March 17, 2003
Houston, Texas

Columbia Accident Investigation Board Public Hearing
Monday, March 17, 2003

1:00 p.m.
Hilton Houston - Clear Lake
3000 NASA Road One
Houston, Texas

Board Members Present:
Admiral Hal Gehman
Rear Admiral Stephen Turcotte
Brigadier General Duane Deal
Mr. Roger E. Tetrault
Dr. Sheila Widnall
Mr. G. Scott Hubbard
Mr. Steven Wallace

Witnesses Testifying:
Dr. William Ailor
Mr. Paul Hill
Mr. Robert "Doug" White

ADM. GEHMAN: Good afternoon, ladies and gentlemen. Welcome to our second public hearing. The subject of this afternoon's hearing is going to be a discussion of the reentry of the Shuttle *Columbia*, and we'll hear from several witnesses this afternoon. The first one is Dr. William Ailor. Dr. Ailor is the director of the Center for Orbital and Reentry Debris Studies from the Aerospace Corporation.

We are very thankful, Dr. Ailor, for you for taking time to come down here and help us walk through this. What the Board is interested is, first of all, a non-NASA view of how things reenter the atmosphere, which will help us form our questions for later this afternoon when we get the detailed analysis of how the *Columbia* entered the atmosphere, and your presentation will help us understand to a much greater degree what we'll hear later.

Dr. Ailor, I would offer to ask you to give us a short bio or your background, if you please; and then if you're prepared to start, we are prepared to listen.

WILLIAM AILOR testified as follows:

DR. AILOR: Okay. Thank you very much. Just by way of background, I joined Aerospace in 1974 and have been basically working reentries ever since that time. I'll go over in my presentation a little bit more detail on some of the ones we've worked on before, but Aerospace established the Center for Orbital Reentry Debris Studies back in 1997 in recognition of the kinds of issues that we expected to see from both space debris and the hazards posed by reentry and in recognition that there needed to be a fair amount of work done to understand the reentry breakup process. I'll go over some of that in my presentation.

So a little bit more background, I did work on the External Tank reentry a number of years ago, one of the issues where it was associated with what altitude did that break up. We worked very closely with NASA in resolving those issues. Then I've also been in various capacities on the Interagency Nuclear Safety Review Panel, which reports to the White House on space missions which carry radioactive materials – so Cassini, Mars Pathfinder, Mars Exploration Rover. We've worked on all of those.

So if I could have the first chart. Okay. Go back one. No, that's good, I'm sorry.

What I'm going to talk about is what we can learn from reentry debris. This is really based on the experience that we've had over the last 25 years in this area, actually longer than that. Aerospace has been working in this area for a long time, and our desire has been really to understand the breakup process. Again, these things coming down through the atmosphere can present a hazard to people and property on the ground. One of our objectives has been to understand what that hazard is and to be able to model it and perhaps minimize it as time goes on.

So what I've got here is an overview of the reentry breakup process. This is just for a standard reentry; and as I'll show you in a minute, we see a number of these a year. For a typical satellite reentering, it slowly comes down through the atmosphere, slowly works its way down out of orbit in an orbit decay fashion or, in fact, you can actually drive something into the atmosphere – and I'll talk about that in a bit, as well.

Basically for unprotected space hardware, the heating and loads will gradually tear it apart. I'll talk more about that in a minute. The kinds of things that we've seen that survive reentry are things that you would probably guess might, things like steel sometimes – I'll talk about that – glass, titanium, and then parts that are sheltered by other parts.

One of the things about the reentry breakup process is that the heating is like, in a sense, cooking an onion. You basically start from the outside; and then as you heat the pieces up to a point where the materials will fail, that will expose some new materials. They'll go through the same process and the object can be broken apart. We do have objects that are melted and shedded away, things like aluminum, solar panels. Things like that come off pretty early. Mylar sheets. Some satellites are wrapped in Mylar sheets.

Once this debris comes off from the parent body, it follows its own trajectory at that point. So it will go on about its business, basically, based on its own properties. If it's a very dense, heavy piece, for example, it may go further. If it's a very lightweight piece like a solar panel or something like that, it will fall early in the trajectory.

Then the debris pieces impact on a footprint on the ground. I've got an illustration there that just shows that typically what we see is initial breakup or shedding of some things like solar panels that come pretty quickly. And we have catastrophic breakup. I'll talk more about that but typically it can be quite a substantial event. There can be secondary breakups that happen when those pieces come apart. Then you see a footprint where you get low-mass debris that comes in early; and typically longer, heavier pieces go late. We'll talk more about that, as well.

Next chart. Okay. So just some characteristics of reentry breakup. It's characterized by intense heating and major fragmentation; and as I mentioned, fragments are shed as the structure heats and fails. Typically we see instantaneous high loads. For example, when an object comes off of a parent body it now experiences the air stream that exists there; and it will respond based on its own characteristics. For example, if you've got a very lightweight piece that comes off of a heavier object that's coming through the atmosphere, it's like throwing a piece of paper out of a car. That will decelerate very quickly, and the same things happens even at Mach 20. So when you do that, you see very high loads; and you can also see very high heating. That can be important if you're trying to understand what actually happened in the process, because now you've got an object that's been separated from a parent body that, just because of its own interaction with the atmosphere, will have seen a fairly severe environment.

You can have some events with moderate velocity increments. What I mean by that is if you've got a fuel tank or something like that that explodes, it's like a balloon. Some of those fragments will pick up some velocity increment from that. We've measured as high as a thousand feet per second. And the initial breakup can be energetic. Basically a typical way for things to break up when they reenter is that they'll come down through the atmosphere for a certain amount of time, they look absolutely fine, we've seen videos of these things where they just like spacecraft coming down, and all of sudden they come apart. When they come apart, they just disintegrate. That altitude typically is around 42 nautical miles, plus or minus a few nautical miles; but that's a pretty good guess. So just as a rule of thumb, it seems like a critical point for space vehicle reentry and breakup is around 42 miles. We have never had any measurements internal to a spacecraft during this breakup process and that's something that we would like to see. It would really help us understand the process better.

Next chart. Survivability depends on a numbers of factors. The material. For example, the melting point of the material, the heat capacity. Just by example, it's very rare to find aluminum on the ground from a standard spacecraft reentry; and finding aluminum on the ground would basically mean that that aluminum was somehow protected as it came down. Steel can survive. It doesn't have to, though. We have cases – for example, there was a Russian satellite that came down in Canada, had steel, a reactor case. That reactor case basically disintegrated during the reentry, but also I'll show you some pictures of steel that did.

Size, shape, and weight. An empty fuel tank, in a sense it's a lightweight object relative to its size. That will affect its survivability, and that can be very important. For example, fuel tanks survive. Things as dense as a battery? We've never found a battery on the ground.

Release conditions. If an object comes out late in the reentry, after being shielded for a portion of the reentry, that means a lot of the energy has been taken out of that trajectory prior to that object's release; and that object is more likely to survive. And shielding. Again, objects that have been shielded for partial reentry can survive; and that's one reason, by the way, that, for example, you can find circuit boards on the ground from satellite reentries. What that means is typically when a satellite is being constructed, circuit boards are built internal to other boxes which are internal to other structures and so forth. Again, if you think about this heating process where you're removing the outer layers as you come in, every time you do that, you're removing energy and then finally these things will be released.

Next chart. When these things come down, there's a typically generated debris footprint. Now, this is a notional footprint here. I've got several breakup conditions separated by about 30 seconds in trajectory time. This shows things like the types of dispersions that we typically see. This has got dispersions in winds. So winds will affect things as they fall, even a big, heavy object, as I'll show you in a minute. Ballistic coefficient is a measure of, in a sense, how dense an object is; and that will affect where things go. Typically on these footprints at least, for example in the red swatch you see up there, things that have gone longest downrange, farthest to your right, would be heavier objects. The lighter objects would hit towards the up-range portion.

Then atmospheric density. We don't quite know what density is in most trajectories. So in that case we have to build a factor in to allow for that. Then also, as I mentioned, it's possible to get some velocity increment as things come down. So we put in a delta feed for that.

So basically what you can see here is these ellipsoids were generated at each of these time intervals, and you can see how they overlay each other. If you look carefully at Breakup 4 down there, that's the one where the trajectory is now healed over a bit and you can see that even though the same types of debris are there, the footprint is inside of the one just prior to that. This indicates that trying to figure out where debris came from on a reentering spacecraft and where it happened is a very difficult process, indeed. These are four specific time steps. What you have to recognize is this is basically happening continuously as the spacecraft reenters. So the footprint is not even as nice as what you see here.

Next chart, please. Noteworthy reentries. Just to give you a little background, it was mentioned earlier that someone said this is not a data-rich area; and I have to agree with that. What you see here are some of the primary data sources for doing this type of work. Cosmos 954 came down in 1978. That was a reactor-powered satellite and there was radioactive debris that came down in Canada. Since it was radioactive, you could find it pretty easily and a lot of that debris was recovered and was examined and documented. That's probably exceptional on these kinds of things. Typically the effort is simply not put forward to find debris on the ground, and so we simply don't have as much.

Skylab occurred in 1979. Some of the debris fell in Australia. There was some debris found, but again there was really no detailed analysis of the footprint itself, as far as I'm aware.

I'll show you some pictures of some Delta 2nd stages in a minute. We do have large debris pieces surviving from that. We did reconstruct the trajectories and try to understand the breakup of those.

And there were two targeted reentries. The ones above that were all basically, in a sense, brought down just by the atmosphere itself. In other words, the atmosphere drags things out of orbit slowly. The last two were actually targeted into ocean areas because of potential hazards they posed. The Compton Gamma Ray Observatory, that was targeted to an ocean area. There was no debris found from that one. And then the Mir Space Station was also targeted to an ocean area. The only debris I'm aware that was found was reported by a guy who was beachcombing down in Fiji, a job I'd like to have. He did have one piece. It's not been substantiated that it actually came from Mir, but likely Mir had debris surviving and it may float up on a beach somewhere.

Next chart. The type of work you can do with a reentry as far as reconstructing what actually happened to it, there are a number of things you need to do. There's maybe tracking data – for example, radar data. Video data, for example, the type of thing that people would take. If people have seen it from aircraft, any of that data can be very useful in rebuilding what's happened in a reentry break. Public sightings and witnesses. On most of the reentries we've got here, the public actually has seen some of these things coming down. That information has been very useful in rebuilding what happened during the reentry.

Debris on the ground. Knowing where things are, what they look like, how much they weigh – all that information can be critical to rebuilding what happened. That's one of the reasons why the work that's going on now, both from the public and other agencies looking for debris, is really critical to this investigation.

Data on the original vehicle. It's one thing to have debris on the ground, but you need to know what the original configuration was like. Sometimes we simply don't have good information on that. If it's a foreign satellite or something like that, we may not know exactly what was coming through the atmosphere. So we don't have a good feel for taking the debris back up.

The next thing you try to do is fuse all that information and basically rebuild the reentry trajectory, try to match the impact locations to possible release points and take any existing weather data, any of that sort of thing in, and then finally conduct metallurgical analyses on the debris to estimate temperatures, really look at what went on, those kinds of things.

Next chart. This is an example of a reentry. This one came down over Canada. This was in 1997. You can see that on that chart we show a breakup altitude at the magic 42 nautical mile number. And there are some fragments. We'll talk more about those, but this is one. This again, the public was out. This was about 3:00 o'clock in the morning. There were reports to news stations and so forth, and we actually used that information.

Next chart. This is some pictures of the debris recovered from that one; and this is one of the larger debris fields, I guess, that we've actually had a chance to see. As I say, typically unless it lands next to a farmer's house as you see in that chart there, people don't find these things unless they happen to be out and about. So what you see in the upper-left corner, this is the original configuration as it was being loaded onto the launch vehicle up there. There actually was a satellite on top of that. This stage was released in orbit and was in orbit for about nine months and then gradually the atmosphere dragged it down.

The big brown tank you see over there is about a 570-pound stainless steel tank. It landed about 50 yards from a farmer's house here in Texas. He was not pleased. The woman you see on the top right actually was brushed on the shoulder by a piece of the debris. Again, she was very lucky; but it's a very lightweight piece.

The sphere you see down here was one of four on that vehicle. That was the only one found, although we believe they all survived. So they're still on the ground somewhere.

The bottom one just shows that these things can survive in pretty good condition. Those are screws that you actually could unscrew. They held an aluminum plate onto the Tank itself. The aluminum is gone, but the screws were still there and just fine.

Next chart. This again gives you a little detail on that one. Again 550-pound tank. 67-pound titanium sphere. 100-pound thrust chamber. Footprint length was about 400 nautical miles long on this one.

Next chart. This is a detail of the trajectory reconstruction. The trajectory comes in from the top and each of those little black dots is about two seconds apart. So you can see just by the spread of those dots that it's moving at a pretty good clip originally. That's up and around 18 nautical miles up. When you get down to around 10 nautical miles, it looks like it does a little dogleg there and that is due to wind. So basically where an object of this type comes into the atmosphere, typically all the orbital and all that motion is gone, the atmosphere has basically taken that energy out, and it will fall from, say, 50,000 feet straight down. That's one reason why when you see debris on the ground, even on the pictures of the farmer's house with the debris there, you'll notice there's really no crater. Most people don't realize these things just fall straight down and they just land. That's just a characteristic of this. That little dogleg is again caused by winds. It hit the jet stream, and it blew it over. This, again, was a 570-pound tank. So you can see that even that can be moved.

Next chart. One of the things that we did was we were able to get a portion of this fragment that brushed Lottie Williams on the shoulder and we actually wanted to find out if, in fact, it did come from the launch vehicle or from that vehicle. We analyzed that and found that – if you take the next page please – that it did. The trajectory time was consistent. She was out walking at around 3:30 in the morning and actually saw the reentry and then this thing came down and brushed her on the shoulder and she recovered that. We did get a piece. We brought it into our labs and did an energy dispersive X-ray analysis of it. There are actually two on this little red chart you see here. There are actually two lines there. One is the original material, and the second is what was recovered. So we are very confident that this material actually came from that vehicle.

Next chart. The second thing we did is take samples from the large tank itself, put it through a metallurgical analysis. We found, for example, that in portions the aluminum actually combined with the stainless steel and that we were able to use that to pin down the maximum temperature on the Tank between 1200 and 1280 degrees centigrade. The other interesting thing, and I'll show you another example of this, is that it appears that this aluminum splashing back – again, aluminum is there on other parts of the structure – that the aluminum splashing back on the Tank can actually oxidize or burn and the heat released by that can melt holes. We believe that's why the hole was actually melted in this tank.

Next chart. Just to show you, this is not all that unusual an event. This is some pictures of basically the same debris objects. These came down near Capetown, South Africa, in April of 2000. So basically the same objects.

Next chart. This is another one we have. This is a solid rocket motor stage that came down in Saudi Arabia. This one is made out of titanium, which makes it a little unusual. The ones you saw before were typically out of steel. This is titanium. It would be expected to survive very nicely. We have evidence again that the hole you see here was actually burned, in a sense, in the casing as the aluminum oxidized on it.

Next chart. So just learning a little bit from the debris and limitations there, we typically model reentry breakup at the macro level. We simply don't have a good understanding of what happens at the micro level with these kinds of things simply because we don't have a lot of data to base our models on at that level. We do have a few reentries where significant debris is found; but, just by way of information, of the stages that came down in Texas and South Africa – we have about ten of those that come down a year – those are the only two we've found, only two where debris was found. So most of these land in the water or in places where they are not discovered. We also see about a hundred reentries of major objects a year. So finding debris on the ground is very unusual, although we do get hits on our website. People email us with things they have found and ask us if that potentially is of that type.

Just by rule of thumb, we would estimate that about anywhere from 10 to 40 percent of an object will actually survive reentry and that can depend on what it's made of. If it's got some big, heavy, empty fuel tanks, that can really be a factor there. There has been relatively little work on reconstructing reentry breakup events. The ones I've mentioned are about all there are. Again, one of the most important features is there's really been no systematic retrieval effort except in a couple of cases. I guess the Cosmos 954 would be an exception and, again, the objective there was to recover the radioactive material.

Next chart. Some observations. As I mentioned, the heating to an object can really be exacerbated by burning of other material. For example, this phenomenon of aluminum melting and splashing back and the heat of oxidation actually increasing the temperature and burning holes, we believe that's a real situation. There are large aerodynamic deceleration loads, and also you've got an object that's already been fairly well heated as the reentry progresses. So that can lead to structural failure and actually can mask other information about what happened during the breakup.

Combining data from multiple sources can be critical for reconstructing a reentry event. Finally, the distribution of debris on the footprint may actually be very useful in providing clues on the breakup sequence itself. So things like if you find objects early in a trajectory, that can be really very critical to seeing how that reentry progressed.

