March 18, 2003
Houston, Texas

Columbia Accident Investigation Board Public Hearing
Tuesday, March 18, 2003

9:00 a.m.
Hilton Houston - Clear Lake
3000 NASA Road One
Houston, Texas

Board Members Present:
Admiral Hal Gehman
Major General John Barry
Mr. Roger E. Tetrault
Dr. Sheila Widnall
Dr. James N. Hallock
Mr. Steven Wallace

Witnesses Testifying:
Mr. Steven Labbe
Mr. Chris Madden
Mr. Jose Caram
Dr. John Bertin

ADM. GEHMAN: Good morning. We'll go ahead and get started. This morning we're going to talk about aerodynamic and thermodynamic events that took place when the Columbia reentered the atmosphere. We have two panels this morning. The first panel consists of the NASA engineers and scientists who are trying to find out what happened to the *Columbia*; and then the second panel is an outside expert, as we usually do.

This morning we have Mr. Stephen Labbe, the chief of the Applied Aeroscience and Computational Fluid Dynamics Branch of NASA; Christopher Madden, the deputy chief of the Thermal Design Branch of NASA; and Joe Caram, an aerospace engineer in the Aeroscience and Flight Mechanics Division of NASA.

ADM. GEHMAN: Gentlemen, thank you very much for helping us through this. Before we begin, we don't swear people in; but I will read you an oath of affirmation and ask you to state that you will give information that's complete and correct, to the best of your knowledge. So before we begin, let me ask you to affirm that the information you provide the board today will be accurate and complete to the best of your current knowledge and belief.

THE WITNESSES: Yes.

ADM. GEHMAN: All right. Would you, please – in order, please – introduce yourselves, tell us a little bit about your background and your current job and not only your full-time job but your role in the MRT.

MR. LABBE: My name is Steve Labbe. I'm the branch chief for the Applied Aeroscience and Computational Fluid Dynamics Branch here at Johnson Space Center. I've been with NASA since about 1981. Prior to February 1st, our branch was not really heavily involved in the Shuttle program because it was primarily – it's an operational system. We were working on the future. Since February 1st, we have been heavily involved in the investigation and supporting the efforts with a team that crosses the agency and the country.

ADM. GEHMAN: Thank you.

MR. CARAM: My name is Joe Caram. I work in the Aeroscience Flight Mechanics Division. For the last six years, I've been the chief engineer for the X-38 project for my division. So prior to February 1st, that's what I was doing. Prior to that, I was in Steve's branch, working in the area of aerothermodynamics, where I focused on the shock-shock interaction region of the wing and boundary layer transition.

ADM GEHMAN: Thank you

MR. MADDEN: I'm Chris Madden. I'm deputy branch chief of the Thermal Design Branch in the Johnson Space Center. My background includes thermoanalysis of TPS systems for reentry spacecraft. Some of that's included analysis of Shuttle flight anomalies and other consultational roles on the Shuttle. For the mission, the Columbia mission, our branch was providing consultation for the work done by USA and reviewed for that.

ADM. GEHMAN: Thank you very much. Gentlemen, you may start. Who's first? Steve?

MR. LABBE: I'm going to start this morning.

Good morning to everyone. I just wanted to thank you for the opportunity to come and present our efforts that have been in support of this. We have a whole bunch of material. So I suggest we just get started.

Go to the second chart, please.

What we're going to cover today, I'm going to give you kind of an introduction and then describe our analysis process, the current approach, what we're doing. In our approach right now, we're starting with an assumed initial damage and then trying to propagate that to reproduce the aero and thermo response. We're assuming the damage existed. We're not trying to find necessarily the root cause. Once our results are then completed, we hope that they will point towards the root cause, but we start with the damage. We're also looking at about the first 600 seconds of entry. We're trying to get from what happened from entry interface to the point where we believe there's a breach in the wheel well and the temperatures start rising. So, if we can get that solved, we feel we'll have made a significant contribution to the investigation.

The reason the three of us are up here together is it's an integrated approach. We don't believe that just aerodynamics or aerothermodynamics or thermo by itself would be a good answer. We need to all be consistent, and our results have to all work together. So there's the three of us here, and we're part of that integrated team.

Next chart, please. This is just a brief snapshot of the organization, and it's really trying to give you a picture of the breadth of the scope that we're working. We have support from numerous NASA centers, the Boeing Company and its different divisions, Lockheed Martin, Sandia National Labs, and the Air Force research lab at Wright Pat. So we have quite a range of expertise, and they are supporting us in a large variety of areas that we represent.

Next chart. Okay. The approach. Basically we're trying to, as I said, start with damage and then take specific actions to investigate how the scenario that comes up can be used and explain the key data events. The first poster board there attempts to illustrate that on the left here, the tall one. I guess the easiest way is to just talk about it from here.

What we have plotted along the top – and I'll go into much more detail there – is the change in aerodynamics that we saw during the mission. It's versus time, and you can see that it's not zero. It's drifting negative and then eventually drifts positive. Down below, it starts here and then drifts so.

What we then wanted to do was find some key events in the instrumentation that corresponded with those changes. So the first thing that we noticed was this first off-scale low temperature – I'm sorry, the bit flip in the wheel well was the first thing that we noticed, the change in the temperature. This is the brake line temperature in the main landing gear wheel well, and at this point it started an upward trend that continued. So this was the first point; and we correlated that, tried to correlate that to the aerodynamic events.

The second point is when we see our first off-scale low temperature. So the first, Point A, suggests a breach, a first initial breach into the wing. There must have been an ingestion of hot gas in order to create that change in the wheel well, and we're going to get you into the details of why we believe that. The second one is a burn-through of the wire bundle that holds all of those instruments, so that whatever was being ingested had to be able to burn through that wire bundle.

When we get to the wheel well breach here, we see a significant rate of change. Instead of just drifting up, now we see a large increase in the rate of change. Also that corresponds to a change in the aerodynamic trend where it was drifting negative and now is starting to go back positive.

So that's the idea. Line up these key events and analyze each one of those and more or less provide what we're calling a piecewise integration of the event as opposed to some time-dependent, multi-physics solution that would explain it from time zero through. We would never get through that analysis.

ADM. GEHMAN: Pardon me for interrupting. On the top chart, I presume that's time after EI along the X-axis?

MR. LABBE: That's correct.

ADM. GEHMAN: In seconds?

MR. LABBE: Yes.

ADM. GEHMAN: Hundreds of seconds. What's the vertical axis? On the top.

MR. LABBE: This is a residual or change in aerodynamic – it's a coefficient form, but it's rolling moment. We express that in coefficient terms. I'm going to show you a lot more detail on this, but this is the change. We would expect it to be drifting, bouncing back and forth around zero. Instead, it's biased off to one direction.

ADM. GEHMAN: What is the big fluctuation right at the beginning up there?

MR. LABBE: Very early in flight, the dynamic pressure is so low that the technique we use here, we're not going to be able to resolve down to this coefficient form. You're essentially – accuracy of the data available. The initial spike there that you see is a roll. This is the first bank maneuver.

DR. WIDNALL: You and I have talked about this before, but have you applied this analysis to earlier flights and satisfied yourself that what can be identified as off-nominal is, in fact, accurately off-nominal? I know we've talked about that before.

MR. LABBE: Yes. We applied the same tool to STS-109, which was the previous flight of *Columbia*; and where we see similarities in these types of traces, we assume that that is just the accuracy level of our capability. Where they drift apart, that's when we start believing that we're seeing something off nominal.

DR. WIDNALL: Okay. I'm sure you'll share that data with me and us.

MR. LABBE: Absolutely.

MR. TETRAULT: You talked about a sensor bit flip. Would you define a bit flip for us?

MR. MADDEN: The bit flip is just the resolution of the instrumentation. So if the temperature change is 1 1/2 degrees – 1 degree, you may not necessarily see that change. So it has to change over about a degree and a half, then it will register a change in the data system. So that's why you see the step-wise plots. It's not a smooth plot because the resolution of the data isn't that tight. So when we say bit flip, we are just saying a change in temperature of about a degree and a half Fahrenheit.

MR. WALLACE: These rolling moments when we see later on what I thought to be yaw corrections, is it a pure rolling moment, or is there a yaw element to it?

MR. LABBE: There's both. There's actually all three axes – roll, pitch, and yaw. There are some deltas that we extracted. This is just the roll axes, but I'll be showing you both the yaw and the roll axes.

ADM. GEHMAN: Referring to the top chart again, the big spike is a roll reversal or something like that?

MR. LABBE: The spike here is a roll reversal and the technique that we use is not as accurate during a roll reversal, but you get a lot of rates in the vehicle.

ADM. GEHMAN: You say you're going to go into that in a little more detail?

MR. LABBE: Yes, sir.

ADM. GEHMAN: Okay. Fine.

MR. LABBE: I think we've pretty much covered what's on this chart, and the next chart is really just another version of the poster. So I'd like to move on to Chart 6.

This is just a definition of what we're defining as these key events, A, B, C, and D. I kind of alluded to this, but there's a hole damage size, there's a breach in the wing at what we call 488 seconds. That's when we see that bit flip. So what can we do? What kind of hole or damage can be created from entry interface to 488 seconds that could produce that initial change in the instrumentation?

Then we go on to the next step. Step B is we burn through that wire in another 42 seconds. So if we pick a location and we have a burn-through, can it then also burn through the wire 42 seconds later?

Then we have the breach into the wheel well at 600 seconds where we see the rate of change. Of course, that has to be consistent with the initial breach and the burning through the wire. So you can see how we're trying to piece all of these together. Then finally we see this change in the fuselage wall temperatures; and whatever is producing that, is the damage consistent with that and how we've propagated it to generate that. Aero, thermal, debris – everything has to be correlated or we did not prove a specific scenario.

Okay. Chart 7. Just another way of looking at the same thing. I really just spoke to this. We're looking at all the data, the flight data, whether it's debris evidence, flight profiles. We're more or less handed a failure scenario from the failure scenario team that's developing those, and then we go and do our analysis and tests in the aero and thermal analysis and tests. We produce our results; we get them back together. Are they consistent? That's the flow of the whole integrated analysis, and what I'm going to do now is take you through the aerodynamics side of that analysis.

If we go to Chart 8, which is also represented here in the poster board. So this is going back to the very beginning, February 1st, you know. What we were trying to do is what happened. We needed to reconstruct the flight, essentially. We had data. We had flight data that was telemetried to the ground. We knew the mass properties. We took that data. We had some tools that had been developed from various programs, the X-40 out at Boeing and the X-38 here at JSC, to get delta aerodynamics from that flight data. And I'm going to explain to you how we do that.

Out of that tool, we get our change in aero. We put that into the flight control simulation and then we compare what the flight control simulation predicts the response of the control surfaces, the ailerons, the elevons, the body flaps, the jets firing, to what was actually indicated in flight. And we iterate around that loop several times to make sure that we have a good comparison. That was our early focus, and that probably took two to three weeks for us to get worked out. We're working on actually working on a final iteration right now.

We do have a good match, and so we're now transitioning into what we call the damage assessment phase. This is, again, more or less saying the same thing. We have this assumed damage. I'm going to go build a model, whether it's in the wind tunnel or computationally, with that damage. I'm going to take measurements or make predictions or make calculations. I'm going to look back at what it's producing. Is it consistent with my change in aerodynamics that I reconstructed? I'm also going to be looking back to the integrated team to make sure we're consistent with each other and the other inputs. And we went down to the Cape on Friday to look at the recovered debris and to try to understand that so that when we're looking at different scenarios, we're also considering what's been found there. Ultimately, if we're successful, we have this piecewise integration of the change in configuration.

Next chart. Okay. How do we reconstruct the aerodynamics? We have a data base, a very well-defined data base. The Shuttle's been flying for 0 years; and this data base has been established through wind tunnel testing, flight testing. It's well defined. We take the flight data, the flight conditions, the Mach number, the angle of attack, the mass properties, the control surface settings, where they are. We feed those into our data book, and it will predict the nominal aerodynamic coefficients that we should get out of that configuration and that flight condition.

We also take the flight data in Step 2 and we put it in the equations and motions for aircraft. Out will come from that what was happening in flight. Now, in flight we were what we call trimmed. The vehicle was not yawing or rolling. It was in a steady, controlled flight, even though it was experiencing these moments. So the second part of that equation essentially becomes zero and the delta – and when we go into the data book and we were putting in several degrees of aileron or is there some side slip on the vehicle, these would produce a moment. So when we delta those down at the bottom in the third step, we're going to get some change in the aerodynamics that the vehicle was experiencing in order for the flight control system to have commanded these settings on aileron and the other control effecters. So that is the process we use to define our delta aerodynamics.

The next two charts go into the details of those results. These are some busy charts, but these really tell the aerodynamic analysts the story of what was happening. This is a change in yawing moment coefficient. Just the change in yaw. Yaw is nose left and right, and it's versus time. We have GMT time on the bottom and time from entry interface across the top. What we would expect on a nominal flight is, like I say, some scatter like so, which would stay near zero the entire time. What we saw on 107 after we did our analysis was this change in the yawing moment that started off drifting very slowly, plateaued, and then sometime around 80 seconds or so before loss of signal, it started to increase rapidly. Then just prior to loss of signal, it increased rather dramatically before we ran out of essentially any available data, which is about 5 seconds after the LOS.

ADM GEHMAN: Okay, we'll just stop here for a second.

DR. WIDNALL: I just want to know whether you feel that that dramatic increase is a valid either measurement or computation or both.

MR. LABBE: I think so now. When we first looked at it, we were not sure, but we've gone back and the team that is recovering the data to support our analysis has confirmed those measurements by trying to look at two sources for it. So, yes, I believe that is really valid.

DR. WIDNALL: Also, with the earlier times. I mean, you mentioned, back one chart, with the earlier times you mentioned, you know, scatter in the data. So would you say from – I can't read your T from zero from here. Is that 13: 50 something or other. Way back at what would be time equals zero on that graph.

MR. LABBE: It's time actually about 300 seconds from EI. 13:50.

DR. WIDNALL: Is that little drop towards negative and then that slight negative plateau, is that a valid indication of off nominal, or would you consider that part of the noise in your data?

MR. LABBE: I would consider that part of the noise for this. When I went back and looked at STS 109, it showed the same signature time frame.

DR. WIDNALL: So, in some sense the valid begins at 13: 52.

MR. LABBE: That's correct. 13:52:17, which also happens to be – we did not look at the data first, but that happens to be when the brake temperature bit flip is also occurring.

A little bit more. There's several lines here that represent the Boeing simulation or analysis technique and the JSC analysis technique, and then the black line represents the model we gave to the flight control community for them to use in the simulation. I won't go through each one of these, but the idea was we correlated things with time on the time line. Yellow is off nominal. Green is a nominal event such as starting of alpha modulation or a roll reversal. Then this red box, this is a design limit for asymmetries. We do expect to see some asymmetries in flight and occasionally we see those, but you can see its level is here and near the end of flight we are on the order of five times that level. So something very dramatic happened at that time which led to the loss of control.

GEN. BARRY: Could you put some of this in context with dynamic pressure? If I remember right, at loss of signal it's about 80 pounds per square foot. Now, that would equate to about 180 miles per hour, right?

MR. LABBE: At sea level. I think it's a little – about 150 miles per hour, somewhere in that neighborhood, though. Yes.

GEN. BARRY: Of course, the air molecules are so far between. We really do have low dynamic pressure. Can you give us a context of, you know, if there's any kind of movement of the Orbiter, how much of a transient force is going to have to be in this case a roll or a yaw moment to be able to counteract this? We know the RCS jets are still functioning here.

MR. LABBE: Here we're in about, say, 10 to 20 thousand what we call foot pounds. So you're pushing with 20,000 pounds a foot away, and that's the kind of moment. That's just a couple of degrees of aileron. One jet firing can manage that. Near the end when we go off in this total value here, that's about0 160,000 foot pounds. That requires all four jets, three or four degrees of aileron, the side slip. Everything the vehicle had to try to counteract that moment, it was using. That's what the flight data shows, and that's what our simulation shows. So that's a very large moment.

GEN. BARRY: If you were to put this in context, if you were trying to put your hand outside in an airplane at 180 miles an hour, you would get some kind of feel for not only do we have the flight control elements on the Orbiter trying to control, but you also have the RCS jets doing the best turn they can to try to hold this in control.

MR. LABBE: That's right. If you hold your arm outside the car, you can feel that trying to pull your arm back. That's the moment is what you're feeling about your shoulder and you're talking maybe, you know, 10 pounds and a couple – 20 pounds of moment. 20 foot pounds of moment. Not very much at all. And we're talking about several – over a hundred thousand foot pounds of moment.

ADM. GEHMAN: Steve, you've got it marked right here is the roll reversal. This spike right here is a normal spike associated with the roll reversal and the stop of the roll reversal.

MR. LABBE: That's correct.

ADM. GEHMAN: I don't know. I mean, the magnitude of it may be a little greater than normal, but a spike normally occurs.

