They only begin calculating from here. And they don't know where OSV.

MR. RANSOM: Right. Is that the need? Is the need only beyond OSV?

MR. DHIR: That's right. That's what I would do.

MR. RANSOM: They always tell you the other region.

MR. BANERJEE: The code doesn't distinguish to recommends this partitioned the heat flux --

MR. RANSOM: Well, the beginning or onset of significant voids is the first region, that's considered the beginning of boiling, even subcooled boiling.

DR. MOODY: You've got one part of your study is -- bubbles, diameter --

MR. RANSOM: So it is not really -- that are being attached to the wall.

DR. MOODY: -- so you could track the life of a bubble, is that right?

MR. DHIR: Yes. You can go to -- detail as you want to, but I think we are first discussing what terms mean, what I'm trying to talk about.

This region the void fraction is very low. We can tell you how much void fraction would be, approximately. But it doesn't mean anything to the code. Code are basically starts calculating void fraction from --

MR. SCHROCK: So that's a separate justification. There has to be a prediction of that and a demonstration that --

MR. DHIR: Exactly.

MR. SCHROCK: -- that amount of void is insignificant in terms of whatever the code is interested in.

But in the region of detached bubbles --

MR. DHIR: Right.

MR. SCHROCK: -- there remains the issue of the volume of steam in attached bubbles.

MR. DHIR: Why are you interested in it?

MR. SCHROCK: Well, it's a part of the total void fraction.

MR. DHIR: Right. The question is you're looking at these bubbles are sitting in here and how is that going to effect your -- if you say it will be a secondary effect.

But key question you are wrestling with it, how is this Y profile developing in actual direction.

CHAIRMAN WALLIS: V.J, everything would be helped tremendously if you had your picture here, and you got a picture beside it which says this is what the code says is happened. Code says you have two fluids at different temperatures and so on, but you have interactions between them.

MR. DHIR: Right.

CHAIRMAN WALLIS: Then you have to somehow go from this picture of reality to the idealized picture in the code. It doesn't have anything on the wall, as I understand it.

MR. DHIR: Yes, right.

CHAIRMAN WALLIS: But it -- injects vapor--

MR. DHIR: Injects vapor is right. Exactly

CHAIRMAN WALLIS: Okay.

MR. DHIR: Then that, I'm going to provide that information to them.

CHAIRMAN WALLIS: Okay.

MR. DHIR: You inject the vapor into that and you inject the -- into the liquid, and you know how much is coming out which way.

CHAIRMAN WALLIS: Then the liquid and vapor then interact because they have different temperatures.

MR. DHIR: Temperatures and that's how it is.

CHAIRMAN WALLIS: There's more heat flux, but this would mean a kind of code phenomena --

MR. BANERJEE: Well, it's not exactly what the code does, that's the problem. What we're wrestling with is the wall's partitioning is really --

MR. DHIR: See, again --

MR. BANERJEE: --to the wall.

MR. DHIR: That's not done correctly. Codes are not doing it correct. So why are we going after that? I think they should rewrite that part and, in fact, what I can give you my conclusion, what I find, and Graham mentioned it correctly earlier. I was surprised. That basically the heat going from the wall, all of the energy goes to liquid. Then part of that is converted into vapor and we track how much vapor is leaving the heater surface and how much is going just -- the rest of it is going just to the --

MR. SCHROCK: I'm glad you said that, because I've written that for so many reports to the ACRS I'm a little tired of saying it. The heat is all transferred to the liquid first and then vaporization occurs within that super heated liquid.

CHAIRMAN WALLIS: Were you surprised because I said something correct?

MR. DHIR: Right.

CHAIRMAN WALLIS: Or were your surprised because I gave you new knowledge which you didn't have before?

MR. DHIR: No, I had the knowledge before. But I was surprised because if you look at the codes, that's what we are talking about. And they keep splitting right over from the wall.

MR. BANERJEE: It's an idealization.

MR. DHIR: Not -- incorrect way of counting.

MR. BANERJEE: Whichever way you think of it. But what's happened is the region of the attached bubbles you have to argue has a low void fraction and therefore doesn't give you any significant void for the reactor dynamics calculation.

MR. DHIR: If you want to interpret -- yes, that's the second issue.

MR. BANERJEE: That's what you have clearly show that the void is --

MR. DHIR: No, no, no. No, no, no. This is a different question you're asking.

MR. BANERJEE: But that is a significant--

MR. DHIR: Yes, that is a significant, we will provide you. Because we know the number density of bubbles. We know -- of the bubbles, so I can give you what the void fraction is if that is needed. But I think the recent question we were asked provided --

CHAIRMAN WALLIS: Okay. Presumably it also increases the interfacial fiction fraction.

MR. DHIR: Right.

CHAIRMAN WALLIS: The bubbles on the wall are like a --

MR. DHIR: Right. It's improved heat transfer, too. Basically we look at heat transfer here, all the bubbles are sitting on the surface, the heat transfer basically single phase, and it's higher than would be without bubbles.

CHAIRMAN WALLIS: Okay. Can we move on to the next linked slide.

MR. RANSOM: I would just like to make one suggestion, and that is that you add interface drag or relative velocity between the phases of significant effect, at least in the work that I've done that seems to be a factor.

MR. DHIR: Right.

CHAIRMAN WALLIS: That is part of how we get the heat transfer coefficient between the phases.

MR. RANSOM: Well, so on that slide it should be --

CHAIRMAN WALLIS: On the slide.

MR. RANSOM: -- a variable.

CHAIRMAN WALLIS: Okay. Ready for the next one.

MR. DHIR: Good.

MR. BANERJEE: Is velocity of variable a

net velocity in your --

MR. DHIR: Yes. In that velocity subcooling.

Okay. So basically single phase, your heat is removed by forced convection. The bubbles that are attached to the heater surface, again although there's some condensation going on at the surface, but some heat is gone as a single phase heat transfer from the wall, but there's no vapor production in terms of vapor leaving and going into the bulk. So all of the heat is basically -- as a forced convection heat transfer into the liquid.

In the region beyond OSV we think from the wall heat goes into the liquid either forced convection or transient conduction. That's the key contribution we're making as the bubbles detached or slide along the surface, they break the thermal boundary layer. It has to redevelop and that's the period during which transient conduction occurs. That's the key contribution, I think.

CHAIRMAN WALLIS: Well, we're not going to talk about the middle region at all, so --

MR. DHIR: No. We are going to talk to you a little bit, no, nothing much. Mostly we'll talk about this region and maybe a little bit --

CHAIRMAN WALLIS: So this QSP and QC, you're some sort of drawing a control volume which cuts out the region where you transfer heat to the liquid and then it evaporates in vapor?

MR. DHIR: Right.

CHAIRMAN WALLIS: That's not allowed. So you've joined their control volume beyond the place where there's anymore evaporation occurring.

MR. DHIR: No.

CHAIRMAN WALLIS: Yes. For some of that single phase from the -- we agree that all of the heat transfer is single phase at the wall.

MR. DHIR: Right.

CHAIRMAN WALLIS: And then you've taken out of that the bit which goes into evaporation and then condensation?

MR. DHIR: Right.

CHAIRMAN WALLIS: And that's called something else.

MR. BANERJEE: That's this force convection.

MR. DHIR: Right. This is transient conduction and force convection contributions. That's the total heat from the wall. Okay.

CHAIRMAN WALLIS: I don't understand that.

MR. DHIR: Because the region where there are no bubbles, in this region, heat is still being removed but that's basically by forced convection.

CHAIRMAN WALLIS: I don't understand the subdivision between transient conduction and forced convection.

MR. DHIR: Okay. Let me describe what transient conduction. Transient conduction, let's say bubble departed from this surface. Okay. It's going to slide along the surface and then lift off from the surface. The process is that a nucleation site above it starts to grow, it grows to some diameter which we call departure diameter, thereafter the bubbles start to slide. And then it grows to a certain size and lifts off from the surface.

As it is sliding along the surface it disrupts the boundary layer and over that period or over that region it is basically removed by transient conduction. And I'll show you how graphically what we mean by it, but for the time being we are saying that the heat is removed over that portion over which the bubbles slide is by transient conduction or if the bubble detaches from the surface in a given location, then the boundary layer has to redevelop around that location and then heat will be removed by transient conduction. And the remainder of the area where there's not much activity, heat will be removed by forced convection.

MR. BANERJEE: But is the bubble that's sliding you're always wiping the area.

CHAIRMAN WALLIS: You always force convect, yes.

MR. BANERJEE: So you're always in transient. It's like a surface renewal --

MR. DHIR: It's a question of the timing. How much time is there? How much time it takes to slide before it lifts off. And that time I'll show you.

MR. BANERJEE: But it'll still be a transient.

MR. DHIR: Right. It's a transient, but maybe I'm really jumping ahead.

MR. BANERJEE: Your tunnel layer will be developing and then destroyed and developing --

MR. DHIR: Right. Exactly. It will be keep repeating that time period. Yes, sure.

MR. BANERJEE: It's always transient?

MR. DHIR: Yes, it's a transient.

MR. SCHROCK: Well, what's the force convection for? What's the initial condition for that transient conduction problem, although that's the problem, isn't it, V.J.?

MR. DHIR: Right. You see -- okay. Let's look at this slide.

MR. SCHROCK: There's a surface renewal.

MR. DHIR: Surface renewal basically, yes.

MR. SCHROCK: Yes.

MR. DHIR: And so you see just once you wipe it out, you start a time sequence to zero, your transient conduction is -- and the heat will be -- heat flux will be dropping as inverse of square root of time, and then forced convection has its own value. We are saying that this transient time will be only up to the point where the heat transfer by diffusion equals the forced convection areas to --

MR. SCHROCK: But you didn't address the point that I made that the initial condition for your transient conduction problem is basically unknown. So you have to put in some idealized initial condition for that.

MR. DHIR: Right. We're saying zero. You just wipe -- you have wiped out the thermal layer completely and you're starting all over again.

MR. SCHROCK: But you cannot do that because you've got a radial temperature distribution in that liquid that sort of overlays the whole thing. The bubbles are disrupting that, but as a bubble goes by it doesn't leave the uniform temperature field behind it.

MR. DHIR: Right. Bubble is sliding on the surface, heater surface.

MR. SCHROCK: Yes.

MR. BANERJEE: I guess that there is some temperature gradient, it's not completely --

MR. SCHROCK: You don't know what it is is what I'm arguing.

MR. DHIR: Right.

MR. SCHROCK: You have no basis for claiming you know a -- a uniform temperature initial condition --

MR. DHIR: But again, that's -- that's assumption you make. You have to make some assumptions. Right. And the key thing is that we say that wipes out whatever the thermal layer existed, therein --

MR. SCHROCK: And then subcooled liquid comes in contact with the wall? The slightest subcooled liquid comes in contact with the wall?

MR. DHIR: Right. That's what we're saying.

MR. BANERJEE: It's a typical surface renewal theory.

MR. DHIR: Right.

MR. SCHROCK: If you bring in the mean subcooling at that point, you're going to way overestimate the heat transfer by this transient process.

MR. DHIR: Right. And so that's true. It depends on how subcooled the liquid is. But basically heat flux it would be calculated to the total whatever you're subcooling is.

MR. BANERJEE: What's delta Tw?

MR. DHIR: Delta Tw is T wall minus T set, and this is the liquid subcooling you have. So this is the -- so the liquid slug of the slab which is coming in has a bulk temperature -- the liquid.

MR. BANERJEE: So it's the full bulk temperature of the wall is --

MR. DHIR: Into a slab which is initially a temperature T liquid.

CHAIRMAN WALLIS: I don't understand this at all. I thought these bubbles were attached to the wall and then they sort of came off --

MR. DHIR: Look, what we see is this. This bubble starts to grow on the surface. It grows to a certain size and then it will slide on the surface.

CHAIRMAN WALLIS: Yes.

MR. DHIR: And as it is sliding, we are saying it's wiping out the thermal layer which is --

CHAIRMAN WALLIS: Which is dragging the same thermal layer along behind it.

MR. DHIR: And then it leans back, goes away. And the new bubble starts, it will start the process all over again.

CHAIRMAN WALLIS: It's like a kind of Reynolds analogy. When the bubbles goes, it brings in some stuff from the cool. It's like Bankoff's sort of, whatever he called it.

MR. SCHROCK: I think Graham just said it, it drags along some temperature structure from the upstream region behind the bubble as it goes. And that upstream region is your region one where the bubbles grew and collapsed in -- and they give you a considerable superheat at the wall. Not a subcooling at the wall.

CHAIRMAN WALLIS: Well, I guess we have to move along. I can see we're probably going to have to discuss --

MR. DHIR: Again, I don't know why that region has an effect. That region brought in thermal--

developed. But we are calling this process as you move downstream and the bubbles are at every location, the bubbles are going, forming and then sliding along the surface and then lifting off. Then merging between with some of the bubbles along the way. And the only function you can argue with me is that when the bubbles slide they disrupt the total thermal layer or not and when the liquid comes in it's at what temperature it is. And the assumptions we are making it wipes out the thermal layer and the new thermal layer starts by the -- or if you consider the -- slab and the initial temperature is this.

MR. SCHROCK: Well, it's not like it has to move radially in and out. It goes around the bubble. The bubble slides through the liquid and liquid is moving around the bubble, not just over the top of it.

MR. DHIR: I'm not saying it -- you're talking about the wall.

MR. SCHROCK: I'm talking about how the liquid is displaced by the sliding bubble.

MR. DHIR: Right.

MR. SCHROCK: Okay. It's not as though the bubble is a ring around the tube and all -- and it has to slide through the liquid in that way, in which case liquid from a region far away from the wall would be induced into that zone.

MR. DHIR: Right. Right.

MR. SCHROCK: And go around the bubble. What you're doing is more akin to what Graham Wallis said. It's like dragging along behind it whatever is upstream of the bubble, it's begun to slide.

MR. BANERJEE: The liquid can't slip onto the wall. The bubbles can slip but the liquid can't in some sense.

MR. SCHROCK: We got on this discussion by my point that the initial condition in a transient conduction modeling of the heat transferred directly from the wall to the liquid is a major problem because the initial condition for that transient conduction model is essentially unknown.

You've chosen to model it as though the mean subcooling comes to the wall instantly as the bubble goes by.

CHAIRMAN WALLIS: It seems upper bound.

MR. SCHROCK: And I think that is a great extreme. I mean, it's --

MR. DHIR: Okay. You have the --

MR. SCHROCK: The temperature of the liquid at the wall is going to be much higher than that and your transient conduction to the liquid is going to be way overestimated with that assumption.

MR. DHIR: Okay. Now I will give you -- we have the numerical simulations also of this process.

MR. SCHROCK: Okay.

MR. DHIR: And if you look at it the liquid that is coming onto the surface after the bubble has gone out is very close to the bulk temperature. I'm not on subcooled case, but the saturated case, numerical simulation. It's close to the saturation temperature, the temperature of the wall almost drops to the saturation value before it picks up, actually.

MR. BANERJEE: In the numerical simulation did you have the liquid laminar or --

MR. DHIR: Laminar.

MR. BANERJEE: -- is giving you next mixing effect to --

MR. DHIR: Right, exactly. And the question now -- you know, we can belabor this point, but it's extremely difficult to see what exact the temperature will be and how much the region is. And when you develop the model you're going to have certain assumptions and now it's questionable assumptions, one can validate them, but those assumptions are based on what we can --

CHAIRMAN WALLIS: I think if you move a bubble through a liquid and allowing the flow of the streamline, it's coming back to about where they started. So you haven't done any mixing at all.

MR. BANERJEE: Well, you have a wake.

MR. DHIR: The wake of --

CHAIRMAN WALLIS: But not in the very low--

MR. BANERJEE: It is not?

CHAIRMAN WALLIS: No. If there's a wake, then they -- okay.

MR. BANERJEE: There will be a wake.

CHAIRMAN WALLIS: It's a wake relative to what? Because the bubble's presumably moving because the liquid's pushing it to the wakes on the other side of it.

MR. BANERJEE: You have to look at it as something --

CHAIRMAN WALLIS: Okay. Okay.

MR. DHIR: Anyway, we've gone farther --

MR. BANERJEE: So did you submit that CFD for review yet?

MR. DHIR: We have done full boiling and

flow boiling as yet.

So basically, you know, from the wall we said energy is going by full convect not transient conduction. Then it split, some goes into the liquid to sensibly heat the liquid and some goes into evaporation, that is how much vapor bubbles -- how many vapor bubbles and what size are leaving the surface. And that's your -- leaving the surface as they were.

Whatever the condensation that occur at the surfaces will be counted in --

CHAIRMAN WALLIS: Those were two different layers. There's a Qfc and Qand a Qtc. It's happening at the wall.

MR. DHIR: Qtc is basically showing what is happening as the bubble has slided and --

CHAIRMAN WALLIS: At the wall. And Ql and Qev are happening somewhere further out.

MR. DHIR: Right. Qev can be happening as the bubble is -- from energy what you dumped in as the transient conduction goes back into evaporation. But we don't know how much that is. We are just looking at how many bubbles are leaving and at what sequence.

CHAIRMAN WALLIS: I think Ql and Qev are what you need to put in the two fluid model for the code. Code's never been to model things like Qtc.

MR. DHIR: The code won't. This is for our purpose.

CHAIRMAN WALLIS: That's it. So they were at two levels?

MR. DHIR: Right.

CHAIRMAN WALLIS: One is for the physics and one is what you need for the code.

MR. DHIR: Right. Exactly. Code doesn't need that first part. And I'll show you both calculations if we get to it.

MR. BANERJEE: As long as the void at the wall is negligible, what you're saying is the case.

MR. DHIR: Okay. What happens if void is not negligible?

MR. BANERJEE: Than you have to make an estimate of that.

MR. DHIR: Estimate of what?

MR. BANERJEE: The void fraction at the wall, not -- void fraction at the wall. What you're doing is you've set up the way to handle the situation for all the detached bubbles. So, see, the way you've got it there is the bubbles are detaching from the wall and you've got a split between vapor generation because it's detached bubbles --

MR. DHIR: Right.

MR. BANERJEE: And, of course --

MR. DHIR: The remainder wasn't liquid.