Next chart. So, in summary, reentry breakup is not well characterized at the micro level. That breakup and subsequent disintegration can and does destroy clues of critical events. The debris field may be very useful in helping to track down what ultimately happened. Data fusing is really a critical part of this. You really must take everything that you can learn, all the data you can get, and try to reconstruct what the event was. Then a final piece of that is laboratory analysis of the debris pieces themselves to look for things that can be shown to have occurred earlier or have been protected by other objects as the event progressed.

I think that's my briefing Sir.

ADM. GEHMAN: Thank you very much, Dr. Ailor. All right panel. I know we've got some questions.

MR. HUBBARD: Dr. Ailor, thanks for being here with us. We appreciate someone of your expertise speaking to us. I have two questions that are follow-ups on some statements that you made. One is about the percentage of material that's been recovered in your previous data base. Where we are today with the *Columbia* is something on the order, by weight, of 15 to 20 percent. So I would like your assessment, based on what you know, of whether you think this is a low or a high or what we might expect in the future.

DR. AILOR: Well, as I mentioned for typical reentries we see between, say, 10 and 40 percent. It really can depend on what materials the object is made of. There may be significant debris pieces that have yet to be discovered, I don't know, but I would say that's certainly in the range of the experience in the past. The other part of this is that we've never had the detailed look or the energetic search for debris that we're seeing now. So it's possible that you may get a higher percentage as time goes on.

MR. HUBBARD: Thank you. The other question was related to your statement about aluminum rarely being found on the ground. We're finding some aluminum, although mixed with other debris or attached to other debris. Can you give us a brief explanation of why that might be the case?

DR. AILOR: Yes. Our experience has been that unprotected aluminum will not survive a reentry event. The heating is just too high. It typically comes off very early in the trajectory. We do find aluminum, say, bits of aluminum that has been flowed back on to tanks and been protected, say, by a titanium sphere or something like that. It will flow onto the lee side and be protected back there. But we typically don't find that. For debris that you're finding now, most likely aluminum on the ground was protected for a significant part of the reentry and probably was released late, when there wasn't sufficient heating to cause it to melt.

ADM. GEHMAN: Thank you.

MR. TETRAULT: Dr. Ailor, one of your charts talked to the five satellites that had broken up in the atmosphere. To put this in perspective, could you tell me how many total pieces in history have we had compared to the 30,000 pieces that we will now be working with from the Shuttle.

DR. AILOR: Well, in history, we actually have examined probably five or six, just to give you an example, the several big tanks and so forth. There was a number of debris pieces that were picked up from the Cosmos 954. I would say in history we're probably talking about in the order of maybe 250 or so that have actually been noticed by humans on the ground and reported.

MR. TETRAULT: Thank you. One follow-up question. You talked about the ballistic coefficient. For everybody's edification, could you kind of distinguish the difference in the ballistic coefficient between something like a tile, a tank, and maybe a landing gear strut.

DR. AILOR: Absolutely. Ballistic coefficient is a measure of how significantly the atmosphere is going to affect the flight of an object. The way to think about it is a very low ballistic coefficient object would be like a feather. Extremely low ballistic coefficient. A Shuttle tile, for example, released by itself, very light object, would have a very low ballistic coefficient, as well. Something with a medium ballistic coefficient would be something like a tank, an empty fuel tank. That big tank I just showed you here has a ballistic coefficient on the order of 15 to 20. Then something like you were mentioning, a landing gear strut, I probably would imagine that would be up to 40 or 50, something on that order. A ball bearing would be something that would have a high ballistic coefficient. So it would be something where the aerodynamic properties really would make it less susceptible to the atmosphere and also its mass properties would give it a lot of inertia.

MR. TETRAULT: Thank you.

ADM. TURCOTTE: In the examples that you gave of the different reentries that you had, they were obviously at different inclinations and they were at different reentry profiles. Would you kind of explain the difference in what you know of the Shuttle's reentry profile at that inclination and some of the data that you've had in the past from the other satellite reentries.

DR. AILOR: Yes. The other satellites that I spoke of either were deorbited or basically were orbit decayed down, had very shallow path angles typically. They flew what we call ballistic trajectories, which mean there really wasn't much lift involved with them. Of course, the Orbiter is a lifting object and lift did play a big role in its trajectory – for a good portion of it, anyway. That trajectory will affect the heating rates and so forth and will affect how the object responds to the atmosphere.

MR. WALLACE: This is the first time we've had a breakup of a vehicle designed for reentry. Is that a fair statement?

DR. AILOR: Of this type, yes.

MR. WALLACE: This ballpark, your 42-mile estimate, was pretty close, given the situation of the *Columbia*. Does the fact that this was a vehicle designed for a safe reentry change some of your estimates about percentage we're likely to find and any other sort of effect on the breakup sequence?

DR. AILOR: Well, it certainly could. As a matter of fact, the fact that there is a heat shielding on at least a portion of all the body for a portion of the time and then some of the body parts after that will affect what survived. That's certainly true. I should mention that the Shuttle External Tank also is a reentering vehicle after it's released from the Orbiter during launch. That typically breaks up at a slightly lower altitude, maybe around 40 nautical miles plus or minus a little bit. What happens there is there is some amount of heat shielding and it does protect it for a little bit. So there are objects where there is a shielding existing and I think the fact that the breakup sequence that can be shown that there was a material loss at a very high altitude for the Orbiter may indicate that the heat shield may have had a problem.

DR. WIDNALL: You mentioned earlier that aluminum rarely survives, certainly in its bare state. Could you sort of go over all of the possible things that you could think of happening to aluminum in reentry both for, say, an individual panel that suddenly found itself all by itself in the atmosphere and also maybe a panel, say, on the leading edge, like leading edge spar of the Shuttle wing, that was attached to the Shuttle but was bare? What are the different range of things that could happen to such aluminum?

DR. AILOR: I'll give you an example. Some of the work we've done has been looking at a large spacecraft that reentered with solar panels and we believe and have data to indicate that the solar panel came off early in that reentry. Some of data we have makes us believe that that solar panel, even with an aluminum structure, actually survived. So that's a case where again you have a big –

DR. WIDNALL: Now, that's ballistic coefficient.

DR. AILOR: That's exactly right. it's a big, flat, plate. It spreads out, stops very quickly, and then essentially just falls to the ground. So something like that could survive. So in that case aluminum could be expected to survive.

If aluminum is being carried along by a heavy object – for example, you saw the Tanks we have here – these were big, solid pieces of material. The aluminum on it is a piece of structure. As it's being carried by that heavier object, it's really governed by the aerodynamic and heating and so forth that's characteristic of that object. That could be much higher than the aluminum itself can stand; and when that aluminum gets weak, it will come apart.

DR. WIDNALL: I'd like to go beyond that. So you're saying melting?

DR. AILOR: Melting. Absolutely.

DR. WIDNALL: Vaporization?

DR. AILOR: Melting, yes. Turn into droplets.

DR. WIDNALL: Well, droplets? How about individual atoms, vaporization?

DR. AILOR: I would assume. You'd have to ask somebody more qualified in that area than I am.

DR. WIDNALL: Oxidation?

DR. AILOR: Oxidation for sure. We've seen evidence of that.

DR. WIDNALL: Of course, another word for oxidation is burning.

DR. AILOR: Exactly.

DR. WIDNALL: The example you gave was aluminum deposited on another tank which essentially burned and created – but I suppose it could also burn all by itself.

DR. AILOR: It could, although aluminum released by itself probably would stay in a droplet form and decelerate pretty quickly. So aluminum that would be carried along by something I think would really be more likely to see that.

MR. TETRAULT: In the hole that was created that you talked about, was that created by the aluminum burning or the alloying effect?

DR. AILOR: It was, we believe, by the oxidation of the aluminum itself; and that raised the temperature up where you could actually see the alloying occur.

ADM. GEHMAN: I was very interested in your comment about the ball of paper being thrown out the window of the car – not just because that's my level of understanding. What you suggested was that in an entry scenario like we're investigating here, there is a heating and an aerodynamic force, one of which is extraordinarily fast, and then when the object then becomes free and floats down to earth, it's still got heat but it's no longer of this extraordinarily short-period high intensity. My question is: When we go looking through debris, should we be able to detect those two phenomena – that is, a piece of metal which has been flash heated versus a piece of metal that's been subjected to prolonged – by prolonged I mean tens of seconds or maybe even more? Can you see the difference, in your experience?

DR. AILOR: For aluminum to actually see, as you say, the flash heating, the way that will work is that when an object is actually kicked off, if it's has got material attached to it – for example, it's tile material with some substructure attached to it – if it comes out in a way where the tile material is forward and actually protects the material behind it, then that might be likely to survive. The problem is going to be with, No. 1, the breakup process is going to continue on about anything, about any object that's put out into the stream that's going to continue to see heating for a short period of time. If there is much material there and it's a very low ballistic coefficient item like a big, flat plate with some material behind it, structural material, that will heat up very quickly, as you say. The aerodynamic loads will also be quite high as soon as it hits the air stream. That can have a tendency to fracture it further. So this breakup process is going to continue as it comes down. Secondly the dynamics may actually get into the process. So this object is tumbling. Then the different sides will see the air stream. So it will be a difficult process, I think, to try to see a piece on the ground and make sense out of it from that perspective.

ADM. GEHMAN: I take it in one of your viewgraphs, for example, of a sphere that came from one of the Deltas or something like that in which all of the burn marks all around the sphere look approximately the same, would it be, in your experience, safe to conclude that that sphere had been tumbling and all of the sides had been subjected to the same amount of heat, whereas the one that had the hole burned in it it's safe to analyze that that was another event of some kind? That's kind of what I was getting at.

DR. AILOR: That certainly can be. You're right about that. As a matter of fact, on one of the Delta tanks, one of the spheres, about a 2-foot diameter sphere, one side actually does have droplets of aluminum that are clearly visible on it. The other side is absolutely clean. So you can say that during the heating phase that one side was facing the oncoming air stream and saw more heating than the other side did. Exactly.

ADM. GEHMAN: Another question. Certainly in the case of those spheres – and by the way, in the case of *Columbia*, I'd ask, Mr. Tetrault, we have found essentially 20 out of 25?

MR. TETRAULT: We found at least 25, not counting fragments, out of approximately 30. I don't know what the exact count is (talking over – inaudible).

ADM. GEHMAN: (To Mr. Ailor) As you predicted, the spheres all survived. But in the debris field, not discounting the spheres, your suggestion is that in the terminal velocity, in the terminal vectors, even when you start off going 10,000 miles an hour, by the time you reach the thick part of the atmosphere, you're essentially dropping vertically.

DR. AILOR: Correct.

ADM. GEHMAN: Therefore, how would you characterize whether or not we should find buried debris or not? Would you expect most of the debris to be on or near the surface?

DR. AILOR: I would expect most of the debris would be on or near the surface. Buried debris would not be typical for a spacecraft reentry. That would require a very dense material and would also require it to have some aerodynamic properties which you're not going to find on a reentry object.

GEN. DEAL: Dr. Ailor, I've got two questions for you. You've probably heard that from the second to the fourth day on orbit there was a piece of debris that was separated from the Shuttle and that went on to reenter, we have some extensive analysis going on through testing at Wright Patterson Air Force Base right now, trying to determine the radar characteristics of it. Are there any type of predictive methods that you know of that might tell us, by the characteristics of its reentry, what type of material it was?

DR. AILOR: Certainly if we had information on the reentry itself, yes. On the rate of decay, the rate of decay from orbit would be indicative of the overall aerodynamic properties of the object and its weight. So that would be some useful information to have. If there's tracking data, for example, on the reentry itself, that can be used.

GEN. DEAL: Then a second question. I looked at your slide that said from a Saudi Arabia reentry back in 2001, analysis is still ongoing, which doesn't bode well for us to get back to our day jobs anytime soon – two years later. Can you tell us what we can expect to find through laboratory analysis of the debris in the short term?

DR. AILOR: In the short term, the critical thing, I think, is going to be to try to center the analysis on certain debris pieces that there's some reason to believe have high value. What I mean by that is if there's debris that can be determined by analysis to have come from a particular part of the vehicle itself, that's of interest. Then you should really focus on that. I think the initiating event is probably what is of interest here. So a lot of the final debris that is in the debris field will have happened well after the initiating event. So the search that's going on for early debris is really very intelligent and the right thing to do.

The other thing would be to look for the debris itself and see again if there's characteristics of the field that would indicate that debris in this area, for example, came from a portion of the Orbiter of interest. So I would really try to focus on that. Laboratory analysis? There's too much debris here to be doing that extensively. So it's going to have to be focused.

DR. WIDNALL: Why do things tumble in the atmosphere, and is there a possible diagnostic use of measurements that appear to show something tumbling?

DR. AILOR: Well, even in orbit, things can tumble. For example, as you come down from orbit, you know, there's still a little bit of atmosphere up there and so as you get into the portion where there's enough to actually affect the dynamics of an object and have that become a more principled player, it will gradually overpower the gravity gradient forces which are there and try to stabilize the spacecraft. That interaction then will cause an object to tumble.

As you come down through the atmosphere, the mass properties and aerodynamic properties of an object will also cause it to tumble. We certainly see that. As to whether or not things like tumble rate could be a factor? It certainly could be, but you'd have to know a fair amount about the aerodynamic properties, about the geometry and other properties of the object to be able to determine that, I think.

MR. HUBBARD: I'd like to pursue a little bit more the question of how we might be able to determine the initiating event and distinguish that from the processes that may have happened post breakup. In your experience, would you say that from directionality of, let's say, a deposition of molten materials or the way the surface had been worn away by heat, we could begin to separate the two? Would that be a fair characterization?

DR. AILOR: Certainly could be. For example, the Orbiter was controlled for a good period of time and if evidence is found that could have occurred during that period and it indicates that a particular flow pattern or something like that, I think that could be very useful. Absolutely. I think the early debris would be really critical to an analysis like that.

MR. HUBBARD: Even from debris on the ground, following the discussion of ballistic entry of a steel strut, if it's worn away sort of equivalently versus something that shows that's there's more deposition or thermal damage on one side or another, it might be a distinguishing characteristic?

DR. AILOR: It certainly could be.

ADM. GEHMAN: Sir, based on your analysis of previous satellite reentries – I don't want to put words in your mouth, but let me make sure I understand it – your suggestion there on kind of your first viewgraph was that the typical reentry, the process starts rather slowly and little things come off but then it reaches some catastrophic point where everything flies apart. I have got that right?

DR. AILOR: That's basically correct.

ADM. GEHMAN: And that is not an unusual scenario, doesn't indicate a design flaw or anything like, it's just that aerodynamics and heating of the things reach a point where it can't tolerate it?

DR. AILOR: Exactly. And basically when the disintegration process starts, it is typified by not a violent event exactly but you can call it a catastrophic event where the spacecraft really comes apart into a number of portions and then from that point on, an observer on the ground would essentially see a number of objects proceeding through the sky.

MR. TETRAULT: We've struggled, like everyone, with how do you separate out reentry heating from the event itself; and our plan is to really look hard at the differences between the right wing and the left wing. I would assume that you would agree that that's probably a good approach in trying to look at the differences between the two?

DR. AILOR: Yes, indeed, I would.

MR. WALLACE: In the civil aviation field where I usually work, we often have the challenge of differentiating damage that may have precipitated a failure event in the sky or damage that was sort of part of the failure sequence versus what was impact damage on the ground, often very critical distinctions to be made; and, of course, here we add in the thermal effects. What are your sort of thoughts on the basic methods you can use to sort those things out?

DR. AILOR: Well, as you say, the challenge here is going to be that the heating itself is going to have the potential of masking the heating and loads during the breakup process; and as an object comes down and continues to break up as it enters the atmosphere, it's going to have this tendency to mask the initiating event. That's going to be really the challenge here. That's why I think that the effort really needs to be focusing on the early debris and on, as you say, the differences. If there are scenarios that would cause differences in some of the debris, that would be very useful to know about. Thirdly, to focus on surviving objects which can be traced back to areas of interest by one fashion or another.

MR. WALLACE: Has there been anything generally in your observation of the *Columbia* debris distribution and recovery process that has sort of surprised you?

DR. AILOR: Well, I've been pleasantly surprised by the efforts that's been made to really recover the debris pieces and get specific information on those things – the weights, the latitude and longitudes of those. The amount of effort that's being put into it, I think, is not really characteristic of these kinds of events and may be very useful. So I would say I've been very pleasantly surprised by that.

ADM. GEHMAN: Dr. Ailor, the two most western pieces of debris that we've found both have been tiles, either a fragment of a tile or an individual tile, not connected to any metal or any structure. My understanding is you are suggesting, then, that a tile would have a relatively low ballistic coefficient –

DR. AILOR: Right.

ADM. GEHMAN: – and therefore the flight path is nearly vertical?