MR. LABBE: Yes. The techniques work best when you're in trim. When you're actually doing a maneuver, you're not exactly trimmed; you're producing rates and roll and yaw, so the technique shows a residual there. It's really the accuracy of our data base during a dynamic move versus static trim flight.

ADM. GEHMAN: But, this one over here is not explained by the roll reversal, though.

MR. LABBE: No, it's not, although we believe that is a normal response that has been seen on previous flights post roll reversal where there's either a change in the density in the atmosphere or the vehicle is adjusting. And we have gone back and seen – the flight control team specifically has seen that type of signature in other flights.

ADM. GEHMAN: Yesterday we heard that there's kind of a magic altitude of around 42 miles or 40 miles which, of course, works out to about 220,000 feet, something like that, at which reentry vehicles seem to hit a wall. Could you tell me about what the altitude of the Orbiter was at that time?

MR. LABBE: I believe it's around 210,000 to 220,000. Very close, I could get you an exact.

ADM. GEHMAN: But we're close. I mean, we could go look it up.

MR. MADDEN: Right. 210.

MR. LABBE: About 210,000 feet, roughly.

ADM. GEHMAN: You've got debris shedding down here. This is kind of Debris 1 through 6, as I read that. Correct?

MR. LABBE: That's correct.

ADM. GEHMAN: Debris 6, as we learned yesterday, was the first large thing that came off. Then Debris 14, have you got that marked here?

MR. LABBE: I do not have that on this particular chart, no. It's later in the time line. Do you have a time for that?

MR. MADDEN: Debris 14.

MR. LABBE: 14 is roughly 13:55, 56 time frame. About a minute and a half later there.

ADM. GEHMAN: 13:56.

MR. LABBE: Right in there. Yes.

ADM. GEHMAN: Okay. So the two big pieces of debris come off and it doesn't appear to trigger an aerodynamic reaction.

MR. LABBE: Can we go to the next chart?

ADM. GEHMAN: Okay.

MR. LABBE: Okay. This is the same plot, but now I'm looking at a change in rolling moment. That was change in yawing moment; this is change in rolling moment. Here you do see a definite correlation between that large debris. Somewhere between Debris 5 and 6 is when we see this event where the rolling moment was drifting negative, the change in rolling moment, and it changes direction. It starts its positive trend. We think this is a very key point for us in trying to understand what happened. Something changed about the configuration, some damage. Since we know we were shedding debris, something significant happened there to change the trend on rolling moment.

Debris 14, a minute and a half later. Again, we don't necessarily see that.

ADM. GEHMAN: It's right about here. Now, what kind of a change in the aerodynamic, the external aerodynamic posture of the vehicle would cause a change in the slope from going one way to going the other way? I mean, damage on the opposite side?

MR. LABBE: I don't think so. You know, you've asked the $64,000 question there, I believe. That's what our work is going to be. You know, what it suggests early on is that I was losing lift on the left wing and then something changed to start creating lift on the left wing or pushing up on the left wing. Whether or not that's opening up a large cavity on the lower surface, I'll show you some results from the wind tunnel that would suggest an opening of a fairly large cavity on the lower surface actually results in what I can think of is the damage is so significant it's creating locally a very high pressure that is on the lower surface of the wing and starting to push up on the wing as opposed to just disturbing the flow.

ADM. GEHMAN: As a non-aviator, let me ask kind of a basic question. Is it possible that the aileron trim, elevon trim, which is, of course, a measurement that you use which is not standard with airplanes, but it is possible that the Orbiter, trying to correct one difficulty, created lift under the wing by the way the elevons are set?

MR. LABBE: I'm not sure I follow the question.

ADM. GEHMAN: Well, in other words, in an effort of the guidance and control system to correct the yaw, for example, that the Orbiter trimmed itself in such a way as to actually – you know, like putting your flaps down?

MR. LABBE: Right. The way the Orbiter flies hypersonically is not your conventional aircraft. There's no rudder available. It's mass, because you're up at a high angle of attack, and you're using aileron and side-slip and then the jets, of course, as your third effecter to try to trim both in two axes, yaw and roll. Everything that we've seen about the flight says that the vehicle was doing, the flight control system was doing the proper response to these changes in these moments to trim out both yaw and roll. So, we were not trimming one and sacrificing the other; they were both being trimmed.

ADM. GEHMAN: You answered my question.

MR. LABBE: Okay.

ADM. GEHMAN: So we don't have an explanation for this?

MR. LABBE: No, not yet, that's our damage assessment work.

ADM. GEHMAN: It's not consistent with other indicators.

GEN. BARRY: You understand, of course, the roll reversal occurs at 56:30. We've got it on the green box there. We have most of our shedding occurring before that because Debris 14 goes off at 56:55. And we have a roll reversal and, of course, what you see after 56:30 there after the roll reversal, how much off nominal is that, compared to other Shuttle approaches? The roll reversal is normal; but at 56:30 she goes right off, you know, starting to gradually increase.

MR. LABBE: Right. How much off nominal here?

GEN. BARRY: Yes. Exactly.

MR. LABBE: I guess, you know, one thing to say, with all that damage, the vehicle executed a perfectly nominal roll reversal in the middle of the flight. So despite all the damage, the flight control system still was commanding the vehicle to do exactly what guidance was telling it to do. In this level here these are small and during that time period are not anything significant. It's almost like the damage has returned the vehicle back to its original flight characteristics; but then, of course, starting here we see a rapid increase and then essentially going off the cliff there at the end.

Okay. We move on to page 12. It's really just a summary of what we found. I think we've discussed just about everything here. The one thing I would like to point out is that the results – we see initially a negative roll and a negative yaw, and there's been a lot of discussion about asymmetric boundary layer transition. When you experience that on the Orbiter, these two increments will have opposite sines. So if you have positive yaw, you'll have negative roll or vice versa. We saw the same sine on this. This indicates to me that whatever was happening early on is not asymmetric boundary layer transition; it's some damage. And just basically the bottom line is at the end, just before loss of signal, we were at or approaching rapidly the trim capability of the vehicle.

Okay. The next topic I want to discuss is now our damage assessment, what is causing this. We have our events, our A, B, C, D and loss-of-signal events where we're trying to look at the aero characteristics I just showed you and now go and try to produce some damage and do some tests and analysis that will generate those signatures. We have wind tunnel testing being done at Langley in their facilities, and we're employing computational fluid dynamics from very simple tools to our highest fidelity tools. Like I said before, we are assuming damage and then creating a model and then measuring or calculating that and then mapping it back to the events.

On page 14, this is just a chart from Langley. They've been doing an outstanding job in supporting us, and we also have a poster of this. Basically this summarizes the three hypersonic tunnels they have there that we are employing in our investigation. There's a Shuttle trajectory here versus Mach number and altitude and then we have the Mach 6 tunnel here and they have a Mach 10 tunnel and then you've heard about maybe the CF4 tunnel.

We do our initial screening in a Mach 6 tunnel, and there's a lot of questions about how that was applied since *Columbia* was at Mach 20 and above when we were seeing these events. When you're at Mach 6, you have all of the physics of hypersonic flow – and they are listed there – but you don't have chemistry. Because of the speed and temperatures, there's a lot of chemistry that goes on.

One way to simulate that chemistry is to go into this CF4 tunnel, and it changes what we refer to as the ratio of specific heats. But what that does to the vehicle is brings the shock much closer, the bow shock much closer to the vehicle. Expansions are much deeper. Compressions are much stronger. So by going into the CF4, we can take a step much closer to flight. We still don't get up to this point here. Loss of signal is actually at Mach 18 or so, but that's where we can employ computational fluid dynamics to get to that next step.

DR. WIDNALL: I want to understand just a little bit more about the CF4 tunnel. When you say it changes the specific heat, how is that actually accomplished? Is that because the gas is actually at the real temperature or because there's a different kind of simulation?

MR. LABBE: Maybe Joe can help me out here. All we've done is change the gas from air to CF4.

DR. WIDNALL: What is CF$

MR. LABBE: It's freon

DR. WIDNALL: So you've basically changed the gas to freon; but, for example, the same temperature on the vehicle would be a low temperature.

MR. LABBE: Relative.

DR. WIDNALL: Relatively low. So it's not like an arc jet simulator or something like that.

MR. LABBE: Okay. I just wanted to give you a snapshot of the tunnels and how we're applying them.

The next chart shows some damage. Here's a picture of the Mach 6 tunnel. There's the model inside the tunnel, and we have a model here for you to also look at. They're about 10 inches long, so they're about three quarters of 1 percent in scale. We've been taking IR images, so we can get thermal imaging of the model at the same time we get aerodynamics. And we've gone in and just done some damage where we notched out the wing leading edge or drill some holes behind the wing leading edge to represent carrier panel damage or even this is like a side shot of the wheel well cavity where we've created a cavity in the lower surface of the wing. What I'd like to do is show you some results of that testing.

Next chart, please. It's again another complicated chart, but what we have across the top is our thermal imaging. You're looking at the lower surface of the wing, and you have missing RCC Panel 6. You have a gouge or essentially what's representative of tile damage right in the middle of the main landing gear door and then you have the holes drilled through the wing, which would represent damage to the carrier panel. What you see here is that the state of the boundary layers essentially indicated by the thermal imaging where you see the increase in heating, we know that we've tripped the boundary layer and it's gone turbulent for this particular run. These are very preliminary results. We like to use those tunnels. We want to use Mach 6 and CF4. This was just the Mach 6 aero results. So it's premature to draw too many conclusions just from this set of results.

We have just completed similar testing in the CF4 this week, and we'll be looking at those real soon. But what this shows is basically we're not getting much in the wind tunnel, not much change to the aerodynamics, even for taking out a notch that would represent an entire missing panel, and yaw or roll.

MR. WALLACE: Just to clarify, when you simulate the missing RCC panel, your model doesn't simulate any flow through the wing and exiting?

MR. LABBE: That's right. It's just an external type of notch, and it's a limitation of the testing.

MR. TETRAULT: Let me pursue that question a little bit. We have debris that is both of the left wheel well forward corners, and the debris indicates that there was a flow coming out from the wheel well outward at those corners. The inboard corner was flowing inboard, and the outboard corner was flowing outboard. What would that do to the flow field? Would that create lift, or what's your sense of how that would affect the flow field?

MR. LABBE: Like I said, we were there Friday and we saw the debris and we were puzzled by the flow patterns. I think if you have a jet, if it's coming out with a strong enough rate that you create a jet or create enough flow out of there, it will set up a shock in front of that which will create a high pressure which would be on the lower surface which would push up on the wing and would probably create more lift. Obviously by the time we've gotten to that point, though, there must be other damage. So exactly how those all work together is our challenge.

MR. TETRAULT: But it could create a lift, as long as that jet was still there?

MR. LABBE: Yes. I would think so. Now, we're looking at all that debris. We are, in our own minds, wondering what happened prior to breakup and what happened post breakup.

ADM. GEHMAN: Let me ask another layman's question here. The patterns that we see up there don't change whether you're in the right-wing-down or left-wing-down pattern?

MR. LABBE: That's correct. These are all, you know – angle attack, the plots show angle attack of three angles of attack – 39, 40, and 43, I believe, is what was tested. The aerodynamics of the vehicle are a function of angle of attack and angle of side slip and Mach number, not bank angle. We bank about the velocity vector. So whether you're left wing down or right wing down, what the vehicle sees is the same from the aerodynamic standpoint.

ADM. GEHMAN: That's intuitively not obvious.

MR. LABBE: I understand.

DR. WIDNALL: Just to pursue that a little bit, in your reconstruction you have really verified that beta, the side slip angle was zero – in other words, there's no question about that, that the side slip angle was zero?

MR. LABBE: In our reconstruction, beta starts out at zero early in flight. But sometime around the time when we see the first change in aero, it starts drifting negative. By loss of signal, it's hanging out at about 1 degree negative.

DR. WIDNALL: Right, I understand that. But do you have beta through the roll reversal, all the maneuvering, so you have a graph of beta as a function of time?

MR. LABBE: Yes.

DR. WIDNALL: And it's what, less than 1 degree?

MR. LABBE: Right. During roll maneuvers it might go up to several degrees.

DR. WIDNALL: I'd like to have a copy of that.

MR. LABBE: We'll get you that.

DR. WIDNALL: Great.

MR. LABBE: Okay, so not a whole lot of damage. There is some CFD results here –

ADM. GEHMAN: Excuse me again. Since we can't really read the scale on that chart, can you give us some kind of indication of whether that's a little heat, a lot of heat, severe heat,
life-threatening heat?

MR. LABBE: I'll let Joe answer that.

MR. CARAM: As you look at the images, you can see that the areas we see of red are indications of fully developed turbulent boundary layers. So you have two types of boundary layer characteristics – laminar or turbulent. The turbulent provides higher heating, on the order of two to three times what you see for the laminar heating.

DR. WIDNALL: You used a key word, and I want to make sure that I understand this chart. The dashed line on the graphs is your calculated differential aerodynamics that you would hope the wind tunnel tests would go to?

MR. LABBE: That's correct.

DR. WIDNALL: So your wind tunnel tests are the solid lines with the dots on them, the dashed line is what you had hoped to get out of that particular wind tunnel test to explain, and then that triangle you said was a CFD – is that what you said?

MR. LABBE: That's correct.

DR. WIDNALL: Okay. That's very interesting. So you're saying that the CFD actually predicts what you hoped the wind tunnel tests would show. Is that what you're saying?

MR. LABBE: That's what I'm saying. And if we go to the next –

DR. WIDNALL: Wait a minute. I mean, I know this is a nasty question because I understand the limitations of CFD, but to what do you attribute the difference between CFD and the wind tunnel tests?

MR. LABBE: Okay. The CFD, this is an Euler calculation –

DR. WIDNALL: It's a challenging calculation.

MR. LABBE: But this is a calculation that doesn't have a boundary layer. And I believe what's happening is when we are tripping the boundary layer here, we're getting offsetting changes. So when I do this computation, I don't have a boundary layer and I'm not getting the offsetting changes.

DR. WIDNALL: Okay.

DR. HALLOCK: My experience is primarily below Mach 1, but one of the issues you have when you're dealing with wind tunnels is matching Reynolds number. Here I see it is 10 to the 6. What is it really for the Shuttle itself, and is that a problem there?

MR. LABBE: This was run at roughly 2.4 million, which is based on the length of the Orbiter. When we are in the flight regime that we're studying, where we're interested is about half a million up to about 2 million.

MR. CARAM: 2 million.

MR. LABBE: So this particular test was at a little bit higher Reynolds number.

GEN. BARRY: If you could just put to bed one final question that we keep getting. Is there anything that could have been done, whether the Orbiter rolled left or right, to minimize the heat as it was reentering, based on any of the testing you're getting on wind tunnel or otherwise?

MR. LABBE: I don't believe bank angle changes your heating profile at all. So the answer would be, no, I don't believe so.

MR. CARAM: No.

MR. LABBE: Okay. The next chart does show just a snapshot of that CFD analysis. This is again done by Langley, using a code call FELISA, and we took out the same RCC Panel 6. You can see the flow patterns, essentially showing the pressure distribution. There's a shock forming. These three thermocouples on the side of the fuselage that showed temperature increases, the shock is in the vicinity of that. We're doing this at Mach 23.8. So it's very close to flight conditions. These figures here show the blue is a clean configuration and then the red would be with the notch and we're showing that the stream lines are tending towards the fuselage. So there's a lot of indications here that wing leading edge damage is consistent with some of the patterns we're seeing in the data.

DR. WIDNALL: Could I have a question? I mean, I think that's a very exciting result. So what you're saying is that the temperature increase on the side of the vehicle could be explained by a shock coming off of this notch in the leading edge? That's the first time I've seen this.

MR. LABBE: Okay. And Joe is going to show you a lot more of that. But, yes.

MR. TETRAULT: Does that explain the temperature that's far forward, the temperature increases in the dump values?

MR. CARAM: No, that does not.

MR. TETRAULT: It does not get to that, it only gets to the side body aft.

MR. CARAM: That's correct. The flow's not going to be moving forward on the vehicle. It's only going to be moving aft.

MR. LABBE: Okay. The next chart just goes into a little bit larger damage. Basically we talked about the wheel well. They took a metal model at Langley and machined out a representative cavity that would represent the main landing gear wheel well. And there are two depths to that, basically, a very deep and then a more shallow. That's what the H over L is representing. It's kind of hard to see; but if you look closely, this shock that's forming in the wheel well in this cavity is much stronger for the shallower.

ADM. GEHMAN: You'll have to describe what we're looking at here.

MR. LABBE: Okay. I'm sorry. This is a Schlieren photograph. What we use that to do is to see the shock structure in the flow field. So what you're seeing is a bow shock on the Orbiter vehicle and then embedded inside of that is a secondary shock where this cavity is and you can see there's this faint line that goes up here is indicative of the shock forming in the wheel well. Those are forming when you have abrupt changes in the flow field. You end up forming shocks, and that would be an area where you could expect high pressure.