MR. BANERJEE: And how much goes into the liquid.

MR. DHIR: Right.

MR. BANERJEE: There were a layer of bubbles sitting at the wall --

MR. DHIR: Right.

MR. BANERJEE: Just sliding along or doing whatever the hell they're doing --

MR. DHIR: Right.

MR. BANERJEE: Depending on the size of the channel --

MR. DHIR: Right.

MR. BANERJEE: -- you know, they may or may not be significant part of void fraction. How big are these bubbles?

MR. DHIR: It depends on the pressure and velocity, whatever.

MR. BANERJEE: Well, it was a size --

MR. DHIR: It's about a millimeter or less.

MR. BANERJEE: Okay. Millimeter or less. So if you have, say, tubes or rods in some areas that they -- what is the typical flow of area?

MR. DHIR: Three millimeters.

MR. BANERJEE: Three millimeters. So the gap itself would be almost -- completely by the -- it would have a significant --

MR. DHIR: Right. Right.

MR. BANERJEE: I mean I haven't done the sums.

MR. DHIR: Right. But, again, that void fraction we can give that value.

MR. BANERJEE: Right.

MR. DHIR: Because we know the number and sizes of the bubble and so forth, and how much packing is there. So one can get an estimate.

So basically an isolated bubble, you're saying that as a bubble slides along your thermal layer is developing and that's the transient conduction is occurring. The region where there's no activity we're saying the heat is removed by forced convection.

MR. SCHROCK: Do your data show that the bubble always begins to slide before it reaches OSV?

MR. DHIR: OSV they're all stationary, OSV. They don't -- they're sizes below what is needed to slide. They never get to that size.

MR. SCHROCK: Your picture shows it's sliding before it gets there.

MR. DHIR: OSV starts here.

MR. SCHROCK: And, see, you got a bubble below that that appears to be sliding.

MR. DHIR: I think that should not be shown, actually. But anyways, there should be no arrow there. This bubble is just sitting there. Beyond that point the bubble start to slide.

MR. SCHROCK: So does that mean that the sliding phenomenon is akin to bubble departure from the standpoint of OSV?

MR. DHIR: Yes. Bubbles have to grow to a certain size before they can slide.

MR. SCHROCK: That I understand.

MR. DHIR: Okay.

MR. SCHROCK: But the question is whether or not OSV is defined in such a way that it means any axal movement of the vapor, any axal movement of the bubble whether it's attached to the wall or detached?

MR. DHIR: That's correct. But the bubble has to --

MR. SCHROCK: I mean, it can be one way or the other.

MR. DHIR: No. Once it's start to slide --

with other bubbles it will lift off when getting the lift off side. So our definition is the moment the bubble start to slide, we say OSV begins.

CHAIRMAN WALLIS: Do the forces from the fluid make it both slide and lift off and is there a lift force on it lifting it off?

MR. DHIR: Yes, that's correct. There is definitely a lift force.

CHAIRMAN WALLIS: What's important is that you break the contact with the nucleation center, and after that figure out what its trajectory is.

MR. DHIR: Right. Yes, and that's a very important thing. But the lift has been ignored in the past and bubbles -- to the surface. And if you make the fourth balance you cannot describe it.

MR. BANERJEE: In fact, if you inject bubbles -- with tiny holes, you see exactly this; that they grow to a certain size and then they slide --

MR. DHIR: Right. Right.

MR. RANSOM: Well, this model is similar I think to -- the other one is the critical enthalpy model which predicts enthalpy the liquid has to reach before a bubble can survive. And that's considered the point of onset of significant void --

MR. DHIR: That's what people have done

mostly.

MR. RANSOM: Right. But this one is quite similar. And I'm not criticizing it necessarily. I mean, because I think you're also trying to predict when will a bubble depart from the wall and can survive in the bowl.

MR. DHIR: Right.

MR. RANSOM: Without immediately condensing.

MR. DHIR: Right. And we are basically saying what is this point. I'm not -- I will show you the data what we got with respect to this point and what old correlations are and so forth, and show you later comparisons. But I am not focusing my attention to just theoretically or mathematically predicting this mark, this location. There's a correlation. But the key issue what we are trying to resolve -- which means beyond this location.

And this is a balance here. How long the bubble sitting here is the balance on how much evaporation is occurring and how much condensation is occurring can you have -- to create bubbles that are large enough to slide. Bubbles have to grow to certain size before they can slide. Smaller bubbles will just sit there.

MR. SCHROCK: Part of the detachment process, I think, has to do with the radial thickness of the liquid superheat. And when the bubble extends a certain distance from the wall, if it's still surrounded over all of its surface by liquid superheat to some degree, certainly a variation over its surface, then where it's superheated, it can -- there's no question it can still grow.

MR. DHIR: Right.

MR. SCHROCK: Whether or not it can still grow goes beyond that --

MR. DHIR: Right.

MR. SCHROCK: And that's the balance between the rate of --

MR. DHIR: Evaporation and condensation.

MR. SCHROCK: -- and the rate of condensation.

MR. DHIR: Exactly. That's what determines its location.

MR. BANERJEE: But the lift off --

MR. DHIR: Lift off is a separate issue. Lift off is a separate issue.

MR. BANERJEE: Because even with air bubbles they will slide for a while and then they left off.

MR. DHIR: Lift off, right.

MR. BANERJEE: Which they're not growing anymore. They stop growing at that time.

MR. DHIR: Exactly. That's lift force. Definitely.

MR. SCHROCK: I guess the point I was trying to make is that there's a thermal condition that's a part of the attachment process. It's not just the flow conditions.

MR. DHIR: Right. But thermal condition gives you -- right. Thermal condition is going to give to you how big the bubble is going to grow at that site. If the bubble does not grow to that size, it's going to sit there. So it's -- thermal conditions basically what size it gets to. And then the forces are the -- how much forces are acting to slide. It can push it out --

CHAIRMAN WALLIS: It can be still growing while it's sliding --

MR. DHIR: Yes, sure it does grow. Yes.

CHAIRMAN WALLIS: So that it may -- it's sense of gravity may detach, but it's --

MR. DHIR: No. Yes, it's still growing. The substantial growth occurs during that.

CHAIRMAN WALLIS: I don't want to take a

break too early, because I want to make more progress.

I think we may have to accept that you got a model here and then go ahead and then sort of see --

MR. DHIR: I just -- right.

CHAIRMAN WALLIS: -- see your experiments.

MR. DHIR: Right. But only thing -- one more thing I would show you that when the bubbles start to merge on the heater surface, are your superheat goes up -- so at least have your criticism on this part. As the bubbles grow nucleation sites become very large. The spacing S can be smaller than the lift off diameter you need or smaller than even the bubble diameter departure. So in this situation the bubbles while they're growing, they're -- and then once they get to that size, they will lift off.

CHAIRMAN WALLIS: They merge together in two dimensions, why don't they produce --

MR. DHIR: What do you mean?

CHAIRMAN WALLIS: This is a one dimensional picture, but presumably they're merging --

MR. DHIR: Right. In that area. But there's always liquid so it's not -- they form like a bridge, like a mushroom, so the bubble mushroom is there and then there are several stems, but the liquid is still there. It's not only that area.

CHAIRMAN WALLIS: -- then you get a raft of bubbles attached to each other, not just a chain.

MR. DHIR: No, no. This is one dimensional picture here. But if you look the other direction --

CHAIRMAN WALLIS: Yes, but in the other direction you've also gotten an S.

MR. DHIR: Right, it's a square grid.

CHAIRMAN WALLIS: So they will touch in the other direction.

MR. DHIR: Right. They will touch like--

CHAIRMAN WALLIS: So you get a complete layer of bubbles coming up.

MR. DHIR: In this model, right. That's correct. The bubbles are coming out just in unison.

CHAIRMAN WALLIS: That's probably what you need for TRAC?

MR. DHIR: This is how we calculate our transient conduction for this case; that all the bubbles lift and then form the thermal layer again and then calculate the -- so this will be at high heat fluxes.

So, you know, I'm skipping these slides. It's just on the conduction calculation, at different times and so forth.

MR. RANSOM: Well, in your TRAC model do

you envision this being a transient effect -- a periodic effect, I guess, right in which bubbles form on the wall and then depart?

MR. DHIR: No. TRAC will just get the source term, how much --

MR. RANSOM: You somehow merge it all together so it's a uniform thing with time more or less.

MR. KRESS: If the -- conditions -- if the -- conditions change then --

CHAIRMAN WALLIS: You still have to split these into the Ql and the Qevs.

MR. DHIR: Right.

CHAIRMAN WALLIS: How do you do that?

MR. DHIR: Ql and Qev -- Qev we calculate from our -- you know, I will show you how we calculate Qev.

CHAIRMAN WALLIS: So you take the total and then --

MR. DHIR: And then subtract Qev.

CHAIRMAN WALLIS: And then you take away Qev?

MR. DHIR: Right. Exactly.

CHAIRMAN WALLIS: Well, how do you know d?

MR. DHIR: You measured.

CHAIRMAN WALLIS: Well, how do you predict it?

MR. DHIR: Correlation. We measured, we got the data and from that we recorded --

CHAIRMAN WALLIS: -- how do you predict Qev -- you need to know frequency in a d cubed and Na.

MR. DHIR: Right, right.

CHAIRMAN WALLIS: And you know all those things?

MR. DHIR: That's exactly what you need to know to predict Qev. That's a key point. That's what I'm leading to. I discuss the model -- right, exactly.

CHAIRMAN WALLIS: Okay.

MR. DHIR: That's the whole point of this present -- but the key point I was trying to make showing you early on this modeling effort that what detail we have to make measurements to get all the ingredients which we need to put into the model. This requires you need to know frequency, number of density, bubble size and so forth.

MR. BANERJEE: How do you measure the rod bundles?

MR. DHIR: We measured most of them on the flat plate. And then on the rod bundle we -- there's some there but just to verify it, but not too much data. The rod bundle becomes very difficult because very quickly the liquid becomes saturated and after that you can't see much. And so rod bundle we got some data, but not whole lot.

Okay. So when we do the experiment basically from the preliminary model, what we see that there are a number of variables which need to be measured in the experiment and here in this table I give you which quantity we are measuring and what measurement that we are using to measure that quantity.

Wall heat flux for the flat plate heater, we measure from the thermocouples that are imbedded in the copper block. And for the rod we measure just from the power that is input to the rod. We have thermocouple embedded in the copper block and so we get the temperature profile and then from that we get the surface temperature. For the rods we have a thermocouple attached to the -- wall and those thermocouples are calibrated and from those thermocouples you measure the wall.

MR. RANSOM: Can I ask a question about that. That I didn't quite understand from the writeup, but you have cartilage heaters and then you're also measuring the temperature gradient using the temperature gradients to extrapolate to the surface and determine the heat flux

MR. DHIR: In the copper block, yes.

MR. RANSOM: I wasn't clear how you separate the effect of the heaters on the surface. Are the heaters on the backside of this copper block or -- so you're only looking at conduction through the copper?

MR. DHIR: Just wait.

MR. RANSOM: I was wondering how you separate the effect of the cooling, you know, from the boiling process from the heating of the cartilage heaters and --

MR. DHIR: Okay.

MR. RANSOM: So where is the heat transfer surface actually?

MR. DHIR: This is the surface.

MR. RANSOM: Okay.

MR. DHIR: And this is a larger area so the heaters are going this way.

MR. RANSOM: Yes.

MR. DHIR: And they're going up to this portion here.

MR. RANSOM: Up to that shoulder?

MR. DHIR: That shoulder or even below

actually.

MR. RANSOM: So do they generate heat over their length?

MR. DHIR: Yes, right.

MR. RANSOM: So there's uniform heat generation --

MR. DHIR: Right. And then we have this section where the heat even if there were some nonuniformities in this portion the heat flux will be mostly --

MR. RANSOM: And that's where you're measuring the gradient --

MR. DHIR: Gradients, right.

MR. RANSOM: -- of the temperature?

MR. DHIR: Right. This is the portion that you see -- we're jumping ahead. This is about 3 centimeters wide for test purpose and about 30 centimeters tall. Okay. And we have 7 axial locations where we put thermocouples. And we -- this is a cross section and this is a treated surface. We have three for thermocouples in the middle, three on the side, three on this side to see if this heat flux is uniform

MR. BANERJEE: It's copper, right?

MR. DHIR: Copper.

MR. RANSOM: Okay. I understand what

you're doing now.

MR. DHIR: Okay.

MR. RANSOM: And then flow is along this block, right?

MR. DHIR: Right.

MR. RANSOM: And it's vertical, is that correct?

MR. DHIR: Vertical.

MR. RANSOM: Okay.

MR. DHIR: Liquid temperature we use a microthermocouple so that we could get temperature profiles in the liquid, at least in the single phase case already close to partial nucleate boiling region. And then ONB we measure for -- of the boiling surface as released from thermocouple outward. Number density of nucleation sites, we took pictures of the heating surface and then counted the number that were active per unit. And, again, the temperature at which we measured the nucleation inside was obtained from extrapolation of the temperature -- temperature profiled in the solid.

MR. BANERJEE: How close to the surface do you have the thermocouples?

MR. DHIR: About 3 millimeters, 2 to 3 millimeters.

MR. BANERJEE: And you can actually see-- do you see any temperature fluctuations or it's too far.

MR. DHIR: No, it's too far.

MR. RANSOM: There's one other perimeter that appears -- yes, the Fourier number there, which has a timed perimeter in it. And I don't see that on here. But I presume that's time from the bubble initiation or --

MR. DHIR: No. That Fourier number is for the -- heat transfer of the condensation when the bubbles leave the heater surface and is moving into the bulk, for the moment it leaves the heater surface, that is the time you start counting.

MR. RANSOM: Okay. So it's the history of the bubble?

MR. DHIR: Bubbles, right.

MR. RANSOM: How do you measure that or how do you determine that?

MR. DHIR: You'll be jumping ahead again.

MR. RANSOM: I am?

MR. DHIR: Yes.

CHAIRMAN WALLIS: He measures time and then calculates --

MR. RANSOM: Time for what? It's time

from when the bubble has departed the wall and --

MR. DHIR: It starts to go into the -- so your condensation starts. Now there's only -- there's no heating from the wall. All the energy what the bubble has is being lost to the condensation at the surface. Bubble is shrinking, so we are tracking bubble trajectory and what the location is from then knowing every point release happens, you know where the position of the bubble is.

MR. BANERJEE: This is like the McMaster experiment?

MR. DHIR: Right, but it's on a heater surface. No, we're not getting -- it's on a boiling surface. The bubbles are creating on the boiling surface of different sizes and so forth. I show you some -- but we are jumping ahead so I have to change the whole thing.

The bubble departure and lift off that -- and location of OSV from visual observation.

MR. RANSOM: Is that how you get the time, you see it lift off and then you follow the bubbles?

MR. DHIR: Actually we do. Let me show you.

MR. RANSOM: Yes.

MR. DHIR: Just wait one second.

CHAIRMAN WALLIS: But the collapse of the bubbles in superheat liquid seems to be the most straight forward part of this --

MR. DHIR: Right, exactly. That was the easy thing to do.

MR. BANERJEE: To measure.

MR. DHIR: Beg pardon?

MR. BANERJEE: To measure.

MR. DHIR: Right. Bubble release frequency in high-speed films and count the number of bubbles at least for a unit of time.

Condensation heat transfer coefficient for attached bubbles, in this case one needs to have a liquid temperature profile and bubble growth rate in the vicinity of the solid surface. And by noting the difference in bubble growth rate for saturated and subcooled liquid, one can determine that how much energy is going to support condensation on attached bubbles.

This exercise requires auxiliary experiments and we have done some for another study, but for this case that portion is lacking. For the time being we are using Ranz and Marshall correlation basically to calculate the condensation heat coefficient.

Condensation heat transfer coefficient for detached bubbles, that we measured and I'll show you some results. Again, from films.

Bubble number density, high-speed films counting the number of bubbles per unit of time. And then the void fraction, we use gamma densitometer.

MR. RANSOM: How do you establish the bubble relative velocity?

MR. DHIR: You look at the bubble velocity.

MR. RANSOM: You know the bubble velocity, what's the liquid velocity?

MR. DHIR: Liquid we are using the bulk as axial to flow.

MR. BANERJEE: No, no, he's measuring the void fraction.

MR. DHIR: Resolution in terms of what?

MR. SCHROCK: Spacial?

MR. DHIR: Spacial resolution. I think it's close to 2 to 3 millimeters closest to the wall we can go -- is about 3 millimeter in size. So we can't go close --

MR. SCHROCK: And the channel thickness is what?

MR. DHIR: Channel is 3 centimeters.

MR. SCHROCK: Three centimeters. So you look at a tenth of the cross section --

MR. DHIR: Average at a given time.

MR. SCHROCK: And do the profile.

MR. DHIR: Profile.

MR. KRESS: Do the bubbles condense so fast that they don't have time to interact with each other? You're looking at individual bubbles.

MR. DHIR: Right. Yes, they don't interact.

MR. KRESS: They don't interact.

MR. DHIR: Different bubbles we are talking.

CHAIRMAN WALLIS: All this is happening in a time scale of milliseconds?

MR. DHIR: Milliseconds, right.

CHAIRMAN WALLIS: So you don't have any time to average the turbulence in the flow. So I think you get a lot of fluctuations because the environment around the bubble depends on the instantaneous contact

MR. DHIR: Right, you see --

CHAIRMAN WALLIS: Average that through the whole --

MR. DHIR: But we have measured the

temperature profile --

CHAIRMAN WALLIS: But it's only an average.

MR. DHIR: Exactly.

CHAIRMAN WALLIS: You get a lot of variation depending upon what the turbulence --

MR. DHIR: That's true, but -- and the question is what level of detail do you want.

CHAIRMAN WALLIS: Well, I'm just saying when you make these measurements --

MR. DHIR: Right.

CHAIRMAN WALLIS: -- you're going to get a fluctuation, get a lot of difference in the results because your instantaneous fluid conditions depend on --

MR. DHIR: Mixing, yes.

CHAIRMAN WALLIS: So there's no time to average them out.

MR. BANERJEE: But you're ensemble averaging --

MR. DHIR: Exactly. We take many of the cases --

CHAIRMAN WALLIS: Your average will be okay, but there'll be a big spread around that average.