DR. AILOR: Well, certainly ultimately will be vertical, yes.

ADM. GEHMAN: What I mean is compared to something with a high ballistic coefficient.

DR. AILOR: Yes.

ADM. GEHMAN: Backtracking into space, then, it would be safe to assume that these things, these tiles came off relatively close to where they were found on the ground, compared to a dense object?

DR. AILOR: Yes. That's exactly right.

ADM. GEHMAN: The fact that in almost all the dense objects that we've found we've found a couple of hundred miles down range, what I'm trying to do is rationalize in my find the dichotomy between something with a low ballistic coefficient that comes off late versus something with a high ballistic coefficient that comes off early, because you could have them found in reverse places on the ground.

DR. AILOR: Well, a lot of that will depend on the timing of the release, too. If you've got something that's released at a very high altitude early in the reentry and it has a very low ballistic coefficient, as you said, that object will, in essence, stop very quickly and flutter to the ground. It's complicated by the fact that if it was simply a tile that came off, that's one thing; but if it was actually bringing something else with it, then there may be more going on there. That other piece of material would have probably increased the ballistic coefficient a little bit, which would make it blow a little further down.

As you saw from the footprint chart that I gave where it had the multiple footprints there, the altitude and what the trajectory looks like as it begins to heal over there will really affect how things fly; but there can be low ballistic coefficient pieces that are released all through that process. So some will be carried further because they're attached to heavier debris. Some will be released and then flutter to the ground. So as you move forward in time, the footprint becomes much more complicated.

ADM. GEHMAN: Another question. You mentioned the inability of aluminum to survive reentry for one reason or another. It either burns up, melts, oxidizes, vaporizes. What is your experience with rubber? We have found five of the six tires, and maybe a fraction of the sixth. We have found five of the six tires, two or three of which actually look like tires.

DR. AILOR: Well, in the first place, I've never seen a spacecraft come down with rubber on it before.

ADM. GEHMAN: You've probably never seen one with wheels either?

DR. AILOR: No, never.

ADM. GEHMAN: You've never seen rubber in the debris?

DR. AILOR: I haven't. I'm sure someone could take a look and basically say if rubber experienced heating of this type, how would it be expected to respond. Some materials can be protected by the fact that they actually shed away external layers, for example, ablative materials that are used on the spacecraft reentries typically. So it may have properties that would enable it to survive of that type.

ADM. GEHMAN: Very good. This debris field that we have here I think you're familiar with. We're talking about just west of Dallas to just over the Louisiana border, which is about 375 miles or something like that. Are you surprised it's that small or that big, considering that, I guess, the first shedding event that we know about was at about 225,000 feet – actually we're going to find that out here in another 20 minutes or so. Right. You had a viewgraph up there that indicated in one of these reentry things it was spread over 400 miles. What do you conclude from this one?

DR. AILOR: That footprint I was talking about was from the little piece that actually brushed the lady on the shoulder. Very low ballistic coefficient piece, probably less than 1 – so it was something that, in fact, did flutter down – to the fairly large objects which were ballistic coefficients up to around 50, 60, something like that. So those are a reasonable range of ballistic coefficients.

The size of the footprint here is about what you would expect to see, I think.

MR. WALLACE: You were very complimentary of the amount of shoe leather that's gone into this recovery. Do you expect that any further major breakthroughs or strokes of luck are more a matter of shoe leather, or are there calculation methods you think might be further explored, backtracking pieces you have found?

DR. AILOR: Well, there's a couple of things. First, I think the work that's going on relative to finding the debris is really an important part; and that has to be emphasized. That's going to be key to solving this puzzle, I believe. The second part would be to look at the debris field itself, but you have to have collected debris in that field. So this idea of going out and finding these things, I imagine that pieces will continue to be found over a period of time and they need to be cataloged and brought in and examined just as they are being now. But to really look for anything that's related to, as I've mentioned before, possible scenarios – for example, the right-wing-versus-left-wing scenario and those kinds of things. So I think that's the way it should go.

MR. HUBBARD: One last question for me at least. Looking at your observations and summary, you bring up the concept of data fusion here. I wonder if you could elaborate on that a little bit. What do you really mean there?

DR. AILOR: Well, basically the data fusion means that, for example, where we have videos that have been taken by private citizens, taking those videos, processing those things, we know the Orbiter's trajectory very well during portions of reentry, in a sense, fusing that data so you take the video data, you marry it with the trajectory data so you know exactly what you're looking at. You can use that information to help derive information about, what objects are shed, where are these objects, what the timing is, what are the characteristics of those objects, things like that. We talked about ballistic coefficient; but you can estimate, based on how fast something separates from the Orbiter in a video, what the characteristics of that object are. So that's what I mean by fusion, just taking all of the existing data and bringing it all together so that you actually have a complete picture, as good as you can do with the data you've got, of what actually happened.

MR. HUBBARD: Would you include thermodynamic analysis, you know, reentry heating in addition to these actual empirical observations?

DR. AILOR: Yes, I think that's true; but the fusing I'm talking about really is more of a trajectory level, if you see what I mean. There's certainly other data. The data on the ground, for example, needs to be brought into this, as well, and should be. So it's really a question of fusing the various data. I come out of the trajectory side of the house. So looking at data from where things happened in the trajectory, tracking them down, trying to derive information on the ground, and then really developing a best estimate of what actually happened is what I'm speaking of.

ADM. GEHMAN: That leads to my last question – that is, if you would, make a value judgment for us on the accuracy and efficacy of this reverse trajectory analysis. In other words, if you find something on the ground, how much effort and what value should be placed on trying to predict the point in the sky that this thing became an independent object? If you would, take a shot at that.

DR. AILOR: That is going to be a real tough problem, quite frankly.

ADM. GEHMAN: You mean because it's just not an accurate process?

DR. AILOR: It's not an accurate process. As I mentioned in my opening remarks, we don't have internal information from a spacecraft that's breaking up as to what exactly is happening with it. So modeling it down and doing computer models of the reentry and breakup of a spacecraft, we recognize that there's uncertainty in there. The problem with taking debris on the ground and transferring it back up is you don't really know how it got here. There will be debris on the ground that will be surprising, very lightweight things, things that in a sense could burn very easily but may have actually survived and impacted the ground. Those objects we know were shielded, because they wouldn't have gotten there otherwise; but where it was originally in the vehicle and then the scenario that it followed for shedding the various layers of material and the changes in the aerodynamic and mass properties of that host object as it came through the atmosphere is going to be a very tough thing to derive. That's why I think that really a key here is to look at the early debris as closely as you can to really try to determine what really happened prior to a lot of that breakup process going on.

ADM. GEHMAN: Of course, it's probably a variable – once again, I don't want to put words in your mouth. For example, if you were to tell me the ballistic coefficient of a sphere, a fuel sphere, I bet you could pin that ballistic coefficient pretty well; but if it was a piece of debris or a jagged-edged thing that was part tile, part metal, part strut, part bar, the ballistic coefficient might be a pretty big estimate?

DR. AILOR: Yes. In fact, again, the ballistic coefficient of what you actually find on the ground was different at say, 75,000 feet or 100,000 feet or 120,000 feet. So the higher up you get, the bigger the changes, if you're talking about going backwards in time. So what you find on the ground is one thing, but trying to translate that back up and say, okay, well, we know it fractured off of something, what was that? We don't quite know what that was.

DR. WIDNALL: From a forensic point of view, what are some of the most interesting observations that you can imagine making on the debris? The second part of that is does Aerospace Corporation have any metallurgic capabilities to help us analyze some of the observations we make on this debris?

DR. AILOR: We do have, and we have analyzed some of the debris in the past. So we have some experience in doing this work. The kinds of things that, again, will be important to look for here are opportunities, if you want to call them that, for preserving some of the original events. That could be where material is found, either heat shield material or something like that is found from areas where it likely came off and protected some evidence of the original events, that would be really critical. So I think it's going to be a question of looking for objects on the ground where it's likely that some of the original evidence from the original burning or fragmentation would be preserved, perhaps behind the wing leading edge or behind tiles, those kinds of things.

ADM. GEHMAN: Thank you very much. Would you like to have the last word? Any advice for us on how to solve this riddle?

DR. AILOR: No. It's certainly a tough problem, but I think the advantage here is that there's been so much interest by the public in actually helping to gather debris pieces. I think that's really to be complimented. We typically don't see that kind of interest, and those debris pieces can really be essential in helping solve this puzzle. So I think that's really been valuable.

ADM. GEHMAN: Thank you. On behalf of the Board, we thank you for your appearance here today and for summarizing what I know is a deeper and more exhaustive study of the reentry physics and aerodynamics. We appreciate your effort and want you to know that we've learned from you and we'll see if we can't solve this riddle with your help. Thank you very much.

The Board will take about a five-minute break.

(Recess taken)

ADM. GEHMAN: All right. Board, we're privileged to have two people who have been studying this tragedy since the first day and know more about it than most other people. Mr. Paul Hill and Mr. Doug White.

Gentlemen, before we start, we don't swear witnesses in but we do ask them to affirm that they're going to tell the truth and the whole truth. So I will read a statement of affirmation to you and ask you, if you agree with it, just say you will. So before we begin, let me first ask you to affirm that the information you provide to this Board today will be accurate and complete to the best of your current knowledge and belief.

MR. HILL: I will.

MR. WHITE: Yes, I will.

ADM. GEHMAN: Gentlemen, we know you, but for the record we would like you to introduce yourself and say a few words about where you work and what your background is and then we would be delighted to listen to as much of an opening statement as you would like.

PAUL HILL and DOUG WHITE testified as follows:

MR. HILL: My name is Paul Hill, and I work in Missions Operations Directorate here on the Space Shuttle. I'm a Space Station Flight Director. I've been a flight director for about seven years.

ADM. GEHMAN: And you are currently – what are you doing for the MRT?

MR. HILL: For the MRT I run a team that's called the early sightings assessment team. After Doug talks about the time line, I'll go into great detail about what we do and how we do it. The short answer is we're trying to make some sense out of the public imagery and any external sensor data that we can get our hands on to tell us what was happening to us as early in reentry as possible and maybe shed as much engineering information as possible on what was going on with the vehicle before we knew what was happening on the ground.

MR. WHITE: My name is Doug White. I'm a director of operations requirements for United Space Alliance. In my job I'm responsible for turnaround test requirements at the Cape. I'm also responsible for anomaly resolution. I'm also responsible for the engineering support during missions. I do have the time line to talk about today. As far as what I'm doing on the mission response team, I am on the team which we call the technical integration team. Basically our job is, from a management perspective, to try to pull together all the different efforts of the different teams, the aero, the thermal, the scenario teams, and try to make sense out of all the data from all the teams and then try to bring a coherent story together.

ADM. GEHMAN: Thank you very much. Which one of you is going to go first?

MR. WHITE: I think I'll go first. I plan to walk everyone through the time line. If you go to page 3 of my briefing, please.

On page 3, this is a graphic showing the sensors that we're most interested in in the left wing. This particular chart shows the sensors in the left wing. There are a number of sensors in the wheel well that we are interested in that we got data from that behaved in an off-nominal way. There are also temperature sensors out in the wing, some of which went off line, which was off-nominal, and some of which did stay on line, which also tells us things that were not affected.

The different colored wires that you see represent the wiring runs for those particular sensors. The pink one is for sensors that were aft in the wing and runs forward past the wheel well and then ultimately into the mid body where some sidewall temperature sensors, one of which has a yellow line coming from it, that indicates the wire run for that particular sensor which was inside the mid body. There's also a green and a gray wire run you see in the back there that goes through a connector box and into the aft. The green wire run is for sensor data from those particular sensors indicated by green dots. Then the gray wire run is for a power cable. It's a little bit different than the sensor wires. This provided power to the actuators and came from a box there which is labeled ASSA4. That stands for air surface servo amplifier. That basically provides electrical power and commanding to the actuators for the elevons on the back of the wing.

ADM. GEHMAN: Doug, before we leave that, pardon me for interrupting. To what degree is that a cartoon and to what degree is that a fairly accurate representation of where the cables actually run?

MR. WHITE: It's kind of in between a cartoon and fairly accurate. For example, the pink wire does run exactly alongside the wheel well and does turn and go in front of the wheel well and does run to a connector right forward of the wheel well, as is indicated there. So those are approximate locations of where those wire runs. Now, in the back there we see the green and gray and pink all together. Those wires may actually be separated in space by 1 or 2 or 3 feet. This is looking down on the wing, and so you can't see the actual vertical separation between these wire runs. Just because they happen to show up on top of each other in the picture doesn't necessarily mean that they're bundled together within the vehicle.

ADM. GEHMAN: What's the little insert box?

MR. WHITE: I'm sorry, I forgot to mention that. That little insert is for some sensors that were forward on the Orbiter. These are temperature sensors on a supply water dump nozzle, which is a nozzle used to dump excess water overboard. Right below that is a temperature sensors for the waste water dump nozzle, again used to dump waster water overboard. Then there's another one forward which is called the vacuum vent dump nozzle. Those sensors also gave us some off-nominal readings. Since they were too far forward to show in this scale, we just put them in as a little inset.

MR. WALLACE: Just to follow on Admiral Gehman's first question, are the Orbiters different? Are there variances in the actual location of the wires in the Orbiters?

MR. WHITE: There maybe slight differences between 102 since it was the first one built. 102 had a lot of wiring which was called development flight instrumentation, a lot of wiring for that. During its most recent major modification period, we removed a lot of that wiring. Some of it we just left in place. So the wiring on 102 was substantially different in the DFI aspect. But for the sensor wiring, it was pretty much the same –

ADM. GEHMAN: DFI? Developmental flight instrumentation?

MR. WHITE: Yes. DFI, developmental flight instrumentation.

ADM. GEHMAN: I'm the acronym police here.

MR. TETRAULT: Let me continue with the wire questioning. We do know that there were actually four cable runs running back aft that went around the wheel well compartment, one on top of the other. Are all of those sensors that you show going off in one those runs or in all of those runs or some portion in each of those runs?

MR. WHITE: All of the ones in the pink are all within one particular cable. We don't have the specifics about whether or not, for a particular part of run, any one of the wires was like at the back of that bundle or on the top of that bundle. There are also more –

MR. TETRAULT: The question is: As I look inside the Shuttle wheel well door and look up, there were four wire bundles that run aft?

MR. WHITE: Right. All of the ones in the pink wire are in a single bundle.

MR. TETRAULT: Okay. Are the red ones in that same bundle, the ones that went off in the aft end?

MR. WHITE: Yes, all of the ones that went off in the aft.

MR. TETRAULT: So everything that went off are in one single bundle?

MR. WHITE: Yes. There are also many other wires, though, in that bundle for which we do not have data.

MR. TETRAULT: Understood. Do we know if that's the top bundle or the middle bundle or the lower bundle?

MR. WHITE: If I remember the picture right, it's the upper one.

ADM. GEHMAN: But we'll find that out.

MR. WHITE: Yeah. And I can give you the more exact answer. I'm just trying to remember it off the top of my head now.

ADM. GEHMAN: We'll go back to the blueprints. Okay. Please continue. Thank you.

MR. WHITE: All right. Next slide, please. This particular time is about 7 1/2 minutes before loss of signal, at a GMT of 13:52, and all of our sensors appeared nominal.

Next slide, please. Now, this slide we didn't show any sensors going off line but we put this in the time line. This particular time 13:52:05 is the first indication that we had some off nominal from an aerodynamic standpoint. We were able to derive aerodynamic coefficients in yaw and roll which showed us that we were flying differently than we expected to. You're going to hear a lot more about that tomorrow, but basically the way we have done that is to look at the way we should have been flying, look at the way we actually were flying, and take the difference between the two and come out with some moments on the vehicle both in the yaw and the roll. This particular off-nominal event, it started first in the yaw component. We are seeing a different yaw here at this point in time than we expected to see.

Next slide, please. This is our first sensor that we saw with a small rise, and I want to stress that this was a very small –

ADM. GEHMAN: Excuse me for interrupting again. If it's okay with you, we'll talk about these things while you have them up.

MR. WHITE: All right. That's fine.

ADM. GEHMAN: This off-nominal measurement we will talk about tomorrow when we talk about aerodynamics and thermodynamics. I want to get to the level of detail that and your team have been going through. You didn't realize this until about Rev 12 or Rev 10. Can you tell me when this became apparent?

DR. AILOR: Well, fairly early on, the aerodynamic guys knew that we had differences in the flight control from what we would have normally seen. They looked at the aileron, and the aileron was behaving differently and continued to behave differently throughout the entry. It took a while before we could back out that particular moment in time that we just went through there was the very first indication that this derived yaw delta was first affecting us at that point in time, but fairly early on we were able to see some of the larger flight control responses that were off nominal to us.