So the results, this is a later time in flight. Now we're 860 seconds and again the same format on the plot that Sheila pointed out where we have the flight data and we think we should be approximating with this type of damage and then the wind tunnel results. And we're getting in the neighborhood. In the rolling moment, the yawing moment, we're only producing about half of what is expected. But that's essentially the technique. We'll look at this. We'll map it back. We're going to get these results out of the CF4 tunnel which will be closer to flight. We talked about the changes. This bow shock will be much closer to the body in the CF4, which would be much more like flight, which should change some of these characteristics of what we're measuring.

ADM. GEHMAN: But that particular measurement was if there was no landing gear door, landing gear door is gone and you've just got a hole there because the landing gear door has been ripped off.

MR. LABBE: That's right. In this particular, we've done calculations with landing gear and main landing gear deployed – or testing. I just don't have those charts.

DR. WIDNALL: I was confused by this chart, are these two pictures of two different landing gear configurations, one deep and one shallow?

MR. LABBE: That's correct.

DR. WIDNALL: And on the two graphs, is that rolling moment and yawing moment?

MR. LABBE: Rolling moment, yawing moment, and we actually tested three depths.

DR. WIDNALL: Okay. Fine.

MR. LABBE: So you're seeing the shallow, the deepest, and then there's an intermediate.

DR. WIDNALL: Okay. So everything is on this single page for these two different kinds of tests or actually three, I guess. Three tests.

MR. LABBE: Three different tests. And the shallowest actually produces the largest change. I think Joe might be able to explain that in the future chart.

Okay. That was just a snapshot of the work we're doing, and we're just getting started on this damages assessment. So my last chart is just kind of a summary. We've looked at these things. One thing that surprised us is when we put this initial damage in the Mach 6 tunnel, we got very small increments and not big enough to explain flight. The CFD suggests maybe there's still something to that. We're going to evaluate those and resolve those differences, apply our higher fidelity tools.

DR. WIDNALL: Well, would that single notch explain perhaps some of earlier part of the off-nominal aerodynamics before you get into the catastrophic failure?

MR. LABBE: Yes, it could. What's puzzling is that if it's also explaining the side wall temperatures, those don't happen until 600 seconds or so.

DR. WIDNALL: Good point.

MR. LABBE: So that's one where we're not integrated with the thermal and so maybe it's not wing leading edge early on or it's a different panel. So we're going to be looking at multiple panels missing and other panels missing, and that's really where our future work is focused, is to first do a survey of the wing leading edge and then start looking at other damage scenarios that try to produce that and then eventually get our higher fidelity CFD analysis tools to get to the actual flight conditions and high fidelity models of this damage.

GEN. BARRY: As you do the piecewise integration, so just your aerodynamic element, just some quick answers. One RCC does not account for what you see. Yes or no?

MR. LABBE: No.

GEN. BARRY: Okay. How about four?

MR. LABBE: To be determined.

GEN. BARRY: Okay. How about a landing gear with an RCC, landing gear down?

MR. LABBE: Landing gear down, we didn't do both; but I guess if you could put them together, landing gear down increments look very similar to just prior to loss of signal.

GEN. BARRY: Okay. Final question is: As I think you told us, if the main landing gear door is gone, the gear is still up, that will not give you enough to qualify, from what you've seen aerodynamically?

MR. LABBE: It would be sometime earlier in the flight, where the increments have not grown to the large level we see just prior to LOS.

MR. WALLACE: Some of your initiating scenarios seem to be distinct. I mean, are you looking at sort of things in combination? I'm also curious as to whether does it remain an issue of *Columbia's* historical wing roughness as a factor.

MR. LABBE: As far as the scenarios, most of the scenarios that have been developed start with a single damage that was relatively small that grew. I believe the scenario team is now, as we bring in some results, starting to rethink some of those, could it have been something more substantial early on; but that's kind of the iterative nature of this evaluation.

As far as the roughness on the Orbiter wing, I think, Chris, maybe you could – from a TPS standpoint, my understanding is that that was recognized and there was a lot of effort to make the *Columbia* wing as smooth as possible by eliminating the sources of that roughness. So it was a very smooth wing.

MR. MADDEN: As far as, you know, the signatures we saw were not anything related at all to any sort of early transition.

MR. TETRAULT: Do any of your future test plans include multiple breaches in the wing?

MR. LABBE: Not right now, but I am open. Our test plans are very fluid. So right now we are trying to – I think the next thing we're going to do after we get the wing leading edge is drill large holes in the wing so you actually have a flow from the lower surface through the upper surface and see what results we get out of that.

MR. CARAM: As well as multiple panels.

GEN. BARRY: A follow-up on Steve Wallace's question. The last STS flight by *Columbia* that had a really early transition from laminar to turbulent flow was STS-73, I think. That was like 893 seconds. Every one after that was pretty nominal. Now, that can be qualified by working the issue and trying to smooth out the wing and in between flows and at the maintenance, is that correct, when we do the OMM?

MR. LABBE: It's either that or – Joe, I mean –

MR. CARAM: I would agree; but when you go back to STS-73, the cause of that that we established is a protruding gap filler. The material that resides in between the tiles sometimes displaces and can reside there in the flow, and it was on the order of about a half inch to an inch in size and sitting about 20 percent along the center line, down the vehicle length. And that we've shown in ground tests, that we can achieve boundary layer transition because of that kind of disturbance.

MR. WALLACE: How do you identify whether there's boundary layer transition? What's the signature?

MR. MADDEN: Well, you would see it on the surface temperature. You would see an immediate rise in temperature on the surface. I was referring to the off-nominal events we saw. Clearly things are happening well before even the earliest transition we've ever seen; and in terms of the roughness, I think what we should do is get you a little report or a white paper on what's been done on the Orbiters to make them smoother.

ADM. GEHMAN: I definitely want to let Steve get off stage here; but I, too, have one more question an that is - One of the first things you said was that you know pretty much about nominal Shuttle reentry aerodynamics – normal. But in my experience, I have experience in aircraft development and procurement – and I won't mention anything specific, but I remember being in a position of authority in the US Navy when an aircraft we were buying had several hundred test flights, several thousand hours of test flying, and we discovered a new, completely new and unexpected aero control problem, which was all in the front page of the papers and everything like that. It caused us a considerable amount of heartache to fix it and convince Congress that we had it fixed. So, I must admit that I require a little convincing that after 113 flights and a few thousand seconds in transition that you say you know a lot about Shuttle reentry and the aerodynamics of all that.

MR. LABBE: I'll offer you one thing and see if this – what makes the Orbiter different from, say, a military aircraft is that while we have a very broad flight envelope in speed, we fly the exact same profile over and over and over again. So, each flight is essentially flying the same profile. We're not trying to expand to this envelope that has very large differences at flight conditions. And we've learned a lot. Believe me, we've had a lot of instrumentation. We by no means had it figured out on the early flights. We did flight maneuvers and so, because of the repetitive nature of the entry profile, along that profile we have it very well figured out. If we diverge from that profile, then what you say is exactly true.

ADM. GEHMAN: I think we better get on to Joe here or whoever is next. Thank you very much, Steve.

MR. LABBE: You're welcome.

MR. CARAM: Page 20, please. Again, this is just revisiting our flow charts. So now we'll be taking about the aerothermodynamics environments.

Next page. This is just a simple chart to try to explain to you the process that we go through when we provide aerothermodynamic environments to the thermo community. Our answers in and of themselves, aren't the final product. We have to provide those to the thermo analysts for the analysis of the structure.

As inputs to us, we need the trajectory conditions, how the vehicle's going to be flying through the atmosphere, its speed and density profile. We also need the configuration – both the nominal and, in this case, what kind of damage scenarios are we assessing.

So as I think Dr. Bertin has already gone through with you, heating is a result of the exchange of kinetic energy of the vehicle to thermal energy in the gas. So you have now high-temperature gas flowing around the vehicle. As it flows around the vehicle, it departs that energy to the surface. So when you consider what you have to do and look at when you're providing aero heating environments, you have to consider the physics and the chemistry of the flow. The physics phenomena, bow shocks, as Steve was talking to you earlier, the shock interaction on the wing, the boundary layer, the state of the boundary layer, whether it's laminar or turbulent and the transition in between the two, any kind of separation zones and reattachment – for instance, the body flap, if that were to deflect down into the flow – the flow upstream of it would separate and then you would have a reattachment point on the body flap where you would see higher heating. So anywhere there's a geometric difference or change, we need to consider that in providing those heating environments.

Chemistry aspect. After I have the physics modeled, we want to take a look at the chemistry. As the air passes through the bow shock, it is heated up to approximately 8,000 to 9,000 degrees Kelvin. At that point the air molecules, the N2, the nitrogen molecule, and the oxygen molecule can split. So they dissociate, and that requires energy to occur. So it's an endothermic reaction.

So now you have these atoms flying around the vehicle. So that changes the chemistry of the flow, and that can have certain effects. You look at the shock angles. The shock angles can come closer to the vehicle. The pressure distribution can change slightly. And you're looking at the difference in heating.

When you talk about TPS environments, thermal protection systems that have partially catalytic coatings on them, you can gain an advantage by not absorbing the heat in the flow field because it doesn't allow those atoms to recombine on the surface. That's called partially catalytic heating, and the Shuttle's TPS is coated with those coatings. So during those times when you have this dissociation, you can gain some advantage in the heating environment. So you have to account for these various physical and chemical phenomena before we provide heating environments for the thermal analysts.

DR. WIDNALL: I'm very interested in this question of surface catalysity, I'm going to pronounce this wrong.

MR. CARAM: Catalysity

DR. WIDNALL: Close enough, I've got some data actually that NASA did and it came out of Professor Bertin's book, but you guys had the courage to run on one of your flights – I think it was STS 2 – where you painted, oh, seven tiles on the Shuttle with a surface catalytic coating, a coating that allowed this recombination of O2 and N2 to occur on the surface.

MR. CARAM: That's correct.

DR. WIDNALL: Roughly speaking, the temperature on the surface of those tiles went up by about a factor of 2 to 3. That's the result.

MR. CARAM: Okay. I would believe that to be true because what you're doing is recovering the energy in the boundary layer.

DR. WIDNALL: Right. And just to get these temperatures sort of on the record, when the gas dissociates from behind the bow shock, roughly speaking, you're looking at a temperature of, what, 3200 degrees Rankine? I mean, that's the temperatures that I got from Steve.

MR. CARAM: At the edge of the boundary layer.

DR. WIDNALL: At the edge of the boundary, there's what I would call stagnation temperature. About 3200, and the reason it's as low as it is because of this, dissociation has taken place.

MR. CARAM: The partially catalytic nature of the material.

DR. WIDNALL: Well, no, you ripped the gas apart, so the temperature's gone down; but you still have this energy potential, should you have a fully catalytic surface, to drive that temperature back up.

MR. CARAM: That's correct.

ADM. GEHMAN: Let me follow on to that. The TPS system, a particularly high reusable system, it's painted to prevent that catalytic action.

MR. CARAM: It's coated.

MR. MADDEN: Reaction-cured glass coating.

ADM. GEHMAN: That's right. But how deep is that coating and is it possible that that coating could be torn or damaged?

MR. MADDEN: Well, okay. The short answer is that every mission there is multiple small damages on the tile. So practically every mission has tiles with coating damaged, which would imply chipped and missing. From that standpoint, the tiles are very robust to survive having the coating missing.

ADM. GEHMAN: What I'm getting at is, that not only does damage to the smooth surface of the TPS create aerodynamic little spots, it also provides an opportunity for catalytic recombination.

MR. MADDEN: Yes. And also without the coating, the tiles suffer from reduced infrared re-radiation cooling effects. So it's a bit of a double whammy, but the bare tile, even though it's not coated, I don't think is very catalytic either.

ADM. GEHMAN: Okay. That's what I was getting at.

MR. TETRAULT: To go back to Sheila's train of thought and inquiry, if you had an exposed wing spar, wouldn't you have a catalytic surface?

MR. CARAM: Before the surface itself oxidizes, yes. But as it heats up and the oxygen penetrates that surface, it will perform an oxidation layer. And Chris has some material on that for y'all today. And that oxidized layer is partially catalytic.

GEN. BARRY: Let me just ask a question on the RCC. At the boundary on the surface of the RCC, temperatures can get as high, between Panels 7 and 12, what?

MR. CARAM: 2950 degrees Fahrenheit.

GEN. BARRY: And how far in front is the boundary layer and what is the temperature, let's say, 6 inches forward of that?

MR. CARAM: Well, as you get to the wing, you're starting to expand over that wing and the boundary layer is getting thinner.

GEN. BARRY: At the edge of the boundary layer, what's the difference in temperature?

MR. CARAM: Probably around 3,000 degrees Fahrenheit, so not significant. Not a significant difference in the edge of the boundary layer.

GEN. BARRY: Maybe I'm asking the question wrong. When you get in front of the boundary layer, what is the temperature? We were told at one time it may be as high as 10,000 degrees.

MR. CARAM: I'm sorry, yes, the gas temperature can be as high as between 9 and 8 thousand degrees Kelvin.

GEN. BARRY: So you go from the edge of the RCC to just 6 inches forward and the difference is almost 7,000 degrees.

MR. CARAM: That's correct.

GEN. BARRY: Okay. Now, if you get a nick or a little bit of damage to the RCC and you have this recombination that you just discussed, does that bring that 10,000 degrees closer in and reduce that 6 inches?

MR. CARAM: No, it does not. It's what the available energy is in the boundary layer itself. It's not bringing that shock layer closer. It's just how you exchange the energy in the boundary layer around the vehicle. So at the boundary layer edge, you're seeing around maybe 4,000 degrees Fahrenheit; but that is also changing as you go down through the boundary layer.

DR. WIDNALL: Wait a minute. I've got a question. The material that John is talking about, if the leading edge is damaged, is carbon. Carbon reacts chemically with the available oxygen and that will, in fact, release –

MR. CARAM: I didn't understand that he was mentioning –

DR. WIDNALL: Yeah, he was talking about a damaged leading edge.

(To Gen. Barry) I think you were. Weren't you talking about a damaged leading edge?

GEN. BARRY: Exactly

MR. CARAM: I misinterpreted his question. This is really more in Chris' area, but you could start oxidizing the carbon and that can result in the carbon receding or ablating.

MR. MADDEN: An uncoated carbon panel – I think that would have been briefed on this – an uncoated carbon panel will oxidize because the carbon's going to react with the oxygen. And it's quite rapid, but as far as surviving a mission, I think, even though you get some damage, in most cases you don't eat through the entire thickness of the carbon. There's catalysis and oxidation on top of each other.

MR. WALLACE: Did you see that in your observation of the debris in Florida?

MR. MADDEN: No. The debris in Florida is – we don't know what happened when there.

DR. WIDNALL: I have another question.

MR. MADDEN: But there was a lot of bare carbon that looked fresh and shiny. It didn't look like it had been oxidized very much at all.

DR. WIDNALL: You seem to be using the word "oxidation" and "oxide" as if it forms a protective coating. Another word for oxidation is "burning." I mean, the experiments that I've seen that NASA has done indicate that damage to the leading edge of a carbon-carbon burns a hole completely through the carbon-carbon structure.

MR. MADDEN: An existing hole would grow, and then a damaged panel would oxidize the bare carbon and eventually would grow a hole.

DR. WIDNALL: Yeah. You would eventually get a hole in the carbon.

MR. MADDEN: It depends on which panel you're talking about and how rapid.

DR. WIDNALL: The only question we're talking about is: What does eventual mean? How many seconds is eventual? That's what we're talking about.

MR. MADDEN: We performed analysis for the investigation on panels with existing holes and how fast they grow and how fast they eat away at the spar.

DR. WIDNALL: I realize that you're going to present later; but as we're talking about this thermal environment, I would also raise the same question with respect to aluminum. I mean, it certainly is true that in our common experience of aluminum, oxide is a protection for aluminum. Otherwise we wouldn't have airplanes and we wouldn't have chairs and all the other things that are made out of aluminum. But aluminum oxide at a temperature of 3,000 degrees Fahrenheit is not a protection. The melting point of aluminum is 700 degrees.

MR. MADDEN: Right. It's going to melt and go away before you see that effect.

DR. WIDNALL: Yeah, very quickly. It is not a protective coating for aluminum at the kinds of conditions we're talking about, and I think that is a subject we want to pursue in more depth.

MR. MADDEN: Well, we've got a chart or two on that, as well.

ADM. GEHMAN: Okay. Board, let's let them present.

MR. CARAM: Next page, please. Page 22. Just to go over some of the models and techniques we're applying in order to provide these environments. The Orbiter has an existing external heat data base that we're using to provide the local heating around the various damage sites that we're considering. We're also using a plume model that was developed for micrometeoroid penetration, so I mean small penetrations on the Orbiter. However, for total environments, both the convective and plume, the models don't exist for the size and scale of damage that we're considering. So, we are having to develop those techniques as we go.

We're also using engineering analysis or correlations that we have available to us, and I'll show you an example of that on the following page when we're dealing with cavity flow heating. We're also using what we have for existing computational solutions on the Orbiter. We have the orbital experiment data from STS-2 that's been calibrated with the computational data. We also have pre-use test data.