MR. DHIR: Even thermocouple when we put, we are looking at liquid temperate -- quite a bit.

MR. SCHROCK: Now in your rod bundles you can't get these gamma densitometer measurements?

MR. DHIR: Right. We look at only mid-plane. We cannot go close to the wall because uncertainty becomes very large.

MR. SCHROCK: So what do they mean?

MR. DHIR: What do you mean what they mean? We are giving -- rod bundles are --

MR. SCHROCK: So I guess I should repeat the question. How do you -- what kind of resolution do you get on your void in the rod bundle measurements?

MR. DHIR: Well, in the rod bundle we have only measured at the mid-plane. We have not done radial profile. We have gotten it because uncertainty is too much.

MR. SCHROCK: What does mid-plane mean? It's a rectangular bundle and you've --

MR. DHIR: Right. In the middle channel, we look at the center channel.

MR. SCHROCK: You make a measurement midway between the rods?

MR. DHIR: Right.

MR. SCHROCK: But the rods are closer than the walls in the flat plate experiment, so how does the --

MR. DHIR: We are focusing the beam through this passage and we are aiming at the mid-plane here.

MR. BANERJEE: How can you focus a gamma beam?

MR. DHIR: What do you mean focus?

MR. BANERJEE: You just said you're focusing --

MR. DHIR: Focusing means you remove the gamma beam, you could be hitting the wall and then you can --

MR. SCHROCK: So you've collumnated to a smaller beam --

MR. BANERJEE: So you go at -- beam?

MR. SCHROCK: You've collumnated the gamma densitometer to a small beam.

MR. DHIR: Right.

MR. SCHROCK: I understood that. But what I don't understand is how the size of that beam compares with the gap between the rods here.

MR. DHIR: The rod gap is 3 millimeters here.

MR. SCHROCK: But you didn't tell me what the collumnated gamma densitometer beam is.

MR. DHIR: I said that initially we had 3 millimeter beam. Then we use a plug to reduce it to about 1.5 millimeter size.

MR. SCHROCK: So for the rod bundles it's 1.5 millimeters.

MR. DHIR: 1.5 millimeter size.

MR. SCHROCK: Compared to?

MR. DHIR: Three millimeter gap.

MR. SCHROCK: Three millimeter gaps. So it's -- and then it's shining through --

MR. DHIR: Shining through here a sequence of two phased fluid which is at one point only one -- only 3 millimeters thick and then essentially is unlimited halfway to the next row of rods.

MR. DHIR: Right.

MR. SCHROCK: So you're averaging kind of in --

MR. DHIR: In this cross section.

MR. SCHROCK: Yes. How do you interpret what it means I guess is the question I'm trying to get at, V.J.? It's an average longitudinally and axially with respect to the beam.

MR. DHIR: The question I would ask you that was raised, this is how distance -- here and here. And the question you would ask is how accurate it is. And --

MR. SCHROCK: No, not a question of accuracy, but just how do you interpret it? What does it mean after you've got the number?

MR. DHIR: Now, suppose I had a code model? Let's say that I had -- I was modeling this in a code and if I gave somebody this information, they should be at least validated to the --

CHAIRMAN WALLIS: This isn't the volume average in the rod bundle, because you're just taking a point --

MR. SCHROCK: That's my point I'm making. It's the volume average in a little one and half millimeter diameter tube running between the rod.

MR. DHIR: Exactly.

CHAIRMAN WALLIS: And that's not the same as the average to the bundle because you haven't counted the bit you couldn't see that's shelter by the rods.

MR. DHIR: That's right.

CHAIRMAN WALLIS: So it's not the average void fraction in the whole section.

MR. DHIR: Yes. But if you're going to validate some code which can do this kind configuration, you can test it --

CHAIRMAN WALLIS: Well, it isn't validate -- it isn't calculating void fraction in a strip. It's calculating an average void fraction for the whole works?

MR. DHIR: No, but if I had 3-D code, why I couldn't do it?

MR. BANERJEE: But you don't have a 3-D code.

MR. DHIR: But they have some 3-D code.

CHAIRMAN WALLIS: But the question is how does this related to what TRAC needs now? What it needs now is an average over everything.

MR. BAJOREK: You don't have it there, but you will have it in your flat plate.

MR. DHIR: Flat plate we have.

MR. BAJOREK: In that case we would be able to get --

MR. DHIR: But if you want to test the flat plate.

MR. BANERJEE: Well, I guess it's history now. But this geometry gamma densitometer is not ideal.

MR. DHIR: Yes.

MR. BANERJEE: Because we made rod bundle void fraction measurements about 25 years ago in neutrons capturing and --

MR. DHIR: But, again, how many things you want to do?

MR. BANERJEE: Right.

MR. DHIR: It's not only we --

CHAIRMAN WALLIS: What do you need to do to get the answers required?

MR. DHIR: WE didn't need --

CHAIRMAN WALLIS: What you want, and you may want all kinds of things.

MR. DHIR: Right. But we don't need -- we are just providing this additional information basically.

CHAIRMAN WALLIS: I think actually we both want and need to take a break fairly soon. Is this a good point to do it?

MR. DHIR: That's fine, yes.

CHAIRMAN WALLIS: We going to move on to a different topic?

MR. DHIR: Yes, right.

(Whereupon, at 3:39 p.m. off the record 3:53).

CHAIRMAN WALLIS: We're now on the record. Get ready to proceed.

Can you start to give us results, or did you not finish --

MR. DHIR: No, I just want to describe the flow loop a little bit, quickly.

CHAIRMAN WALLIS: Because we do want to finish up before 6:00, so we're going to have to move along here I think.

MR. DHIR: Okay.

CHAIRMAN WALLIS: If there's no argument about modeling concepts, it might move along much quicker.

MR. DHIR: Right. Okay. First, our graphic -- flat plate and this was followed by a 9-rod bundle and we did fabricate two 9-rod bundle. The first rod bundle got destroyed during the experimentation or got degraded in some sense, so we had to rebuild another one.

MR. KRESS: But you joined the nucleus -- your departure --

MR. DHIR: No. No. It was degraded -- instrumentation. Thermocouple failed and so forth.

And on the flat plat we carried out 125 flow boiling experiments. The pressure in our experiments was with one bar, Marked velocity was varied from about 124 to 898 kilograms per meter squared, liquids are cooling on t to 50, wall heat flux around 2 to 113, wall plus centimeter square and contact angle from 30 to 90 degrees.

MR. KRESS: A question about those. Do those correspond decay heat levels?

MR. DHIR: Those correspond to the operation levels, right. From 2 to 113.

MR. KRESS: And the flows are what's calculated to exist during the -- level --

MR. DHIR: Right. Right.

MR. KRESS: Okay.

MR. DHIR: This a schematic of the facility flow loop, so forth. We have two tanks of each one 1.25 cube in volume and the liquid is stored in one of these tanks and its conditioned to bring it desired temperature and then it's pumped through a preheating section so that we can correctly control the temperature of the liquid that enters the first section. And after that it is dumped into another second tank.

Now, this is a photograph of the facility. Basically you see those two tanks and preheater. And this is -- where the test section is placed, either rod bundle or the flat plate. And this is our power supply, and this power supply is rated at 40 volts and

2.225 amps, so it give you 100 kilowatts of power. And this we have gotten through our grants, and not NRC.

This is how the test chamber for the flat plate tests. A converging nozzle was followed by a flow technique section about 61 centimeters upstream of the trail section. Then 30 centimeters downstream there was a rectangular section and followed by a -- nozzle.

CHAIRMAN WALLIS: That's a --

MR. DHIR: Beg pardon? Centimeters.

CHAIRMAN WALLIS: The dimension are really in -- 30.5 is

MR. DHIR: One feet.

CHAIRMAN WALLIS: 61 is 2 feet.

MR. DHIR: Two feet, right.

CHAIRMAN WALLIS: Okay.

MR. DHIR: And the cross section -- it's a square cross section 4.2 centimeters each side and copper block faces the one side and three sides you have glass windows.

MR. SCHROCK: And at these low temperatures you have no problems with glass windows?

MR. DHIR: No.

MR. SCHROCK: No itching of the windows?

MR. DHIR: No. You have -- still using a

-- not different, but rod bundle up to 3.5 baud.

This is -- you are seeing the best block.

MR. RANSOM: Just out of curiosity, why didn't they use a transition region --

MR. DHIR: What do you mean transition?

MR. RANSOM: Well, normally you'd use like triangular section or something to minimize the distortion, you know --

MR. DHIR: Right. But this length was sufficiently long enough. This region was sufficiently long enough to give us --

MR. RANSOM: Well, you're measuring the gradient through that nose more region, right?

MR. DHIR: Right, this region.

MR. RANSOM: Well, didn't you tell me the cartilage heaters extend all the way through the block?

MR. DHIR: They go up through here, up to this length.

MR. RANSOM: Yes, that's what I thought.

MR. DHIR: And beyond that, then the heat has to flow through this section.

CHAIRMAN WALLIS: It's not a very one dimensional looking -- when you think of solving the conduction equation. Maybe all the differences -- the differences are small anyone.

MR. DHIR: Very small difference. You'll see that in a minute.

And this is for the rod bundle. Rod bundle, the rod tubing is Zircalloy-4 and the rod is only is 1.1 centimeter, the sheet thickness is 1.5 millimeter. And we arrange in a 3 x 3 grid. A total of 140 subcooled flow boiling experiments were performed. These experiments have been performed at 1 bar, 2 and 3 bar. And in the 1 bar case, we varied the marked velocity from 186 to 2800 which is 20 centimeters to 2.8 meters per second. So quite large range.

Subcooling from 2.7 to 69 degrees at inlet. Heat flux 1.6 to 25 bar per centimeters. Current contact angle was about 57, hydraulic -- was 1.23

CHAIRMAN WALLIS: You say P was 1.03 just because of the elevation of your lab or something?

MR. DHIR: Elevation of the lab and the pump is in -- you know, the well was there, so there's--

CHAIRMAN WALLIS: Is that sort of pressure?

MR. DHIR: Yes.

CHAIRMAN WALLIS: Because atmospheric pressure varies by ten percent or something anyway.

MR. DHIR: Right.

CHAIRMAN WALLIS: So did you adjust for variations in atmospheric pressure?

MR. DHIR: No. This is the pressure --

CHAIRMAN WALLIS: Oh, so this gauge pressure?

MR. DHIR: No, no, no. Absolute pressure, but the pressure constance is calibrated.

CHAIRMAN WALLIS: Absolute pressure?

MR. DHIR: Right.

CHAIRMAN WALLIS: And you adjust something to make it 103 when the outside pressure is 105?

MR. DHIR: We not have 105. I don't think we got 105.

CHAIRMAN WALLIS: You don't?

MR. DHIR: I don't think so. Usually it's below what it must be at most of the time. We are close to the ocean.

CHAIRMAN WALLIS: Yes, but the barometric pressure when storms come by varies by plus or minus 5 percent.

MR. DHIR: Right. Most cases it was 1.03 but again we can -- this is a trivial item.

MR. SCHROCK: Not on experimental days.

MR. DHIR: No, this is the measurement from the pressure -- I'm giving you 1.03, not all experiments would have 1.03.

CHAIRMAN WALLIS: Oh, okay. Okay.

MR. DHIR: So it's not --

CHAIRMAN WALLIS: It's a nominal pressure.

MR. DHIR: Right, nominal.

And this is how the rod bundle looks like. And I thought the rod bundle is 91 centimeters. Again, we have a -- flow welding section and this is the photograph, you can see how it looks like. And all four sides of the -- are glass windows.

CHAIRMAN WALLIS: It's prestressed. It looks like a prestressed thing with tables holding it together.

MR. DHIR: Right.

MR. DHIR: Yes, you have pins loaded actually, pins holding it together.

CHAIRMAN WALLIS: Bungee cords.

MR. DHIR: After you heat there is some expansion.

MR. KRESS: Where does the power come in at? Through the bottom?

MR. DHIR: Through the top and bottom.

MR. KRESS: Through the top and the bottom.

MR. DHIR: And in the rod bundle we have placed thermocouples about 18 centimeters apart and is about 6, 7 locations. And the filler material we used in two bundles. First one was lava and the second one we used G-10 insert and there was a slot cut in the G-10 on lava and the thermocouples were carried through to the slots. And this was filled with high thermoconductivity poxy and kind of pushed it to the surface.

MR. RANSOM: Were these fresh ZR-4 tubes?

MR. DHIR: ZR-4.

MR. RANSOM: You expect a high oxidation level to change the nucleation density or --

MR. DHIR: We had no change. But in -- water we did not see degradation. Copper it's much more.

MR. RANSOM: I was concerned about the reactor case where you probably have a high --

MR. DHIR: I'll show you something with boron.

MR. RANSOM: Oh, okay.

MR. DHIR: Boron does more than just --

MR. RANSOM: V.J., what is lava? Is that

the lava I know or --

MR. DHIR: Yes, that's the lava.

MR. RANSOM: Is that lava rock?

MR. DHIR: Right. You can get lava rock pieces. And it's a --

MR. SCHROCK: Isn't that a commercial product you --

MR. DHIR: Yes.

MR. SCHROCK: -- you make. It's sort of a ceramic after you cook it.

MR. DHIR: Cook it, right. A similar tool, you know.

MR. SCHROCK: But it's machineable.

MR. DHIR: Yes. You can get rod bundles and rods --

MR. RANSOM: A manmade product --

MR. DHIR: Yes. Okay. First with the flat plate, we looked at how uniform the heat flux was along the axial direction. And, as you can see, for this case about 42 -- this is at those several locations how the heat flux varied on the thermocouple.

CHAIRMAN WALLIS: Oh, you did the measures across the plane?

MR. DHIR: Across the plane. I don't have it here, but does not vary more than 5 percent. There was some drop on the edges, but it's fairly uniform.

CHAIRMAN WALLIS: Heat loss?

MR. DHIR: Heat loss, although it's insulated, but still there is a heat loss.

CHAIRMAN WALLIS: You think it'd be higher at the edges.

MR. DHIR: No, no. Temperature drops but the heat flux is higher. So if you look at the temperature uniform to along the surface, the temperature is lower on the outer side.

This is the wall temperature as a function of distance for one case. And you can see initially it's a subcooled flow, forced convection and then boiling starts somewhere around here. There's some temperature drop and then it stays fairly constant flow.

This is the temperature profile in the liquid with the thermocouple which -- outward. And most of the drop occurs very close to the wall, the laminar sublayer. And as we go farther downstream and the outer region of the thermal layer expands and you can see the thermal layer becomes quite thick.

CHAIRMAN WALLIS: The top one of this with the pinky triangle there.

MR. DHIR: 24?

CHAIRMAN WALLIS: What TRAC is doing is taking some average which you would say would be 88 or something, or is TRAC taking 85, or what does TRAC take as the temperature of the liquid.

MR. DHIR: Bulk 35.

CHAIRMAN WALLIS: No, that's not. The average is 87 or something.

MR. DHIR: Average if you look at over the whole cross section is close to 85.

CHAIRMAN WALLIS: Isn't that what TRAC uses, the average over the whole cross section?

MR. BAJOREK: It would know the 85 degrees in this point.

CHAIRMAN WALLIS: It wouldn't know that -- no, 85 at all. It would just know the average. TRAC doesn't calculate the peak or minimum. It just takes the average.

MR. RANSOM: Yes, it's the bulk --

MR. DHIR: The -- it would be 85.

CHAIRMAN WALLIS: No. The average is above 85.

MR. RANSOM: Well, it's got to increase as you flow down the --

MR. DHIR: Right. But how much -- you

know, if you integrate those over there, how much increase is going to --

CHAIRMAN WALLIS: But TRAC would say that the top, the average bulk temperature is 85, although there is water -- 85 --

MR. DHIR: Higher than --

CHAIRMAN WALLIS: Say the bulk temperature was 87. Now there is water 85 in the middle.

MR. BAJOREK: Yes, but most heat transfer correlations are using that bulk temperature, not an average temperature.

CHAIRMAN WALLIS: That's right. So it -- what's the difference? What's the difference?

MR. BAJOREK: Barring what little bit you have in the boundary layer.

CHAIRMAN WALLIS: What do you mean by bulk?

You mean -- is wider than that.

MR. DHIR: No, channel is -- channel is the 4 centimeters wide.

CHAIRMAN WALLIS: So the bulk temperature is something like 87 when you average over the whole thing. It's not 85, although there is liquid at 85 in the middle.

MR. DHIR: Right.

CHAIRMAN WALLIS: When you're doing your condensation on these bubbles --

MR. DHIR: Right.

CHAIRMAN WALLIS: -- you're something average. If they go out in the middle, they disappear.

MR. DHIR: No. Bubbles were declining only up to about here.

CHAIRMAN WALLIS: Only up to about there?

MR. DHIR: Right. So I'm making the local--

CHAIRMAN WALLIS: What you see is the -- temperature than the bulk?

MR. DHIR: Right.

CHAIRMAN WALLIS: Of course, these transverse things are not modeled in TRAC at all.

MR. SCHROCK: Now, M.J., this acts as a single phase set of measurements.

MR. DHIR: This is single phase.

MR. SCHROCK: Yes. So there's no --

MR. DHIR: Right.

MR. SCHROCK: Once you start getting two phase, this gets all changed.

MR. DHIR: Changed, but still outer regions you'll have still some cooling.

MR. RANSOM: I think you had some arguments in the paper that it's still measuring the liquid temperature or approximately the liquid temperature?

MR. DHIR: Right.

MR. RANSOM: But you do use that data to establish the temperature of the liquid where the bubble is at, right?

MR. DHIR: Exactly. That's what we do. And the first the exercise we made it was kind of a test how good experiments you're doing, we calculated from the wall side and if we take this gradient does it match. And this gradient we have much more uncertainty because its profile is so steep. But we didn't -- about 20 percent it matched with what we were putting in from the other side.

This is how the heat transfer coefficient looks along the copper block -- single phase flow. So you can see it's just developing flow. It's like -- flat plate and the -- is decreasing. In this case the narrow number at the end about -- less than the what we need for transition -- to turbulent flow.