ADM. GEHMAN: I could look it up here, but you may be able to tell me. We are approximately what altitude and what speed here?

MR. WHITE: I don't have those numbers. There are versions of this that do have all those numbers on there. I guess I could look it up, too. I have some notes here.

ADM. GEHMAN: But we're approximately 235,000 feet.

MR. WHITE: That's about right.

ADM. GEHMAN: Okay. Please go forward.

MR. WHITE: All right. This is the first sensor that went off line. This is a left main gear brake line, Temperature D. It began a very slow rise. We call it a bit flip, which is essentially one bit in the data stream showed that it was rising. And we believe this is the first indication that there was an off-nominal event and something was going on with the Orbiter inside that was causing that measurement to rise.

Going on to the next page, these are the supply water dump nozzles A and B that I talked about. There are three nozzles to the forward there – the supply water dump; the vacuum vent dump, which is the very forward one; and the waste water dump, which is actually below the supply water dump. These nozzle temperatures A and B both began an off-nominal rise rate. If you look at the graphs, you'll see a very small knee in the graph where the two sensors are rising at a particular rate and then there's a bend where they start rising at a faster rate. This continues for about 15 seconds or so and then it bends back over and starts rising at the same rate that it had been before, at the nominal rate.

MR. WALLACE: This picture doesn't tell you where that is, does it?

MR. WHITE: Well, again, that's why it was an inset. They're very far forward on the Orbiter, just right at the beginning of the wing. That little diagonal you see there is the very beginning of the wing chine, and they're just aft of the crew module portion of the vehicle. They're on the side wall. We're just showing them on the top for visibility. They're actually both on the side wall, just above the wing.

MR. HUBBARD: Now, this anomaly is in a completely different place – as you say, well forward. Is there anything that would lead you to believe that this is, in fact, a sensor malfunction, you know, something wrong with the box, the electronics box?

MR. WHITE: It does not appear to be. We don't know of failure scenario that would explain this as a sensor malfunction. We think it is real data showing us there was a change. Now, whether or not the change that caused these temperatures to rise is related to what ultimately caused our tragedy, we don't know. They may be connected, they may not. So we're including this in our data, and we'll continue to look at it until we can explain it.

MR. HUBBARD: So you're including that, this is real data, from everything that you know?

MR. WHITE: Yes.

DR. WIDNALL: How anomalous was this anomaly? Have you looked at early Shuttle flights to see if you had similar events?

MR. WHITE: For this particular measurement, we did look at every single mission; and every single mission, these vent nozzle temperatures rise at a very straight, steady rate. So this is an anomaly in that the rate changed; but it was a very short duration, about 15 seconds or so. They were rising at a higher rate; and after that, they went back to their same nominal rate. So whatever caused them to rise at this higher rate was a transient, at least locally transient event.

ADM. GEHMAN: I'm just stating the obvious here. Obviously this is pre-video here. We're out over the ocean?

MR. WHITE: Right. This is out over the ocean. If you notice in the lower left, there's a ground track trying to show approximately where we were with regards to the ground tracking. We're still well off the coast.

ADM. GEHMAN: So if something was going on, we have no video of it.

MR. WHITE: Right.

MR. HILL: We are within a few minutes of having our first video when we see this.

MR. WHITE: All right. If you go on to the next slide. This is the vacuum vent, just a few seconds later. It began its rise as well.

Next slide. Now we're back into the wheel well. This is the left main gear brake line temperature A. This is down on the strut for the landing gear, and it began a very slow rise. Again, all of temperatures in the wheel well first exhibit a very slow rise rate. It wasn't until about two minutes from now in the time line that they began a much more rapid rise rate.

ADM. GEHMAN: We're both trying to do the same thing here. We're trying to characterize the heat in the wheel well.

MR. WHITE: Yes.

ADM. GEHMAN: Can you describe to me exactly where the sensor is? Is it inside a block that's measuring the hydraulic fluid temperature, or is it up against the block where the sensor is out?

MR. WHITE: This particular one is on the hydraulic line that's on the strut. So it does have some exposure, fairly good exposure to the atmosphere in the wheel well.

ADM. GEHMAN: So it's not buried inside a great big block or something?

MR. WHITE: That particular one is not; but, you know, there is a heat sink of the actual strut itself. That provides some heat sink. Some of the temp sensors down in the wheel, you have the heat sink of the wheel itself. Many of the temp sensors that you see lined up four in a row that are on the side wall, some of those are actually under epoxy covers and so would not have a good exposure to radiation or convected heating.

ADM. GEHMAN: But this particular one?

MR. WHITE: This particular one would have a fairly good exposure.

ADM. GEHMAN: Thank you.

MR. WHITE: Next slide, please. This is back on the side wall. Again, this is the left main gear brake line temp C. Again, beginning a very slow rise.

Next slide, please. All right. Now we start to see things going on in the wing and we believe this is directly related to some sort of burning or disintegration of that pink wire run that's affecting these sensors. The reason we believe that is because some of the other sensors nearby them don't show any effects and these sensor do start to show effects. So we think it's happening away from where those sensors are.

It's showing not completely colored in. It's off line. These sensors, we've done some testing that when you burn through the wire, you end up with a variable shorting, a variable resistance in the wire and you start to see the sensor kind of trail-off in time. It doesn't immediately just go off to its off-scale low reading. So this particular sensor at this time began to trend down.

Next slide, please. Then a few seconds later that sensor was completely off line.

Next slide, please. All right. Here's another indication that we put in the time line of another off-nominal aero event. This is the first clear indication. We mentioned before that we had the derived yaw moment showing us we're off nominal. At this point we began to have an off-nominal roll component to the aerodynamics.

Next slide, please. Again, this is another sensor in the wing which began to trend down. This is the hydraulic System 1 left inboard elevon actuator return line temperature, and it began its movement downwards.

Next slide, please. Hydraulic System 3 on the left outboard elevon –

MR. HUBBARD: Just clarification as we go here. The ones that you feel fairly certain are showing the actual wire damage, have you been able to back up and reconstruct in the wire bundle what was where?

MR. WHITE: No, that's one of the things that we don't know. The drawings are not specific enough to allow you to reconstruct which wire might have been on the outside of the bundle, if you will, and which wire might have been farther back in the bundle, which wire might have been right in the center. We don't have that level of detail to know what the placement of each single wire was within its larger bundle.

MR. HUBBARD: Is there a hope of reconstructing that from closeout photos or as-built drawings or anything or is that pretty much –

MR. WHITE: No, we will not be able to reconstruct that.

ADM. GEHMAN: Are the wire bundles themselves encapsulated or covered other than the individual wires being covered?

MR. WHITE: Individual wires, sometimes you have like twisted shielded pairs and you have shielding around those; but then once you make a larger wire bundle, no, the wires themselves are not covered with any kind of insulation. We do, for a lot of our wire runs, put convoluted tubing around, that black crenelated tubing that provides some impact resistance for people working around the wire. That's made out of a Teflon-like material and provides some impact resistance, but it wasn't designed to provide any kind of a thermal barrier or anything like that.

ADM. TURCOTTE: As you're talking about all the wire here, all of this wire that you are talking about is all Kapton wire. Is that correct?

MR. WHITE: Yes. This is all Kapton-covered wire. Yes.

All right. We'll go to the next slide. This is the hydraulic System 3 left outboard elevon actuator and return line temp that actually finally went off line. As I said, it had begun its little – it takes a few seconds for these things to go down. Some of the ones that I'll show you a little bit later actually took quite a while to go off line, which indicates to us that maybe they were shorting or that part of the wire was burning through more slowly at that point.

Next slide, please. This is back to the system 1 on the inboard. That one has now gone off line.

Next one. This is hydraulic System 1 on the left outboard. That particular sensor is now gone off line. Again, as I said before, the reason we believe that the damage is occurring away from the actual location of the sensor is because you see that green dot right next to it and that particular sensor was not reading anything off nominal at that particular time. So whatever was causing the damage was happening somewhere else.

Next slide, please. This is back to Hydraulic System 2 left inboard elevon actuator. Return line temperature again started its slow change to going off line.

Next slide, please. Now we'll go back forward, and you notice that our supply water dump nozzles have now come back to their nominal rise rates. So whatever effect was going up front is now not there anymore and the supply water dump temperatures are back to their – they're still increasing. That's nominal, the way they've been for every other flight.

Next slide, please. Then also the vacuum vent nozzle also at the same time went back to nominal. You can see at this point we're just now crossing the California coast and just about to pick up video, which Paul will talk to you about in a moment.

ADM. GEHMAN: Doug, the sensors back by the elevons, all of them back there – I've got the same thing in front of me that you have. For the people in the audience, there's a time line, this little sliding scale across the top of the viewgraph.

MR. WHITE: Right.

ADM. GEHMAN: The first sensor. I'm talking about just the sensors that dropped off scale low. The first one is 52:56, and then the one just before this you've said was 53:35. So essentially that scenario that you just went through with these five sensors, that happened in 40 seconds. By my arithmetic it took about 40 seconds, that little scenario you just went through. If we assume that you're right that the insulation of the wires were melted and they shorted to each other or shorted to ground or opened – and by the way you should be able to tell us that, right?

MR. WHITE: Well, again, we have done testing so far to where we took – we're planning on doing more tests to get a more representative case, but we took a wire bundle, we attached sensors to the end of it, we put a torch on it, and we looked at the characteristics of the sensors going off line, and they do look similar to what we saw in the vehicle. We do see them begin to do a slow decline, and then they eventually go off scale low.

ADM. GEHMAN: So just for my mental picture, then this little scenario of whatever happened in that wire bundle took about 40 seconds, according to my arithmetic.

MR. WHITE: Yes.

ADM. TURCOTTE: Before we continue, could you explain the physical – I guess the void that is the wing, is it possible, for example, for air to flow freely in there? Is it a sealed compartment? Could you explain that as you're looking at the sensors – in particular, the relationship?

MR. WHITE: Let me see if I can explain a little bit. If you see the panels all along the edge there of the wing, those are the reinforced carbon-carbon panels or RCC panels. Behind them is an aluminum spar that runs all the way down the length of the wing. You see the vertical lines. Those are solid aluminum spars with some cutouts through them that would allow a vent passage, if you will. There's one main vent passage pretty much where the pink wire runs, which is how you get through those spars. The horizontal lines are representative of rows of boron aluminum rib struts which are basically tubes that are there for reinforcing the structure of the wing. So that area from up and down on the slide here would be all open; but in each one of the spars, which are those vertical lines, you're closed out except for some small openings.

ADM. GEHMAN: And the wheel well?

MR. WHITE: The wheel well is completely enclosed from the rest of the wing. There is a hole in the very front of the wheel well that's about 5 inches in diameter which would allow some flow into there. There are some other drain holes and some small openings around some of the hinge covers which would allow a very small amount of flow out. The square area of the hole into the wheel well in the front is about 19 square inches. The remaining holes altogether total less than 1 square inch.

ADM. GEHMAN: So the forward bulkhead of the wheel well, there's a hole with a screen –

MR. WHITE: Yes, it does have a screen on it.

ADM. GEHMAN: – which allows kind of free communication into this what we call the glove area.

MR. WHITE: That is correct. Yes.

ADM. TURCOTTE: So it's safe to say that an air molecule, once inside the wing, is pretty much free to flow around the inside of the wing?

MR. WHITE: Through the vent passages. Right. Also there's another hole between the wing glove area and the mid body that's forward, about where that yellow arrow is. There's another hole in the mid body there which is rather large. That particular hole is about 146 square inches.

DR. WIDNALL: What is the material that the wheel well structure is made out of?

DR. AILOR: It's made out of aluminum honeycomb.

DR. WIDNALL: How thick is it?

DR. AILOR: I do not know that thickness. We can get that for you.

DR. WIDNALL: Okay. But it's basically a thin piece of the honeycomb and another piece?

MR. WHITE: Right. A thin face sheet, some honeycomb material, and another face sheet.

Next slide, please. All right. We've annotated the debris events. We are over California now and we'll see in the videos from the public that we were starting to see debris being shed from the Orbiter. This is the first one that we've seen in any of the videos that have been provided to us. So we call it Debris No. 1. The timing on that is plus or minus 2 seconds, which is about the best we can resolve from the video.

Next slide, please. Debris No. 2.

Next slide. Debris No. 3. Coming off relatively rapidly.

Next slide, please. You notice with the little time hack up at the top there, we're starting to put triangles below the line for the debris events. The diamonds along the line there are for the off-nominal sensor readings, and then the two triangles on the top of the line are for the aerodynamic readings. That's how you read that little graph up at the top.

Next slide. This is the fifth debris.

Next slide. Okay. Now, we start to see another temperature rise in the wheel well. This is again also on the strut. Also should have some fairly good communication with the flow of whatever is happening in there. This is left main gear brake line Temperature B.

MR. TETRAULT: Can I ask a question about that? This one is probably the most confusing sensor to me personally. Line Temperature A went off – and I notice that you appear to have changed the timing on this a little bit – went off at about a minute sooner than this. Line Temperature A and B are about – the sensors are about 2 inches apart.

MR. WHITE: That's correct.

MR. TETRAULT: At the same time, you have D and C which have gone, which have significantly gone off already early, significantly separated both in the X, Y, and Z dimensions, which would tend to suggest that the entire wheel well compartment is warm. Why do you see this big, huge time lapse between A and B, which are separated by 2 inches? Is there any explanation that you all have come up with, or at least theory on why there is this big separation in time?

MR. WHITE: Right now we do not know of a good theory that holds together that says why one would show the rise and not the other. At about this time now, the rises are starting to become significant. So we don't have a good theory. It may be the amount of heat sink, the way it was attached to the strut itself that provided some more resistance to temperature rise. We really don't have a good theory right now for why one 2 inches away would rise earlier than another one.

MR. TETRAULT: It's significant in terms of the time. A minute in this entire time frame is a virtual eternity.

MR. WHITE: Yes. One possible explanation that we've been kicking around is the fact that whatever the event is that is causing heating in the wheel well might not be constant in the sense that it's continuing to direct flow into the wheel well. Perhaps we were directing flow in at one point in time and through the dynamics of the vehicle through the evolving change in the damage to the vehicle that the flow was redirected to some other part of the wing for a time and then came back.

MR. TETRAULT: You're talking about the equivalent of a run-away fire hose kind of thing.

MR. WHITE: Something like that. I wouldn't describe it quite that way; but, yeah, something like that where if you had some sort of a plume heating into the wing that maybe it was pointing one direction first and then another and then back again.

DR. WIDNALL: Given the extensive damage that has already occurred to the vehicle at this early time, I guess I'd question the use of the word "early debris." I guess from my point of view I would call them mid debris. I mean it's clear to me from the time line that things must have fallen off in the ocean well before California. And we don't know obviously.

MR. WHITE: Right. We don't have any evidence of that. These are the first debris events that we see. So we just started at 1.

DR. WIDNALL: But at this point you've already got some kind of hole in the vehicle, you've got a wire bundle that's either completely burned through or burning through, you've started to pick up what I interpret as flow inside the wing. So clearly some structural damage has already taken place, by whatever mechanism.

MR. WHITE: Right. We do believe that we had structural damage somehow at this point in time that was allowing flow into the wing. Whether or not we had shed any debris out over the ocean earlier, we can't say one way or the other. It would be speculation.

MR. HILL: We call them early debris to distinguish them from the actual spacecraft breakup over Texas.

DR. WIDNALL: I understand that.

ADM. GEHMAN: Doug, in your machine here, you don't have the sister viewgraph?

MR. WHITE: I do, but they told me they could only project one at once. If you want to see the other one – you're talking about for the vertical elevations between these?

ADM. GEHMAN: Right. If you could do one of them. I don't know if you could do the companion to this one or not.

MR. WHITE: Well, if they want to go ahead and bring it up, it's called Part 2.

ADM. GEHMAN: Well, okay. Let's not do that.

MR. WHITE: Okay. We could do that. I think they only have the capability to show one at once, though.

All right. Let's go on to the next slide. All right. You asked about how early we were able to see things. The start of the slow aileron trim change – again, I put the triangle up on top of the line there – this was one of the early aerodynamic things that we noticed. The two events that we talked about earlier took some time for us to back out and reconstruct.

From examining the data shortly after the accident, this was one of the things that we noted pretty early in the data. So this is another aerodynamic event that's off nominal. We started to see a slow trim change in the aileron.

In the Orbiter there is no real physical aileron like you might have in an airplane. The aileron is a theoretical difference between the elevon position on one side of the vehicle and the elevon position on the other side of the vehicle. So by adjusting the relative different positions between those, you can create the aileron effect. So that aileron effect was keeping the vehicle flying the way we wanted it to. So as the forces began to change on the vehicle, the trim changed; and we saw that in the data.

MR. HUBBARD: Doug, I just want to check and see that we're working from the same time line here. What I've got is what's called Rev 15.