We're also using, as Steve described earlier, the current activities at Langley and the wind tunnel testing that we're doing to look at the local heating environments as a result of damage to the early metal. What we're trying to do with the more high fidelity tools such as computational fluid dynamics is to verify those environments because we are going through different environments as we're coming through the atmosphere. Early on, it's more applicable to use a direct breakthrough as the Monte Carlo technique; and since we are assessing damage that existed, we're assuming, at entry interface, you want to verify that the heating environments that we're providing are accurate in those regimes.

So the following page gives you an example of the cavity heating models that we're using. The cavity heating – for instance, many of you have one tile lost or three tiles lost. The heating down in that cavity will vary, a function of the length over depth ratio. And that ratio changes the heating. If you have a ratio of 14, over 14 you have a closed cavity and under 14 you have what's called an open cavity flow. It does not say it's penetration. It's a description of a flow inside that cavity. So with open cavity flows you tend to have less heating on the floor than you do with closed cavity flows because with closed cavity flows the flow has the opportunity to reattach to that floor and then start heating up the floor there before it separates again and reattaches on the outside of the cavity.

You also have to consider whether the boundary layer is laminar or turbulent upstream. That can change how much energy is being provided inside that cavity. So, it could change the types of coefficients you're using. Typically, you apply coefficients down the cavity and you assume upstream is the nominal heating. So you have the nominal heating factors times the cavity factors, and that's how you derive your heating.

Most of this data was established with 2-D environments, 2-D testing. There's some data with three-dimensional effects, but that data is just along the center line of the three-dimensional object. Why I mention that is because if we're assessing cavities on the carrier panel tile areas, that flow is sweeping outboard on the wing leading edge and it's highly three-dimensional. There's a lot of cross-flow. So again, I want to be sure that the environments we're providing are accurate.

So, the next page is an example of how we're doing that. Again, this is the schematic of the open cavity flow typical for a single lost tile. On the right you see a close-up view of the pressure distribution from a CFD solution from an STS-2 CFD solution using the LAURA code at Langley. Forward, the nose is this direction. Outward is the wing. You can see the outline of the main landing gear door. The symbols in red are higher pressure. The blues are lower pressure. And the high pressure in this region is a result of the shock interaction zone. So you have a higher pressure leading up from the leading wing edge and then flowing inboard and aft from that region.

So, we take information from the external flow field and provide that as input conditions to a cavity flow solution. And this solution here is a direct simulation Monte Carlo solution of 2-D cavity flow at high altitude. Why I wanted to present this is because what the direct simulation Monte Carlo is doing is giving you an indication of what the high altitude effects are doing in your cavity flows. So you can see it's almost a merge between what you have for open cavity flow, between that and a closed cavity flow. So we want to know that information in order to make sure our heating environments that we provide the thermal guys are accurate.

Next page. This is an example of the wind tunnel testing we've been conducting at Langley. These particulars runs are from a Mach 6 air facility. I will be showing you runs from the CF4 facility. Again, as Steve mentioned, we've been looking at notched wing leading edges. On the left, you see a nominal configuration Orbiter, a side fuselage heat transfer. This was done with the infrared system at Langley. In order to acquire heating rates, we measured the temperature, assume a short delta time in the tunnel where the image was taken, and then 1-D thermal analysis to back out the heat transfer coefficients.

The two reds dots indicate the side-wall fuselage temperature measurements that showed off-nominal behavior. The red zone is the shock interaction zone on the wing leading edge, and this area here is the attachment of the flow coming around the chine of the vehicle, scrubbing along the side of the vehicle. So this is what it pretty much looks like in a nominal configuration.

When you take out Panel 6, as Steve showed you previously, you then have this shock impinging on the side fuselage. In this case since we're in the air facility, so we're at Mach 6 at air, you see that it doesn't show that it interacts with the sensors at this location.

So we also took a look – next page – at Panel 9. Again, here is Panel 6 in comparison to going further out on the wing, removing Panel 9. Again, Panel 9 is in the region of the double shock interaction zone. So not only do we have the effect of Panel 9 but you also have the effect of the higher energy because of that double shock interaction zone. So can you see between the two that Panel 9 moves the disturbance further aft on the vehicle.

DR. WIDNALL: You said these were Mach 6?

MR. CARAM: These were Mach 6 at air.

DR. WIDNALL: Okay. I mean, at Mach 20 those shocks are going to lean over.

MR. CARAM: Next page.

DR. WIDNALL: You got it.

MR. CARAM: In order to do that, we're first using the CF4 facilities; and we're also using our computational techniques, as well. As we talked about earlier, this is a comparison between the air facility Panel 6 and Panel 9 to the CF4 facility, which simulates the high-temperature gas effects. Again, what we're trying to do with that by changing the gas is to model the high-temperature gas effects; and what you're getting there is that the shocks are moving closer to the boundary, to the body. The pressure distributions are changing slightly, and this is the result. So you see that even for Panel 6 you see the heating – or in this case this is just a temperature map. This is qualitative data only at this point in the analysis, but the high-temperature area moves slightly aft from Panel 6. With Panel 9, it moves further aft and the distribution changes. So you're getting the effect of the simulated high-temperature gas in this facility and at this point you can say that Panel 9 shows the influence over those gauges.

ADM. GEHMAN: Joe, speak about heating forward.

MR. CARAM: Okay. We really aren't seeing any changes forward of these damaged locations, other than this flow right here. Forward, where the vent nozzles are, you're not seeing any changes where those are occurring. Now, you have to realize when you're doing this experimental technique you're taking snapshots of the image right after the model's inserted into the tunnel. These imaged times can vary. The model baseline temperatures can vary. So you might see small differences in the reduced heating that you get out of the test, but in this case we're not seeing hardly any changes as expected within the uncertainty of the test techniques aft forward. Most all the effect is on the side wall and aft.

DR. WIDNALL: Did you go above Mach 6? That's my question. My question is a geometric question, not a real gas question. If you were able to – and I understand the limitations of tunnels – if you were able to run such an experiment at Mach 20, your shock would be way leaned over from Mach 6 geometrically.

MR. CARAM: No, because the –

DR. WIDNALL: Are you saying it gets into a Mach number independence regime –

MR. CARAM: At a point. But then you have the chemistry effects that take over. So those chemistry effects will change your Mach angles, your bow shock angles. So it's not going to change significantly. When we obtain heating data in both these facilities, it matches within flight within 15 percent. So you're not seeing a large change in the way the flow is flowing around the vehicle. It accurately models the hypersonic flight environment.

MR. TETRAULT: Would you bear with me a minute because I don't know much about wind tunnel testing. I know nothing. So, let's start from there. What you're doing is looking at the external or exterior environment here. Can you use the wind tunnel test to test the internal environment? Like you just put a notch in the wing. Can you go up and down the wing and see what the thermal conditions, say, inside an RCC panel is, using this mechanism?

MR. CARAM: This is the scale and type model we are testing.

MR. TETRAULT: Well, you could drill holes in it, right?

MR. CARAM: We could drill holes through the wing, but it would be very difficult to obtain the heating and the proper scaling inside that area, on a larger scale? Possibly.

Next picture. Next page, please. All right as a follow-on, again, we're trying to verify these environments; and we're using the higher fidelity techniques. This gives you an idea of where we're at currently in this process. We've established a common service grid. Since we have these multiple organizations working on this problem, one of the issues with computational fluid dynamics is that we can have differences just because of the grid topology. So we've established a common one between all the organizations, and so all the organizations will be using a similar topology.

We can use that same grid system to implement or embed damage in various locations on the wing leading edge, along the fuselage of the vehicle. And we'll be using those to provide and verify the environments for the damage scenarios. So we can do both the nominal geometry and damage. We're also continuing to do the wind tunnel testing both in air, as an initial screening, because that facility is able to turn around the tests faster than the CF4 facility, so we'll do initial screening in air and then go to the CF4 facility to observe the simulated high-temperature gas effects.

So out of this, we get not only updated heating environments going to the thermal analysis group but we also provide inputs to internal heating environments. We have the outside boundary layer conditions at the local areas where the damage or breach is occurring that we're trying to model. And since we are accurately trying to provide the heating distributions, as a by-product you have the pressure distributions and from there you can provide the aerodynamics. So we can provide that information to the aerodynamics communities for the various damage configurations that we're looking at.

DR. HALLOCK: Depending a lot on the CFD and also the other types of models here – and you're sort of referring to them as being the truth of what's going on – how do we know these models are actually predicting or calculating what's actually going to happen?

MR. CARAM: We're using the wind tunnel data, as well. So what we're trying to do is calibrate, for instance, at the Mach 6 conditions; we want to run those conditions, as well. If you can establish that you can correlate well with that data, then by changing your free stream Mach number and adding the chemistry in, we feel confident that we can get the accuracy that we need. We'll also have to do grid resolution studies, so to make sure that there is no grid sensitivities in the solutions that we obtain out of the CFD.

DR. HALLOCK: Do these models include the chemistry effects also –

MR. CARAM: Yes.

DR. HALLOCK: – or are you actually adding that upon the normal solutions?

MR. CARAM: No, they're embedded into the solutions.

Now, we've talked about the external environment. I want to move on to the internal environments. This is a more difficult, I believe, and less established approach. Now, I know this is a busy chart; but it's actually quite simple to go through. It just gives you a road map of how we're trying to handle the internal environments.

Again, one of the customers for the internal environments group is the external environments, so they feed right into the internal environments group. What the internal environments group does is provide heating environments not only for plumes, but looking at, beyond the plume flow field, what is the internal convection inside the wing, where is the energy being distributed inside the wing and the wheel well. To do that, we're requiring several phases of the analysis.

We've already provided this 1-D heating methodology. This is a plume model that gives you the heating along the axis of the plume only. It's fully equilibrium heating. So it's going to be the worst-case heating and also captures the turbulent reattachment. So it is the worst-case heating as far as plume heating is concerned; but in order to look at the various scenarios, we need to have models that provide off-axis heating. So you have to assess whether, if your plume's not impinging directly on the object that you're worried about – for instance, the wire bundles – we have to provide heating environments off axis. So that's what this is attempting to do, and we'll be updating our models for that.

Then there's other kind of configurations of plumes. You have wall-bounded jets. So there's a jet orifice that is immediately adjacent to a wall. So the heating along that wall is going to be different than what you would see with an asymmetric plume.

DR. WIDNALL: Can you tell me how you would do the calculation of a flow impinging on a flat, bare aluminum plate that is, in fact, a leading edge spar?

MR. CARAM: If we can go to the next chart, I think I can try to do that. Basically what you're looking at is a description of a plume entering, for instance, the interior area or the spar of the vehicle. On the outside, you have the boundary layer. Then you have this external pressure. It's that external pressure in combination ratio to the internal pressure, which will obtain what is your geometry of your plume. And this plume can exist, this core environment can exist up to 20 diameters or greater, 20 whole diameters or greater downstream. And that's where you're getting your high heating area.

DR. WIDNALL: Roughly speaking, what is the stagnation temperature of that jet and what is the gas composition?

MR. CARAM: Again, well, it depends on what your external conditions are and how big the hole is. So a large enough hole, you can probably swallow the entire boundary layer. So you can have gas temperatures up to 9,000 degrees Kelvin entering –

DR. WIDNALL: Then you're assuming the gas is not dissociated.

MR. CARAM: No, it can be dissociated at that temperature. It is dissociated at that temperature. It requires that temperature for dissociation.

DR. WIDNALL: Right. But the outside gas, the stagnation temperature is basically 3200, based on the fact it's already dissociated.

MR. CARAM: But if you're swallowing the entire boundary layer and beyond that, you can get basically the post-shock gas temperatures.

DR. WIDNALL: Anyway, order of magnitude. Fine. Okay. So you're saying that you could have a dissociated gas flow at a temperature of 9,000 degrees Kelvin hitting some structure.

MR. CARAM: Yes.

DR. WIDNALL: Then what boundary condition would you assume for that structure?

MR. CARAM: As far as the chemistry is concerned?

DR. WIDNALL: Yeah, as far as the chemistry is concerned.

MR. CARAM: We're applying equilibrium heating. So it's fully catalytic.

DR. WIDNALL: Okay, and reactive.

MR. MADDEN: Not right now.

DR. WIDNALL: Not right now. Okay.

MR. CARAM: At this point when you have fully catalytic, you're obtaining all the heating from the chemistry that you're going to –

DR. WIDNALL: So assuming no chemical reaction.

MR. CARAM: No chemical reactions with the material. That's correct.

MR. TETRAULT: Is one RCC sufficient to, as you said, swallow the boundary layer, the entire boundary layer so that you're getting the 9,000 K in?

MR. CARAM: I would say so.

MR. MADDEN: Just because you swallow the entire boundary layer – you still have to transfer heat from that gas. So, just because the gas is 10,000 degrees doesn't mean this surface it's impacting is 10,000. That heat has to be transferred via another boundary layer.

DR. WIDNALL: You also have stagnation, which is going to raise the heat.

MR. MADDEN: It still has to transfer the heat.

DR. WIDNALL: Yes, but it will raise the temperature. The stagnation will raise the temperature; and then you're, I would say, halfway there.

MR. MADDEN: I don't understand. What you do you mean, halfway?

DR. WIDNALL: Well, if you stagnate a high-speed jet, you're going to get an increase in temperature.

MR. MADDEN: Correct.

DR. WIDNALL: Then the viscous process that transfers through the boundary layer –

MR. CARAM: It's true. It's almost like having another bow shock.

DR. WIDNALL: Yes, exactly. It's like having another bow shock.

MR. CARAM: Agreed.

DR. WIDNALL: So it's an internal reentry problem, unfortunately.

MR. CARAM: Which again, on the scales that we're talking about for this type of damage, we're having to create these models because if you have a large enough damage – for instance, in this picture you have, eventually you will get turbulent mixing with the available or ambient flow in the cavity; but if your hole is large enough or you're close enough to the structure, you can have underdeveloped plume heating and that can be on the order of two to three times higher heating than you would see with a fully developed core flow. So again we're building these models. We're updating them for these phenomena for off-axis heating and for wall boundary jets. So these tools are in work, and we provide those environments to the thermal community.

Next chart, please. Part of this analysis also involves, outside of the plume environment, where is the energy going inside the wing. Currently we're using the Orbiter baseline venting model to provide that information. You have the various vent locations in the fuselage, in the mid wing going aft to the aft wing and then out the spar. You also have the vent going into the wheel well.

What this doesn't provide us is information on what the high-temperature gas effects are because now that you're ingesting high-temperature gas, it can change the way the mass flow is being distributed inside the wing and the fuselage. So what we do is, in conjunction with thermal analysis that Chris has been doing, we can get an idea of where the energy is being distributed inside those volumes. We're also looking at the possibility of what we call unmodeled vent areas such as drain holes or gaps between closeouts. To the venting guys, these are just bonuses; but to us it's critical because that will determine where the mass flow is going inside the vehicle and where the energy is going. Our colleagues at Marshall are developing complete Orbiter venting models that account for these high-temperature gas effects using a quasi approach. It's not modeling the chemistry precisely but if you're changing just some of properties of the gas as it goes through the volume. The idea with this is that we can then capture the phenomena and then couple it with a thermal model so we can get an idea of how that energy is not only being distributed inside that volume, but also being deposited onto the various surfaces.

Next page, please. This is an example of that. This is a thermal model of the internal wing. You have the truss structure and the spar areas. Each of those are being modeled thermally, and coupling that with a venting model will give us an idea of where the energy is being distributed. We need this in order to reduce the number of scenarios that we have. Yes, we can burn through a wire bundle; but where is the rest of the energy going? We have sensors inside the wing, the fuselage, that don't respond. So we're using that not only to test against the data that went off nominal but to test against the data that remained nominal until LOS. So it gives us a way to differentiate the different surfaces. So we're coupling this model of the mid wing and aft to a wheel well model in the forward glove, and this is being done at the Marshall Space Flight Center.

Next page. Again, this is just a summary of the forward plan. I pretty much discussed all the items here and where we're headed. We've already provided a simple plume model to assess heating at the core. We are expanding that for off-axis heating, taking a look at different types of plumes. We're using as calibration these benchmark cases you were mentioning earlier, Dr. Hubbard, to verify that the modeling that we're doing is accurate before we're applying the flight conditions and then using that information to upgrade our engineering model.

So we're not applying the CFD directly, we're using it to build the engineering model so they can apply it in the thermal analysis. We have the wing-venting model coupled to a thermal model in work. We're also looking at CFD of the wheel well so we can get an idea of what the internal flow structures would be when you have a penetration of the main landing gear bay.

ADM. GEHMAN: It seems to me that this is a real challenge because in the case of the external thermodynamic heating models that you do, you have the aerodynamic forces to bounce them against. In other words, you've got kind of a check and a balance here.

MR. CARAM: Exactly.

ADM. GEHMAN: But internally, you've got no check. You've got nothing other than the temperature sensors. It's a one-dimensional theme here. And you could hypothesize any internal rearrangement of those spars and sturts and thin aluminum walls in there and you've got nothing to check it against. Other than the heating scenario, you don't have a second scenario. And as we have hit on pretty hard here, once you get the very, very hot gases in there, the aluminum doesn't stand up very long.