MR. RANSOM: What did you say the Reynolds number is?

MR. DHIR: Based on the length.

MR. RANSOM: Yes, is what?

MR. DHIR: It's about close to 10 above 5.

MR. RANSOM: Ten to the 5th, right?

MR. DHIR: Right.

MR. BANERJEE: Based on the length.

MR. DHIR: Length. Right.

MR. RANSOM: Distance. REL?

MR. BANERJEE: Right.

MR. RANSOM: Is that a curve a model?

MR. DHIR: No, just to the data.

MR. RANSOM: It would have been helpful to -- how did it compare with --

MR. DHIR: This is a laminar -- flow -- we can apply, but you see I don't have it here. I think that it is one of the reports that was discussed, what difference. But we find the -- value is about 20 percent higher than what you'll get for laminar flow.

MR. RANSOM: Which is 20 percent higher?

MR. DHIR: This value here.

MR. RANSOM: Is 20 percent higher than what we would --

MR. DHIR: Then you'll get for -- profile for example is you calculate what --

MR. BANERJEE: So you should be able to trace the --

MR. DHIR: Oh, yes, right. We did that. I think it's in one of the reports. But the key point here was it looked --

CHAIRMAN WALLIS: In a square geometry.

MR. DHIR: Right, so there will be some difference. And also we have not taken any precaution to make the flow laminar exchange, so there will be some difference.

And this is on the rod bundle, single phase heat transfer coefficient.

CHAIRMAN WALLIS: That's length the axis there?

MR. DHIR: Axis? Yes, it's not missing here. It's these, distance from inlet.

CHAIRMAN WALLIS: It's also showing a big entrance length effect.

MR. DHIR: Yes. You see almost 50 hydraulic damages.

CHAIRMAN WALLIS: So how come it correlates so well on the right hand side?

MR. DHIR: Just one thing. I'll come to that.

This is -- flow and you see out 50 -- damage it becomes almost fully developed and the colored symbols are for the central rod. And the open symbols are for the rod which is at the corner and facing -- thermocouple is facing outside, outward direction. So it's in the quadrant. And that thermocouple -- reduced from that thermocouple is about 15 to 20 percent lower than the central rod.

MR. SCHROCK: So would you say again whether those numbers are X over D or just X?

MR. DHIR: This is rod bundle, this is just Z centimeters.

MR. SCHROCK: Z?

MR. DHIR: Z, centimeters.

MR. BANERJEE: And the hydraulic damage is about

MR. DHIR: 1.2

MR. BANERJEE: So this is in turbulent zone?

MR. DHIR: Yes, 11,000 yes.

CHAIRMAN WALLIS: So it's developing pretty slowly?

MR. DHIR: Yes.

CHAIRMAN WALLIS: It is, yes.

MR. SCHROCK: It should go faster than that for Reynolds of 11,000 I think.

MR. DHIR: 11,000 I don't know.

CHAIRMAN WALLIS: Anyway, what's the right hand side?

MR. DHIR: Okay. And the right hand side is we take these values here and we develop a case and we are plotting them for the Weisman number based on this fully heat transfer coefficient normalized the -- number to the .4 power we are plotting against -- to the .8 power. And these are all of our data covering a range of 8,000 to about 95,000

MR. RANSOM: Just a little bit of clarification. The heater rods continue on in unheated party? I mean --

MR. DHIR: No.

MR. RANSOM: What is the zero to 100, that's only the heated section?

MR. DHIR: Heated section ends here.

MR. RANSOM: And where does it begin?

MR. DHIR: Middle.

MR. RANSOM: And the leads and the other parts of the rods --

MR. DHIR: They're still longer -- so much longer, but our measurement start at --

MR. RANSOM: Okay. But what I'm wondering about, where does the viscous layer begin? You know, you have a viscous boundary layer and you have a thermal boundary layer.

MR. DHIR: Right.

MR. RANSOM: Obviously the thermal boundary layer begins at zero in this case at the heated point.

MR. DHIR: Right. Right.

MR. RANSOM: But presumably you must have a fully developed viscous layer.

MR. DHIR: No I've seen the other kind of grid to which these rods were sitting. So the floor is coming through holes.

MR. RANSOM: Through spaces?

MR. DHIR: Kind of spaces, but it's like a grid plate where the rod was sitting in.

MR. RANSOM: Where do the grid space start then?

MR. DHIR: Just above zero. You know, they're just sitting here.

MR. RANSOM: So you mean the flow comes in like jets?

MR. DHIR: That's right. The flow is coming in like through those holes, passages.

MR. RANSOM: So it's not a fully developed turbulent situation at the beginning of the heated section?

MR. DHIR: It's not fully developed flow, yes.

MR. RANSOM: It may be one reason the heat transfer coefficient is bigger at the beginning. It actually generates some extra -- with these jets.

MR. DHIR: Possible.

So what we find is the fully developed values for this range of -- number are about 16 percent higher than Dittus Boelter correlation. And the chain line is the Weisman correlation for a square grid type of arrangement and the rod bundle -- somewhat smaller than what we have, and his real number range was on the higher end. It was about from 30,000 to about 700,000 and yet on the low end about 8,000 to 95,000 but we are predicting lower heat transfers then will be predicted from Weisman's correlation.

MR. RANSOM: I'm back to Professor Sanjoy Banerjee's question, why do they agree down at the lower end, because they seem to be in quite a bit of disagreement, at least that is bolder on the left hand one, and yet the low Reynolds number on the right hand plot they seem to be in quite good agreement.

CHAIRMAN WALLIS: Well, it's actually quite close because there's a false origin on the left hand side.

MR. DHIR: Right.

MR. RANSOM: It's what?

CHAIRMAN WALLIS: It's a false origin. You know 2500 is the base and the left hand side the percent disagreement is not very big. Because go all the way down to zero.

MR. DHIR: Because zero is --

MR. SCHROCK: They're everywhere within 30 percent.

CHAIRMAN WALLIS: Anyway, the interesting problem is the two phrase, isn't it?

MR. DHIR: Right. But at least it gives you -- this range was not available in the literature and there's some interest in that range.

CHAIRMAN WALLIS: All right.

MR. DHIR: Because of application to -- and then we go to ONB. So now these are not -- if you see this 4, it's a 4 item which I showed you on the table, what phenomena we were trying to model or understand or measure and what the instrumentation was.

MR. BANERJEE: Claussius Clapeyron.

MR. DHIR: Yes.

MR. KRESS: I had a question about this, V.J.

MR. DHIR: Yes.

MR. KRESS: It seemed to me like that psia ought to be proper from the Claussius Clapeyron equation, the one on the right hand side of the first equation.

MR. DHIR: They put it at saturation temperature corresponding to the pressure in the vapor.

CHAIRMAN WALLIS: Which is the same as --

MR. DHIR: No. Liquid pressure is less. So the liquid is at saturation temperature. Pressure in the vapor bubble is higher than the pressure outside. And the temperature of the vapor has to be cooled to or at least the saturation temperature cause under the pressure in the bubble. So the temperature of the vapor is higher than the liquid, and that's the reasoning you made that the vapor bubble has to be surrounded by superheated liquid for it to go.

MR. SCHROCK: But the difference is small through bubbles of this size.

MR. DHIR: What size?

MR. SCHROCK: The average size they have when they're detached from the wall. There's not much--

MR. DHIR: Right.

MR. SCHROCK: Not much delta P involved once they've detached.

MR. DHIR: Well, how did we jump to detached bubbles. First I'm talking about onset of nucleate boiling.

MR. SCHROCK: Oh, yes. You're right. You're right. I'm not paying attention.

MR. DHIR: So we're talking about bubbles forming on the cavities --

MR. SCHROCK: Right, right.

MR. DHIR: -- which is a very, very small number.

MR. BANERJEE: So this is really right in the cavities?

MR. DHIR: Cavities, right. You know, as I said, initially we want to predict where the boiling starts. And if you're not going to predict that right and then you keep on adding the arrows you move downstream. So there are a number of correlations models that have been proposed since '60s. You all know them, know about them, I don't need to repeat them. But basically HSU it was proposed in '62, very simply matched or said the minimum superheat will be the case when temperature profile in the liquid is simply tangent to the superheat you need to -- because of the evaporation in the bubble.

And then Bergles & Rohsenow, Rohsenow followed that same idea, but they placed the properties of the fluid in terms of the pressure. And Sato and Matsumara again did a similar thing. Davis and Anderson added a constant C_1 to account for different contact angles.

MR. SCHROCK: Actually, the vapor inside the bubble is slightly superheated, but it's negligible importance.

MR. DHIR: Yes.

MR. SCHROCK: Rohsenow worked that out from a free energy argument years ago. And there's a physical model --

CHAIRMAN WALLIS: I think Maxwell did it, somebody like that.

MR. DHIR: It's higher than --

MR. SCHROCK: It's Helmholtz.

CHAIRMAN WALLIS: Helmholtz, somebody.

MR. DHIR: Right.

MR. SCHROCK: On a physical model.

MR. DHIR: Yes, Kandlikar.

And see those kind of correlations are modeled work when the liquids are partially breaking the surface. And Hahne, Spindler and Shen in 1990 looked at freons which -- the surface well and they found those correlations really under predicted the wall superheat at nucleation. And from experiments they found that -- could be written empirically like this, and if you use that corrective style you can calculate the 1B superheat and then you substitute that into the -- balance and this is a superheat and the liquid subcooling is there, multiple by heat transfer coefficient, that gives the heat flux and ONB. So you get delta to ONB and heat flux ONB both.

This is what -- see how our data looks like on the flat plate for different heat fluxs. This is the cover I show you earlier. This is a single phase heat transfer. And these are the plots we see as increase --

CHAIRMAN WALLIS: I didn't understand your little vertical things where you said this is where the two meet. I couldn't see. Either the numbers in the text don't agree with the position of those little vertical lines, and also I don't understand how they related to the curves.

MR. DHIR: Okay. Let me explain what we're blocking here.

Let's take this curve. Higher heat flux, okay. The heat transfer coefficient, it decreases and then increases and increases and then finally becomes almost constant. So we are plotting here is where we saw ONB and bubbles start to form on the surface. Visually and by noting the minimum in the curve.

CHAIRMAN WALLIS: Oh, the minimum.

MR. DHIR: Right.

CHAIRMAN WALLIS: I thought you said it was where there was departure from single phase, which would have put it way over to the left.

MR. DHIR: Right. That will be left. But minimum --

CHAIRMAN WALLIS: When you say minimum in the text, it says --

MR. DHIR: Minimum is the heat transfer improves after the bubbles start to form.

CHAIRMAN WALLIS: But it's really where it departs from single phase that's something's happened.

MR. DHIR: Right, but single phase it departed, visually we see single phase, and this is the two phased region.

CHAIRMAN WALLIS: I didn't understand this minimum idea at all. Because I was looking for where the one curve leaves the other one, which is actually further to the left. Okay. Now I think I understand it. No, I understand what you've done with the minimum part.

MR. DHIR: Right. But these are different heat flux curves.

CHAIRMAN WALLIS: Yes, but minimum wasn't clear to me that minimum meant anything.

MR. DHIR: What we find, if I set the heat flux and measure the heat transfer coefficient along the length of the plate, you will see heat transfer coefficient would decrease, a minimum value and then increase.

CHAIRMAN WALLIS: Okay.

MR. DHIR: And the minimum point almost coincided where the nucleation starts.

CHAIRMAN WALLIS: Well, why does it leave the single phase flow curve before that?

MR. DHIR: What do you mean before that?

CHAIRMAN WALLIS: Well, you dashed -- your colored red curves leaves the black curve way up at the left hand corner of the picture.

MR. DHIR: This one?

CHAIRMAN WALLIS: No, the curve.

MR. DHIR: This curve? This is single phase.

CHAIRMAN WALLIS: The red curve leaves the black curve at a point which is almost on the left hand corner up there at 6,000.

MR. DHIR: Right.

CHAIRMAN WALLIS: So really you shouldn't--

MR. DHIR: All these points should be one point.

CHAIRMAN WALLIS: No, no, the right curve. You put a curve in there. You've only really got red points, right? If you'd shown a straight line through the red points hitting the black line, then I would have believed something. But you fared in a curve. And the red curve leaves the black curve at about 2 in terms of Z. You see what I mean?

MR. DHIR: Right. This -- okay. The key point you want to make here is that you increase the heat flux, you leave this curve either later or earlier.

CHAIRMAN WALLIS: Come down the black curve.

MR. DHIR: Okay.

CHAIRMAN WALLIS: And then when you get into the right curve -- you're on the Metro, right?

MR. SCHROCK: Right.

CHAIRMAN WALLIS: When do you get onto the red curve?

MR. DHIR: That's true.

CHAIRMAN WALLIS: When does your finger go from the black curve to the red curve?

MR. DHIR: Okay. The question is here this represents some of uncertainty of measurement for each experiment. Actually this should be one curve.

MR. BANERJEE: Yes, the heat flux shouldn't have an effect.

MR. DHIR: Effect on the single phase heat transfer coefficient.

CHAIRMAN WALLIS: Okay. But you come down the black curve.

MR. DHIR: Yes.

CHAIRMAN WALLIS: Now put your finger on the black curve.

MR. DHIR: Right.

CHAIRMAN WALLIS: Come down there -- don't -- don't go so far.

MR. DHIR: Okay.

CHAIRMAN WALLIS: Now go up some more.

MR. DHIR: Okay.

CHAIRMAN WALLIS: Go up some more. Go up.

MR. DHIR: Okay.

CHAIRMAN WALLIS: And you still haven't met where the red line comes in.

MR. DHIR: Right.

CHAIRMAN WALLIS: The right line comes in up there somewhere.

MR. DHIR: This red line and this solid should be the same curve.

CHAIRMAN WALLIS: Well, then you should draw them the same.

MR. DHIR: Again, I have my data. The data says each time I take the experiment I have data difference. I'm not treating it.

MR. BANERJEE: --down there which is much closer.

MR. DHIR: Right. So that's what I'm saying --

MR. BANERJEE: So why do you draw it --

MR. DHIR: Oh, you could draw it here and then --

CHAIRMAN WALLIS: Then it would be clear where it left. You see, the thing is where do you leave one and hit the other? And you curved it like that, it looks as if it leaves at 6,000.

MR. BANERJEE: But there's no logic for you to miss that red point.

MR. DHIR: Again, it's just the line fell through the data. It's not specific. The key question is the idea we should be talking about does the minimum represent onset of nucleate boiling.

CHAIRMAN WALLIS: You see your text doesn't say anything about minimum. Your text says where the volume departs from the other line, and that is way up where I was trying to get you to go, and that's very misleading to the reader.

MR. SCHROCK: What is that inset ONB location, what's that legend mean?

MR. DHIR: ONB location, this is visual observation. Visually we see on the -- on the plate, you know the location --

MR. SCHROCK: So it's a vertical line not a horizontal line, but there's a solid one and a dashed one.

MR. BANERJEE: The first one is the minimum.

MR. DHIR: Dashed one represents the minimum, the heat transfer coefficient curve.

CHAIRMAN WALLIS: And the minimum should be ONB. But, anyway, we should probably move on. It's confusing to the reader when he sees these things.

MR. RANSOM: I can't even tell which one's dashed and which one's not because the dash is much different.

CHAIRMAN WALLIS: Which goes with which curve is also a question.

MR. DHIR: No, all these four curves should be one.

CHAIRMAN WALLIS: Up to some point

MR. DHIR: Up to some point. Because then they should diverge on each case.

CHAIRMAN WALLIS: Right.

MR. DHIR: But we are being honest to our data that what -- I plotted. So I could have plotted an average of these and then draw it, and then it will be clear, there'll be -- in that main curve.

MR. SCHROCK: So the visual and the observation from the HZ plot are sometimes one way in relationship, sometimes the other way.

MR. DHIR: Right. Because thermocouples are made indiscreetly so you're not exactly locating that -- from the plot you cannot exactly locate that.

MR. SCHROCK: Okay.

MR. KRESS: For the blue line the visual and the HZ are on top of each other?

MR. RANSOM: There's only one vertical line on that one.

MR. KRESS: Yes, it must be on top.

CHAIRMAN WALLIS: Anyway, you just have to clarify it.

MR. DHIR: Right.

MR. BANERJEE: What is the other one?

MR. DHIR: What? The other one is simply locating where the ONB occurs, how it's influenced by flow velocity and there are two different flow velocities, liquid subcooling and contact angle. Because the boiling has shifted. Superheat has shifted depending on the contact angle or your flow boiling -- flow velocity.

So basically this plot is telling you that if ONB to occur at this location, then delta $T_{W,ONB}$ would be higher if I have a high flow rate.

MR. SCHROCK: When they use this in their interpretation in the code evaluation, they're going to have to do something about the contact angle as a function of pressure. Are you providing those data for them or --

MR. DHIR: No, not as yet. Not as yet.

MR. SCHROCK: Has that come up in your discussion with the sponsor?

MR. DHIR: No.

CHAIRMAN WALLIS: It's a function --

MR. SCHROCK: But you agree, it depends on surface tension, which depends on temperature --

MR. DHIR: Surface tension is one really. It depends, you know, solid liquid also surface tension.

CHAIRMAN WALLIS: It depends on the age of the fuel.

MR. SCHROCK: It depends on a lot of stuff.

MR. DHIR: Lots of stuff.

MR. BANERJEE: So the contact angle has a larger effect than the flow velocity?

MR. DHIR: On what?

MR. BANERJEE: On the ONB.

MR. DHIR: That's true. In this situation you can see onset of nucleate boiling contact angle has more effect.

MR. BANERJEE: Lots more. I mean, the major effect.

MR. DHIR: Right.

MR. SCHROCK: See, at the outset I was a little puzzled by why the emphasis on low pressure for your experiment. In the TRAC code it seems tome they need the ability to solve this problem for any pressure that may occur during an accident transient or transient of any kind. And that would seem to cover a substantial range of pressure, not just low pressure.

MR. DHIR: Right.

MR. BANERJEE: But during the AP600 runs the low pressure behavior in the subcooled region, at least of RELAP-5 was --

MR. SCHROCK: That's what led them to think they had a problem.

MR. BANERJEE: Yes.

MR. DHIR: Right.