MR. WHITE: Yes. This should be Rev 15.

MR. HUBBARD: Now, you skipped past what are labeled "Unexpected Com Dropouts." Is that because they are not part of the temperature sensor story?

MR. WHITE: When I was coming here today and preparing for this, it was a question to myself whether I should brief from the time line that has every single event in it or I should brief from this more graphical presentation which did leave some of the events out. This particular graphical presentation does not have every single event like some of the com dropouts. To this point we've already had numerous com dropouts that we consider anomalous. We just did not model those in this particular graphical presentation.

MR. HUBBARD: So I guess the follow-up question to that is: Where are the avionics boxes or the antennas or whatever associated with those and can you make any connection between this set of anomalies and the com dropouts?

MR. WHITE: Well, we are trying to do that. We are trying to create an entire picture where we can explain events that would affect everything that we see. So com dropouts would be one of the things that we would try to explain. As for the location of the actual avionics boxes, they're in the avionics bays which are forward in the crew module; and the antennas are in the crew module region, on the top and the bottom of the vehicle both.

MR. HUBBARD: So this is work in process.

MR. WHITE: So they're well forward of this area where we're seeing the heating, but that's not to say whether or not some disturbance in the hot gas flow around the vehicle may or may not create a situation that would cause the com to drop out. We were at fairly good look angles between us and the satellite. So we should have had good communication in this region. We have looked at past flights. So we did have good communication in these regions. So again, that's why we consider some of these com dropouts as anomalous events.

MR. TETRAULT: Have you seen any relationship to the com dropout and the debris event?

MR. WHITE: I'd have to look at the timing that says how close one was to the other, but I don't believe we have been able to link any of those very closely.

MR. HILL: There are debris events that are within seconds of some of the com dropouts. That doesn't necessarily tell you they're related, but there are debris shedding events in this same time frame.

MR. HUBBARD: Okay. So the set of charts here, Rev 15, just looking quickly through those since you're not going to cover these, I see up through Com Event 14. How many of those are there?

MR. WHITE: Well, let's see here. Let me get my other version of the time line. We had at 13:52:09 through 13:52 – well, let's back up. 13:50:00 through 13:50:43, we had five periods of com dropout from one to six seconds each. 13:52:09 through 13:52:55, there were four periods – again from one to six seconds each. That would cover Events 6 through 9. Then again, 13:53:32 through 13:54:22, which would be right in this period here, there were two more periods. One was two seconds. One was 8 seconds. Those would be Com Events 10 and 11. There are some more events, 12 and 13, that are down in the 55, 56 time frame; and Com Event 14 was down at 13:56:55.

MR. HUBBARD: Okay. So can we expect to see some point in the near future a composite plot or a plot like this that shows the antenna wire, the antenna, where the avionics is and so forth and kind of be able to put it together?

MR. WHITE: Well, the scale – we could probably do on a separate page just because of the scale. Yes, we could go ahead and do some kind of a graphical representation of that. Again, we don't see anything anomalous in the behavior of the com system other than com wasn't getting through to the ground. So there may not have been anything physical going on within the Orbiter itself at that location on the vehicle itself.

MR. HUBBARD: It could have been some interference between the Orbiter and receiving stations?

MR. WHITE: Yes, it could have been, again, as I said, some kind of disturbance in the hot gas around the vehicle at that time possibly.

MR. HUBBARD: Okay. Thank you. We'll, I'm sure, be pursuing this further.

GEN. DEAL: I'd like to bring up a question about Dr. Widnall's statement about perhaps earlier debris that was not witnessed. Can you kind of put it in context, when we saw heat onset and also the beginning of peak heating?

MR. WHITE: Let's see here. Let me look at my really detailed time line and the event times for that. The beginning of entry interface, which is about 400,000 feet, is 13:44:09. The start of peak heating is at –

DR. WIDNALL: 50.

MR. WHITE: 50. Okay. Thank you.

GEN. DEAL: The reason I ask that is to underscore her statement. There could have been things that weren't witnessed because you are starting to experience heat before we started seeing –

MR. WHITE: Right. There could have been.

DR. WIDNALL: About the com. I'm very interested in the com. Is that anomalous for the whole range of Shuttle missions, this loss of com?

MR. WHITE: Yes. For this particular period, we have called these losses of com "anomalous events." We've compared them to other flights of *Columbia* on similar trajectories and we believe we should – again, because of the look angles and where we were, we believe we should have had good com in this period.

DR. WIDNALL: So it wasn't just a simple matter of shielding by the vehicle of some antenna? You've already dismissed that possibility?

MR. WHITE: Yes. We've looked at that, and we truly believe there is something anomalous going on here. Now, what it was and how to describe the effect, we're not sure how to do that yet. We're still working on it; but, yes, we do believe that the com dropouts in this period were anomalous.

ADM. TURCOTTE: This is one of the first aerodynamic events that you've indicated here and I'm guessing you're interpolating here roughly we're in the 220s, probably lower Mach 20s. What kind of aerodynamic pressure is the air foil experiencing at this point?

MR. WHITE: Again, I don't have those numbers in front of me. There are versions of this that have –

DR. WIDNALL: Fifty.

MR. WHITE: Thank you. I was going to go look that up in my notes.

ADM. TURCOTTE: If you were to put that in layman's terms, we're looking at, say, around 120 knots or something like that –

ADM. GEHMAN: Less. The QBAR was 29 PSF.

MR. WHITE: Okay. That's pounds per square foot.

ADM. TURCOTTE: Probably roughly 80 knots, something like that.

ADM. GEHMAN: And the Mach is 22.7. So you used PSF?

MR. WHITE: Yeah. QBAR is in pounds per square foot.

ADM. GEHMAN: Yeah, I know that. When you're doing conversion to knots, you use PSF? So something like 75 or 80 knots air speed, something like that.

MR. WHITE: Okay.

ADM. GEHMAN: And we are in a stagnation temperature now of 2850.

MR. WHITE: Yes.

ADM. GEHMAN: So we're peak heating.

MR. WHITE: Yes. Very high heating at this time.

ADM. GEHMAN: I think the point is that there is not 10,000 knots of air flowing past this vehicle.

MR. WHITE: Right. We were at a very low dynamic pressure at this region. Right. Lots of heat but very low dynamic pressure.

ADM. GEHMAN: But things are falling off.

MR. WHITE: That is correct.

Next one, then. This is another temperature. This is on a left main gear strut actuator temperature.

Next slide, please. This is a side wall temperature. This is the left aft fuselage side wall temperature. Now, this particular temperature is about where it's indicated there on the left aft side wall, almost at the end of the wing. This is another indication that something going on externally in the flow above the wing is causing this heating up on the side wall that far aft.

ADM. GEHMAN: Now, would you attribute this more to external heating rather than internal heating?

MR. WHITE: Yes, I would. We have done some calculations, though, that say you could theoretically get enough flow or heating internally to cause this to rise. We have shown, though, that externally, if you were just missing the blankets, you wouldn't have enough heat to cause the temperature to rise. But theoretically it would be possible. We've done some numbers that said you could have had heating from internal. That's also possible.

ADM. GEHMAN: Is this sensor right underneath the blanket –

MR. WHITE: Yes. This is on the skin right under.

ADM. GEHMAN: On the skin right –

MR. WHITE: Underneath the blanket. Yes, sir.

ADM. GEHMAN: Thank you.

MR. WHITE: Next slide. Now, we're back to the left main gear strut actuator temperature. This particular temperature is on a strut when the gear goes down that supports and braces the gear, and again this one saw a rise. Again, you also notice, as you mentioned earlier, there are other sensors in the neighborhood that are still showing nominal at this point.

Next slide. Flash 1. The triangles below line there, this is another debris event. We saw a brightening of the Orbiter image on the video, which occurred where the Orbiter was; and then as the Orbiter moved away, the splash tended to persist in the trail that was showing behind the Orbiter.

Debris No. 6. Next slide, please. Debris No. 6 is the sixth piece of debris that we've been able to observe in the video. This one I used a larger triangle, to indicate that this was a relatively significant piece of debris compared to the other ones. Debris No. 6 and Debris No. 14, from the video that we have, appear to be the largest and brightest debris.

DR. WIDNALL: Could you back up one?

MR. WHITE: Yes.

DR. WIDNALL: Do you have an explanation for Flash No. 1?

MR. HILL: We think Flash No. 1 is attributed to Debris 6 actually separating from the vehicle. We just don't see Debris 6 as a separate object until a few seconds later, but we really do think this is the initial event as that object came off the vehicle, crossed through the plasma wake and shock wake.

ADM. GEHMAN: But we're going to get a chance to talk about that.

DR. WIDNALL: Yes. Tomorrow.

MR. WHITE: Debris No. 6 was right after that. And next slide, please.

Now we start to see some temperatures on the wheels themselves. These temperature measurements are down on the body of the wheel. This is the first one of these. So we're starting to see a little bit of a rise. Again, we noted there was two bits. There was a very small increase in the temperature of the wheel.

Next slide. Debris No. 7. Again, we are over Nevada.

Next slide. All right. Another temperature measurement on the side wall of the wheel well. This is System 3 left-hand forward brake switching valve return line temperature.

Next slide. Debris No. 8. Approaching the Utah border.

Next slide. Debris No. 9.

Next slide. Debris No. 10. These all come off relatively close to each other.

Next slide. Debris No. 11.

ADM. GEHMAN: And you're going Mach 22 at this time with a QBAR of about 35 PSF.

MR. WHITE: Thank you. Next slide, please. This is another temperature on the side wall. This particular one is on the sill, which is actually the top of the wall. It would be underneath the payload bay as the payload bay door comes up and over. This particular temperature would be sitting about right here, just under the door, on the top of the side wall. So we're getting some more heating up there. Again, this leads us to believe that we had something going on with the external flow that was causing higher-than-normal heating above the wing in this region.

ADM. GEHMAN: At this point, the Orbiter is flying with its right wing down, left wing up.

MR. WHITE: Yes.

ADM. GEHMAN: Yes, it is. Hasn't done its roll.

MR. WHITE: Hasn't done the roll reversal, yes.

ADM. GEHMAN: So these are left fuselage measurements here.

MR. WHITE: Yes, they are on the left side.

ADM. GEHMAN: Left side of the body. Is there a hotter side or a cooler side? I know the bottom heating is uniform, but is there any reason aerodynamically or thermally to account for the left side being warmer? In other words, should I read anything into it? Would you expect the left side to be cooler, this particular side, since it's up and away?

MR. WHITE: Well, I think you really need to ask the thermal guys tomorrow.

ADM. GEHMAN: You're right.

MR. WHITE: Generally, from what they've told us, it should be about the same and we believe these rises here were from some off-nominal event causing more heating on the left-hand side. As compared on a normal entry, one roll reversal compared to another roll reversal, I really can't comment on the relative slight differences you might see in temperature.

ADM. GEHMAN: We'll pursue that tomorrow.

MR. WHITE: Next slide, please. This is Debris No. 12; and we're just crossing the Arizona border.

Next slide. Debris No. 13.

Debris No. 14. Next slide. This again is a very large debris relative to the other debris events. So we show the triangles a little bit larger at this time.

ADM. GEHMAN: So it's Debris No. 6 and 14 we want to pay attention to.

MR. WHITE: Right. Paul's going to talk to you about that, about our efforts to track Debris No. 6 and 14 and see if we can figure out a footprint and perhaps recover those debris.

All right. Next slide, please. Now, we lost these five wing temperature measurements early on; and now we are starting to lose some more. This particular one is the left lower wing skin temperature. This measurement is on the lower wing skin itself, right on the bottom side of the vehicle. This one is starting to – this decline. And as you'll notice, these took quite a bit more time to go off line than the previous five that did go off line.

ADM. GEHMAN: Now, these five that went off earlier, I can't tell from the color code whether or not they are in the same –

MR. WHITE: Yes, they are in the same wire bundle as the five that went off.

ADM. GEHMAN: They're in the same wire bundle, but they're not on the same circuit. It kind of shows that they are pink.

MR. WHITE: Well, yes. Each one of these sensors would have its own wire within the wire bundle, yes.

ADM. GEHMAN: So we should not read anything into the fact that there's a difference between these five going and these two here. I mean they're just different wires.

MR. WHITE: Different wires within the same bundle, yes, sir. And, you know, I was talking about twisted shielded pairs earlier. These wires for each one of these sensors is actually, if I remember right, a triplet of wires which is then encased in Kapton and then that particular wire that's formed from the triplet is one wire of many in the larger bundle.

Next slide, please. This is Debris No. 15.

Next slide, please. Now, we have another wheel well temperature. This is a left main gear uplock actuator temperature. This is the actuator that holds the gear in the lock for the gear, locked in the up position; and we're seeing an off-nominal temperature rise there. Also notice that there's another sensor on the side wall. We've colored it orange, which means its temperature rise now has exceeded 15 degrees from what we would consider nominal. So the temperature on the side wall continues to increase.

Next slide, please. Now, there's another skin temperature. This one happens to be the upper wing skin temperature. It's approximately above the one in the lower but on the upper surface of the wing, and this one is starting to go off line. You also notice that the lower one hasn't quite failed all the way completely yet by this point in time.

Next slide, please.

ADM. GEHMAN: Excuse me. Now, what should we read into the fact now that on your cartoon here every sensor on this line here has now failed? Are there other wires in that bundle?

MR. WHITE: There are many other wires in the bundle.

ADM. GEHMAN: In the same bundle?

MR. WHITE: In the same bundle. Yes, sir. These are the only – on that particular bundle, that pink that we indicated in pink there, those are the only ones that we have data for. The other wires in the bundle are either not used anymore because they were development flight instrumentation which we are no longer using or they're a series of instruments that are recorded on what we call our Orbiter experiment recorder, which records measurements and then we dump the tape when we get it to the ground and look at the values for that; but they're not available to us in realtime. One of the things we've been hoping to find in the debris is that recorder to see whether or not any of the tape survived that may give us some of the data to tell us how other measurements in this area were faring at this time and so we can learn more about the event.

ADM. GEHMAN: Would you estimate how many of those sensors there are in there?

MR. WHITE: I went and got the number once for somebody. I do not remember the exact number off the top of my head.

ADM. GEHMAN: Dozens more?

MR. WHITE: It's on the order of a dozen or so.

ADM. GEHMAN: Thank you very much.

MR. WHITE: Next slide, please. Okay. This is Debris No. 16. This is a debris event that was picked up in the Kirtland video, which I'm sure everybody's heard about a video shot by some of the folks at Kirtland Air Force Base; and we were able to see a debris event from that particular video.

Next slide. All right. This is the main landing gear. Back on the tires again and on the wheel. The main landing gear left-hand outboard tire pressure No. 2. It's starting to show a little bit of an increase, only one bit.

Next slide.

ADM. GEHMAN: Could we back up just a second here? I think for the time line we need to determine when the roll reversal was. I think it happens right about 56:55. About 30 seconds ago we did the roll reversal.

MR. WHITE: That's correct.

MR. HILL: We start at 56:30 and finish at –

MR. WHITE: Right. 56:55.

ADM. GEHMAN: So the roll reversal is now complete.

MR. WHITE: Yes. That's the complete of the first roll reversal.

ADM. GEHMAN: Now the left wing is down.

MR. WHITE: Right.

ADM. GEHMAN: People keep telling me that that doesn't make any difference in coordinated flight, but I think it helps to understand.

MR. WHITE: All right. Next slide, please. All right. This is the lower wing skin temperature finally completes its descent down to off-scale low. It did take a little longer than the first five. Again, to us that just indicates that the rate of burning or the rate of shorting of that particular wire was different than the first five – again, possibly indicative that whatever was causing the burning was changing direction or heat rates or something like that.

Next slide, please. And then the upper wing skin temperature follows that shortly.

Next slide, please. Now, we start to see finally the last of the hydraulic measurements in the wheel well start to go up. You can notice some of the other measurements have now turned orange – again, indicating that they are continuing to rise and have gone more than 15 degrees above what we could consider nominal for this particular point in the flight.

Next slide, please. This is what we're calling Flare 1. This is another event that we observed out of the video taken at Kirtland Air Force Base. We see an asymmetrical brightening of the shape. In the video you can see one side of the Orbiter image get brighter than the other side.

DR. WIDNALL: Which side?

MR. WHITE: It appears to us to be the left side.

Next slide, please. Then Flare 2. Again you see another little bit of a flare, again apparently from the left side.

Next slide, please. This is another aerodynamic event that we put in here graphically. This is the start of the sharp aileron trim increase. Remember we've been doing a slow aileron trim increase, trying to keep vehicle flying the way we want it to fly, trying to make it respond. At this point there is some event that happens that causes the aerodynamic forces to require a much greater trim on the aileron and so the trim begins increasing very rapidly here. Again, you'll have some charts tomorrow, when the aerodynamics guys talk, to show you how rapidly that aerodynamic set of forces was increasing.