MR. CARAM: No.

ADM. GEHMAN: So, you could make yourself a new thermodynamic path in seconds and you've got no second part of analysis to check that.

MR. CARAM: That's correct. That's why we think that these temperature plots and our interpretation of them is important in how we define our scenarios. We have the first bit rise as indication to us that there was a breach, but later on you have a rapid rise in those temperature measurements. At that point, we are saying there's a breach inside the wheel well so that the hot gas has penetrated at that point. So that's just the various parts of the piecewise analysis that we're doing.

ADM. GEHMAN: Are you finished?

MR. CARAM: Yes.

DR. WIDNALL: Can I have a question? I just wondered at what point in your CFD analysis would you allow the aluminum to interact and react with the dissociated gas.

MR. CARAM: I don't think we have currently models to account for that in the computational area.

DR. WIDNALL: Do you have the resources to find out?

MR. CARAM: I'm working with some of the folks at Boeing Huntington Beach who are looking at the combination of the heating and the thermal response.

MR. MADDEN: We're going to get a group of guys together to go and address that. Now, I don't think it's coupled with CFD per se, I will be we're going to look at hole growth and the effects of oxidation, any possible –

DR. WIDNALL: This is obviously an extremely difficult area. I mean, nobody would ever build a reentry vehicle out of aluminum. So clearly you're trying to do the kinds of calculations that we have just never thought about doing. There are some resources. In fact, a lot of this early work was really done by NASA Ames. A lot of the expertise that exists in this area belongs to NASA.

ADM. GEHMAN: Okay. Before Chris gets started, I'm going to declare a ten-minute break here so we can pay attention. For the members of the press in the room, please, this is not a press conference. So leave them alone. You all are excused for ten minutes.

(Recess taken)

ADM. GEHMAN: Gentlemen, thank you very much. We are not concerned about time up here. We've got to get this right, and you're a great source of information. So the only time constraint I have is that we don't want to overstay our biological warning signs that we're not paying attention anymore. So thank you very much for bearing with us.

Okay. Chris, you have the floor.

MR. MADDEN: My name is Chris Madden. I'm in the thermal design branch. I just wanted to start off with a summary of what we've been doing. Our branch has been part of this investigation, performing thermoanalysis and support of test planning and analysis.

What I'm going to show you is a series of preliminary results. The first several slides, you'll start to see that, with enough damage, you can breach the vehicle in several different ways. And this is the way we attack the problem in the first few weeks of the investigation is: Hey, can this damage blow a hole in the wing? Can this do it? Can this do it? And the answer always kept turning out that, well, if the damage is big enough, sure, big enough damage is always going to breach the wing. You'll see some of that in the slides.

So I just want to caution everybody that if you see a slide that says a hole burned through in 500 seconds, it doesn't say that's it; it says that could be it. And what we've done is evolve from that and after getting frustrated with everything shows that it could be the culprit, we started going to this plan where we're saying, look, okay, while the configuration is semi-stable before we have the debris shedding a little before 600 seconds, what can we learn or what do we know.

So, there are several knowns that we've had to make engineering leaps in saying that, okay, at 488 seconds when we saw our first bit flip that was the breach. So that's a time hack we're going to have some level of faith in for the time being so that we can perform some analysis based on that. Based on that 488 seconds, 42 seconds later the first measurement was lost. So, I'm going to show you a plan on how we're going to take that 42 seconds to determine where the damage site was and how big it was. We've also got another time hack at the wheel well temperature rise. We're going to say, okay, our engineering leap is that was breach of the wheel well. So now you've got 12 seconds between the first breach in the wing to the breach in the wheel well, and we'll try to figure out how that happened.

ADM. GEHMAN: I think that the board understands the assumptions you're making for the purpose of building a mathematical and an engineering model of what happened, but I can assure you we don't necessarily agree with those assumptions. What I mean is the breach could have occurred two weeks before that.

MR. MADDEN: Sure. And it certainly didn't happen after.

ADM. GEHMAN: We understand the mechanism of why you've got to pin something down so you can do the analysis. So we're with you.

MR. MADDEN: Okay. I appreciate that.

Okay. So the next slide, this is part of the energy balance stuff we did at the beginning. I'm going to show you a series of slides of what we've done. This is explained, the early bit flip or a small temperature rise on the brake line. The analysis assumed here that you boil a hole, and here we did it at 480 seconds. This is the amount of energy in BTUs per second that enters into the wheel well.

Okay. The next slide shows the predicted based on that energy coming into the wheel well via the healthy vent would, indeed, see a temperature rise on the same order of magnitude that we saw in the flight data. So the shorter answer is that, yes, a sudden ingestion of hot gases into the wing, flowing into the wheel well, would be indicative of the bit flip that we saw on that very first measurement. So this is kind of lending credibility to something happened at 488. Now, agreed, it could have happened earlier and you're just now seeing the heat coming in because the gas, although as I think we discussed before, has a high heat transfer rate to the surface, the amount of mass involved in the gas is low and therefore the amount of BTUs the gas molecules can contain is low. So you may not see the temperatures until this time, anyway in the wheel well.

MR. TETRAULT: You're using just a 5-inch diameter vent hole to calculate this? You have not added any of these additional transfer patterns?

MR. MADDEN: Right, this is a healthy wheel well assumed. The other thing you see from this analysis is that, at least for this measurement, later on you're going to need additional heat to explain the temperature rise. There is another measurement here on this poster that it start going up at about 600 seconds. There's some other ones that begin rising at 600. For some reason this brake line was delayed a little bit. This was behind a fiberglass cover, so that could explain that.

DR. WIDNALL: Could I just raise a question? Sort of philosophy, could you back up one slide. I mean, I think this is the point where one then needs to begin to challenge the model because you have a conclusion on this slide; and your conclusion is additional heat is required to explain the flight data. So I think that's a point at which we need to challenge the model because then I would ask the question: Does your model include a directional jet or is it what I would call a heating and vent kind of analysis that you would use if you were trying to build an air conditioning system for your house? It's kind of a different kind of analysis.

MR. MADDEN: And this model is certainly challengeable because this is an engineering method where we just broadcast. All we know at this time is that this amount of BTUs per second came into the wheel well. How it's distributed, we have to wait on CFD. So at this point all I was trying to say was: "Can be explained."

ADM. GEHMAN: Maybe I misunderstand, and I'd like to understand it. What I read from this, though, Sheila, is that this graph supports your position. What I mean is that just by the model he has here, which he has a healthy wheel well with nothing broken except heat's getting into it, works for a few seconds but then after that it doesn't work anymore.

DR. WIDNALL: Right. No, I think that's right. It's just that when you see something like this, you really have to make sure that you understand the model and that it's pointed out that the model itself is the simplest level of calculation that one can do.

MR. MADDEN: Sure. Excellent point. This is a very simple energy balance type analysis.

ADM. GEHMAN: One of the things that I'm really interested in, of course, is that I'm interested in the very first off-nominal reading.

MR. MADDEN: And this is it.

ADM. GEHMAN: I understand that, but you have little red dots here that show flight, actual telemetry data. Of course, you didn't put all of them on there; but you've been monitoring that temperature for days.

MR. MADDEN: Right.

ADM. GEHMAN: So the point is that you started here at – this is EI. Is that correct?

MR. MADDEN: Correct.

ADM. GEHMAN: So you started here because that's kind of where the interesting part is.

MR. MADDEN: Right. It had been decaying down slightly; and you see that in this plot, too.

ADM. GEHMAN: My question, though, is that because these temperatures were essentially nominal and even though you are in extraordinarily thin atmosphere with very few air molecules, the Orbiter is heating up out here.

MR. MADDEN: It's heating up on the outer surface.

ADM. GEHMAN: Yes. Where does peak heat start? Do you know where peak heat starts?

MR. MADDEN: At about 300 seconds. Okay. What you're seeing is inside the well wheel.

ADM. GEHMAN: I understand that; but I'm saying even back here at 200 seconds or 250 seconds and 300 seconds, even though you're not at peak heating, as the orbit decays, as the Orbiter comes down, the heating increases. External heating.

MR. MADDEN: Okay. Correct.

ADM. GEHMAN: And so what I'm trying to get at is whether or not we should feel that whatever access allowed the external heat to get in, whether it was a preexisting condition or whether it started – whether that access opened right about here.

MR. MADDEN: That's challengeable. Whether or not that this was the first bit flip just because – the hole was there the whole time in the wing and you just see the bit flip just because that's the period of time it took for this low-density gas to raise a high-density brake line to 1 degree.

ADM. GEHMAN: Or, if just 1 or 2 seconds or 10 seconds before here is when the fault manifested itself.

MR. MADDEN: Right.

ADM. GEHMAN: We don't know.

MR. MADDEN: We don't know; and that's why we're making these assumptions, to see if the whole story fits. If it doesn't, we'll have to revisit everything.

ADM. GEHMAN: Are we on the same sheet of music here? In other words, in my mind I don't know. And, of course, it bears on a lot of things because if the fault just manifests itself right here, even though the aerodynamic pressures are practically nothing but might be enough to remove something or cause something that was weakened, then all this stuff about on-orbit photography and stuff becomes irrelevant because if there was no fault that you could see – I mean, it was a weakness clearly and something failed. So, I mean, it's important to know whether or not the Orbiter had a preexisting condition that started, you know, way back over there, which then didn't manifest itself heat-wise until you got enough heat.

MR. MADDEN: Right. There is another piece of analysis that we don't have in our charts that we did make that assumption that, okay, let's say the hole was there the whole time. Those transients, the analytical transients didn't really jump up. There's no reason for them to jump up at that time. In fact, it wasn't enough heat for them to really respond until out here at 7 or 8 hundred seconds. So, that's another little piece of data that kind of suggests that something happened there. I'm not saying it's a fact.

ADM. GEHMAN: Right. If I could ask Steve a question here, back to this first graph over here. You say that these numbers – 'cause they're ratios and they're ratios of irrelevant numbers at that particular time – but because of this bias that the Orbiter had in its control surfaces, where, compared to 400, 300, 500 seconds after EI do you start believing your own data?

MR. LABBE: For what's on that particular plot, I would say it's more like 500 plus seconds.

ADM. GEHMAN: Yeah. So it's right in here.

MR. LABBE: It's close to that, but maybe a little bit further, maybe another 20 or 30 seconds after.

ADM. GEHMAN: So even though we have an indication of temperatures, we have another indication of what the aero surfaces were doing that are to the left of whatever, this 480 seconds after.

MR. LABBE: So it's close. I would say if you look at that plot where you see the downward trend where you see the slope really go away from zero, right there, that's where I'm saying I have a clear indication. What's happening before that...

ADM. GEHMAN: That horizontal but left bias, you're less confident.

MR. LABBE: I'm less confident because when I did STS 109, I got very similar results.

ADM. GEHMAN: Very similar things.

MR. TETRAULT: Would you help me with regard to bit flips – I'm going to go back to this – that's the indicator that shows that you're going off nominal. Can you tell me, off nominal to what? Is that the average for that STS for that Orbiter in terms of prior history? Is it average of the entire fleet? What is it off nominal to?

MR. LABBE: It's off nominal, to what would be to our data base, which is for the entire fleet. So it's off nominal from previous flights. Now, we haven't gone back and applied this analysis to every single flight; but what you would expect to see again is even if you had a slight bias down like that, was that that would stay there, maybe drift back towards zero. It's not going to get significantly away from zero.

MR. TETRAULT: This is important because a slight change in when you make a call of what's off nominal can change the entire time line of where the heat is coming from. So I would like to continue to explore this just a little bit. In terms of when you make that call – and I've looked at some of these plots that we have and they appear absolutely straight to me and all of a sudden there's a call that it's off nominal – how accurate do you feel that call that it's off nominal is?

MR. LABBE: Okay. I think what we've done and what's not shown here is you look at the rolling moment, you look at the aileron response, you look at the side slip –

MR. TETRAULT: I'm talking about off-nominal calls on just temperature sensors.

MR. MADDEN: Well, the previous missions have – they've always kept decaying down. Although the surface of the wheel well on the door is being heated to very high temperatures, that heat soaked back into the structure of the door and then, via radiation, into the brake lines. It doesn't occur until much later. So this we're pretty confident was a beginning of off-nominal event. There have been bit flips before, but they've always kind of came back down. So the typical response is a downward trend and you might see a flip up but it would come back down and stay down.

ADM. GEHMAN: Of course, you have the same measurement in the right wheel well.

MR. MADDEN: Correct.

ADM. GEHMAN: Which doesn't show anything like that.

MR. MADDEN: Right. And it does the typical decaying down until much later.

Next chart, please. The next few charts are the quick assessment of how extensive the tile damage would need to be to burn through the skin of the wing. In this case we can predict, and what you're seeing is temperature versus time for the outer face sheet and inner face sheet of the sandwich. Our simulations can predict the burn-through in this case is late.

Next slide, please. This shows it on the landing gear door; and this, based on the configuration of the structure itself and the heating rates and heating factors and the size of the damage, it's earlier. That's more around the time where the breach was observed. I'm not saying it's the door. I'm not saying it's the wing. It's just showing that it's highly dependent on the damage you have to assume. Like I said, at some point there's going to be enough damage to burn through the wing.

Next slide.

GEN. BARRY: Chris, let me ask you a question on temperature inside the wheel well. What's your best guess, if you have any, of the temperature getting about 700 degrees? The reason I'm asking that question is the pyrotechnic inside the wheel well is supposed to be cooked off at about 700 degrees.

MR. MADDEN: There are massive pieces of structure from the flight data on the strut actuators that don't rise over, I think, 120 degrees or so. You would think that the pyro would be the same order of magnitude. We will have a chart. I'm very unsure of the math model. We have a math model of an entire wheel well, and we will confirm that the pyro didn't go early.

GEN. BARRY: Did not go early.

MR. MADDEN: Right now I think it's very unlikely.

DR. WIDNALL: I have a question. You did a calculation of burnthrough of the skin, and obviously what's the skin made out of?

MR. MADDEN: Aluminum.

DR. WIDNALL: You know what I'm going to ask. What sort of boundary condition did you use for the surface catalysity and/or reactive behavior of the aluminum?

MR. MADDEN: The reactive behavior was not simulated. There's no oxidation for those analyses.

DR. WIDNALL: So you basically got a melting hypothesis as opposed to burning.

MR. MADDEN: Right. And thermomechanical effects were not simulated. So we're just trying to see can you get to the melt temperature; and, of course, you can.

Okay. This is analysis of the thermal barrier and pressure seal around the door, if the tile adjacent to the thermal barrier is severely damaged and you basically expose that cavity in the pressure seal to the external environment. You see two different assumptions here, but basically they both do the same thing. The pressure seal will fully demise a little before 500 seconds. So again, bad enough damage, you can breach the wing. And this one is via the wheel well. We're not concentrating on this one so much anymore because of the timing between the wire burn and the pressure or temperature rises seen in the wheel well.

Next slide. Okay. This is analysis to explain the side wall temperature rise. What we did here is at 600 seconds we applied ten times the normal convective heating environment to the exterior of the TPS in this region; and that, we actually back-calculated it ten times. That shows that the analysis can predict the flight data with ten times the heating rate to the surface. That ties into what Joe's studies have done. His team has shown that you get a bump factor two to ten times. This is at the upper end of that, but it's the correct order of magnitude and in the same ballpark. So the conclusion here is that this could be explained by external heating due to shock hitting the side wall.

GEN. BARRY: But it could be explained by convective heating.

MR. MADDEN: Internal convective heating. There is enough heat, if it's distributed to this zone. We don't at this point know how the air flows within the mid fuselage and whether or not it would make it back to this region and heat the back side of the sensor, but certainly it is possible.

DR. WIDNALL: Can I ask a question? Is it also, I know I could not do these calculations myself, but are you also considering thermal conductivity through the structure itself?

MR. MADDEN: Right.

DR. WIDNALL: So that's part of it.

MR. MADDEN: Right. We looked at that, the conduction effect. We looked at a very hot wing, can it conduct up to this sensor quick enough to see this response; and it really couldn't conduct fast enough to see this. So conduction was ruled out.

Next slide, please. Okay. This is just to show you that we've also been looking at leading edge damage. The Huntington Beach guys have developed math models of damaged RCC in support of the micrometeoroid studies that were performed. They've used those techniques to assume a hole size and then they simulate the thermal response of the insulation and the fittings and the spar and they're able to show that Panel 9 with the four to six initial holes starting at the beginning here, could burn through the spar within about 500 seconds, in other areas where it wasn't predicted to burn through and oxidation was not accounted for.

DR. WIDNALL: Do we know what the catalytic properties of that pillow insulation are?

MR. MADDEN: That's Inconel covered, and it's likely catalytic.

DR. WIDNALL: Okay. Was that considered in their analysis?

MR. MADDEN: The plume, yes.

MR. CARAM: Anything that was applied was fully catalytic.

DR. WIDNALL: Fully catalytic.