MR. BANERJEE: That's really what happened historically. We had a lot of trouble trying to interpret this result. Whether they are true or not, we don't know. Because maybe the -- for all we know. But that was the reason.

MR. DHIR: But at that time thinking was that these codes do well for at high pressures, but not at a low pressure.

CHAIRMAN WALLIS: We've got to five slides out of 83 in about --

MR. SCHROCK: How do we know? I mean, you've identified what the real dependence is here. And it's contact angle.

MR. DHIR: Right, it's quite important.

CHAIRMAN WALLIS: A elusive problem.

MR. SCHROCK: That means the code needs good contact angle information, and I don't think it has it.

MR. DHIR: You know, at least it's 30 points of whatever the key variable you need to know.

MR. SCHROCK: Right.

MR. DHIR: And then we come back and say rather what we want to do in the code.

MR. SCHROCK: Yes.

MR. BANERJEE: How did you vary the contact angle?

MR. DHIR: How did I vary the contact angle? For copper block we polished the surface and when you polish the copper block and use water, you get contact angle close to 90 degree.

Then we follow the standardized procedure where we put the copper block in the air and heat it so it gets oxidized. But controlling the oxidization, we can change the contact angle. And so we went down to about 30 degrees.

And generally when you like polished copper, after you're done with the experiment contact angle changes. And then we had to have some sort of an average for that run. But when you're at 30 degrees still same, for example, after you are done --

MR. SCHROCK: And for your Zircalloy you did it on a piece of flat Zircalloy with drops --

MR. DHIR: Right. Flat. And then we also put on the rod very small droplet and see what the contact angle was. And as you'll see in there, the contact angle is given for the --

MR. BANERJEE: 37 or something.

MR. DHIR: 57.

MR. BANERJEE: 57.

MR. SCHROCK: It's hard to measure well with little drops.

MR. DHIR: With the plates, yes, you can do that. Yes. But, again, the question is are you -- you know, we can spend all of our time on contact angles.

CHAIRMAN WALLIS: With little drops because the contact angle then varies over the surface?

MR. SCHROCK: Well, it's just very hard to see where the contact line is.

MR. DHIR: Again, then you can get in discussion of whether it's microscopic contact --

MR. SCHROCK: And you measure the --

MR. DHIR: So, but at least it gives you a perimeter which you can measure.

MR. SCHROCK: Yes.

CHAIRMAN WALLIS: That's an elusive perimeter. I remember going back to Burnstein's experiments and change the surface and a lot of things change.

MR. DHIR: But the question you ask yourself if it's elusive perimeter, it is an important perimeter. If it's not important, let's forget about it.

CHAIRMAN WALLIS: But it is important.

MR. DHIR: That's what I'm saying.

MR. BANERJEE: Well, your experiments show that it's --

MR. DHIR: It's extremely important.

MR. BANERJEE: -- the main perimeter.

MR. DHIR: That's right.

MR. BANERJEE: One of them.

MR. DHIR: In the past we have -- you know, somehow ignored it whenever the problem occurred or it's elusive problem and let's --

MR. SCHROCK: Because it's hard to measure and it's inconsistent.

MR. DHIR: Right.

MR. SCHROCK: We'd never get agreement.

MR. DHIR: But if you think of, again --

MR. SCHROCK: Subtle operational conditions.

MR. DHIR: That's true. But let's say I give you 57, you may come out at 52 or somebody comes with 62, it's not going to be 5 degrees.

MR. SCHROCK: Yes. That's right.

MR. DHIR: So that's what we should shoot for.

MR. SCHROCK: But the difference between 60 and 30 is big.

CHAIRMAN WALLIS: We need to move on.

MR. DHIR: So we have proposed our own correlation for predicting the onset of nucleate boiling. What we are saying is that the corrected size of the cavity is given by -- through the analysis, but the probability of finding this cavity diminishes as the contact angle decreases. This cavity may not be available to nucleate as at first it becomes more ready. So that's the --and this function F which corrects the cavity size we get empirically by correlating all the data that is available in the literature. And varying from the contact angle of one degree to almost 90 degree.

MR. BANERJEE: What is phi?

MR. DHIR: Phi contact angle.

MR. KRESS: And how are they supposed to know what that is in the code?

MR. DHIR: Code? If they're working with Zircalloy -- what's stated is they would know about 57 degrees.

MR. KRESS: That's the unoxidized state?

MR. DHIR: Right.

MR. KRESS: Okay.

MR. DHIR: So that's all I can say at the moment. But with the lowest thing it does effect -- it does depend on pressure as well.

CHAIRMAN WALLIS: -- contact angle is in the cavity, isn't this different? How do you measure that? It's not the same as on the surface.

MR. DHIR: I don't know. That's the proposal I have for research.

CHAIRMAN WALLIS: The cavities may be there because they are different.

MR. DHIR: Yes. We have looked at again, now we're going back to study. We did about 12 -- 12, 15 years ago and we looked at the shape of the cavities microscopically. And then for my polishing the surface and see what kind of cavity it really nucleated. And we were able to relate the trapment of gas in the cavity to a contact angle.

CHAIRMAN WALLIS: What I'm saying is suppose you have a clean surface, a clean line.

MR. DHIR: Yes.

CHAIRMAN WALLIS: And after a while it may develop cavities because of erosion and corrosion phenomenon.

MR. DHIR: Yes.

CHAIRMAN WALLIS: And because of this corrosive phenomenon what's in the cavity isn't the same as what's on the surface.

MR. DHIR: Yes.

CHAIRMAN WALLIS: And therefore what contact --

MR. DHIR: That's possible, yes. But again, that's possible but it's going to be -- first order of effect to second order effect.

MR. BANERJEE: I mean, BWI is adding zinc and its cobalt and all sorts of stuff was on the --

MR. DHIR: You know, again, we just did this -- now I'm jumping, but maybe -- Zircalloy, fresh Zircalloy and water we found contact angle was about 57. Then we did some experiments with boran and water. We put 7,000 ppm of boron in the water. And that water we used to measure the contact angle. It was about the same. Because the number's different with boron. And then we also, you know as you run that experiment, boron deposits from this cladding. And then we measured the contact angle again, it was not much different than 57. So that is what evidence we have. However, nucleation sites and then boron crust was on the surface, but much more, because you formed the porous structure --

CHAIRMAN WALLIS: Well, close around --

MR. DHIR: Right. So that increase the number.

CHAIRMAN WALLIS: You distill. You distill the water away and leave the crud behind.

MR. DHIR: Right. And then that crud is porous.

CHAIRMAN WALLIS: Yes.

MR. DHIR: And you form -- there. And in fact we found -- I'm giving -- with boron your nucleate boiling heat transfer was higher but single phase heat transfer was lower after the crud was formed.

So this is all of the data we have and which we put together in the literature. And you can see data varies from contact angle of 1 degree FC72 to about 90 degrees with copper, maybe 35 degrees with copper.

CHAIRMAN WALLIS: What's the pressure range?

MR. DHIR: Most of the data it's at -- of pressure but some is at high pressures as well. There the contact angle was given. I'll show you later on. I think it's -- it's Bergles & Rohsenow high pressure data.

MR. BANERJEE: And this is for flat plates, or does it also have rod bundles?

MR. DHIR: Rod bundles are there. It's the 57 8 points 2 bar, 6 points at 3 bar and about 7 points of water. With boron and about 19 points with rod bundle. So you have several data points.

MR. SCHROCK: These are all calculated from the equation on 34, the previous page?

MR. DHIR: The previous page, right.

CHAIRMAN WALLIS: This all assumes you have enough nucleation sites that you're not limited by the numbers, by Hsu criteria.

MR. DHIR: Hsu criteria gives us the -- sites. Then we are saying.

CHAIRMAN WALLIS: If they don't exist, then you won't get --

MR. DHIR: That's what -- nonexistence we call the F function. That's what accounts for nonexistence.

MR. SCHROCK: There's a note on that slide that says for small superheats. What's the one --

MR. DHIR: Oh, because we expanded the pressure difference to saturation temperature difference due to Clausius Clapeyron. And if you go to high superheats that doesn't work, you know. You can't expand like that.

MR. DHIR: Because of the Clausius Clapeyron?

MR. DHIR: Clausius Clapeyron, right.

MR. BANERJEE: But you could use it on Hahne's --

MR. DHIR: Right. On Hahne's equation you can use it. Go to steam table --

CHAIRMAN WALLIS: If you had a surface with no cavities in it and everything would be different?

MR. DHIR: Right.

CHAIRMAN WALLIS: Like boiling on mercury or something?

MR. DHIR: Mercury or, you know, again, but in the limit if you say contact angle goes to zero --

CHAIRMAN WALLIS: Well, no, just contact

angle. It's also a crunch of -- you have to have enough cavities for this --

MR. DHIR: That's true. You know, it's like glass. You can have one crystal, you won't get anything.

MR. KRESS: Why does the Hayes's alloy look different than all the others. It's those little crosses up to the top.

MR. DHIR: Cross, yes. That's the -- this that R11 which --

MR. KRESS: Freon.

MR. DHIR: Freon. Freon, and you know that was the number we got, but then we don't know what the reason is. Somebody's -- let's put all the data we have.

MR. SCHROCK: What is the largest superheat you had in your test tube?

MR. DHIR: My test the highest is about 15 degrees C.

MR. SCHROCK: 15C?

MR. DHIR: 15 to 20C, yes. That's how high we have gone. But there are others who have gone quite high. See, our data is mostly here, you can see. ONB's low superheat, but doing the experiments we have gone higher.

MR. SCHROCK: Okay.

CHAIRMAN WALLIS: Okay. The next one.

MR. DHIR: Okay. So we not able to only put it to ONB -- but also Q_{ONB} because it's a no single phase heat transfer coefficient --

CHAIRMAN WALLIS: If you don't put the -- effect in you get far more scatter?

MR. DHIR: That's right. But here you can see Q_{OMB}, we have gone about 4 orders of magnitude. Okay. This has all the high pressure data as well.

MR. BANERJEE: Which is the high pressure data.

MR. DHIR: That is this one, water and nickel. That -- high heat influx.

MR. KRESS: How is the contact angle determined in all these experiments?

MR. DHIR: Some are reported, but we have measured this to a droplet. We place a microdroplet --

MR. KRESS: Drop a droplet on there and as it --

MR. DHIR: Then take a photograph.

MR. KRESS: Okay.

MR. SCHROCK: Graham, how did you see the contact angle effect on his graphs? I didn't understand your point.

CHAIRMAN WALLIS: About what?

MR. BANERJEE: Well, it's collapsed through the --

CHAIRMAN WALLIS: I assume that if you don't put contact angle in -- they have a formula for using contact angle, f equals minus 6. But if you simply puts f equals 1 you get presumably much more scatter. It will be useful to show that, I think.

MR. DHIR: You should show that.

MR. BANERJEE: What happens if you put f--

MR. DHIR: You'll certainly underput.

MR. BANERJEE: Yes. If you take the exponential term out --

MR. DHIR: Right.

MR. BANERJEE: Phi is in radiance, right?

MR. DHIR: Right.

CHAIRMAN WALLIS: How much does f vary?

MR. DHIR: Oh, varies quite a bit. I'll show you next slide.

CHAIRMAN WALLIS: How much is quite a bit?

MR. DHIR: How you can go to -- you can go to as close as zero.

CHAIRMAN WALLIS: You said it varies. Does it vary --

MR. DHIR: Close to zero.

CHAIRMAN WALLIS: No, but isn't it from 4 degrees to 70 degrees?

MR. DHIR: Let me show you next group.

MR. BANERJEE: Well, if 5 goes to zero, then f is equal to zero?

MR. DHIR: Right.

CHAIRMAN WALLIS: But it is off the graph?

MR. DHIR: Right. You got to -- nucleation temperature, that's what we say.

This is one example how that f does it. They assume the correct size is 5 micron and then you see how -- when we would change. If I just kept 1, ONB would be only what you have here. Delta T_{ONB} over delta be homogeneous nucleus and we're plotting here. And you're close to .03 or .02. And because of the f function and eventually when this goes to zero, you're going to homogeneous nucleation temperature. That's how we effect the whole curve.

MR. BANERJEE: How well does Davis and Anderson correlation true?

MR. DHIR: It doesn't -- you know, if we account for their pressure -- it works okay. Not Davis and Anderson, but that was --

CHAIRMAN WALLIS: What happens if you use pi?

MR. DHIR: Beg pardon? Just one second.

CHAIRMAN WALLIS: You won't wet the surface at all?

MR. DHIR: Your question was -- Davis and Anderson doesn't do it that well with just pi.

Yes, what was the question?

CHAIRMAN WALLIS: If pi is pie, the liquid doesn't wet the surface at all?

MR. DHIR: Right. We have gone up to 9 degree even, now you can go on further. You go to zero.

CHAIRMAN WALLIS: Well, it goes to 1 and your correlation doesn't go to zero.

MR. DHIR: Right. One is just normalized. You know, with homogeneous nucleation. So your cluster size would determine.

MR. RANSOM: Isn't value T home?

MR. DHIR: Homogeneous nucleation.

MR. RANSOM: Oh, homogeneous nucleation.

CHAIRMAN WALLIS: So the water boiling on mercury or the contact angle is pi? It also has no nucleation centers.

MR. DHIR: Right. Right.

CHAIRMAN WALLIS: All right. We need to move along then.

MR. DHIR: Okay. Then we look at nucleation site density.

MR. KRESS: Now I want you to pronounce that. I want you to pronounce that name.

MR. DHIR: I can pronounce it. Kocamustafaogullari.

CHAIRMAN WALLIS: Yes, it's easy. Can you do it?

MR. KRESS: No.

MR. DHIR: Okay. Oh, maybe 18, 20 years ago these guys predicted that nucleation site density would correlate like this or the number density was normalized -- which was taken from FRIGG correlation. And now you can see FRIGG correlation is for pool boiling, not for flow boiling and the characteristic site would differ anyway.

So that is their model.

Wang at UCLA did theirs about 7, 8 years ago. We looked at pool boiling and we came up with number density like this. It depends on contact angle. And again, contact angle was very important variable, that's what we found.

CHAIRMAN WALLIS: What is D_c?

MR. DHIR: D_c is the captured --

CHAIRMAN WALLIS: Oh, that one. Okay.

MR. DHIR: And it's mostly proportionate to superheat.

CHAIRMAN WALLIS: It's surface perimeter.

MR. DHIR: And so the superheat, you see the power is 6 and very highly nonlinear. If you're now going to put it nucleation site, then see how do you hope to predict heat flux.

CHAIRMAN WALLIS: This is a very dimensional correlation.

MR. DHIR: Yes, it is dimensional. The cavity sizes and micron, and so forth.

So this is a picture we see, same surface, copper and two different contact angles. Same superheat. And left hand side 30 degree contact angles, right inside is 90 degrees.

CHAIRMAN WALLIS: Same history, too.

MR. KRESS: How did you vary the contact angle on it?

MR. DHIR: We discussed earlier, but what we have is the copper surface, we oxidize it.

MR. KRESS: You oxidize. Okay.

MR. BANERJEE: But nucleation site then simply is changed, too.

MR. DHIR: Yes, that's what I'm saying. Site density is strongly dependent on contact angle.

CHAIRMAN WALLIS: This is with all the cavities active because you know you can -- you know, snuff them out by boiling and then cooling down and pushing the liquid into the holes.

MR. DHIR: Yes. But when you go to higher superheat that effect is gone. But clearly you can see the difference. You know, I have refuted this with different number of students. So I may -- personally to ask them, give them a test score and then do it. And every time we see this --

CHAIRMAN WALLIS: You can do this snuffing experiment easily in there.

MR. DHIR: Yes, you can do it.

CHAIRMAN WALLIS: But there's no gas involved in the cavities. It's all just pure liquid?

MR. DHIR: There is always some trapped gas to start with, yes. And you can -- play games like that, you can have the cavities, then pressurize it or some you could subcool and then kill them. They will not come --

CHAIRMAN WALLIS: Right.

MR. SCHROCK: These equation that's per square centimeter from your graphs --

MR. DHIR: Right.

MR. SCHROCK: Per square centimeter.

MR. DHIR: In the literature you will see there are lots of -- and information with respect to flow boiling, especially in nucleation site density. Many people believe that all nucleation site density is effected by flow rate, it's effected by subcooling. But we find none of those effect it. The key variable is while superheat then contact angle. Okay.

And these are the data you see for our two flow velocities and fixed contact angle. And I can see there's hardly any effect of flow velocity.

MR. BANERJEE: And you just counted the sites?

MR. DHIR: Yes, photograph like I showed you and you can know the area and you can see how many are there.

MR. SCHROCK: You take multiple photographs and get the average then.

MR. DHIR: Repeat them.

MR. SCHROCK: Right. Yes.

MR. DHIR: It's a tedious job. And this is now flat plate, but two different subcoolings. So there's no, you know, there's a clear distinction on two subcoolings and we don't see any effect as long as your contact angle is fixed and -- so that will simply life some ways that you have only two variables.

And this is what we see from our experiments which we have done. And this is all of the data we got.

CHAIRMAN WALLIS: It's really four bounds, though.

MR. DHIR: Beg pardon?

CHAIRMAN WALLIS: Five. It's five groups.

MR. DHIR: Right. Five different contact angles.

MR. DHIR: Okay. This line and this dotted line is the correlation developed currently here from pool boiling data. And that correlation was for -- superheat greater than about 15 degrees corresponding to cavity size of about 5 --

CHAIRMAN WALLIS: So if you didn't control contact, you could go for a factor of thousands or so?

MR. DHIR: Yes, sure. That's why boiling curve shift all over the plate. That's the key ingredient. Although -- cavity size of cavities, side density doesn't play any role.

CHAIRMAN WALLIS: We should have both of you together.

MR. DHIR: We have. We were there in Illinois in May. We were there and there were -- so we had good discussion argument.

CHAIRMAN WALLIS: Was it a refereed discussion?

MR. DHIR: It will be published.

CHAIRMAN WALLIS: Okay. Let's move on.

MR. DHIR: Yes. Okay. So even you see there's a big variation in the number density with contact angle. And we would look at Kocamustafaogullari data and predict that, that's what he find.