Next slide, please. We're also seeing an increase now in the derived rolling and yawing moments, those moments I told you that we were able to back out way up early that showed something off nominal. Again, the slopes of these moments are starting to change substantially at this point.

Next slide, please. This is on the tire itself. This is main landing gear left-hand tire pressure No. 1. Again, it's starting to show this damage trend as it's going down. Again, as you mentioned earlier, one of things that's a mystery to us is why the measurements on the tire seem to hang in there for so long whereas other measurements farther back in the wheel well seem to be significantly off nominal by this point in time. Again, it may have something to do with how well those measurements are protected by the tires themselves and the heat sink and the mass of the wheels themselves.

Next slide, please. This is on the other tire. This is main landing gear left-hand inboard tire pressure No. 1. It's showing some damage trends.

Something else I might say at this point too is you watch all these temperature measurements and pressure measurements for the wheels go off line. We saw these in a staggered kind of a fashion, which indicates to us that the tires themselves did not rupture or blow up, at least not at this point in time. That may have happened after our loss of signal, but at this point in time these measurements are going off in a staggered fashion. That says that the tires were still intact at this time.

Next slide, please. Back to the left outboard wire damage trend showing on one of the sensors there. Wheel temp.

Next slide, please. Back to the inboard one. Damage trend there.

Next slide, please. We finally get the landing gear left-hand outboard tire pressure No. 1 to go completely off line.

Next slide, please. Now the left outboard wheel temp goes off line.

Next slide. Now, the landing gear left-hand outboard tire pressure No. 2 starts to go off line.

ADM. GEHMAN: Doug, once again, the people in the audience can't see the companion viewgraph that goes with this that shows the actual temperature sensors.

MR. WHITE: Right.

ADM. GEHMAN: But I'll describe. I'll hold it up, for example. Which one are we on? The left-hand outboard tire pressure. The temperature is normal. There's no rise in temperature, and then the thing drops off.

MR. WHITE: The thing just goes off. Right. The temperature is constant, and then it just drops off. Right.

ADM. GEHMAN: And that's true of all of them.

MR. WHITE: Right. That indicates to us that the tire was intact, that we weren't seeing some sort of a pressure increase in the tire that it was about to rupture and that there was damage to the wire for that measurement that caused it to drop off line.

ADM. GEHMAN: And whatever heat was causing all these temperature sensors to rise, that heat was not present up here and –

MR. WHITE: Well, it was present to some different degree. It was having different effects. Again, since it's difficult to model the propagation of how the heat was getting in there – and we're working on that and it's a difficult thing – but it was obviously having different effects there than it was farther back in the wheel well.

ADM. GEHMAN: Let me rephrase the question. These temperature sensors here are all rising.

MR. WHITE: Yes.

ADM. GEHMAN: These temperature sensors here, there's no temperature rise in any of those sensors. They just drop off.

MR. WHITE: They just drop off, right, which says the wires were getting damaged.

ADM. GEHMAN: I understand neither you nor I can figure out why that happened, but these temperatures are rising and some of them have now gone orange, indicating that the rate of the rise is now alarming, whereas these don't show any rises whatsoever.

MR. WHITE: That's correct.

DR. WIDNALL: Where is the cable located for those wires, the blue ones?

MR. WHITE: The ones on the wheels themselves, the lines run on the back of the gear, on the back of the strut and they run up the strut.

DR. WIDNALL: Can you show it?

MR. WHITE: They run along the strut here. They come up to the back of the wheel well. They come to actually a kind of a junction box here and they run across the ceiling to the front of the wheel well and then they run out through a connector into the mid body about there.

DR. WIDNALL: So they're inside the wheel well structure?

MR. WHITE: Yes, they are inside the wheel well structure.

DR. WIDNALL: And at least over part of the area, they're mounted on the front bulkhead.

MR. WHITE: Yes.

ADM. GEHMAN: But I think Sheila's point is very pertinent because even though these sensors did not show any temperature rises, the wire that feeds these temperature goes all the way back into this region?

MR. WHITE: Yes.

ADM. GEHMAN: And then comes back out of that region again because of the way the landing gear was folded back over on itself.

MR. WHITE: Yes. And if you want to surmise that maybe we're just today burning through wires here, you would want to think that it was down closer to the sensors themselves on the strut because there are other temperature measurements again that are coming in this bundle across the top of the wheel well and then out through that connector that are still reading and acting just fine. So some kind of burning was going on there. It was most likely down on the strut next to the wheels themselves rather than up on the ceiling of the wheel well.

ADM. GEHMAN: Thank you.

MR. WHITE: Next slide. This is main landing gear left-hand inboard tire pressure No. 1 has gone off line.

Next slide. This is main landing gear left-hand inboard tire pressure. Again it's showing a very slight increase in tire pressure. A 3 1/2 pressure rise in two seconds. That didn't last very long because that sensor went off line shortly thereafter.

Next slide. You see right there in the next slide it started to go off line and that measurement started to trend down.

Next slide, please. Another main wheel well temperature that went off line.

Next slide. Then the next-to-the-last one went off line.

Next slide. Then finally the last one. So all of our sensors, both temperature and pressure on the wheels, have gone off; but again since it was a staggered fashion, we don't believe that one or the other of the wheels let loose, which would have lost all of them simultaneously.

Next slide, please. This particular measurement, the change here, this is called the left main gear downlocked. This is a sensor which tells us that the gear would be down and locked. This particular sensor changed to a 1 state, which is an off-nominal reading for this state. We did do some wire testing to see how this particular sensor would fail if its wire was burned through. It would fail to a 1 state. So this could be either real, that said that maybe the gear did come down at this point and we got a 1 because we were suppose to, or it could be just that the wire had burned through. The other sensors in the wheel well, you can see the other three red squares there, they were still all reading their nominal values, which told us that the door was up and locked. We have three other sensors. We have the door up, a gear up, and a no weight on wheels; and all of those were reading their nominal values. However, from testing that we did from wire burning to see how those would fail, those could fail in their nominal state if their wires were burned through. So it is possible that those wires were already failed but we didn't know it. It's also possible they were reading exactly the way they should have because the door was still up and locked at this time.

ADM. TURCOTTE: Is this the same location of the previous tire pressure wire bundle that you described before and that is located along the center line of the gear?

MR. WHITE: Right. This particular one is along the strut. Now, the one that you see very forward there, that particular wire bundle runs all by itself across the front of the wheel well and up to that connector. It's not in the same bundle until very late with this particular one that's failed here. So that's a separate bundle, but the three on the gear there are all in the same bundle.

ADM. TURCOTTE: So that's the one that's located on the trunion assembly by the dust cover where it goes through into the wing?

MR. WHITE: This particular one is on the strut itself, but the wires then run as you described back into the mid body there across the top.

Next slide, please. Right. This is sensors starting to go off line, one of the ones that had been reading temperatures, system 2 left-hand aft brake switching valve return temperature, starting to go off line.

Next slide, please. Now, this other wire that goes to the ASSA that was the gray wire that actually looks kind of purplish here, this is starting to show that it was burning through somewhere and shorting. We have evidence that our air surface servo amplifier was shorting out and was not providing power the way it should have to Channel No. 4 for the elevon actuators, but the inboard and the outboard we begin to see off-nominal events and in the detailed time line there are quite a few off-nominal events. This is right before LOS or one second before we lost signal here, but this does indicate to us a sequence of events that I just labeled with this one event here, that we were burning through this power wire, causing shorting to go on in that air surface servo amplifier. What we also see from the data here at this point is that the other three channels were taking over and the redundancy management that's built into the system was working the way it was supposed to be working. The other three channels took over and were in control even though this system was failing.

Next slide, please. This is just prior to loss of signal. You can see all the things off line.

MR. HUBBARD: Doug, before you get to that loss of signal. If you were to come up with some kind of a metric of event as a function of time and you plot that from the beginning to this point, do you imagine that that's linear or is there some knee in the curve? Is there some point in this nine minutes or so here where things pick up?

MR. WHITE: Yes. I would call the knee in the curve the place where we showed the start of the sharp aileron trim increase, which is back up with one of those triangles there on the top. The vehicle was in control and was responding to commands up to that point, and after that point something changed apparently and it still continued to be in control and still continued to respond to commands but the rates and the amount of muscle it needed to continue flying the vehicle the way it should be flown was continuing to increase. Something definitely happened at that point. Again, we don't know what; but something definitely happened at that point to cause the flight control system to need more muscle and start to have to fight harder to control the vehicle.

MR. HUBBARD: And that was at about?

DR. WIDNALL: I think that's about 57.

MR. WHITE: Yeah. That would be about right.

DR. WIDNALL: I guess the comment I would make – because I have looked at that particular instance of time – that really coincides with a rather sharp increase in the rate of rise of dynamic pressure.

MR. WHITE: Yes, it does.

ADM. GEHMAN: Okay. Thank you.

MR. WHITE: Right. That's as far as I planned to brief in these charts. As you know, there is some data that we recovered from the satellites post-LOS. If you want to talk about that, I can answer questions about that; but I don't have any more charts.

ADM. GEHMAN: Okay. Let's let Paul have the floor for a few minutes and then questions.

MR. HILL: Okay. Now, as I mentioned before, what my team has been doing is evaluating various public imagery, various external sensors and trying to make some sense out of the data and see if we can get smarter about what's coming off the vehicle earlier on as far west as we can, as well as get some engineering data to tell us specifically what those objects are and where they're going.

I don't really have prepared presentation charts. I'm going to wander through some discussion on this map. I have a few other pictures I'm going to show you, and I did bring a composite video that shows examples of continuous video from the California coast through about mid New Mexico. Since this video was put together, we have added one that takes us about 50 miles offshore California and we have some video from Kirtland Air Force Base that takes us through just about the New Mexico, Texas border. Those aren't going to be on this tape that we're going to see here in a few minutes.

Let me start with the process, then we'll play the tape. To give you an idea, when we first starting getting these videos, our first job really was to put them in chronological order. That's still photographs, video, et cetera. We very quickly focused on just the video and saved a lot of the still photography analysis for later.

Our first goal is to establish some absolute reference for time in each one of the videos. Once we have that, we can put them in chronological order. As we were going through that process, probably three or four days after the accident, we first saw in these videos individual debris shedding events; and that was our first indication that something, in fact, was coming off the vehicle early on, that we didn't just start having structural damage, say, over west or east Texas. You'll see, as we play the tape, some of the things that we use for cues in establishing time and establishing relative geometry. There are a couple of celestial references in a couple of the tapes. You'll see a star. You'll see Venus crossing, which will be very clear. At least half the photographers snapped their GPS location so we know exactly where they were standing. In the case of the Venus crossing, because we know where that photographer was standing and we see the Orbiter actually flying in front of Venus, we can calculate when in time that had to have happened. So now we can put that tape exactly where it was in time and we know exactly where the Orbiter was in space and then we can sync the videos that preceded that one and the ones that followed to that tape. We had a few other cues like that in other tapes, and I'll try to describe those as we go when we play the tape.

As we started seeing these debris shedding events – and you'll see these in the tape, although some of them you do have to look closely because they only last in the order of a second or second and a half in cases, we then set about calculating the exact times that the debris was coming off the vehicle. As we established those exact times, we went to work, trying to do relative motion and ballistic analysis. I'll come back and talk about that here in a few minutes.

Interestingly, not only was NASA not aware that debris was coming off that early before we looked at this video but most of these photographers did not see any debris shedding in their own photography until they heard about the accident on the radio or on TV and went back and played back their video. Then they could see them. Like I said, in most cases debris flash or the speck that you see in the video lasted for a second and a half or so, in most cases less than a second.

The types of things to look for in the video. In some cases there's flashes, like Doug talked about. In other cases you can see a bright dot which is Orbiter and plasma wake behind the Orbiter, and then you'll see another dot come from a dot. And you'll see when we play the video we are not seeing images of an Orbiter against a dark sky where we can clearly make out the planform and shape of the spacecraft where we can clearly resolve down and see where some object is coming off the vehicle. We see a dot, we see another dot appear from that dot, and one of the dot goes away. And we will talk about that some more as the video plays.

The other thing to think about as we watch the video is we are making some speculations about what we are seeing. We think that the brighter objects are more massive, are more significant, potentially higher ballistics numbers. Certainly the things that the individual light for the individual pieces of debris persists longer, we expect that those objects are more massive, higher ballistic number because we think that the reason they persist longer is they are moving faster. So they stay lit. They have their own plasma wake, longer than, say, some lighter thing, say, an individual tile comes off versus maybe some other heavier object. But I'll also say we cannot just look at these videos and just determine what is it that's coming off the vehicle. Are we losing a tile here? Are we losing some section of the thermal blanket that's on part of the external surface of the vehicle? We can't tell that, and to this day with the good data that we have on the ballistic motion and the ballistic analysis and the footprints, we still cannot say exactly what it is we see coming off. We are making some judgments on which of them are more significant or more massive than the others. And we talked about Debris 6 and Debris 14. When we play the video, you'll see why we're focusing on those.

So why don't we go ahead and play the video and then we'll come back and I'll talk some more about what we've done on trajectory analysis.

ADM. GEHMAN: You can feel free to stand up and narrate or point. However, you feel comfortable showing us what happened.

MR. HILL: This is just after the California coast. As I mentioned, you see a dot. That's the Orbiter. And the view looks more or less like this as we change the vantage point. We'll start picking up the con trail.

Now, if you blinked you missed that, that was Debris 1 and that was Debris 2. Those little dots that came off, that was debris. As I mentioned, you can't make out the planform, you really can't see the Orbiter, and you have no idea what's coming off. Also, as I mentioned, on some of these or most of these, the debris itself doesn't last very long at all.

ADM. GEHMAN: Now, this is a significant event.

MR. HILL: Yes. Now this bright dot you see here, this is Venus. When our flight dynamics folks saw this, they were very excited because this allowed us to put this video within plus or minus a second of where it actually happened.

Now, you can see the flash persist in the wake and then you see Debris 6 come off. Even though they're separated by a few seconds there, our speculation is the flash was some burning event associated with Debris 6 and then that object coming off the Orbiter.

ADM. GEHMAN: If I understand it, Debris No. 6 is the one you tracked to the vicinity of Caliente, Nevada, and we are valiantly trying to find.

MR. HILL: We do think that is Debris 6, and I'm going to show the footprints for that and explain that a little bit more.

There you saw Debris 7 come off. Now, again, also just for a reference, all of these are taken with camcorders. These are commercial camcorders. This is somebody in the public, standing outside with a camcorder, generally zoomed way in, trying to track the Orbiter flying overhead at 12,000 miles per hour by hand.

ADM. GEHMAN: You recommend people pay attention to Debris No. 14. That's the other one.

MR. HILL: Now, as we come up on Debris 14, the thing to think how is bright that flash was before Debris 6. Compare that to what Debris 14 looks like. Also, for comparison, Debris 6 was lit from between 6 and 12 seconds.

Now, there you saw how bright that was and also you saw that you have this cloud where around the Orbiter, the video itself or the pixels became saturated. That is the most bright – the brightest object that we saw in any of the video. And I'm going to come back and talk about its relative motion and Debris 6's relative motion here in a few minutes.

You can see here we're getting further east. We're getting out over New Mexico. The sky is lightning up, which makes it more and more difficult in the videos that we have out there to track the Orbiter and specifically to pick out individual debris shedding events.

ADM. GEHMAN: But in your experience and the experience of the experts, that hot gas envelope right there looks just like any other entry that you know about?

MR. HILL: That's right. Except for any of the flaring or flashes or anything else, the bright spot you see there looks like just all the other videos that we have. As a matter of fact, one of the photographers that sent us this video sent us six previous entry videos that he took, most of which with the same camera, and looked just like this except absolutely no flares, no dots coming off.

ADM. GEHMAN: The number down in the right-hand corner is what's on the camcorder, but that's not calibrated time. Your times are in the bottom left-hand corner.

MR. HILL: That's right. Now, we have done a fair amount of work. Again, about half of these photographers were amateur astronomers and they had synced their clocks themselves to atomic clocks. Some of them went back and taped the atomic clock so that we could do our own calibration, and some of them did some of that afterwards.

Now, the things you're seeing here are just prior to or including the main breakup.

ADM. GEHMAN: But this is post loss of signal.

MR. HILL: Correct. We left this in here for completeness. We're going to talk a little bit about post-breakup and pre-breakup trajectory analysis. I thought we would go ahead and run the tape through this to give us a place to start from. These videos were all taken from Texas, of course.

This was taken from an Apache helicopter, looking through its forward-looking IR targeting sensor. Now, the thing to think about here – we'll come back and talk about this in a while – is the significant number of secondary and tertiary breakups that you see in these videos. That will be important when we talk trajectory analysis.