MR. MADDEN: I'm glad to make it to the next chart where you've got a couple of bullets on chemistry. As you pointed out, we didn't design for aluminum to be in this atmosphere. So areas where we have addressed it is for reentry of space debris. We have done some co-development and studies of that, and we have included chemical convective heating in those simulations. It's an engineering method where it's basically ratioed to the heat rate and the heated formation of aluminum oxide.

I ran that code when I understood you were curious about this. This simulation is a ballistic trajectory. This isn't the Shuttle flight. It's just an aluminum sphere on a ballistic or reentry flight; and it's showing that the heating due to the oxidation of the aluminum, assuming it's bare, was 10 percent of the total heating. And it's pretty constant the whole way up. I also included aluminum nitride formation. That's exothermic as well, and that was another 7 percent. The assumptions that went into this analysis assumed that all the available oxygen and nitrogen contributed, all of the heat from the exothermic reaction itself is liberated to the surface and not carried on into the flow. So a worst case, if you will. So, in engineering terms, it's a fairly small percentage of the total convective heat, at least for this case, a sphere.

DR. WIDNALL: I obviously want to look at that more closely.

MR. MADDEN: And I do and I will point that out. So if you're looking for a reason why, you know, that's one of the reasons why.

The Koropon could also hinder it while the debris still had Koropon on it. That likely goes away at 400 or so degrees, though. Then I here try to point out that, well, the aluminum oxide could self-arrest basically and perform a protective coating on the surface of the aluminum and knock that chemical heating back down. I don't know how much of that happens. I'm certainly not an expert in that area.

DR. WIDNALL: Well, it was kind of interesting because yesterday we got a very different picture from the reentry of, what was it, a steel tank from the Delta 2, I guess.

MR. MADDEN: And that was Dr. Ailor pointing that out. And I think it was a titanium tank.

DR. WIDNALL: Right. Some tank made out of –

MR. MADDEN: Right. Titanium, I think the reactions there are an order of magnitude higher in terms of heat.

DR. WIDNALL: No, but I think what was pointed out was that an aluminum layer deposited on a titanium tank would act as a fuel and destroy part of the tank that, otherwise, would not have been destroyed.

MR. MADDEN: That's certainly interesting. The titanium use on Orbiter is very limited. I think it's limited to pressure lines, hydraulic lines and things like that. So I'm not so worried about any titanium reactions with hot aluminum. I do want to check into this more, along with some other pieces of physics, and see if we really understand how holes grow in aluminum. Right now it's been real simple engineering.

Next slide. We also understood you were curious about the catalytic heating. As Joe summarized, atomic recombination effects are going to be probably more significant than chemical heating. A lot of times, it's a 30 to 40 percent bump factor. An aluminum surface will act as a catalyst and encourage this recombination and liberate additional heat to the surface. A lot of times this could be 30 to 40 percent, if you're using finite-rate chemistry calculations. In our cases, for the plumes we're using equilibrium heating; and that's very close to fully catalytic, anyway. So I think in terms of catalysis and the plume heating analyses and analysis we're doing on the plate burning, we've already accounted for catalytic effects.

Okay. And then these points, I just wanted to point them out. The extent, to my knowledge, is pretty limited here; but things like auto-ignition, the studies that you see in the literature, I think, a lot of times it's at very high pressure and what's called oxygen-rich environments. Here I'd have to say we're oxygen poor; and you certainly, as you descend in an atmosphere during post-breakup, you're going to see these effects probably a little more enhanced than you would in the early part of the flight which we're in.

Like I say, I do want to address the oxidation, just to make sure we understand what's going on there. The melting, of course, any ignition effects, and any sort of vaporization or sublimation of the aluminum. So we're going to get a team, a group together to address that.

Okay, the next slide. I just want to summarize. The work we have going on now is what we call our engineering methods phase. Again, we're kind of concentrating in this area of time here. If you notice, we're talking about bit flips. Okay. So we're trying to explain. The ability to explain these bits flips before the configuration really goes chaotic after 600 seconds, 700 seconds, you know, it's a tough job.

So what we had to do was make these big assumptions like we've gone through. The bit flip at 488 is a breach in the wing. The wheel well rise at 600 seconds is a breach of the wheel well, and the off-scale low is a burning of the first cable. That's very likely. But these two, they are admittedly, they're engineering leaps we feel we have to make to create knowns so that we have the same number of equations and unknowns through our solution space, so we can get solutions and argue about them and refute them and discuss them and see if they make sense.

ADM. GEHMAN: But the second assumption there, the wheel well temperature rise around 600 seconds is a breach of the wheel well, that doesn't necessarily mean it's breached through the door, though?

MR. MADDEN: Correct. And for these solutions, we're going to try to breach the wall, the internal wall. Okay. And what that means in terms of brass tacks? Burn a cable in 42 seconds. We're going to figure out how to do that and the wheel well wall in 112 seconds. Again, we'll cross-check the aerodynamics and the forensic data.

These charts are a sample. There's a whole series of analysis we're doing on varying the distance away of the hole size. There are a lot of parameters. So I just wanted to show a sample of a plume being applied to a flat plate; and we get a temperature response on the next slide, 46.

For various hole sizes, you'll see the temperature transients versus time; and the ones that exceed the aluminum melt temperature in around 0 seconds are going to go into the next series of plots on the next page. You see that show up right there. That would be hole size you need. In this case the spar and the distance away it would need to be to burn that wall in 112 seconds. From this distance away, we can go and look at each panel. Okay. This is Panel 5 region. The hole size needs to be 3 inches. Okay. Then now we are going to cross-check that to the wire-burning analysis and also the aerodynamics.

Next slide, I think, is the wire burning. Here it's kind of explaining how the cables of what we call the bundle, which is the whole series of wires that you see in the pictures, those consist of smaller harnesses and then cables. So we're developing this math model and correlating it to some burn tests that were performed to make sure that we at least macroscopically and engineering-wise can predict when these cables fail.

The next slide shows some initial results from that type of analyses. You see the time to failure and the distance away from the plume. These types of data will be compiled into very similar plots that you saw for the flat plate, and they'll be cross-checked to see. Because we have to burn a wire in 42 seconds that's right next to a wall that we burn in 112 seconds, assuming we just have one plume. So we'll make sure that those make sense with respect to one another.

GEN. BARRY: Chris, the wiring you're burning is Kapton wire, right?

MR. MADDEN: Correct. Kapton coated.

DR. WIDNALL: Another question. You are going to run some experiments on Kapton. Are you planning to run any experiments, say, with an arc jet with dissociated oxygen and the right kind of –

MR. MADDEN: Yeah, we're starting to think about arc jet tests.

DR. WIDNALL: – of aluminum plates or honeycomb or structures and compare that with your analysis?

MR. MADDEN: Yeah. I guess two things. We have started thinking about arc jet tests for burning the wires. It consists of a test where you have a hole, you blow the arc jet gases on it and see how fast it burns the wires. Coupled with that test, we could look at – we were initially thinking of having that hole in the plate that the hole goes through water-cooled, but we could do tests where we –

DR. WIDNALL: Basically burn it.

MR. MADDEN: – cool it and see how fast it grows. So we certainly should think about that.

GEN. BARRY: Let me ask you about the assumptions on the wire bundles. We understand that in *Columbia* it was different. In the well wheel area, there were like four large bundles as opposed to the other Orbiters have like seven; and there's a lot of wires in there that were disconnected that didn't go anywhere because they had been disconnected from sensors over the years.

MR. MADDEN: Right.

GEN. BARRY: Did they have the right diameter and the right combination?

MR. MADDEN: Well, we think so in terms of diameter. The cables that are in those bundles, I think there were only seven that were being recorded; and all seven of those eventually failed. Where they were within the bundle is unknown. So that's another thing we have to deal with. What we're going to do is assume that some of them are very embedded into the bundle and assume those are the ones that go later and slower; and, in fact, the tests that the guys at JSC are performing on the burning include the effect of being inside the bundles.

GEN. BARRY: When you do the testing, is it going to include not just going to the center of the bundle but going through the different sides of the circumference, I would assume?

MR. MADDEN: Well, it's got to hit a side.

GEN. BARRY: But it could be at an angle and not go right to the center, is what I'm saying.

MR. MADDEN: Yes, of course. What we have to assume here is that the plume is hitting, is smart enough to hit cable. And that's likely not the case but it's certainly bounding. This is going to give us the farthest distance away that the hole in the skin needs to be to burn that cable in X amount of time. If it's off axis, it would have to be closer in.

GEN. BARRY: Or hotter.

MR. MADDEN: So we'll be able to determine a region that could exist –

ADM. GEHMAN: Or bigger or hotter.

MR. MADDEN: Yes, sir.

MR. TETRAULT: Let me go to the RCC panels. As I understand it, you've run two thermal analyses, one on a 4-inch hole and one on a 6-inch hole. Why aren't we looking at things like T panels and an entire RCC section and that sort of stuff?

MR. MADDEN: Let's see. The cases we're running for thermal analysis were holes in the panel. Why aren't we looking at missing panels?

MR. TETRAULT: Yeah, or T sections. Does anybody know what the equivalent size of a missing T section would wind up being, if you took that line that then becomes available for air to pass through?

MR. MADDEN: With the missing T seal? Of course, that's a function that's to protect that gap between the panels.

MR. TETRAULT: Right. So what would the gap be in an equivalent hole size?

MR. MADDEN: You still haven't breached the wing in those cases. And there's a whole other set of analyses that kind of the earlier part of my slides that were trying to explain how do you get from the entry interface to the letter A.

MR. TETRAULT: It depends on how all the RCC panels line up. In fact, if the T seals are missing, it may give you a gap.

MR. MADDEN: Well, it will give you a gap.

MR. TETRAULT: A gap in the leading edge.

MR. MADDEN: But not the spar.

MR. TETRAULT: Not at first.

MR. MADDEN: Correct.

MR. TETRAULT: I'm trying to compare a missing T seal to the analysis that you've run based on a 4-inch hole or a 6-inch hole. I mean, what kind of –

ADM. GEHMAN: Order of magnitude.

MR. TETRAULT: Is it less than a 4-inch hole?

MR. MADDEN: I would say it's less than.

And, Joe, would the heating effects be reduced because it's not concentrated?

MR. CARAM: It would be distributed around the leading edge panel. The T cell, as I recall, is about a quarter-inch thickness. So you have to fit it in between two panels. So you're talking three tenths, four tenths of an inch in thickness for a gap. So then you have to account for the area around the circumference of the leading edge. But the characteristic dimension would be your smallest dimension. That would be the size – that would dictate the size of the jet that you're getting in between there, would be the slot width and not the circumference area.

MR. TETRAULT: Just one other comment. You talked about your calculation on the wheel well seal and it's probably not as significant at this particular point as it might have been. But if you look at it from the fact that the heat and the pressure did enter the wheel well and then escaped out the corners, as the debris seems to indicate, then the seal well had to have failed at some point in that. So it may, in fact, be an important number at some later point, so put that in your time line.

MR. MADDEN: Maybe so. But the debris that you see, the evidence you see in the debris is an outward flow. And that would obviously come from higher pressure on the inside and erosion from the inside.

MR. TETRAULT: Right. That's exactly what I've said.

MR. CARAM: Which meant you already have the penetration into the wheel well and the damage is done at that point.

MR. MADDEN: And we're talking about areas out here now in terms of time and we're really trying to figure out what the condition was right here.

DR. HALLOCK: Have you been looking at the fact that when you have the roll reversal occur, it looks to me like that we are seeing the plume actually moving grossly and just because of the fact that it has gone back now and is on the left wing, which may sort of start some of these calculations all over again in different locations? Have you seen that effect, or are you looking at that issue?

MR. CARAM: Again, when the Orbiter is flying, it's typically the heating distribution around the vehicle is dictated not by roll angle but by angle of attack and angle of slicing.

DR. HALLOCK: Now assume that you're actually in the wing itself at this point, so you do have this plume moving around, trying to figuring out where to go. If you look at before and after when you do get the roll reversal, it's a different regime where some of the problems are happening. In one case you're seeing the shorts of the wire and in the other regime you're starting to see all the temperatures starting to change. It's as though the plume was at one point and then when it completed its roll, it's suddenly pointing somewhere else and finding a new path.

MR. CARAM: Well, the wire bundles that he's talking about run right alongside the wheel well wall, on the outboard side of the forward bulkhead. So the plume doesn't have to move around much to get to both.

MR. TETRAULT: Let me be sure you understood the comment I made last time. On the corners, if there's a vent that's there, the wheel well door had to be there, otherwise the vent wouldn't have occurred. So breaking the seal and the time line for breaking the seal may play into your overall scenario to tell you how long the door was there. So I just wanted to be sure that you understood the comment that I was making.

MR. CARAM: Valid point.

GEN. BARRY: Let me put you on the spot a little bit. Now that we've gone through the analysis that you've gone through on a basic attempt to put all this together synergistically, what can we eliminate as an entry point for the heat? If we follow the heat, what can we eliminate right now as an entry point?

MR. MADDEN: We diamonded the door. Okay. From the list of scenarios that the team at JSC has come up with, there are several of them that we called diamond; and we basically tabled them and concentrated on three or four scenarios that we felt were more likely. One of the ones we diamonded off was any sort of breach through the door. The main reason for that was the wires. If you see in a time line, the first wire was burnt before you see hardly any temperature rise in the wheel well. So for a jet to find its way through the wheel well, out a vent, and find a wire and raise that to 900 degrees before seeing any indication in the well itself, we felt, was quite unlikely; and so we are tabling those sorts of analysis at this time.

GEN. BARRY: But you haven't tabled either in front of the main landing gear under the wing, either in front or behind it, but you have eliminated on the main landing gear door.

MR. MADDEN: I wouldn't use the word "eliminate." Probably we might get ourselves into trouble reporting this, but I'd let the Shuttle program maybe answer those types of questions.

GEN. BARRY: Okay. We're getting closer.

ADM. GEHMAN: Okay. Anybody else?

Well, thank you very much, gentlemen. I appreciate your patience with us today and your energy and the zeal and the professionalism by which you are approaching this. We admire it very much.

I've made several notes here. Several of the board members have mentioned what about this and what about that and what about this and the other thing. It occurred to me that we are now at the point where some of these future tests should be mutually agreed upon because if we have some favorite scenarios that we want explored, we should let you know about that so you can take them into account when you're designing tests and things like that. So I think that's very important.

The second area that I noted is the area of the initial assumption concerning a breach. It's not clear to me – and I don't want to settle it right now, just in the interests of time – but it's not clear to me how you have a scenario, the real scenario, the data from the *Columbia*, which suggests to me a changing geometry, and yet what we're trying to do is take a single event and backtrack it. In other words, you take a 4-inch hole. Well, it might have been a 4-inch hole at one point, but it might have been a half-inch hole at the time and an 8-inch hole later on. So I'll have to reconcile in my head how you propagate a casualty over time versus one of those graphs. I don't want to get into it right now, but I think it's very interesting.

I would like for you to also pass on to your colleagues – I know that you represent the tip of an iceberg of a lot of people who are working very, very hard and diligently to try and solve the riddle of this tragedy. We realize that, and I would like to have you pass on to all of your colleagues our admiration and our thanks for all the work that they are doing. They don't get to go to press conferences and things like that like we do and they don't get a lot of notoriety, but I know how hard they're working and I know how hard they want to solve this, too.

Thank you very much. You are excused. And we will call John Bertin, if he's here, and we'll go right to work.

JOHN BERTIN testified as follows:

ADM. GEHMAN: Dr. Bertin, welcome. Would you please introduce yourself and tell us where you hang your hat and what you do for a living.

DR. BERTIN: On Continental Airlines, coming back and forth to Houston.

When I graduated from Rice with a Master's, I went to work for the manned spacecraft center across the street and then got my Ph.D. part-time at Rice and went to UT Austin and taught for 0-something years. I did some research on the Shuttle before it flew. Did some things with reentry heating, tile misalignment, shock-shock interactions. And then after it had flown, we did some analysis on asymmetric transition and anomalous findings from some of the flights, with some of the people who have been giving the presentations up here today. After my kids grew up and they were all out of the house, I left Austin and went to Sandia for a few years; and I teach now at the Air Force Academy.

ADM. GEHMAN: Thank you, sir.

DR. BERTIN: Can you get 18 up here for the viewgraphs?

I thought since we talked about temperatures and we talked about catalysity and we talked about some in degrees Kelvin and some in degrees Fahrenheit and some in degrees Rankine, I thought what we might do is talk about the flow field in general, with one set of nomenclature and what have you.

So if you look at the Orbiter coming in in this orientation, it's at approximately 40 degrees angle of attack. So the velocity vector is coming in like this and the flight path angle, and it's not rolled or yawed or anything like that. It's at an angle of attack of about 40 degrees. So you see it in this picture here.

Okay. This is a wind tunnel test and they talked about Mach 6 in the wind tunnel and it didn't do this and it didn't do that. So let's look at and talk about Mach number and hypersonics and some general features. So if you're going to be flying in a vehicle in the atmosphere, the Mach number is going to be velocity over the speed of sound, whether you're in the wind tunnel or in the atmosphere. So in the atmosphere, no matter what altitude you're at, the speed of sound is about a thousand feet per second. So the Mach number is about the velocity at which you're flying in thousands of feet per second divided by a thousand. So if you're at Mach 6 in flight, you're flying 6,000 feet per second.