So for all the data we have developed a correlation and -- less than 15 degrees number density varies as delta T to the square. But superheats it's delta T to the 5.3 power. Okay.

CHAIRMAN WALLIS: Next one shows the correlation.

MR. DHIR: And then the --

MR. SCHROCK: What happens to them at 15 degrees?

MR. DHIR: What 15 degrees.

MR. BANERJEE: They would discontinuous.

MR. SCHROCK: They're discontinuous.

MR. DHIR: Yes, they're the discontinuous. Because it depends on the -- you know, the surface. The superheat becomes large and then they just take off.

So you can see it's lots of data, lots of time was spent on this. And this is all the data we have and it's easy to get an error in this, especially when you're -- say over 1 centimeter square area, you have one cavity or two, you're a factor of 2 off. And so your densities and you see some scatter out here. And then high heat flux as the bubbles start to -- is very difficult to delineate how many cavities are there. So you see scatter out there.

This scatter is puzzling. This is the data we took very early and we found many more cavities than you will suspect from all the other data. And that's when we were just starting to experiment. My guess is that we had too much gas in the water, we had not aerated the water. We have not gone back and reproduced this data, so it's still there.

MR. BANERJEE: This is all your own data?

MR. DHIR: This is all our own data, but we -- as I showed you earlier, the data of Klausner -- we got.

See, most people don't give you contact angle or superheat. And if you don't have it, you can put it wherever you want to. And so we tried to void it.

CHAIRMAN WALLIS: Right. Right.

MR. DHIR: Next we go to bubble diameter and departure and lift off. And so what we find, here we plot bubble diameter departure. Departure means the bubbles start to slide on a nucleation site. Lift off is when it takes off, now going to the surface. Okay.

And here this typical data. We have more sets of data, but this for flat plate with velocity of about 35 centimeters per second and three different subcoolings.

As we increase the subcooling you can see the bubble diameter departure. As we increase the wall superheat it increases. We relate this to the inertia as bubble goes faster, there's more liquid inertia to be encountered. Bubble go to slow down with condensation, inertia is less.

And similar -- so we find bubble diameter departure going about square root of wall superheat and that's lift off diameter, which is larger than the departure diameter. So the bubbles grow as they move along the surface.

MR. BANERJEE: Why is this vertical line, like vertical scatter?

MR. DHIR: It's a measurement arrow you see once sometimes bubbles munch.

MR. BANERJEE: I see. It's not just the distribution of the --

MR. DHIR: Right. No, no. And this is from flat plate.

MR. BANERJEE: Right.

MR. DHIR: Now you could do some cavity experiments which you are doing also, you can get very clean data, the scatter won't be there.

CHAIRMAN WALLIS: Well, this next one you have a characteristic link which depends on G?

MR. DHIR: Yes.

CHAIRMAN WALLIS: Why is that?

MR. DHIR: Because even in the wall the bubble is attached there is a buoyancy actually.

CHAIRMAN WALLIS: So this is only for vertical upflow?

MR. DHIR: Vertical upflow.

CHAIRMAN WALLIS: If you have vertical downflow, it would be quite different.

MR. DHIR: Different, right.

CHAIRMAN WALLIS: Horizontal flow would be quite different?

MR. DHIR: That's right.

CHAIRMAN WALLIS: And we have done separate study which shows those things.

MR. BANERJEE: The microgravity?

MR. DHIR: Yes, different.

CHAIRMAN WALLIS: Yes. If you go to -- well, microgravity everything goes off scale here.

MR. DHIR: This one would go off scale, but you see that lift becomes extremely important, microgravity.

CHAIRMAN WALLIS: So this is a big correlation without much mechanism behind it?

MR. DHIR: That's right.

CHAIRMAN WALLIS: Right.

MR. DHIR: We have -- I'm not showing here. Where we're doing the medical simulations and data from that, we can do the correlation. But this is just from this work.

Basic physics is that superheat is important, subcooling is important and that's all I can say.

MR. BANERJEE: The length scale is surface tension to some sort of --

MR. DHIR: Buoyancy, yes. Typical end scale in boiling.

MR. BANERJEE: But if G is zero then you have a problem.

MR. DHIR: As I was saying again, it's

very specific to upflow, 1G.

CHAIRMAN WALLIS: And this surface tension comes in because the bubble is hanging onto the surface.

MR. DHIR: Hanging on to the surface and that's what is --

CHAIRMAN WALLIS: I think it would depend on the contact angle then.

MR. DHIR: Yes, this is -- again, this is a 30 degree contact angle. Contact angle is a variable.

CHAIRMAN WALLIS: Oh, you have a correlation involving --

MR. DHIR: Not as yet.

CHAIRMAN WALLIS: Okay.

MR. DHIR: We're not done with that. So this is only for 30 degree, one contact angle, although it should be stated there.

Now we just said okay, let's go to the -- and see what's out there, and this is what we find. This is the velocity we got from our previous graph which I showed you --

CHAIRMAN WALLIS: The curve is yours?

MR. DHIR: Yes. And this is all the data. You know, some people don't give you again, superheat, whole subcooling, local values and just see how much scatter is off all the data, but it seems like the velocity effect we're getting seems to be okay.

But to put all this data in perspective, we need to have, you know, information about what the superheat, local superheat was, subcooling was, contact angle was.

MR. BANERJEE: So this Unal's data is the one that Lahey used?

MR. DHIR: Right. Unal went to high pressures, too, you see. It's a larger angle pressure. And Unal's data is here.

CHAIRMAN WALLIS: It works best a high pressure.

MR. DHIR: Yes. But we don't know what the contact angle is for that case. Okay.

MR. SCHROCK: You probably could get a reasonable handle on it knowing the materials, huh, in Unal's data?

MR. DHIR: Approximate, yes. Contact angle, but not superheat.

MR. SCHROCK: Yes, not superheat.

MR. DHIR: Yes, and subcooling.

MR. BANERJEE: What is that curve you just fitted it?

MR. DHIR: We just plotted our curve, that velocity effect I got from the previous viewgraph, and that's just --

MR. BANERJEE: I see.

MR. DHIR: Without subcooling effect or superheat or contact angle. Just to see. If I had just done this, how far I could be off. And it also shows you that the velocity set probably is taken into--

CHAIRMAN WALLIS: Okay. I think we have to move on. There's a fantastic amount of information here.

MR. DHIR: So next is OSV. There's number of correlations starting with Bowring, '62 and it's kind of dimensional correlation. This delta $_{OSV}$ means that what is the liquid subcooling when the bubbles start to migrate into the bulk. So -- and they're relating -- flux and velocities.

And Levy did -- he accounted for the turbulent profile in the thermal boundary layer.

Dix correlated again delta $_{OSV}$, heat flux, single heat transfer coefficient.

Saha & Zuber which we were talking about earlier, this was basically telling you when OSV was not correct, but heat flux. It doesn't tell you heat transfer coefficient. People are using it.

And Zeitoun recently came up with a different correlation.

But you can see all of them somehow form a -- number which is --

CHAIRMAN WALLIS: D.J. I need to replace your battery. That's why it's clicking.

(Whereupon, at 5:01 p.m. off the record until 5:02 p.m.)

MR. DHIR: We are only halfway through.

MR. BANERJEE: But you've still got an hour.

CHAIRMAN WALLIS: You've got an hour.

MR. DHIR: Okay. I'll move quickly. But this is --

CHAIRMAN WALLIS: What we found is we didn't see this before. We saw some stuff, but most of this wasn't in it.

MR. DHIR: So we have looked at -- you know, from our data where the OSV occurs initially and those are the data you see here. And -- given location, this increase the flow rate, you need to have high heat flux. That's what it does.

And if you increase the subcooling, then also you need higher heat flux.

MR. BANERJEE: How are you defining onset of significant void here?

MR. DHIR: When the bubbles start to migrate.

MR. BANERJEE: Okay.

MR. DHIR: And some people have defined very differently, so there's always that struggle we had what did they mean. Some people may have the void fraction when they see some increase in void fraction, that's what -- they would call. But then that's way downstream you see.

MR. BANERJEE: Even if you have a millimeter bubble on a 1 centimeter diameter pipe on the wall, then you've got a void fraction of about 10 percent that's due to the millimeter bubble?

MR. DHIR: Right.

MR. BANERJEE: It's not trivial.

CHAIRMAN WALLIS: Because the ones on the wall are more significant?

MR. BANERJEE: Well, they appear --

CHAIRMAN WALLIS: That's right, so they're a lot --

MR. DHIR: So our proposal is based on this, that if the bubbles just before departure is smaller than the thermal layer thickness, then presumably the bubble will start to slide and eventually detach at high subcoolings. If on the other hand bubble is larger, then condensation occurring, then the liquid subcooling has to be less for bubble to grow to its desired size.

CHAIRMAN WALLIS: There's no further mechanics in this?

MR. DHIR: No. At the moment it's just--

CHAIRMAN WALLIS: I would think that motion of a bubble would depend on the mechanics.

MR. DHIR: Right. See, that's again -- it'll take some time. And we are looking at numerical simulation and then single bubble experiments. But that's funded through NASA. And that gives us this information. But right now it's amazing hypothesis. But we tested this hypothesis by taking all the data, Dix's data, we have all the water data and flat plate and rod bundle. And we found that this DD over delta correlated with the constant -- empirical constant C like this. So our correlation is very simple correlation, it's like dimension less wall superheat if we could do a constant, then OSV occurs.

And that constant we have gotten empirically. And it includes Dix's data, all data with freon and we have Bowring's data you'll see in the next viewgraph, and it seems to do for all of those data more reasonably well.

Bowring's data at high pressures and Dix's for the freon, and our data.

So up to now this is simply empirical.

Bubble release frequency, how do we get it. Here I think you can see what happens to the bubbles as they grow. I mark here this arrow. And here the bubble is growing, start to grow. This is the bubble which is growing. And now you see clearly this bubble is --

CHAIRMAN WALLIS: It looks like 2 bubbles.

MR. DHIR: Well, this a reflection.

CHAIRMAN WALLIS: Oh.

MR. DHIR: And growing, growing. You see the arrow is almost wanted -- cavity is. And now it start to slide. This is where the bubble was initially, now it's moved over. It continues to slide, slide and at that point it lifts off. And now after waiting --

CHAIRMAN WALLIS: And another one starts?

MR. DHIR: Beg pardon?

CHAIRMAN WALLIS: Then another one starts?

MR. DHIR: Another one starts.

MR. BANERJEE: But actually, you know as

soon as it slides it seems to be within the second slide already slightly lifted off if you look at the reflection.

MR. DHIR: Right. You know, that is a key question. Is there a layer underneath so create a liquid layer. And I don't know. That's a question I have myself. That is a bubble sliding on a thin film of liquid or is still in contact with the solid direct.

MR. BANERJEE: Well, if it is, then it's violating a no slide boundary condition.

MR. DHIR: Right.

MR. BANERJEE: Unless it's rolling.

MR. DHIR: Right. That's what Steve --

MR. BANERJEE: Steve Davis.

MR. DHIR: Steve Davis, he said that maybe the bubble is rolling, but it's very hard to --

MR. KRESS: It didn't look like the bubble changed sides much during the slide period.

MR. DHIR: Oh, it grows.

MR. KRESS: You think -- it didn't look like it grew.

MR. DHIR: No, it grows. And if you look at -- maybe it's not growing. It's bigger than the previous and then eventually --

MR. KRESS: It just maybe from here --

MR. DHIR: Yes, it grows. And I show you those lift off diameters, they're bigger. About 50 percent.

CHAIRMAN WALLIS: Okay. Okay. So you can get a frequency from this?

MR. DHIR: Yes, right.

MR. SCHROCK: You're comparing with Dix and Bowring, and as I remember both of them, they extrapolate the axial void profile to zero void and say that's the point.

MR. DHIR: Right.

MR. SCHROCK: So it's a little different meaning than yours.

MR. DHIR: Right, there is some difference. Right. That's the key issue we have.

And the waiting time at least you can see here. That is important because in some situations waiting time, transient conduction may have -- waiting time. And this is based on the data we got for different subcoolings and superheats.

Again, these -- what I'm going to show you here is not finalized. This is the stage where we are.

MR. BANERJEE: What do you mean by the waiting time here?

MR. DHIR: Once the bubble leaves the nucleation site, another bubble doesn't form right away.

MR. BANERJEE: Okay.

MR. DHIR: You wait for a while --

CHAIRMAN WALLIS: What's BG?

MR. DHIR: BG is the growth period of the bubble at the nucleation site.

CHAIRMAN WALLIS: Before it slides?

MR. DHIR: Slides, right.

So key thing we are saying is that with subcooling -- subcooling increases at a given superheat, you see the waiting times become longer. And at high superheats subcooling plays little role, waiting times become quite small in comparison to the growth time.

CHAIRMAN WALLIS: I presume where there's an intercept at one here where the waiting time is everything, that it's always waiting and there's this very occasional flip.

MR. DHIR: Right.

CHAIRMAN WALLIS: That's when there's a certain critical delta T for something to happen on the top there.

MR. DHIR: Top, right. That's what would

happen. I was hoping that this will go out to our OSV.

CHAIRMAN WALLIS: It doesn't?

MR. DHIR: I don't know. We have to test it. I asked them to test it. See if it goes to OSV condition. It should go to, you know, 1.

And this is the growth period -- growth period with -- subcooling and that's what the correlation we have so far. Again, one contact angle, 30 degrees.

You know, generally the bubbles slide -- can slide quite a while if you did not have any nucleation site on their part. This is a separate experiments we did where we had just a single bubble sliding over a surface, no other nucleation site. And--

CHAIRMAN WALLIS: This is still boiling, this isn't an air bubble or something like that?

MR. DHIR: No, no, no boiling. One on a single nucleation site.

And this bubble, as you can see, for 30 centimeter velocity has slide almost 18 millimeters before it lifted off.

MR. BANERJEE: How is the velocity defined here?

MR. DHIR: The distance the bubble travels from the nucleation site.

MR. BANERJEE: Is the velocity of the bubble?

MR. DHIR: Bubble.

MR. BANERJEE: Not the velocity of the fluid?

MR. DHIR: No, no. Velocity of the fluid is the parameter here. This is fluid velocity.

MR. BANERJEE: For which?

MR. DHIR: This is the fluid velocity.

MR. BANERJEE: Ah, so that's what I was asking.

MR. DHIR: No, no, this is liquid velocity.

MR. BANERJEE: How is that defined? What velocity is it? Is it bulk velocity?

MR. DHIR: Bulk velocity of the liquid. And I'm plotting the distance it slides as a function of the bulk velocity. But we can get the --

MR. BANERJEE: Is this for a specific bubble size, right?

MR. DHIR: Right, for these conditions. Single bubble -- liquid is saturated.

MR. BANERJEE: How big was the bubble?

MR. DHIR: To start with it's about 1.5

millimeter or so.

CHAIRMAN WALLIS: Well, now we get to a bit that we got a report on, the bubble collapsing.

MR. DHIR: Right.

CHAIRMAN WALLIS: That looks like a relative straight forward.

MR. DHIR: Straight forward, right. Should I go over it? No.

CHAIRMAN WALLIS: Quickly.

MR. DHIR: Everything is quick.

This is another picture of the bubbles are formed on the heater surface. You look at this bubble and this bubble detaching from the surface. It has detached. And now we are looking at its size and its position. And these are .8 milliseconds apart, these photographs.

And knowing the position we can calculate its velocity, local velocity and we also know from the photograph what the size of the bubble is.

CHAIRMAN WALLIS: So you know how far it is from the surface?

MR. DHIR: Oh, maybe a few millimeters, 2 or 3 millimeters.

CHAIRMAN WALLIS: You don't measure that, although the reflection probably tells you.

MR. DHIR: Reflection tells us where you start with.

CHAIRMAN WALLIS: It does tell you how far it is from the surface?

MR. DHIR: Yes, right, exactly. And that's how you calculate the distance.

CHAIRMAN WALLIS: Yes.

MR. DHIR: And knowing the bubble size as a function of time, you can deduce what the heat transfer coefficient should be.

And these are some of the correlations which are --

MR. BANERJEE: Provided you know the --

MR. DHIR: Liquid subcooling.

MR. BANERJEE: Yes, at that point.

MR. DHIR: At that point. But we have measured that liquid subcooling with a thermocouple. Not during that experiment, but with the same conditions we have measured what the temperature.

MR. BANERJEE: So the average?

MR. DHIR: Average.

MR. RANSOM: These are the overall heat transfer coefficient I guess. Now you could envisualize it as having a heat transfer coefficient on the interior of the bubble and, you know, heat transfer coefficient on the exterior, and some condition at the interface on interfacial temperature. And I gather this is from saturation temperature to whatever liquid temperature surrounds the bubble?

MR. DHIR: Right.

MR. RANSOM: Yes.

MR. DHIR: But the pressure in the bubble is, you know, not much different than outside. It's large bubble relatively, unless it becomes extremely small. But by that time we call it zero size.

MR. RANSOM: Are most of these limited by, say, the conduction in the liquid.

MR. DHIR: Yes, of course.

MR. RANSOM: Pretty much, I guess. What's the mechanism inside the bubble?

MR. BANERJEE: It's all pure steam, right?

MR. DHIR: Steam bubble.

MR. RANSOM: And rushing to the interface.

CHAIRMAN WALLIS: Rushing to the interface.

MR. DHIR: Right. So there is assumption there.

MR. SCHROCK: The heat transfer coefficient in the initial number has a delta T. I guess you've already responded to that. It's the bulk liquid temperature and --

MR. DHIR: Local temperature. Local liquid temperature.

MR. SCHROCK: And not a cross section?

MR. DHIR: No, where the bubble is.

CHAIRMAN WALLIS: That's the delta T --

MR. SCHROCK: I don't know what that means.

MR. DHIR: Okay.

MR. SCHROCK: You don't know what the temperature structure is in the cross section?

MR. DHIR: That's what I said, but we measured the temperature distribution in the liquid.

MR. BANERJEE: But it's only an average.

MR. DHIR: Average temperature we measure. I show you the temperature profiles in the liquid.

MR. SCHROCK: But that's axial.

MR. DHIR: Normal. No, no. That's normal to the surface. Very early I show you liquid temperature profiles normal to the surface.