DR. WIDNALL: Can I ask a question? Are there any gaps in time missing, where you don't have video? Is there a continuous time line between the first sighting and these later pictures? Are you missing anything?

MR. HILL: There is a small gap in the East Texas or the East New Mexico, West Texas area. It is not as big as represented on this tape.

DR. WIDNALL: How long is it? A minute?

MR. HILL: I would say it's on the order of a minute or two minutes. Everything else west of Albuquerque, we have near-continuous video for. Now, it shifts around from vantage point to vantage point and there are dropouts in individual video. As a matter of fact, if you segue into the map here for a few minutes, the blue dots that you can see on the map, those represent where the individual photographers were standing. If you take this one, for example, here, this is in Flagstaff. This blue line extending out this way, there's another that extends out this way on the map, that wedge represents the full part of the trajectory that that photographer filmed in his camcorder. It doesn't necessarily mean that that photographer has continuous coverage of the Orbiter for that full swath because many of them dropped track, lost the Orbiter. They'd look away from the view finder. The camera came down, and they had to go find it again. But for the most part, with all of the overlapping video we have from California all the way through New Mexico, we've been able to piece together essentially continuous views of the Orbiter.

Now, the other important thing is on some of these objects when we see them coming off the Orbiter in one view, we may not see that same object coming off for another second or so in another view. In some cases we don't see it from a different vantage point of the same incident. Some of that is because one observer, say, may be looking from the north side of the trajectory and the folks down here are videoing from the south and one of them may have the Orbiter itself maybe obscuring the view of, say, the flash or the individual debris coming off. Since that debris only persisted for maybe a second in most videos, it wouldn't take much obscuration at all for one video not to see it. The short answer is we have near-continuous video until right about here, and that's east of Albuquerque, New Mexico, and there's this gap and we pick up with that Texas video of the main breakup. South of Dallas.

DR. WIDNALL: You have a gap between Albuquerque and –

MR. HILL: Albuquerque and about the Dallas area, which I guess you would expect because of the relative population. Most of the video we have, even out here in Arizona and New Mexico, which is relatively thinly populated, most of that we have from Albuquerque, from Flagstaff and from Las Vegas. And the one from Flagstaff in particular, they tracked for a significant period of time, from horizon to horizon. So that's our explanation for the gap there.

Now, going back to the video a little bit, you see the type of relative motion or the type of relative distances you see in the objects that come off the Orbiter. We're able to zoom in on those objects. We're able to zoom in on the Orbiter. The imagery folks here at JSC are able to take all that jitter out so that there's no motion except for the relative motion between the object and the Orbiter. We can then measure how that object moves away from the Orbiter; and since we know exactly where the Orbiter is in space relative to the photographer and we know exactly what the timing is, we can calculate the ballistic number of that object, based on how it moves relative to the Orbiter, because we know the Orbiter's ballistic number, of course. We then take that ballistic number for the object and we propagate that down and build a vector so that we can propagate the object forward all the way down to the ground. Then we generate a series of footprints at 80,000 and 35,000 feet and ground impact.

If we can put up page 2 of my charts. We've done a couple of things. What you see here is a very generic footprint. We started with this. Before you could calculate relative motion and ballistics off the video, we made some simple assumptions like we were shedding a tile every two seconds from California all the way to Texas. Based on the known ballistic properties of the tile, that gives us a debris swath that looks like this, which is still enormous; and it's about 30 miles above, 30 miles below the ground track for that full distance. That's what we knew very quickly, within a day or so of the accident.

If we move on to the next page, a similar footprint based on the main body breakup, also based on various simplified assumptions on ballistic numbers, both the light and heavy objects. This footprint is for the debris field in East Texas; and it, in fact, is centered right over the debris in East Texas. On the far right side down in the lower corner, that's near Fort Polk, Louisiana, which, in fact, is where main engine components have been found. Now, again, these are both very generic and they're based on relatively wide simplified assumptions.

If we go to the next page, this is based on Debris 6. This is that object that we see coming off somewhere near the Nevada, California border. In fact, this footprint, this blue line here, that's the Nevada, Utah state line. This small box you see here, if we exactly nailed the debris shedding time, if we exactly nailed our ballistic analysis, that's where you would expect that object to be laying, if it also didn't generate any lift.

We've done a bunch of other detailed analysis. If you go to the next page, just for comparison sake, depending on the errors that we had, it is just as likely that the object, instead of landing in that no-lifting box here in the middle, could have drifted off track to the north, off track to the south, just by generating lift. If we had some error in the time that we calculate in that object coming off or in our ballistic analysis, then it could also fall short up here in this part of the footprint or along down here.

Could we back up a page, please. Now, this is Debris 6. This is the first one we had analysis on. We were able to get analysis completed on this one earlier because we had that Venus crossing and we really knew the relative motion of this one much better than we knew everything else.

After we built the footprint, then the process would be go through the FAA radar data which we have saved off and recorded; and we're working with the NTSB for them to search that radar data to find patterns that would not normally be noticed by air traffic controllers. In that process we have found a thread up here in this area which is just inside Nevada before crossing into Utah and another one down here just south and then another one over here in Utah near Mount Zion National Park. These are the first three radar threads that we found; and, in fact, these are the three areas that we have been trying to search here for about a month now.

The one in Utah is very mountainous terrain and is most likely only going to be searched by air. It has been searched already by air. We're talking about doing some more air search. This one up here in Nevada which is near a place called Caliente, Nevada, we have had folks on the ground there, searching. It's also snowed out there about five times, to the tune of 4 to 5 inches of snow each, since February 1st, which certainly our problem of searching and finding things.

We also say again we don't know what this object was. We know that, based on its relative motion, it has a ballistic number on the order of 3.75 to 4.75, which compared to the Orbiter ballistic number, which is on the order of 100 to 110, makes it something that's relatively small and light.

Like you said, Admiral, we expect this object to be Debris 6. I mean, the objects that we're finding the radar threads for, we expect it to be Debris 6 because it lies right in this Debris 6 footprint and so close to the no-lift in the box. We don't know for a fact that it is because, as Dr. Ailor said, as these things come off the vehicle, they could continue to fail, break into smaller pieces, which then could completely changes their ballistic properties. Our general process is the same, though. We calculate relative motion, calculate ballistics, propagate out this footprint, and then we search the footprint for radar threads.

If we go to the next page again, this is Debris 14. That is that second object that was so bright compared to Debris 6. Let me correct something that I told you on Thursday.

Debris 6, you can see, persists, depending on the video you look at, for between 6 and 12 seconds. Debris 14, we see, persists for 4 1/2 to 7 1/2 seconds, depending on the video you look at; but Debris 14 is also much, much brighter than any other object, including Debris 6.

How do you interpret that? We're not sure. We do think that relative brightness is an indicator of something that's larger and more massive. We think that the amount of time that individual flares or the light around that debris persists is also indicative of the larger ballistic numbers, which tells you you're dealing with something that's probably larger and heavier. That's as much as we know. We know how these things behave ballistically way up high when there's not a lot of air.

In addition to just searching these footprints for FAA radar, we've also moved all the way out west to the west coast of California and we are searching all air traffic control radar anywhere it intersects our ground track or that wide generic swath around the ground track to again see if we see any patterns of *Columbia* debris falling through that radar that would have been ignored by air traffic control. To date, we still have not found any threads out there; and as you know, we have not found any of the *Columbia* debris laying on the ground out west, based on these threads.

Now, searching the radar data bases is relatively labor intensive. Clearly, putting people on the ground out there to search even 5 square miles is labor intensive. We have since started testing various Shuttle components up at Wright Patterson Air Force Base at the Air Force research lab.

Our initial focus was on that Flight Day 2 object and to try to determine what we could do to identify what may have fallen off the Orbiter or fallen out of the Orbiter – if, in fact, that's what that object is attributable to. So for those radars, we specified a list of thermal protection system, predominantly a couple of different of types of tiles, a couple of different types of blanket type insulation that's on the outside of the Orbiter. We're also going to send up an RCC panel, a carrier plate, and the horse collar, that thermal seal that goes around the carrier plate. Those are all in work right now. And we sent up some different types of thermal insulation that go in the payload bay.

Once we had that in work, it occurred to us we could do similar type radar testing also at Wright Pat that is tuned towards the radars, these air traffic control radars, that we are looking for our debris falling down through. And that also is in work. For many of those materials, that testing, too, has already been completed and we are expecting detailed results sometime this week.

By the same token, we are looking to identify a set of SRB components and ET components and we'll have the full set tested for the C band radars we track their ascent, UHF radars we track while they're in orbit, and then the L band air traffic control radars that would drop debris down through the air. All of that is supposed tell us is it reasonable to expect that we could track the materials that are most likely to come off the Orbiter or, to look at it another way, how big would those materials have to be. So would we have to have a tile the size of a car to be able to track out here, or is it reasonable to think we could track a single tile or piece of tile? I expect that we'll have information on that here within the week.

That gives you an idea how we think we're going to find any of this debris. Also, as Dr. Ailor said, the key to finding or looking for this debris is we know what happened more or less in East Texas, at least at the gross level. It will be difficult for us to do trajectory work with the debris we find in East Texas and back it up to the vehicle and try to determine what was happening over Texas. This debris could tell us where the breach started; and if we can locate some of this and use it to isolate where the breach on the outside of the vehicle started, that's going to make us immensely smarter on exactly how the failure started in the first place.

Now, at the same time there are some folks out at Ames Research Center in California that are capable of analyzing the spectral data, the luminosity in the video and the still photography, and it's possible they'll be able to get us some engineering data on exactly what's burning, exactly what they see coming off in the plasma wake. Probably the easier of the two analyses will be looking at the relative luminosity, and it is possible that by looking at and measuring the luminosity of the debris in video, comparing that to the Orbiter's luminosity where the Orbiter is not saturating the video, we know what the Orbiter's instantaneous drag is, we can use a ratio of that drag and the luminosity, compare that to the debris, and it's possible we'll be able to estimate the actual drag on the debris, which then makes us smarter about what's coming off.

Our initial hope was to also get good enough spectral data to resolve down the actual material. Unfortunately, we expect that the three colors we can get from commercial camcorders will not be good enough. In combination with the distances they were shot through, the fact that a lot of this light was having to go through both the Orbiter plasma wake as well as some plasma wake around the debris, our hopes are much lower that we'll get good spectral data, but we're setting up feasibility tests for both of those out at Ames Research Center and we expect to have those tests set up and in the works sometime during the very near future.

The last thing I'll tell you about is the miscellaneous sensor analysis we have in the works. Again, the first one is something that we were originally very hopeful and we are much less hopeful now. And that will be the infrasonic analysis or infrasonic data. There are various type of microphones that are set up across the continental United States and out in Hawaii. They did measure sound data on the Orbiter during this entry. They have similar data on previous entries. We thought that it would be possible potentially to bring some of that sensor data back to the Orbiter ground track and essentially give us a calibration or a signature of these debris shedding events as they occurred across the ground track. We have since found that the various variables associated with bringing that data back to our ground track and back to our place and time in the sky are probably going to be large enough that we're not going to be able to do that. So we expect that not to pan out.

We have various other DOD sensor data like radar, and then there are other types of data like that that we also have evaluated and we have put on the time line. You have seen some of those. Most of that data also, regardless of the type of sensor, is not good enough to specify, say, engineering properties or specify any kind of properties on any individual tracked object, unfortunately. We had originally hoped that we would be able to track individual pieces of debris coming off the Orbiter, specify the vectors on those things, and use those to be smarter to get them all the way to the ground. And across the board, the types of sensor data, the external sensor data that we have is not going to be good enough to do that and, interestingly, the public video we have is probably the best data we have to try to find some of this debris out west.

The last thing I guess I could tell you. On the ground track here, without going into a lot of detail, I mentioned these blue dots are the photographers. The white dots you see on the ground track, each one of those is an individual debris shedding event. If you stand back and just kind of look at the view from 10,000 feet, you can see that from California pretty much all the way to Texas you see a relatively steady stream of objects coming off the Orbiter. Now, there's a few places where you don't see as much. That doesn't really necessarily mean we don't have small pieces of debris continuing to come off the vehicle. It could just be the perspective and point of view during that phase of flight and the photographers just couldn't see it. Likewise, you don't see any of these white dots out here where we don't have video because we don't have any way of seeing it, but I think it would be valid assumption that we are continuing to drop debris all the way through. And it is likely that if we had video during this time frame, because we had a lit sky, we wouldn't have seen individual objects coming off unless they were relatively large and we saw some bright flare.

MR. WALLACE: Paul, why don't you show with your pointer there where this west piece of debris was found.

MR. HILL: Let's see. The westernmost piece of debris was found just south of Lubbock, which I would say is right around in here. Let me also say for that westernmost piece of debris, that Littlefield tile, which is generally how we refer to it, we have done some top-level trajectory analysis on that. We expect that piece of tile came off somewhere in this time frame here, potentially while we had video from Kirtland Air Force Base, but that also is based on the mass properties and size of that tile in its state on the ground. Of course, it was part of a larger piece higher up in the air and it probably also came off much earlier than that.

ADM. GEHMAN: That trajectory analysis you just spoke of, that does include true winds of the day.

MR. HILL: Yes, sir, it does. Now, what doesn't include true winds of the day is that generic swath you saw from California all the way to Texas, although we are in process of putting real winds of the day in that.

Let me go back up a page in my slides, please. Now, I don't show the radar threads here but, again, I mentioned here around this band there is a radar thread, probably the radar thread we were most interested in that we followed, where radar thread is just the long string of radar hits that we followed in this pattern on air traffic control radar that we think is a attributable to Debris 6 or some piece of Debris 6. Now, that radar thread started right about here. Again, right on the ground track, right where you would expect a non-lifting object to be, and then it tracked to the north and east, which also was with the prevailing winds of the day. So our interpretation of that is, as that object dropped down into the heavier air where you would acquire it on air traffic control radar, which is about 80,000 feet, then it fell ballistically above that, got down into heavier the air, started becoming more lifty, started wafting with the winds, and again then started tracking here in the north and east as it came down lower. If you look at the topographical map of that radar site and where that object lost track, our speculation there is that we tracked that object to within about a thousand feet of the ground, which is why we think we have about a 5-square-mile search area for that object out west.

That was everything I was going to tell you in a big picture and how we're doing what we're doing. In general, we're continuing with the relative motion analysis on all these objects. I expect here in the next couple of weeks we'll have ballistic footprints rolling in at a relatively regular rate, starting with Debris 1 and 2 out west and then working its way east. We also expect that we're going to see those footprints start to stack up and overlap significantly with Debris 6 and Debris 14, and then we're working on figuring out from those overlaps how to come up with concentrated search areas based on where we think it's most likely we'll find any and all of this debris out west.

MR. WALLACE: So this piece that you tracked to a thousand feet above the ground, there's no question that that arrived at the ground; but is there a question about a lot of this other debris is likely to have just been burned up?

MR. HILL: Let's see. The debris we have radar threads for, any one we have radar threads for, if you assume that those are our debris – which is still somewhat of an assumption – then we are relatively confident that those are on the ground somewhere near where we lose track of those objects. Now, the other things we see in video very likely could have either burned or completely disintegrated from G loads or aerodynamic forces before they got to the ground. We don't know.

MR. WALLACE: When we say 1 through 14, can you say how many of those came up on radar.

MR. HILL: Well, I can answer a different way. We have about four key radar threads that we are searching out west. There's these three here that are in the Debris 6 footprint, and there's another one in Albuquerque that did not come from this analysis. It was started based on some folks in Albuquerque who thought they heard something fall through the sky and impact the ground, and NTSB found those radar threads. Now, if you assume those are ours, we are reasonably confident that those things are on the ground somewhere. All the rest of these that we don't have any radar threads for yet may or may not have made it to the ground. We have just now started searching the Debris 14 footprint for radar threads. So we could go another one to two weeks before we finish searching all of that radar to determine whether or not we see these.

MR. WALLACE: In how much of the area that you're searching are you dealing with snow-covered ground?

MR. HILL: All of these areas out west, certainly in the Nevada and Utah area, have been snow covered off and on at least four or five times since February 1st. As a matter of fact, the primary search box out there in Caliente, Nevada, was on hold and we had about 15 percent of that area to finish searching and it's been like that for two weeks, maybe going on three weeks now, all because it was snow covered. If you're looking for something small like a piece of a tile, it's reasonable to assume they're not going to find that on snow-covered ground.

ADM. GEHMAN: What can you say about still photography? Has that been of any value?