Now, there's a lot of kinetic energy in that flow and as the flow approach – so if you're doing a wind tunnel test, to have that much energy, you damage the wind tunnel. So what they do is they run the speed of sound down to where it doesn't simulate the same gas chemistry. So the gas chemistry in a wind tunnel is very, very different than the gas chemistry in flight, even though both flows are hypersonic. Okay.

So now the vehicle is flying along at, say, 6,000 feet per second. It's at an angle of attack of 40 degrees. Why isn't it flying at a low angle of attack like airplanes, which fly about like that, right? Because the heating goes as density to the one-half velocity cubed divided by the bluntness. Since the velocity cubed is large, the heating is large. So what you want to do is counter that by giving as blunt a vehicle as you can. Okay.

So as the vehicle is flying through the air, the air is coming rushing along at 6,000 feet per second and it has to turn to go parallel to the flow's surface. To do that, it goes through a shock wave. I'm sure you've heard the witnesses talk about hearing the sonic boom. The sonic boom is caused by that shock wave. See this thing going up here? That's the bow shock wave. Now, it decelerates and turns the flow. So as the flow decelerates from a high kinetic energy flow to one of low kinetic energy, the temperature is going to go way, way up.

So the temperature is going to be the atmospheric temperature up here a few hundred degrees and it's going to be much, much higher back here, depending upon what part of the vehicle you're in and where you are. But in this region near the nose, you're going to see the highest temperature and we'll use equilibrium and we will use degrees Rankine. You're going to see temperatures of 10 to 12 thousand degrees Rankine.

Now, obviously there's going to be some chemistry going on with these kinds of temperatures and you're going to see a strong shock wave. So the density is going to be changing very dramatically. The pressure's going way up, the temperature is going way up. Density is changing very dramatically. And you know how when you look in water and a fish is here but it looks like it's over here because the light rays are bent? Well, that's what's happening here. The light rays are bent. They pass light rays through the tunnel, and the density changes allow you to see the light being bent. So you can see the density changes downstream of the shock wave; and they're caused by, like I say, the pressure changes and the temperature changes and what have you. So up here the temperatures are on the order of, say, 10,000 degrees, maybe 10,000 maybe 12,000 and again there's some chemistry, there's some non-equilibrium, there's some things going on.

Now, the flow expands around from the nose. Just like when you put your hand out the car window and stuff like that, you feel the force on your hand. Well, the flow accelerates as it goes around your arm, right, and you feel the velocity. You drive down the street and in the windshield you see the stream line patterns taking place in running rain across your windshield. So there are stream line patterns coming here and the flow accelerates to where the temperature of the air in this region is more like 6 to 8 thousand degrees Rankine because the pressure has dropped. The flow is accelerated. The pressure has dropped and the temperature has dropped, so 10, 12 thousand up here. Very high heating rates because it's got a small nose radius and temperature dropping 6 to 8 thousand outside of the boundary layer.

Okay. What is a boundary layer? If you've ever gone to the beach on a cold wintery day, if you're late and it's sunny, if you lay down, you feel relatively warm. If you stand up, you feel much colder. Right? Well, what you're feeling is the change in velocity as it goes from the surface to a much higher velocity a few inches away from the surface. So that's a boundary layer. So you're going to get shear going on in that. Just like when you rub your hands together, you're going to get heating.

So the boundary layer causes the air, by rubbing against each other and fluid particles, to give you more heating than you'd expect from just a few thousand degrees. So you want to protect the vehicle from this heating. Okay. So you put high-temperature materials along the parts of the body that have a small radius, like the nose and the wing leading edge, and you can use less robust materials over areas where the heating drops.

I said the heating varies as rho to the one-half D cubed divided by the bluntness. Well, only a fraction of that energy actually gets transmitted into the vehicle. Most of it goes flowing past the vehicle in the air stream et cetera.

Now, we talked about the tiles. The tiles fill most of the area here, and they're black. They have a thin coating, and the thin coating does several things. We talked about the catalysity and non-catalysity. So the thin coating is non-catalytic, but it's also like Scotchgard. If you look at the thing, if the vehicle's sitting on the pad and it rains, if the tiles didn't have the coating, they'd soak up a lot of the water. So the coating prevents some of the water from getting in.

If you go back to your freshman physics course and you did the little heat transfer thing, the energy coming in can be radiated back out, right? And if the energy is radiated back out, what's the best color for radiating outward? Black. So the coating is a thin, black coating that gives you several type features; and it goes to a much lower temperature.

ADM. GEHMAN: Let me ask a question, Back to wind tunnel, if this is a good time to talk about wind tunnels. As I understood you, the way they achieve the very, very high speeds, the very, very high Mach numbers without tearing the wind tunnel apart is by changing the gas in the wind tunnel to where the speed of sound is a lower speed of sound.

DR. BERTIN: They run the wind tunnels, where the speed of sound is an order of magnitude, or close to it, lower than would be normally in the normal atmosphere.

ADM. GEHMAN: So they're using some other gas.

DR. BERTIN: Or they're taking the air and causing the pressure and temperature to drop way low. The temperature is just above liquefaction of oxygen. If you ran the tunnel any differently, you'd get liquid oxygen going down your tunnel.

ADM. GEHMAN: So any other properties, then, of the results that we should be suspicious of?

DR. BERTIN: That's going to give you some changes in the density ratio. And the density ratio, I think Dr. Widnall talked about how the shock wave is going to change its inclination as you go up in Mach number. It's going to change its inclination as you go up in density ratio. And the density ratio in the flight case is near 20. Maybe 12, maybe 15, maybe 20. The density ratio in the wind tunnel is going to be 6. So it's going to have a much different shock structure. We're going to talk about that in terms of the shock-shock interaction in the Kirtland photos.

ADM. GEHMAN: That was going to be my next question. I'll wait.

DR. BERTIN: Okay. So we have these things going on. So the wind tunnel is just a simulation of parts of the flow, and what you want to look for is some general overall things that you can then compute and then correlate them in some fashion.

Okay. So we have basically now these tiles over much of the surface, and they're giving us many features. We've got carbon-carbon along the wing leading edges, and they go to higher temperatures. So the boundary layer is relatively thin, maybe a few inches by the time you get to the end of it, and so the flow going over that adjusts into – from the zero velocity, the Mach 2 or 3 locally, so the Mach number in this region is supersonic. So if you had a disturbance way down here, it would not feed forward.

You asked the question about would any of this explain what happened to the water being dumped. I don't think so. That may be a problem, but it would be a different function because the disturbances won't propagate upstream unless you have some strong shocks that make the flow subsonic.

ADM. GEHMAN: Well, the reason I asked the question was because one of the gentlemen said that in experiments with the body flap that they had – the first time they entered, they had the wrong pitch set in the body flap and when they started moving the body flap, there were some changes in the shock pattern, the properties of flow.

DR. BERTIN: There will be some changes in the shock pattern, but they'll be limited to the region within a few distances of the body flap. So they can propagate upstream because you're having shock waves, but they won't propagate unless you've got a spectacular flow. They won't propagate very far upstream. So you have that.

Then if you look at the model from this standpoint and you rotate it about its velocity vector so it's still a 40-degree angle of attack, if you look at this picture, it's going to have a shock wave over the bow, the fuselage, the nose region, right, and the shock wave is going to wrap at fairly close angle, like this. If you imagine that you just rotate the model from like this to like this, you'll have shock waves that occur that kind of envelop, form an envelope over the fuselage.

What's going to happen when those shock waves reach the wing leading edge? Because the bow shock wave will be at about this point on the body, right? So what's going to happen? There's going to be a shock wave set up for the wing leading edge. And when the shock wave from the bow shock wave intersects the shock wave from the wing leading edge, you're going to get an interaction that could cause the heating to go up, depending upon what the sweep of the wing is relative to the oncoming flow. So it works out where this kind of delta-wingish type thing has relatively low severity in the shock-shock interaction. If the wing were onswept, you would have great severity in the shock-shock interaction because you're taking a flow going this way and causing it to intersect a flow that has a much stronger shock that's going this way.

So if you are missing maybe not one panel but maybe two panels and maybe it's downstream from the initial column that you had and stuff like that, then you've got like two teeth missing from the leading edge and you've got a little notch in there. Now the flow can go in that notch and create a shock pattern that, in my mind, kind of looks like what the Kirtland photograph might be telling you, in that something is not missing, something is added. And it could be the density gradients of the shock waves in a shock that's been changed shape because you've had some damage that has grown in time. So that would explain some of the additional features.

Then the other thing is, if you look at airplanes flying in high-humidity air, the pressure is higher on this side, right in general, and lower on this side because you're generating lift. So when you get to the wing tip, you form a vortex, wing tip vortices if you're a pilot for the trailing weight and counter hazard. If you're an engineer, you've got these beautiful pictures and wind tunnels and stuff like that. If you're in CFD, you've got beautiful pictures and colorized computer outputs. But for a variety of reasons, you have a vortex. And the vortex is basically a horizontal tornado and the velocity can be very, very high speed and circulating, just kind of like the flow going down your sink or a tornado that's being spawned by a front coming through and stuff like that. So you look at that.

Now, if that tornado came from someplace in here through your gap in the shock wave, not only do you change the shock wave out here but you get the possibility of some kind of vortex coming and striking part of the vertical fuselage. And it could be only limited.

I remember back when I looked at the data from the Gemini project, the GT2 was an unmanned test vehicle and the Gemini had umbilicals that brought the electronic wiring from the booster into the command module or the spacecraft and the umbilical – the Gemini came in at a slight angle of attack and a vortex pattern that had been set up by the flow over the umbilical caused minute holes to occur in the surface of the Rene 41 of the Gemini and they had little holes.

So the vortex can be very localized and it can be very hot, depending upon where it touches down and how much it touches down and what the shape of the vehicle is. But you can see a progressive situation where if you lose a panel or two, you'll get a vortex that could scrub the vertical surface and you get a shock that forms with the shock-shock interaction that creates the image of something that is different than just the main planform of the vehicle. I say you could, 'cause I need more looking at that.

Okay. Is that kind of good as far as – overall as far as where temperatures are high and how they change and what they do?

ADM. GEHMAN: You covered this but I want to be sure I understand that when we're talking about these boundary layers, in accordance with this picture back here, for example, we're looking at boundary layers which are kind of spreading apart and are measured in tens of inches or something like that toward the tail but at the nose we're talking about –

DR. BERTIN: It's going to grow. And this is a 100-foot long vehicle. So it will grow over the length of the vehicle so that it's, say, fractions of an inch, so negligible at the nose, grows to a few inches and greater toward the trailing surface. That's why when you have surface roughness like misaligned tiles, a misaligned tile toward the end of the vehicle is not nearly going to have as dramatic effect as a misaligned tile or a chip in the front of the vehicle because the boundary layer is so much thicker that the disturbance doesn't –

ADM. GEHMAN: But on the front edge of a leading surface like the RCC or the nose of the vehicle, these boundary layers are compressed down to fractions of an inch. So the distance between the temperatures that the vehicle sees, 2750, 2900, and these 10,000-degree temperatures which are measured in little bits of –

DR. BERTIN: The differences between the temperature at the edge of the boundary layer, being 6 or 8 thousand degrees and the temperature wall being 2 or 3 thousand degrees are going to take place over fractions of an inch, which is why the heat transfer rates become so large because those temperatures are gradients.

Then another thing that's going to happen, like I say, is if you imagine rubbing your hands together, you're going to get some friction and the temperature within the boundary layer may even be greater than the temperature at the edge or at the wall because you have this frictional dissipation going on. Because you're going so fast. Your air particles are moving so fast that the rubbing together creates the heat transfer that's unique to hypersonic flight.

DR. WIDNALL: John, you're talking about basically the temperature distribution around the vehicle for a gas that is fully dissociated.

DR. BERTIN: In equilibrium.

DR. WIDNALL: In equilibrium. Dissociated.

DR. BERTIN: The numbers I gave you were equilibrium. If you had non-equilibrium or you're fully dissociated, your temperatures would be a little higher. If you had recombination, your temperatures would be a little bit different again. So your temperatures – mine were based on kind of an equilibrium model.

Now, if you do some computations and you keep it to simple global areas, because the heating is such a small fraction of the total energy available, within about a 20-some percent model, whether it's fully catalytic or non-catalytic over the length of the thing will not change too dramatically. Now, if you compromise a leading edge and you expose some metals and stuff like that, then, yes, your catalysity probably is a major factor like you've been suggesting.

DR. WIDNALL: You know, this is a subject I absolutely hated in graduate school, I have to tell you; but my reading and study of this indicates that the effective surface catalysity has a larger effect on temperature than it does on heat transfer rate.

DR. BERTIN: Well, now, you remember the temperatures were backed out of the heat transfer rate. I mean, the heat transfer rate's going to be backed out of the temperature.

DR. WIDNALL: Right. But the temperature that's being affected is sort of stagnation temperature and recombination.

DR. BERTIN: Okay. You're referring, I believe, to some tests that were initiated at Ames Research Center.

DR. WIDNALL: Well, not only that. Just thinking about a stagnation point.

DR. BERTIN: Now, at a stagnation point you're going to have the velocity of the gas is going to be different than it is going to be moving around the vehicle. So your residence time is going to be a little different and so your effects are – so you would have to take that into account. You'd have to take the shape of the vehicle into account and you'd have to take whether you were looking at the stagnation point, whether the stagnation point was catalytic and the local surface was not and things like that.

ADM. GEHMAN: Speaking just aerodynamically, forgetting all about heat – even though I've already learned you can't do that. Shuttles have returned safely from voyages in which as many as a dozen tiles were missing and weren't even there. Based on the presentations that you've heard and based on your knowledge of this leading-edge shock wave kind of thing, on the Shuttle what kind of a deformation – I'm not asking you to predict what was missing – but what kind of deformation in order of magnitude should we be looking for? Are we talking about inches or feet in order to significantly change the shock wave and, therefore, the shock wave also determines the exterior heating wake?

DR. BERTIN: If I were trying to relate the aerodynamics – and most of the stuff I've done has been aero-thermo and it's been with the heating and transition environment and not with the small increments to the aerodynamic coefficient – but if you had one of the T fillers missing and stuff like that, I think the mechanism for heating would be different than if you had two or three of the RCC panels missing. Because I think with just a filler bar missing, I think you'd start the process and you'd have some situation where you would have to do some analysis of flow in a narrow gap. Because if you just did from a two-dimensional analysis of like the flow in a cavity like he was showing some of those things with the flow coming, the flow would pretty much skip over a T cavity.

So you'd have some flow getting in and it would have to start a process that led to more damage, in my mind, to get significant changes. I think people who have looked at the data that they're obtaining at Langley have said that having the one little RCC missing, the No. 6 one, did not give them the aerodynamic changes that they saw later on. And I would believe that. I would believe the T would give only slight changes, that what it grew into when it lost maybe – like I say, if you were going to suppose or opine – when it grew into something that had multiple RCC pieces missing so that you had kind of the bow shock changing significantly, that would change your aerodynamic forces significantly and that would be consistent with some of the later things going on.

DR. HALLOCK: Can I ask you a question? We've heard the term "shock-shock interaction" used many times. I think it would be useful if we could define what that means; but also, as part of that, go back to the fact that, as you mentioned, you can even see this in a photograph at Kirtland. The question is: Why can you see this in a photograph?

DR. BERTIN: If I have a vehicle like this, it's going to have a shock wave that looks –

ADM. GEHMAN: You're welcome to sit down, even though I know all professors do better waving their arms around.

DR. BERTIN: I'm Italian.

If you look here, this is the shock wave standing off from the surface; and it causes the flow to change direction and the pressure to increase. And with the pressure increase, the temperature increases. So it would be about some small distance off the surface. If you rotate it and look at the picture in this plane – you're not rotating the model, you're just looking at the picture in a different plane – you'd see also the shock wave having about the same standoff distance, right? So it would come in and intersect this surface. Right? But what's going to happen to the surface out here? Because that shock wave is only changing things inside within its dimensions. So it's only changing things between the shock wave and here. So when it hit the wing, it wouldn't affect this at all out here. Right?

So another shock wave has to form to cover this part of the body, and it would depend on what the angles were and the radii and how fast you were going. So you'd have a situation where you had a shock wave up here and a shock wave here. Now, when they intersect, you have changes in pressure that are different in here than they are out here.

So there has to be something happening in the fluid mechanics to change so that the pressures become continuous and you don't have just sudden gaps in your flow and stuff like that. So the interaction you get depends on whether the wing is like this or like this or like this. So the bow shock is going to be – and then all that is changed by the fact that if something happens so that you get a stronger shock, you'll move the flow.