MR. SCHROCK: I thought that was axial.

MR. DHIR: No, normal.

CHAIRMAN WALLIS: Anyway, there's a whole other correlations here.

MR. BANERJEE: What is data?

MR. DHIR: Data is the ratio of the bubble, instantaneous bubble diameter to its initial diameter.

CHAIRMAN WALLIS: And -- numbers are just surrogate for T, it's a dimensionless time.

MR. DHIR: Right. And the time starts when the bubble detaches.

CHAIRMAN WALLIS: Right.

MR. DHIR: So it's local liquid temperature, not average temperature.

See, the temperature is changing. Let's say this is the wall, the temperature's decreasing normal to the surface. So we have a thermocouple with which we get temperature distribution before we look specifically at one bubble here.

MR. SCHROCK: Okay. So the wall is the vertical boundary?

MR. DHIR: Vertical line here.

MR. SCHROCK: And you've measured temperature and function of --

MR. DHIR: Temperature distribution.

MR. SCHROCK: Y, for example, and --okay.

MR. KRESS: And we assume the bubble is always at the one position?

MR. DHIR: This is one bubble I'm showing.

There's another bubble at different position.

CHAIRMAN WALLIS: Moving relative to the fluid, that's where H comes from.

MR. KRESS: Right.

MR. SCHROCK: When you speak of thermocouple in this -- in this bubbly field --

MR. DHIR: Right.

MR. SCHROCK: -- you're getting time average of something --

MR. DHIR: Right.

MR. SCHROCK: -- sometimes the bubble is on it.

MR. DHIR: Bubble when we know the temperature goes up that the bubble crosses that thermocouple, we know that. That's not we don't take care of it.

MR. SCHROCK: No. But some fraction of the time the thermocouple is influenced by the vapor, not the liquid.

MR. DHIR: Right. Right.

MR. SCHROCK: Although it probably remains wet.

MR. DHIR: But this is, again, a time average.

MR. SCHROCK: Yes.

MR. DHIR: That's what we're using.

MR. SCHROCK: Anyway, that defines what it means.

CHAIRMAN WALLIS: And we're moving along. You have further mechanism you account for the thermal boundary layer effect?

MR. DHIR: Right. But keeping -- we are saying is that as the bubble is condensing, the thermal boundary layer thickens and that has to be counted for.

CHAIRMAN WALLIS: Right.

MR. DHIR: In the past it has not been done so. And our correlation, I'm going to jump to the correlation now.

CHAIRMAN WALLIS: It's much better than anybody else's except the Sideman ones.

MR. DHIR: Sideman, right.

CHAIRMAN WALLIS: Which doesn't have your corrections.

MR. DHIR: No, it does not.

CHAIRMAN WALLIS: It's much simpler, but it still works as well as yours.

MR. DHIR: Works almost, yes.

And the key premise we have is that as the bubble shrinks, the thermal boundary layer is actually thicker than it would be if it did not shrink. And so we think that -- number is effected by how long the condensation has been going on along the bubble surface.

MR. BANERJEE: The only thing is the exponent on the --

MR. DHIR: Right.

MR. BANERJEE: Of course, the bubbles are fairly small, but usually for a presurface problem that would be to the half.

MR. DHIR: Presurface, that's not presurface.

MR. BANERJEE: Well, it depends on how big the bubble. If you have circulation around the bubble, you wouldn't get -- that's a solid boundary condition.

MR. DHIR: Right. But see the range of numbers we have used --

CHAIRMAN WALLIS: The numbers, it doesn't vary very much.

MR. DHIR: Right.

MR. BAJOREK:

MR. BANERJEE: So you probably should not show that because that's surely something which any reviewer will jump on, including Gary Leedle and people like that.

CHAIRMAN WALLIS: Don't send it to him then.

MR. BANERJEE: Because it's a analytical solution for, you know --

MR. DHIR: You have something?

MR. BANERJEE: In the book even.

MR. SCHROCK: You have a correlation then which involves a transverse temperature profile which you have found from your data, but is a variable that the TRAC code doesn't have. So there's going to be a problem in applying that correlation until they're also given a basis for the transverse temperature variation.

MR. DHIR: In other words?

MR. SCHROCK: It's a catch 22.

MR. DHIR: Right. But the question is, firstly I want to know how with the physics we have. The next question you're asking how do I implement it.

MR. SCHROCK: Yes.

MR. DHIR: And as I said, we have not given that too much thought to that. That's all I can say.

CHAIRMAN WALLIS: So can we move to the next part, the void fraction?

MR. DHIR: Okay. So --

MR. BANERJEE: Well, one question.

MR. DHIR: Okay.

MR. BANERJEE: The correlation that involves the -- number and also the -- number.

MR. DHIR: Yes.

MR. BANERJEE: Now, that means that you're looking at some fluid motion due to the collapsing bubbles.

MR. DHIR: That's what we are seeing, right. That as this bubble is shrinking, it's carrying with this -- it's boundary layer around it is thicker than it would be if it was just a solid --

CHAIRMAN WALLIS: Compresses the layers of liquid around it.

MR. DHIR: Right.

MR. BANERJEE: But it's not moving very rapidly.

MR. DHIR: No, they're moving.

MR. BANERJEE: It's relative to the liquid.

MR. DHIR: The liquid, no. The velocity of the liquid is much higher than the bubble velocity.

MR. BANERJEE: So wouldn't it strip off--

MR. DHIR: Again, this is maybe some

mixing going on, but --

CHAIRMAN WALLIS: Can we move on to the next --

MR. SCHROCK: Is your -- number the same as Zeitoun?

MR. DHIR: Zeitoun. Where is Zeitoun? Number he based on -- on the diameter. No, it's different.

MR. SCHROCK: Different.

MR. DHIR: No, sorry -- number is same. Same. Same.

MR. SCHROCK: And you measure time in that from the onset of the bubble motion.

MR. DHIR: Motion, right. This zero is when the bubble leaves the surface and starts to roll.

CHAIRMAN WALLIS: Well, I'll ask again if we can move on to the next subject.

MR. BANERJEE: Trying to get on --

MR. DHIR: Get on what?

MR. BANERJEE: Never mind.

CHAIRMAN WALLIS: Well, there's so much here that we haven't seen before. That last subject was one we did get --

MR. DHIR: What did you see before? I don't -- I don't know. I don't know the context.

MR. BANERJEE: Well, the papers we have on this discuss void fraction.

MR. DHIR: Oh, I see. Because there is some papers you may not have seen.

MR. BANERJEE: Yes.

MR. DHIR: Okay. So I don't show you anything with respect condensation?

CHAIRMAN WALLIS: No, that was in -- no.

MR. DHIR: The correlation and stuff.

CHAIRMAN WALLIS: Now void fraction.

MR. DHIR: Next is the void fraction. And these are -- you see the photographs of boiling on the flat plate. And at different heights from bottom. Vapor film.

CHAIRMAN WALLIS: What's that got to do with bubbles?

MR. DHIR: No, it's a two phase mixture.

MR. BANERJEE: Is it full of bubbles or is it --

MR. DHIR: Bubbles, yes. Bubbles and liquid mixture.

MR. BANERJEE: But it's not a film yet?

CHAIRMAN WALLIS: It's the extent of the two phase --

MR. DHIR: Two phase mixture thickness

should be there. And it's not a vapor film, continuous vapor film. It's a mixture.

CHAIRMAN WALLIS: Oh, this is just a flash and very --

MR. DHIR: Yes, yes, sure. It's one time -- it changes. How this layer develops as you move down stream. That's our key point here. And it becomes thicker and thicker as you --

MR. BANERJEE: There's still subcooling of--

MR. DHIR: Yes.

CHAIRMAN WALLIS: It seems to have a structure, though. It's almost -- in all your models I'm assuming these bubbles go off and behave in some way, but you don't model this layer. So maybe the layer itself is doing something, has waves on it or whatever. Looks as if it's certainly not a smooth layer.

MR. DHIR: It's not.

CHAIRMAN WALLIS: So --

MR. DHIR: But it keeps -- time also.

CHAIRMAN WALLIS: Well, that probably effects things, too.

MR. DHIR: It's possible. Again, you can start somewhere.

CHAIRMAN WALLIS: Y is distance from the wall?

MR. DHIR: Y is the distance from the wall and alpha is the wall stretch, and average amount of the span, right. Span boils average of the flat plat.

And the right hand side is basically you see the edge of this two phased mixture layer as observed from the movie and the gamma densitometer. Gamma densitometer seems to correlate fairly okay.

MR. BANERJEE: From the movie how do you get this?

MR. DHIR: Your picture, you see the picture I showed you last time and now I look at the edge.

MR. BANERJEE: Oh, just looking at the edge?

MR. DHIR: Yes.

And this is the void fraction we talked about earlier in the rod bundle. And looking at one location. And how the rod bundle average basically was.

CHAIRMAN WALLIS: So shooting through?

MR. DHIR: Through, right.

MR. BANERJEE: It says qualitative stuff.

MR. DHIR: I don't know if it's

qualitative.

MR. BANERJEE: Qualitative in the sense that it gives indication, but it's sampling many different gaps, basically?

MR. DHIR: Gaps, yes. But it's average, as I said, across.

So basically what you would expect as we increase the heat flux at a given location, void fraction goes up. And if you increase the flow velocity, and even at a given heat flux the void fraction goes down, as you would expect.

Okay. And if you extrapolate those profiles, you see where -- would be and then we have measured, they're not too far off but there's a difference.

Next is kind of boiling curve, they're all random. And basically you see single phase forced convection stays there and then some point boiling starts. After boiling starts the temperature of the surface stays fairly constant. There's constant heat flux.

Then we come to last task. So procedure for calculating this wall heat flux and then coming back to this plate of heat flux. And we say, that okay you should give input, the geometry of the heater, marked velocity, contact angle, wall heat flux or wall superheat, liquid subcooling and pressure. If you give that kind of information and the fuel, whatever fuel there is, then from the correlation we have developed you can calculate ONB, OSV, bubble diameter departure, lift off diameter, number density of active sites. The sliding distance -- the force -- coefficient for force conduction. And then you look at whether your lift damage is less than the spacing between cavities. If it is, bubble damage is less than the spacing, then you are in partial nucleate boiling where the bubbles will slide and then lift off. Or if the bubbles depart and lift off damage is greater then the spacing, the bubbles will -- lift off size and then leave.

CHAIRMAN WALLIS: Where do you predict void fraction here?

MR. DHIR: Beg pardon?

CHAIRMAN WALLIS: Where do you predict void fraction?

MR. DHIR: You don't predict one. I can predict from the number density if you want what is the wall void fraction.

CHAIRMAN WALLIS: This is of interest, though, isn't it? Void fractions are interesting output from this?

MR. DHIR: No.

CHAIRMAN WALLIS: No.

MR. DHIR: Void fraction would be -- to calculate void fraction it will provide the source -- how much vapor is coming into the bulk.

CHAIRMAN WALLIS: Well, I'm just trying to make the bridge to the code. The code wants to predict a void fraction, doesn't it?

MR. DHIR: Right.

MR. RANSOM: It seems -- I can't quite put it together myself. But I mean it seems like it's an attempt to utilize variables available and calculate what regime you're in.

MR. DHIR: Right. You're in partial nucleate boiling or wall nucleate boiling. I'm still looking at the wall. I'm not looking at the flow. And the void fraction in the flow to calculate you need to know how much vapor I'm adding from the wall, what is local liquid subcooling, how much vapor is condensing and then you should be able to calculate how the void is building up as you move downstream. We are not doing that.

MR. RANSOM: That should be part of the code calculation.

MR. DHIR: Code calculation. Our part is only to tell what is happening at the wall.

CHAIRMAN WALLIS: Well, I think your next slide --

MR. RANSOM: They didn't ask you to get rid of the partition, you're saying it's more of a two step process now. You look at conditions based on namely bulk variables and what you think you know about the cladding, the contact angle, things like that and calculate conditions at the wall. And then from your other correlation or condensation we're going to be able to calculate the net to the cell.

I think most things are there minus some-- you know, good questions on what is that temperature profile which we need to the condensation, you know. Are we going to -- getting to the right contact angle and that higher pressure.

MR. DHIR: I don't -- first, I would say that I would build this in your code as, you know, a subroutine if you want to call it, and test it out as can you predict it. We tested it out and again our data and our correlation seems to work too good, I was surprised. But, again, we want to do more of this validation ourselves before I would say --

MR. BANERJEE: Yes, your correlation for

the heat transfer coefficient condensation if it was in the code would do difficulties because you have a Fourier number there, which means you'd have to track the bubbles to know what their lifetime is.

MR. DHIR: Right.

MR. BANERJEE: It would be much better if you could get a heat transfer correlation independent of your number.

MR. DHIR: You could -- average it out and do it.

MR. BANERJEE: But we have to look at the data in these cases and see.

MR. RANSOM:

MR. RANSOM: It would nice to fill this out because --

MR. DHIR: Actually the spacing between the cavities.

DR. MOODY: Like centimeters or --

MR. DHIR: They're really much smaller, millimeter or even less sometimes.

MR. RANSOM: Yes, quite a bit is missing from here like what you need to know about the velocity shield and if you do need this time in order to calculate the Fourier number --

MR. DHIR: mass velocity is there,

geometries there, you calculate it.

MR. RANSOM: Right. Those are fine.

MR. DHIR: Yes.

MR. RANSOM: But, again, like the Fourier number would be how do you evaluate it?

MR. BANERJEE: It doesn't track the bubbles.

MR. RANSOM: Well, there's no way of doing that in the codes at the present time.

MR. BAJOREK: You know the evaporation rate, so you can get effective bubble lifetime out of that. You can't integrate it down to zero. You're going to have to truncate it, but you should be able to get the --

MR. DHIR: It depends on your -- number, too, you know. Because that's a variable.

MR. RANSOM: This would be a great model for the old discon code that we wrote that you tracked all the bubbles. And you did know all this kind of information. But I doubt if you want to put that kind of model in TRAC.

MR. DHIR: We have to sometime -- that this is what we have developed and this is what TRAC would do. Now how do we transfer this -- we have to go through that part.

MR. RANSOM: Yes.

CHAIRMAN WALLIS: I've been looking at your slide. I think what you're doing in the next few slides is just a pulling together what you told us already --

MR. DHIR: Exactly.

CHAIRMAN WALLIS: -- into the pieces of this.

MR. DHIR: That's right. Exactly.

CHAIRMAN WALLIS: So maybe we don't need to go into the details.

MR. DHIR: Oh, but I can show that as well.

CHAIRMAN WALLIS: That's right, because you've sort of taken the relevant parts of your previous pieces.

MR. DHIR: Right. Now we have gone subprocesses, now we go to total processes.

CHAIRMAN WALLIS: Right. So how well does it work?

MR. DHIR: Too well.

CHAIRMAN WALLIS: Too well.

MR. RANSOM: Makes you suspicious.

CHAIRMAN WALLIS: Very suspicious.

MR. DHIR: That's what bothers me.

MR. BANERJEE: Must be plotting the same thing against --

MR. DHIR: I hope not. It works too well.

So let me just show you what we are calculating and how we are -- what is the transient conduction heat load and what is the forced convection contribution and how it changes at vault superheat. Okay. So as you're going from partial to fully developed nucleate boiling, the heat loads are changing. It's not a set variable, set number. The number is changing with superheat.

So here we plot the ratio of Q total, show a Q to Q total what the wall --

CHAIRMAN WALLIS: These are all predictions?

MR. DHIR: These are predictions, right.

CHAIRMAN WALLIS: There's no data to compare?

MR. DHIR: No. These are predictions.

MR. BANERJEE: What are those points then?

MR. DHIR: Points are predictions.

CHAIRMAN WALLIS: The line is just a line through.

MR. DHIR: Just a line through there predictions.

CHAIRMAN WALLIS: So there's no comparison with data here?

MR. DHIR: I'll show, yes, later on.

But this is the transient conduction contribution. I will say initially transient conduction is zero before the boiling starts, just as the boiling starts. Because transient conduction, this comes from the bubble motion.

CHAIRMAN WALLIS: Yes.

MR. DHIR: And as we continue to high superheat it wraps itself -- wall superheat divided by wall superheat at OSV. And as you go to high superheat about two times this delta OSV, very high heat flux. About 70 watts per centimetered square, now most of the heat is going through transient conduction. Very little from forced conduction.

MR. SCHROCK: Looks like you could have drawn a perfectly reasonable line to pick up that stray point in --

CHAIRMAN WALLIS: Oh, come on. It's just putting --

MR. SCHROCK: Isn't that a lot of nitpicking?

CHAIRMAN WALLIS: No. Let's move on. Line and points are the same.

MR. DHIR: Right. And then we do a different flow rate. And as you increase the flow rate or flow velocity and you can see the forced convection continues to persist for a longer superheat -- for higher superheats.

MR. RANSOM: What are the differences between the lines and the points?

MR. DHIR: Points are just -- points are predictions from the model.

MR. RANSOM: Yes.

MR. DHIR: And lines are just -- through the prediction.

MR. RANSOM: Why wouldn't you just draw straight lines and connect them all? I mean --

CHAIRMAN WALLIS: Okay.

MR. RANSOM: It's quite confusing.

CHAIRMAN WALLIS: Now the next curve is similar?

MR. DHIR: Yes. Next it's similar. These are flat plate. No -- but next is important one.

There we now having the total, we split it to how much is going into vapor production to the bulk and how much is going to the liquid either through condensation or just post convection, or some bubbles taking some hit liquid with them. And so you see the first diamonds are what is going into the liquid either through condensation or directly from the wall. The open triangles are what is going to the bulk as vapor. And the circles are condensation occurring at the bubbles either back to the surface or sliding along the surface.

MR. BANERJEE: That's the Qc sub atc.

MR. DHIR: ATC. Flow condensation attached bubbles which are either sliding or sitting.

So initially you start with all the heat is going into the liquid. And as you go to high superheat and for this particular case, 70 percent -- 60 percent is going into the liquid, about 30 -- about 40 percent is going into the vapor production. Out of that 60 percent for the liquid, about 15 percent is coming via condensation. Okay?

And a similar case we do it on the right hand side for higher flow rate and lower subcooling.

CHAIRMAN WALLIS: Then you do the same thing for the rod bundle?

MR. DHIR: For the rod bundle we do the same thing. And, again, transient conduction and forced convection at high superheats or upper -- sorry, not high superheats. Upper portion of the rod bundle because as the liquid heats up it becomes saturated and you see that most of the heat is again going through transient conduction. And very little goes through forced convection, but early on -- at the start you mostly by forced convection.

And, again, we have done two cases different flow rates and different subcoolings.

CHAIRMAN WALLIS: I'm a little concerned about all the heat going to transient conduction because that -- I'm not sure I can figure out how that would be modeled.

MR. DHIR: This model, because bubbles merge. I show you earlier, the bubbles merger model. We assume the bubbles when they are growing they merge with the neighboring bubbles, form a big bubble and leave.

CHAIRMAN WALLIS: They just leave the --

MR. DHIR: As the transient conduction is occurring before the bubbles form and new second bubbles form is the waiting period.

CHAIRMAN WALLIS: So the liquid's completely replaced when they leave?

MR. DHIR: Right. But there's no flow. This is another interesting thing. Here is that forced convection, that dies down. And that was the data I showed also. If you plot full boiling curve and forced convection, and you go to fully developed nucleate boiling, there's no effect of flow field. And that's what we are seeing.

And now to obtain --

MR. BANERJEE: This is a total?

MR. DHIR: Yes. Now we are breaking it up now into evaporation, condensation and going into the liquid in this graph. And as you can see what this particular set of conditions, rod bundle, contact angles would be 7 degrees. Initially the total heat flux was -- initially all of the heat is going into the liquid and has moved downstream. At about 70 centimeters downstream the liquid bulk becomes saturated in this case. And at -- of the bundle we see that now about -- only about, oh maybe 5 percent or 10 percent of the energy is going to the liquid and 90 percent is going into vapor.

Condensation play a very small role and it dies down just before the liquid becomes almost saturated.

MR. RANSOM: The point where the liquid becomes saturated in your case, though, the bulk is still subcooled, I guess?

MR. DHIR: No, bulk is saturated.

MR. RANSOM: The bulk is saturated?

MR. DHIR: Yes. Liquid is subcooled here.

MR. RANSOM: Well, by bulk you mean where the bubble is located, though --

MR. DHIR: No, no, no. The liquid is saturated.

MR. RANSOM: The entire --

MR. DHIR: Liquid, right. Right. That's the whole point of this. That you're describing --

MR. BANERJEE: So once it's saturated, then it's just split.

MR. DHIR: Right, to vapor production.

MR. BANERJEE: Was it heating up the liquid and --

MR. DHIR: Transient conduction and then it's --

MR. SCHROCK: When the bulk liquid is saturated, there is the possibility that part of it is subcollected and part of it's superheated? Liquid real close to the wall is superheated.

MR. DHIR: Right.

MR. SCHROCK: Liquid near the core is --

MR. DHIR: But I'm saying there's no subcooling. The liquid near the wall is always superheated.

MR. SCHROCK: Would this model then

transition to an accepted, say, saturated nucleate boiling model?

MR. DHIR: That's what it is. Beyond this point it's all saturated.

CHAIRMAN WALLIS: So now we get to the comparison with --

MR. DHIR: Right.

CHAIRMAN WALLIS: This is rather like the code assessment where no matter what's in the code --

MR. DHIR: This is just all the data we predicted and experiments.

MR. BANERJEE: But this is total, right?

MR. DHIR: Total. Wall heat flux.

CHAIRMAN WALLIS: And, of course, your model was itself deduced from the same experiments?

MR. DHIR: Yes, that's true. But the data -- the pieces were -- you know, developed for each --

MR. BANERJEE: They were all consistent and treated each of them well, the this is what you would expect?

MR. DHIR: That's true.

CHAIRMAN WALLIS: All right.

MR. DHIR: And that's what I said, it works too well. You need to test for different pressures and different data points and see if --

MR. BANERJEE: But you haven't --

MR. DHIR: No, not as yet. But you can see, you know it's -- I think NRC got its money's worth.

MR. BANERJEE: It's all self consistent.

MR. DHIR: Right. That's what it shows.

MR. KRESS: That's good, yes.

MR. BANERJEE: That's better.

MR. DHIR: So you can see all of the data is within about 20 percent of what we get from the model. And this is what is embarrassing in some sense, it's too good.

And these are the data for flat plate.

CHAIRMAN WALLIS: It's probably the same reason then, and you actually do experiments you used to develop the model, so --

MR. DHIR: Right, but the model has now bubble frequency, bubble diameter and now the transient conduction, force convection.

MR. BANERJEE: It all hangs together?

MR. DHIR: It all hangs together.

CHAIRMAN WALLIS: Right.

MR. DHIR: And this is the data and this is our prediction. And the good part was you see the media tracking it when it becomes -- nucleate boiling, the number densities is there and the model where the bubbles merge is included in there.

MR. BANERJEE: The only way to tell if it works really is to do an experiment in a slightly different diameter?

MR. DHIR: Right. Blind experiment, I would want to do it. And that's a standard problem, you do a blind experiment, give all that information. Somebody does the experiment, see how good it comes out. Maybe you should do the experiment.

MR. BANERJEE: I'll do the prediction.

CHAIRMAN WALLIS: I'll do the reviewing.

MR. DHIR: So this is for the rod bundle. We tried to put it -- the wall temperature for the heat flux is given. And these are the data which we measured for this particular set of conditions. And the triangles are the data and this is our prediction. And we marked out so where we put it to ONB to occur-- experiments where we saw ONB occurred. OSV where we occurred --

MR. SCHROCK: Is this the best comparison or is this --

MR. DHIR: This is one we did. We have not done many. These are the ones we have done. So there was no attempt to make the -- show you the best one. But I was kind of surprised. I thought there was much more difference, but it seems --

MR. BANERJEE: What if you did good job in correlating each piece, right?

MR. DHIR: Within the limitations we have, we did it. But, again, I'm not given credit --

MR. SCHROCK: Why does the rod bundle data expand a much smaller range of heat flux?

MR. DHIR: Because power input, see, we could not go too much power. We put in rod bundle, you know, enthalpy is increasing. Heat flux -- total heat input is about 60 kilowatts.

MR. SCHROCK: So it's just total surface area.

MR. DHIR: Is so large, right.

See, the flat plate we were putting only about 15 -- 10 to 15 kilowatts and here we are putting about 50 kilowatts.

And should I describe the boron?

CHAIRMAN WALLIS: Yes, I think you do, and we're doing very well.

MR. DHIR: So, you know, one of our -- as I said, the rod bundle has degraded. So we said let's -- why not use it before we discard it to study some effect of boron. So we added boron to water, about

7,000 ppm. Generally at the startup it's about close to 5,000 I think. And so we looked at different -- velocity, liquid subcooling was kind of fixed, but different heat flux. Up to 30 watts per centimeter squared. And as I said, contact angle with boron in the liquid we found was the same as was without boron.

CHAIRMAN WALLIS: And does boron get deposited on the wall in the reactor?

MR. DHIR: Yes, that's an issue.

CHAIRMAN WALLIS: So as crud thickness builds up on the --

MR. DHIR: On the rods, yes. That's an issue. Axial offset anomaly.

MR. BAJOREK: One of the big problems right now is called axial offset anomaly. And we believe what's going on is hot assemblies are up into the range where a good part of it is in subcooled boiling. The boron is platting out and then being such a good neutron grabber, that's causing some very oddball --

CHAIRMAN WALLIS: This is in normal operation of a reactor?

MR. BAJOREK: It's in normal operation.

CHAIRMAN WALLIS: Actually get boiling?

MR. BAJOREK: Yes. Oh, yes.

CHAIRMAN WALLIS: Oh, well --

MR. DHIR: So it's a very important piece of information which we got.

And this outer surface likes like it was kind of photographed.

CHAIRMAN WALLIS: 50 microns sounds to me like a lot.

MR. DHIR: Beg pardon?

CHAIRMAN WALLIS: 50 microns is a lot of degradation.

MR. DHIR: Yes, 40 -- 45 microns is developed in 12 hours about, 11 hours. And you see the surface, you see how it's structures, like a porous structure on the surface.

MR. BANERJEE: This was at low velocities or --

MR. DHIR: No, the velocities were as I showed you last viewgraph. I don't remember it.

CHAIRMAN WALLIS: You get enough of that in the reactor, it would shut it down.

MR. DHIR: Yes. Velocity was about 60 centimeters per second.

MR. BANERJEE: Okay. So it's low.

MR. DHIR: Low. But this boron concentration was high, at 7,000.

CHAIRMAN WALLIS: This is boric acid, this is boron --

MR. DHIR: Yes, boric acid.

CHAIRMAN WALLIS: So what's on the surface then? So it's not pure boron is it? What is it that's on the surface?

MR. DHIR: What do you mean? I don't -- boric acid, I guess.

CHAIRMAN WALLIS: It's boric acid?

MR. DHIR: Right.

MR. BANERJEE: It's tomoxide.

MR. DHIR: Tomoxide. We have not looked at the composition.

CHAIRMAN WALLIS: So what's the pH on the surface? Do you have a --

MR. DHIR: We measured the pH. I don't remember now. But not at the surface. But in the liquid what the pH was we measured it.

MR. SCHROCK: How do you measure that thickness?

MR. DHIR: That's a good question.

CHAIRMAN WALLIS: This is concentrated boric acid --

MR. DHIR: See that removable thermocouple? And thickness is very small. So we put a big dial so that when we move the micrometer close to the surface, made the contact and then backed off how much we back off from the clean surface and from that we deduced how much it was.

CHAIRMAN WALLIS: This is a Zircalloy surface?

MR. DHIR: Zircalloy.

CHAIRMAN WALLIS: Did you get zirconium borate or something formed on the surface?

MR. DHIR: No, no. I don't think it's a chemical reaction. It's just a deposition on the surface.

And we are doing now various detailed experiments, it's funded from DOE looking at a single bubble in boron and see how this deposition occurs during subcooled boiling. And we see very nice interesting patterns how it forms.

CHAIRMAN WALLIS: You get more nuclei with boron then?

MR. DHIR: Yes.

So next is nucleus and site density and you can see how it looks like. In the upper surface is clean surface and lower is with boron at same superheat.

CHAIRMAN WALLIS: And we should see more

nucleation sites?

MR. DHIR: Yes, that's what you should conclude. And that's where we plotted. These are all bundled with boron, 35 micron or 40 micron layer on it. And these are the clean surface.

MR. SCHROCK: Is the solution conducting then? Is this an electroplating process?

MR. DHIR: When it evaporates you taking only the liquid out and boron is left behind. With a concentration, local concentration exceeds the saturation limit.

MR. BANERJEE: It doesn't dissolve again, right?

MR. DHIR: It builds up with time, but it may be dissolving but the rate you are producing it more than it's dissolving back.

MR. BANERJEE: Well, but you know if there was a fluctuation of liquid over it --

MR. DHIR: Right.

MR. BANERJEE: -- it would tend to dissolve. So there's some irreversible process going on which doesn't allow it to go back.

CHAIRMAN WALLIS: If you stop boiling and flushed it with water, would it -- with just boric solution, would it dissolve the boron again?

MR. DHIR: If I flushed with clean water, I think so.

CHAIRMAN WALLIS: Or with the boric solution.

MR. BANERJEE: Do you think so or do you know so?

MR. DHIR: I think so I said.

CHAIRMAN WALLIS: You just --

MR. DHIR: It's a guess. I have not tested it.

MR. BANERJEE: It's not obvious that that happens.

MR. BAJOREK: I think it would behave very much like the calcium sulfate that you see in a lot of heat exchangers. And even if you have a flow going over, you still have the no slip condition at the boundary or near your surface. Even if it's flow, you're going to continually build up this crud.

MR. DHIR: But even if water --

MR. BANERJEE: I don't think it's going to dissolve.

MR. DHIR: No. Even water we have found -- clean water and you always have some contaminants. And when you do boiling after a while something is left on the surface.

And we have numerical simulation, too, to predict it. And basically some microlayer underneath where you evaporate and your concentrations go way beyond saturation limit and that's just there. Now how the -- I don't know the mechanism. But I'm just saying it's left behind.

MR. BANERJEE: There's not a soluble form then?

MR. DHIR: Right.

MR. BANERJEE: Something happens

MR. DHIR: So something has to happen.

CHAIRMAN WALLIS: Maybe it reacts with the zirconium?

MR. DHIR: Could be. But maybe we can take a sample and see how -- what it does.

MR. BANERJEE: Now in the reactor it's not the boron that's directly platting out. What they think it might be are other contaminants within the -- nickel coming out of the tube and iron platting out forming a crud and then the boron getting trapped in that matrix.

MR. DHIR: This is the boiling curve we got, like starting without boron in water. And that's what we had done earlier. And now then we tracked after every set of experiments. These are the three sets of experiment, like for 3 hours and 6 hours and 11 hours or something. And as you see with time, we find that single phase heat transfer goes down, but the boiling heat transfer goes up.

CHAIRMAN WALLIS: Well, this water's in the reactor for days and months, it's not just --

MR. DHIR: Right, but the concentration we used was higher than would be in the reactor. See, that's one other way. But the key thing was it's surprising result in some ways that in nucleate boiling your heat transfer is higher with boron because of the more -- nucleation sites. It also indirectly tells you that -- site density is important to know.

And in the single phase case is drops down because of the thermal resistance of this layer.

So what the future work, we are saying is that we still need to measure the void fraction in the rod bundle in a more detailed fashion, and especially also at higher pressures. And that's what we are doing now.

And then we have to generalize the models and correlations to other pressures.

CHAIRMAN WALLIS: Then are you going to take these models and apply them to some data which was taken at more --

MR. DHIR: Conditions, right. Right. That's my idea, to see how far we are predicting.

MR. SCHROCK: What do these negative delta T wall mean?

MR. DHIR: T wall is less than T_{sub}.

CHAIRMAN WALLIS: It's T minus T_{sub}?

MR. DHIR: Right. Okay.

CHAIRMAN WALLIS: Well, you're very courageous to do this. To give up all these complicated models for difficult looking phenomena and put together a way of predicting boiling heat transfer.

So I invite the Committee to send in comments and make comments now if there are any.

DR. MOODY: Just a question that goes way back to your page 55 where you made that correction.

Page 55 where you made a correction in that correlation.

MR. DHIR: Number?

DR. MOODY: Page 55. It's the label number 10, condensation heat transfer coefficient.

MR. DHIR: Just one second.

MR. BANERJEE: With the famous Fourier number.

MR. DHIR: Yes, 55. Okay. I don't have the transparency, but I have the sheet.

DR. MOODY: Yes, that's fine.

Now in the material we got --

MR. DHIR: Right.

DR. MOODY: -- there was a figure 7 that showed some spread in your data versus Fourier number.

MR. DHIR: Right.

DR. MOODY: And I'd just appreciate what you did. You took that data and brought it together with this correction?

MR. DHIR: Right.

DR. MOODY: And that's really a key --

MR. DHIR: Right.

DR. MOODY: In the whole contribution you have here?

MR. DHIR: At that part, not the total.

DR. MOODY: Yes, okay. And then you carried that over into the Nu number.

MR. DHIR: Nu number correction.

DR. MOODY: Okay. I just wanted a little--

MR. BANERJEE: That's how the Nu number correction was made?

MR. DHIR: Correction was made, right. And then that correct double diameter as well.

DR. MOODY: Just off hand, how do you make that correction? Is this a computer program that tells you what exponents --

MR. DHIR: No. It will be part of it. It also that I thought there should be some effect of the history. And then we went back and see how we could decide it. And that's how we put it --

DR. MOODY: So a little insight, understanding, a little -- yeah, yeah. Okay.

MR. DHIR: And it is published in international journal --

DR. MOODY: Yes.

MR. BANERJEE: But Eisenberg and Siesman correlation seems to do pretty well?

MR. DHIR: Right, pretty well, right.

MR. BANERJEE: Considering that they're not -- number there doesn't have a Fourier number.

MR. DHIR: Right, right. So it's kind of -- or whatever it does. That's the closest --

MR. BANERJEE: But effect is fairly small, right?

MR. DHIR: Right. But it becomes important when -- number is large. When high subcooling it's very important.

MR. BANERJEE: I guess because you get

rapid --

MR. DHIR: Rapid condensation, yes, that's what we see.

CHAIRMAN WALLIS: Any other words. Ready to close this session?

MR. BAJOREK: Just maybe to add from our office, we're very pleased with the work. We think it's really identified a lot of the fundamental physics and we think it gives us now a basis for developing and trying to come up with models that can put into the code.

Dr. Ransom's gone, but we wish we had been in a state where we could have started development on this sometime in the past. But it's in our model development plans and we hope to try to develop the routines, find exactly the ways to put this into TRAC-M over about the next year.

CHAIRMAN WALLIS: TRAC-M's going to calculate things like waiting time and --

MR. DHIR: There is no need for them.

CHAIRMAN WALLIS: No need for that?

MR. DHIR: They don't need to, we can give them recipes that this is what you do.

CHAIRMAN WALLIS: You mean boil this down into --

MR. DHIR: Right, into something which is manageable. They don't need to do it. Once we have validated our modeling, then other sets of data, we are confident, then we can give them what --

CHAIRMAN WALLIS: We still have to calculate all these things, don't they, in order to get your answers you have to calculate these waiting times and things?

MR. DHIR: They would need those in that information.

MR. BANERJEE: They're all phrased in terms of the parameters, right?

MR. DHIR: Right.

MR. BANERJEE: So that means you just make it a little black box and feed in these parameters--

CHAIRMAN WALLIS: Out comes a table lookup thing. If you have this, this flow rate, this temperature, this -- and you just --

MR. BANERJEE: A net it does it for them.

MR. SCHROCK: You're going to have to have a prescription for contact angle. You're going to have to have a prescription for transverse temperature distribution. And you're going to have to have a model for calculating alpha -- all those things.

MR. DHIR: Right.

MR. SCHROCK: I think they'll need some help getting that.

CHAIRMAN WALLIS: I think we're done. We are done.

(Whereupon, at 5:59 p.m. the meeting was adjourned.)