So if I put a gap in here, a significant gap in here, when the flow comes down here, it strikes not the wing first but it strikes the teeth that are missing and kind of flows into that cavity and splashes up against the rear wall of this. So it creates a shock wave going out. And that shock waves gives you density gradients just like these and they'll cause light waves to be bent and give you a different pattern in the flow picture. So you could see – and they unfortunately didn't have them. But if you roll the model to where you were in basically at a 90-degree bank, you would see the shock-shock interaction structure.

On the X-15 back when they did the last flights of the X-15, they hung a hypersonic research engine underneath it and they hadn't taken into account the fact that there was a bow shock wave coming off the main fuselage of the X-15 and there was a second shock wave, completely different, coming off the hypersonic research engine which was kind of underslung off the ventral fin. And when the shocks came together, it caused a strong change in heating. The perturbations in heating can be factors of 10, 30, and more when you get the shock-shock interactions, depending on what the sweep angle is.

For the Shuttle without damage, the sweep angle is such that the interaction effects are relatively benign. So that while there's a shock-shock interaction, the highly swept leading edge prevents you from having strong interactions. If had an unswept leading edge, you would have strong interactions and very large heating going on. So that would be something to look at.

MR. TETRAULT: Doctor, I'm told that the shock-shock interaction occurs normally at RCC Panel No. 9 on the Shuttle. Is there anything that would cause that to move, say, to a different location, say, closer to the fuselage or further out on the wing?

DR. BERTIN: I'm assuming that RCCs possibly were lost in time so that, in a very early one, maybe one would be missing, maybe more, but then because the understructure is exposed, that some additional damage occurred and other ones would have come off in some fashion. Just from my standpoint, with just one missing, you could get the damage that maybe was observed eventually; but for seeing the Kirtland one, I think you'd have a pretty good piece missing.

MR. TETRAULT: I wasn't talking specifically about any damage. I'm just talking about in normal flight, I'm told that the RCC Panel No. 9 is the location of the intersection of the shock wave.

DR. BERTIN: Oh, yes, 9.

MR. TETRAULT: My question is: Is there anything that could happen in flight that would change where that shock wave location would be? I mean, if you are experiencing yaw, for instance, would it tend to move closer to the body?

DR. BERTIN: If you're going to change the orientation of the vehicle, the angle of attack, the yaw angle, these things – the shock-shock interaction pattern would be a function of geometry. It would be a function of angles.

MR. TETRAULT: But simply going from right wing down to left wing down would not change that intersection. Is that correct?

DR. BERTIN: If all you were doing is changing the bank angle from this to this where you had the 40-degree angle of attack, you shouldn't change. Now, if you change the yaw and roll angle at the same time –

MR. TETRAULT: Then it would move.

DR. BERTIN: – then it would change some things. If you change the angle of attack, it would change. If you significantly changed your Mach number so that the gas chemistry changed, that would change. In other words, the shock-shock interaction pattern at, say, Mach 15 in the wind tunnel might be substantially different than the shock-shock interaction pattern in flight because in flight you would have significant real gas effects, you'd have significant dissociation. In the wind tunnel, you'd probably have a perfect gas and a density ratio of 6.

ADM. GEHMAN: Doctor, you heard the previous presentation in which Steve Labbe mentioned the *Columbia* data showed a relatively early roll and yaw bias to the left or showed control surfaces trying to control that relatively early, earlier than previous – different from other flights. Can you draw any conclusions or insights from that? Particularly what I'm interested in is the statistics, the chart that he showed where it showed this left bias very, very early, before the first temperature rose, before the first debris came off.

DR. BERTIN: The only thing, based on my limited experiences with the aero increments, the only thing that I was looking for when I talked to him about these very items was he talked about – I was thinking that one of the possibilities would be premature boundary layer transition due to damage on one side as opposed to the other. 'Cause I was worried about that being one of the multiple players in a breakup scenario. So I believe he – in fact, several people on the panel, in my conversations with them – I believe the fact that they got the same sine for the increments of the yaw and roll and for – when they got asymmetric transition, they always got opposing sines, that that was one factor that says, okay, it's probably not premature boundary layer transition on this particular flight.

Another thing. If you go back and look at all the things, the sensors that went out, there were several near the trailing edge near the elevons and stuff like that; and it worried me that maybe that's a sign that those were going out early because of premature boundary layer transition. But if you look, almost all the ones that went out early went out because they came from bundles that were near the left main gear area. So you could trace the ones that went out near the trailing edge back to bundles that went near the damage area, and the other ones that stayed on came from other parts of the vehicle.

Then, the third piece of collaborative information. The vehicle broke up at altitudes that I think are just above where we had ever seen the earliest transition, or close to it. I don't think we had ever seen transition that early, even in the anomalous flights. So for those three reasons, in my mind, I kind of said, okay, damage notwithstanding, there was not a premature transition event that led to some additional failures.

MR. WALLACE: In the anomalous flights – and I understand there were cases with *Columbia* where the boundary layer transition took place maybe at numbers as high as Mach 18 versus typically Mach 6 –

DR. BERTIN: I think it's Mach 8 and 150,000 feet. Mach 8, give or take one, and 150,000 feet, give or take about 10,000 feet.

MR. WALLACE: Give or take in those anomalous events, if you know, did the boundary layer transition happen sooner on one side or the other?

DR. BERTIN: There was one that was significantly asymmetric and I think most of them could be traced – it's been a long time since I looked at those data, but I think asymmetry was significant as far as its resulting affecting of force on one flight. In two others, it was just early.

MR. WALLACE: Is it fair to say we have the piece – well, you talked about the shock-shock and we have the shock-shock on either side. So I guess my question is, having stood under the Orbiter down at KSC, it looks like one big wing to me –

DR. BERTIN: Yeah.

MR. WALLACE: But does the – boundary layer transition can happen really distinctly separately on either side?

DR. BERTIN: Boundary layer transition is the growth – occurs because of disturbances grow to where the flow breaks down to where it kind of swirls and twirls. So you could have a piece of damage, a tile bar filler – I believe that was one of the sources of one of the flights where they had – the gap filler sticking up about half an inch or more, and it would trip the area. It would affect the flow downstream of it because, again, we're locally supersonic so disturbances won't propagate upstream. So if you put a gap filler bar up in front, you would have the transition promotion in kind of a wedge downstream of that.

MR. WALLACE: So you could just have kind of a localized area where –

DR. BERTIN: Localized but broad coverage. But it would start at the bar and go down in some kind of wedge.

DR. WIDNALL: John, how would you calculate the temperature at the stagnation point of an aluminum sphere that was reentering the atmosphere at Mach 20?

DR. BERTIN: I assume you mean the entire temperature profile and not just the temperature at one –

DR. WIDNALL: Well, I'm interested in the temperature stagnation point. I assume that's easiest to do relative to everything else you might want to calculate.

DR. BERTIN: Okay. But just like with the vehicle in general, the stagnation point has a temperature at the surface and it has a temperature of the air outside –

DR. WIDNALL: I'm interested in the surface temperature.

DR. BERTIN: At the surface temperature, I would assume you would use, depending upon your altitude, a Navier-Stokes code or the classical fluid mechanics code with chemistry. And I'd be willing to bet people at Ames have a code like this to calculate the chemical reactions which would be dependent upon the density and the velocity of the vehicle at which you were flying. And then you would have to do a kind of thermal surface response. But you would have a non-equilibrium flow with a surface catalysity of the material in there and you could get a pretty good idea of what the temperature would be of the material. And like I say, I think it would be very sensitive, if you had an aluminum sphere, as to what your thermal mass was because the aluminum sphere would not only be catalytic, but it would be a good conductor. So some of that energy would be immediately conducted into the vehicle.

DR. WIDNALL: Well, let's make it a thin-shell aluminum piece.

DR. BERTIN: Okay, a thin shell with an adiabatic back piece?

DR. WIDNALL: Whatever.

DR. BERTIN: Okay. Then you could do some similar things like in your heat transfer model just have the thing go up in response to the environment you put it in. You could do a non-equilibrium computation with a reacting surface. And, in fact, I would think codes exist for simple shapes like the sphere that you're talking about.

ADM. GEHMAN: In the debris associated with this tragedy, there are some 25 spheres which have been recovered. All the fuel thanks, 25 out of 30.

DR. WIDNALL: But I don't think any of them were made out of aluminum, were they?

ADM. GEHMAN: No, but the question I'm asking is when you take everything into account that you know that this Orbiter was subjected to, starting at about Mach 17 and then finally breaking up at Mach 15, something like that, and you take into account the discussion we've had about chemical reactions and catalytic reactions and ionization, what would you suggest that we should be looking for in the debris? I mean looking for in the chemical sense – that is, in the sense of deposits and discoloration and oxidation. What kind of testing and metallurgic kinds of evidence should we be particularly sensitive to that might give us a clue as to how this thing started, particularly if we can juxtapose the left wing and the right one?

DR. BERTIN: Jim Arnold and Don Rigali and Howard Goldstein and I were here about a week ago, and we talked a little bit about forensic-type looking at the deal. And I think several people have talked about how the flow – there's indications along the front part of the wheel well, the left landing gear box, the door covering, that indicate the flow was actually from the inside out, that there were stream line patterns in the surface there and there were dark – and you could see little stream line patterns. So this would indicate that, in my mind, that at least at this time frame there was flow going through, whether it was, as you talked about, a 4-inch hole, an 8-inch hole that had grown to whatever, flow had gone in there, was impinging on the tires and kind of coming back out, not necessarily filling all the cavity but impinging on the tires and coming back out. So I would think you would want to do some things with – doing some analysis of the surface in that area, find out if it was aluminum from some places, if it had tire type things in it. There was, like I say, a recommendation made by Jim Arnold that I thought had some good things in it.

Backing up in time to find out when things first started, I would think you would want to do something like some free molecular flow calculations in some scenarios where you either had a pock of damage or a crack or a split or some kind of realistic T bar filler missing, some kind of realistic thing to see how that would affect the back surfaces and the aluminum facings and stuff like that to start your damage pattern. And then something in the middle where you had a jet of hot air going in through the damaged substructure and creating more havoc. But then you're in kind of a continuum environment at about 70,000 feet, even before you get to peak heating. That's kind of what I put together. And then you have the tests at Langley with the RCC panels missing to see if you could kind of reproduce the Kirtland photograph.

ADM. GEHMAN: My last question is, based on your fairly extensive knowledge of both aero- and thermodynamics, do you feel that after this total of 13 flights in this regime that is winged, manned, recovered flights, that our knowledge of this region is – are we at the beginning, the middle, or are we fairly mature in our knowledge of this region of science?

DR. BERTIN: I think it was Mr. Caram that said that – or one of them said that almost every trajectory flies right down the same path. So it's not like we've had, you know, each one as a new environment. They kind of go along the same path. If you overlaid the velocity altitude time, there would be very nominal type performance. So in that sense we have a lot of experience with what happens nominally if nothing has broken, if nothing has come off or if what has – if a tile is missing, it's a tile in some place that's fairly benign or there's a structure underneath that caused the tile, the heating to be conducted internally and not out. So I'd say from that standpoint we have a lot of information.

From the standpoint of what could happen if something came off and hit something and damaged it in ways that had not been done before, it's a very unique and very harsh environment. I doubt that we'd know even something as simple as the initial flow field that caused, say, the initial – say, a T gap had been missing or a small hole in the RCC. I think that would be a challenge to look at and say, okay, I think this happened in detail.

Like I say, if it's nominal, everything's sealed and things going on, we've got a lot of information. If we're substantially away from nominal, it's a very, very harsh environment and very, very sensitive to the individual details, I would think, of what actually happened.

MR. TETRAULT: Let me ask you one question. As we heard in the last presentation, very late in the event, the rolling motion seemed to change and that change required that there be lift under the left wing. They talked about running analysis based on the wheel well door being open which might have created it. Can you think of anything else that would create lift on –

DR. BERTIN: The shock-shock interaction – if you look at the Orbiter like this, the normal shock-shock interaction, like I say, is going to trace a bow shock that comes along here, intersects the wing in about here, and then another shock that's going to be like this. If we had the two or three pieces missing by that time here and we had a shock that looked like that, which is kind of what the Kirtland photograph – and again, don't overinterpret this – that needs more work. If the Kirtland photograph is saying we had a shock-shock interaction like that, that's going to be a much stronger shock. The modified one, the one with the pieces missing is going to be a much stronger shock with much higher pressures than the original shock would have been at, say, while the vehicle was still intact.

MR. TETRAULT: And that could have gone under the left wing?

DR. BERTIN: That could have caused the pressure to be higher and giving you an asymmetric force.

DR. WIDNALL: I was rather intrigued by the suggestion that came up earlier that perhaps a jet coming out of the wheel well door could create a local shock in the area around the wheel well and lead to increase pressure. Of course, obviously it depends on the volume.

DR. BERTIN: It would do that also because obviously if the flow is coming from inside out, that's not a normal passage. So as it comes oozing out or flowing out or however fast it was coming out, it would thicken the boundary layer; and thickening the boundary layer would change basically the flow over the surface some small amount.

DR. WIDNALL: But it could lead to a shock, a local shock.

DR. BERTIN: And it could lead to a shock interaction that would cause locally higher pressures in the area of the landing gear well.

MR. WALLACE: The prior panel described their various scenarios that they were then going to try to fit into the aero picture, the thermo picture and on the sensory. Any thoughts on those scenarios in terms of other scenarios that you might suggest?

DR. BERTIN: I think they're working with the tools they have in a logical sequence of steps. If I were kind of setting up things, I might try to spend a little additional time kind of coming up with cartoons of what the flow might look like if it were coming out of the wheel well and saying how much does that modify the flow, to try to get me some additional things that I could compare with some of the observations that you made. Like if the thing was generating more lift at some point, could I get a shock-shock interaction to explain that, could I get flow coming out of the wheel well creating a shock.

So in addition to the things they are doing, which are certainly good steps along this line, I think I would try to get a cartoon strip saying like this is what's happening here, this is what's happening here, this is what's happening here and try to get some engineering assessment.

It's a very, very difficult problem to do either experimentally or computationally. So you kind of want to, like I say, have some pictures of what do you think is happening and then run some tests or do some computations to see if that's what you get out of your models. I think somebody pointed out the fact that the model fell apart later on. Well, why did it fall apart? If one third is going like that or one third is going like that. So do you need to upgrade your model? Do you need to improve the rigor of what you're looking at?

MR. TETRAULT: I know you haven't had the opportunity to see some of this debris, but let me describe at least one of the vents that's coming out and maybe give you a sense of how large it may appear to be. Then maybe you can tell me whether you would think this would be fairly significant in terms of disruption to the boundary layer. It appears that the vent goes out and actually covers three adjacent tiles, which would mean that it would be probably in the range of 18 inches. It actually melts the tops and surfaces of those tiles. So it would have to be extremely hot. And it is perpendicular to the normal flow that you would expect the boundary layer to be going over the aircraft at. And you see it –

DR. BERTIN: You're talking about the main landing gear cover?

MR. TETRAULT: Right. This is the forward inboard corner.

DR. BERTIN: Yeah. I looked at some pictures. It actually even erodes away the metal.

MR. TETRAULT: It erodes away the metal structure on the inside. That's the aluminum structure, which you expect because it's obviously very hot. It's hot enough to actually erode ablative tiles.

DR. BERTIN: No, but you can see on what's left of the tile patterns, you can see black surface which is stream lining out. Yes, I would think that would cause a significant increase in the boundary layer thickness, some strength of a shock – 'cause, I mean, if gas is coming out, it's changing the surface of the pattern.

In other words, if gas is coming out, it would be like if I took a little jet in here and blew air into the surface. That's going to cause the flow to turn, have to turn around the jet. So you would have a shock wave. You would have a shock boundary layer interaction. How strong that was would depend on how much flow you were coming out with, but that would certainly be a parameter that would be in addition to the notch on the wing leading edge. And it goes in the same direction.

ADM. GEHMAN: Thank you very much, sir. I'm going to ask that, by virtue of being the chairman here, I'm going to ask one last question. Then we'll close up shop here.

Based on your knowledge, would you make a recommendation to us as to how much latitude there is in the reentry profile, you know, to reduce heating or to reduce stress, even if you wanted to increase heating but reduce stress or something like that? How much latitude is there in the reentry profile?

DR. BERTIN: That's not one of my areas of expertise. But in talking to others, your entry angle is somewhat limited because if you – and you have the weight of the vehicle. So unless you can throw things overboard to significantly change the weight of the vehicle, your entry angle has a certain range that you can come into. And you're going out there. I mean, you're orbiting at 20,000 feet per second. You've got a lot of energy. You've got to dump a lot of that energy, and there's only so much drag you can do, it's my understanding, with the flight path. So limited.

ADM. GEHMAN: That's what we've been told by several people, and I just wanted to get your opinion.

Dr. Bertin, thank you very, very much for helping us solve this mistery. Your knowledge and your professionalism and your ability to explain complex things to us is very, very greatly appreciated. We appreciate you taking time to help us with this; and if we have any further questions, we probably will get back to you. Thank you very much.

The press conference will start promptly at 1:00 o'clock, for any of you that are interested. For those of you that aren't, have a nice day. For those of you who don't have any choice, be here anyway.

(Hearing concluded at 12:32 p.m.)

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