MR. HILL: We're doing some work with still photography. There is photography that was taken from California, in particular, time-lapse photography that may yield us the best spectral data. It did give us a few more cues when we were trying to narrow down maybe one or two seconds on debris shedding timing. I don't expect we're going to get a whole lot smarter from the still photography than that, however; but we are buying still cameras from many of the photographers, just like we are on the camcorders so we can try to calibrate what we're seeing in the film and get a better idea of what kind of spectral data we can pull out. In the ideal case, we'll be able to take some of that still photography and clearly show that we have aluminum burning in the plasma or maybe silica or maybe RCC. We'll see.

ADM. GEHMAN: Did you want to talk about the Kirtland photographs?

MR. WHITE: I can talk about that a little bit. I've been working on a tiger team to try to understand the images there. There were a number of images acquired at Kirtland by the folks there who were doing that on their own time, not using the Starfire Optical Range equipment. They did have some pretty sophisticated home-built stuff, but it wasn't the Kirtland Starfire equipment.

They did manage to get four videos and three stills. I think some of those have been in the media already. We are trying a number of ways to deconvolute those photos to try to make them as precise as possible to see what sort of images we can get off of them at that time. There do appear to be some irregularities in the shape that we see from the still. We have to still run that down and find out, you know, what exactly the shock wave field should have looked like from that point of view around the Orbiter at that time, whether or not we would have expected to see it look like that, whether we would have expected to see it be different. As you know, we've already shed quite a few pieces of debris by the time we got there. We were also able to pull one more piece of debris out of the Kirtland video in the two flares that I talked about.

MR. HILL: Let me put that another way, Admiral. We are capable – using the same techniques we used for measuring relative motion from the video, we are capable of drawing pictures of exactly what the Orbiter should have looked like to its Kirtland photographers, whether it's for their still photo or for their video. We're then capable of using computational fluid dynamics and projecting what the flow field should look like around those pictures and then we're also capable of taking that and handing it off to plasma physicists like at the Ames Research Center and generating what the plasma wake should have looked like around those still images. Then we can compare those against what's in video and what's in that still photo.

I would caution anybody in reading anything into either the video or the still photograph until we've gone through that process. The vast majority of people that have studied those images are imagery experts. They're not experts at what the Orbiter looks like during entry, the flow field around the Orbiter, the plasma dynamics or anything like that; and we're definitely premature trying to read engineering conclusions into any of those images before we've gone through that process.

ADM. GEHMAN: Thank you very much.

Members of the Board here.

DR. WIDNALL: I want to make sure I understood something that you said. I asked you about whether there was a time gap in the coverage. You said there was – basically you don't have any video pretty much between Kirtland and the more spectacular big events.

MR. HILL: That's correct.

DR. WIDNALL: You said that you thought there you expected that during this time gap that there probably was continual debris shedding but that we just didn't have pictures of.

MR. HILL: I think it's reasonable to assume that.

DR. WIDNALL: But it also might be possible that there was, in fact, a catastrophic event such as losing a wing or something like that.

MR. HILL: While I can't say that technically –

DR. WIDNALL: But it can't be ruled out on the basis of the data that you have.

MR. HILL: It would definitely surprise me personally that we would have something significant like loss of a wing that is not covered in the later video that we have of the main body breakup, based on what we have in telemetry and we know how the vehicle was flying and we know the sensor data that we have. My personal expectation is we capture that in the video, just based on what we see in the time line.

DR. WIDNALL: So where is loss of signal relative to the gap that you have in the video?

MR. WHITE: Loss of signal is over Texas. So we have data from the vehicle.

DR. WIDNALL: You're saying you have data from the vehicle that covers this region in time –

MR. WHITE: Yes, we do.

DR. WIDNALL: – where you don't have video.

MR. HILL: That's right. These red dots you see here, all of these represent actual GPS vector measurements.

DR. WIDNALL: So you do have data during that period.

MR. WHITE: Right. We do have data through that video gap period. So, yeah, it's highly unlikely that any large piece of the Orbiter like a wing would have come off, because we still have data from all of our systems that show that, even though they were failing, they were still there.

MR. HILL: Another way of saying that, if you look at the map, is these blue lines show you everywhere we had video. Everywhere where a line is red on the ground track, we had data coming down from the Orbiter. Then where it's yellow is the LOS time frame.

DR. WIDNALL: Okay. Fine. Then the second question really concerns this Debris 6 and the flash. As I understand the observations that were made in California of the flash, the flash was unusually persistent and it also was stationary in the atmosphere. So the question is: What is it? What do you think it is? Do you think it is aluminum burning in the atmosphere?

MR. HILL: It is possible that it is something that burned and came off the vehicle. It is what you would expect to see if we were to, say, vent a fluid or if we were to burn something and as we gave off combustion products, significant combustion products, not something on the order of, say, one of our reaction control system jets, but if we were actually burning something substantial and as we put that out in the plasma wake, you expect because that would have relatively no mass, certainly compared to an object, that those combustion products would immediately go essentially static compared to the Orbiter or compared to what we consider normal ballistic behavior for an object that has significant mass. So it is reasonable to assume that something came off that was very light or that that was some kind of combustion product like potentially aluminum slag that also was burning as it came off the Orbiter and then went stationary there in the wake.

DR. WIDNALL: So are you ruling out the possibility that there could be a chemical reaction that was stationary? In other words, are you assuming that as soon as it was all by itself in the atmosphere, it was not reacting.

MR. HILL: I'm not assuming that at all.

DR. WIDNALL: That's what your words seem to indicate.

MR. HILL: All I'm trying to say is it is difficult, if not impossible, for us to get much more specific about what we're seeing technically other than we see this bright thing come off the Orbiter and there are a handful of things that that could lead you to believe as to what those objects are or what the phenomena are, like a flash or the persistence of that flash. I agree with you that the persistence of that flash certainly indicates that you either have continued plasma wake around something or some continued reaction. The fact that it becomes more or less stationary would also suggest that it is something that is extremely light, probably more like a cloud or a combustion product.

DR. WIDNALL: Okay. I just want to make sure that we're talking the same language.

ADM. GEHMAN: But the best that you've been able to analyze so far is that flash that precedes Debris Shedding No. 6 is not merely a disturbance in the hot air. It's not just a wave or of the hot air or hot gases around the Orbiter.

MR. HILL: Probably not. Just due to its persistence, it is telling you that it is more than just something crossing through the wing. Something else is happening there.

MR. WALLACE: A question on the far end of the time line. The SSMEs. I've heard some opinions that those three bright objects you see in the last daylight video might be the SSMEs. I would like your opinion on that, and I haven't heard that we've recovered much of the SSMEs. Do you expect to? What are your thoughts on that?

MR. HILL: First of all, we do expect that those three bright dots in that Apache FLIR video are Main Engines or large components of the Main Engines. If you look at how they're behaving ballistically, they are certainly objects that are very heavy, relatively high ballistic numbers; and because they're so bright, they're continuing to move really fast. We also know from radar data and from, in fact, the SSME components we have found in Fort Polk, Louisiana, that, in fact, the engines or the large components thereof did stay intact for a long period of time and did go further east than any of the rest of the vehicle. I don't know personally – maybe Doug does – how much of each of the Main Engines we've found. I know that we do have main engine components that have been found and shipped to KSC.

MR. WHITE: Yeah. That's true. I don't have a reading of how much of each engine we've found. I can get you that number.

MR. HILL: That does beg a question on what we can learn from post-breakup trajectory analysis. Everything that I have talked about is pre-breakup. My entire team's focus has been pre-breakup. Everything that we have been trying to do is figure out what's coming off as early as possible and where is it so that we have some idea of where did the breach start, what caused the waterfall of events. It is certainly the opinion of the trajectory experts here at JSC that, taking the debris field as we find it in East Texas and trying to reverse-propagate it back to the vehicle is not something we are capable of doing. Again, going back to the FLIR video from the Apache helicopter, you saw all the secondary and tertiary breakups. As soon as you have additional breakups and those objects then become free fliers, they each have their own individual ballistic behavior. They're all now going somewhere else in the sky. We take the GPC we find laying on the ground in East Texas, we can back it up into the sky to some altitude but at some point we lose all truth, we lose all accuracy because that GPC at some point was in an avionics bay which at some point was surrounded by a compartment and at some point –

ADM. GEHMAN: What's the GPC?

MR. WHITE: General purpose computers.

MR. HILL: The fact that we know it behaves ballistically doesn't mean we can take it all the way back up to the Orbiter. At some point it was surrounded by another structure. If we could take the initial main breakup and assume that all the components we found in East Texas became free fliers at that point, we could do a pretty good job backward-propagating those things all the way up to the Orbiter; but we know, in fact, that it didn't happen that way. As Dr. Ailor said, even the individual components, say, individual pieces of tile that we find on the ground, whether we find them out west or the, say, the Littlefield tile, we don't know that that tile or object came off the vehicle looking like that. We have a full expectation for something fragile like a tile that, in fact, it did come apart.

Using some of the video, we know in several cases that the object, when you go frame by frame in the video, anyway, as you're looking at the object, you see a white dot come off the Orbiter and then you see that white dot shower into a lot more dots and then you see all the light go away. Probably indicative of something breaking. Now, is that several tiles coming off together and then flying apart? Is it a tile coming off and shattering into a lot of pieces? We have no idea.

MR. TETRAULT: As you're probably aware, we have found both of the forward corners of left wheel well structure; and that's where the wheel well door interfaces with the structure itself. So you have the inboard and you have the outboard corners, each of which demonstrates some venting coming out from the wheel well itself. My question is: If that's, in fact, going on, wouldn't you have an interruption to the plasma and wouldn't that show itself, to some degree perhaps, as a flare?

MR. HILL: Maybe. I hate to not be more specific; but, again it depends how did that hot gas get into the wheel well, was it flowing in or was it flowing out.

MR. TETRAULT: We're talking here about an outflow from the wheel well at the corners, forward in.

MR. HILL: Probably.

MR. TETRAULT: And it has an effect on the tiles at least, it's a guesstimate, 12 inches to 18 inches outboard from that venting. So it's quite a vent, if you will.

MR. HILL: Possibly. I mean, if you assume that that occurred pre-breakup and while the Orbiter was intact and still flying through the sky, it's possible that a jet like that coming out of the wheel well might change the plasma wake, might change what the Orbiter looks like to video taken from the ground; but we don't know. It depends on what direction was the shock, what direction was the plasma wake flowing in that is normally around the Orbiter, and did that jet actually make it all the way to the normal plasma wake and cause a disturbance or was it hidden or shielded behind the plasma wake that already existed around the Orbiter. We don't know the answer to that.

MR. HUBBARD: Two kinds of questions. First type has to do where all the material, raw material came from. Obviously we owe the public a great debt of gratitude for such cooperation. Can you tell us how many different submissions or contributions there have been and how many you sorted it into and a little bit about how you determined what was useful and what wasn't?

MR. HILL: Sure. Within three days of the accident, we had almost a thousand reports. Probably within a day or so of the accident actually, we were approaching a thousand different reports that varied from people calling in or sending E-mails and saying, "Hey, I looked up in the sky and saw this bright dot overhead," to, "I saw something happen and I want to talk to somebody about it," or videos where somebody called and said, "I have a video and I think I see something coming off the Orbiter," or," I have still photography and I think I see something coming off the Orbiter. Do you want it?" For the first day we spent most of our efforts sorting through a stack of close to 1,000 reports and, within about two weeks, about 3,000 reports that were all across the map. Just like that. We very quickly figured out if we were going to learn anything technically or anything of engineering value, it probably was not going to be in a report where people say, "Hey, I looked up and saw something in the sky," unless they said, "I looked up and I clearly saw something fall through the sky and smoke was coming off and that thing hit the ground close to my house." And there aren't very many of those.

So we very quickly narrowed it down to let's look for videos as far west as we can, let's look for still photography of the Orbiter in the sky as far west as we can, particularly time-lapse photography, and let's look for people that are amateur astronomers because those people are going to have a lot better secondary data like GPS coordinates on exactly where they were standing, exact zoom settings on their cameras, things like that, or exact time references, say, in the case of the video.

Within a week we had it narrowed down to about 15 videos that form the core of what we now have on this map, with the videos that actually show debris shedding that we were able to time correlate to within plus or minus a second. Then we spent some time after that first week or so prioritizing which of those we have the best celestial cues in, which of those that we think we are most likely to be able to calculate relative motion, and then which of those, like Debris 6 and 14, did we think would be so substantial that we might have a chance of getting them all the way to the ground and finding them in radar and putting boots on the ground and go and collect the hardware.

So I would say it took us about a week to sort out the initial round, maybe a week after that before we knew very well which of the videos, which of the stills were going to give us any meaningful data. From there on, it was a continuous process of analyzing the video, measuring the relative motion, generating these footprints, and then searching through radar. And without the public having taken these pictures on their own – because, to our great surprise, people are still very interested, apparently, in the space program and these folks got up before sunrise and went out on their own and stuck their cameras up in the sky and most of them also knew exactly where to look in the sky because again they were amateur astronomers – without those folks, we wouldn't know any of this. I mean, these people are definitely our heroes. And there are about 15 to 20 of these people or these videos that are probably the most key to us having been able to do any of this analysis.

ADM. GEHMAN: We join you in being thankful for that. We're also thankful for a crystal-clear morning across the entire southwest part of the United States.

MR. HUBBARD: Just a follow-up. There was a lot of debate early on about whether or not we were seeing some type of just bright gas or whatever. How confident are you, when you label the event in the time line as debris, that it actually is debris?

MR. HILL: I'm not sure how to answer that. We are reasonably confident. Again, I would say I am confident, if not sure, that many, if not all, of the things that we labeled as debris shedding events are, in fact, some object coming off the Orbiter. Can I tell you is it golf ball size or is it the size of this sheet of paper? I can't. It could very well be something as small as a marble in most of those videos and the ones that we think are so significant and that have gotten us so excited, those things could be golf ball size. We really don't know. We know relative sizes, relative motion, but we don't know specifically what they are. But we are very confident, based on the way they behave after they separate from the Orbiter, that they are, in fact separate ballistic objects or objects that have mass, in almost all cases. In the case of some of these flares, they could be something different like combustion products.

MR. HUBBARD: Just a final follow-up to this line of thinking here. When somebody sends something in, how do you determine that it's the real deal and not cooked up by a photo shop somewhere?

MR. HILL: For one thing, for most of these videos, we have had them for – we got them probably within a week. First week to ten days. Well, we got them within a week to ten days of the accident. In some cases we had them before that. It is possible, I guess, that some people could go and doctor them up. My expectation is we got most of these so quickly they didn't have the time to do that.

The other thing is in most cases we have overlapping videos, so we have redundant cues. In fact, we are taking advantage of that. We measure relative motion from one and we go back and measure relative motion on the other and we compare them. I would say they would have to be really darn smart to have doctored two opposite videos and give us the same relative motion in the two.

MR. WHITE: Our image analysts have also discovered some hoaxes that have been out there in the public and know they're hoaxes. They've also identified some things that have been anomalies or quirks of the way the photograph was taken – a jiggle of the camera, for example, that produced an effect in the photo that looked real but was not real, was an artifact of the way the photo was taken. They've also dispelled some things. Some of you may have seen what looked like a triangular shape when we were zoomed in close on the Orbiter that appeared to actually be showing the Orbiter in some detail. That wasn't it at all. So they have been able to sort out the hoaxes and the false images and the artifacts from the things that are real.

MR. HILL: Actually, most of our early hoaxes – and we did get some early on – were cars driving down the road with their headlights on. It was relatively clear to us that it wasn't something in space.

ADM. TURCOTTE: One last question from me. With your analysis of the radar and your being able to integrate the time line and the photographs together, are you surprised at the amount of wreckage that we have, i.e, do we have more than you expected from that analysis or do you think that you're surprised at that, at the amount that we do have?

MR. HILL: I'll give you two answers. Pre-breakup, I would say we continue to be shocked that we had debris coming off the Orbiter as we crossed the California coast and were dropping debris, clearly had an external breach in the vehicle and had hot gas somewhere in the left wing for that significant period of time and the vehicle flew perfectly, no indication of what was going on at flight control and virtually no indication of what was going on in telemetry on the ground other than we saw a few temperature pressure indications that didn't make sense to us and we had a few sensors that dropped off line. Aside from that, the vehicle flew like a champ until right up to the breakup. So that did surprise us.

Now, from things we are finding in East Texas, are we surprised that we only have 15 to 20 percent by weight of the Orbiter? I don't think so. I think when you first see the debris count and you see how many individual pieces of debris, our first reaction was one of surprise, how could we have gotten that much of the Orbiter down from 200,000 feet intact. Of course, I think you've also seen at KSC what they have is a whole lot of little, tiny pieces of what used to be an Orbiter. If you go look at it laying on the ground at KSC, you don't have a spacecraft lying there; you got a whole lot of nothing. I think that does fit in with what our conventional wisdom was prior to this happening.

GEN. DEAL: Follow-up to Scott Hubbard's question. Are you still expecting any more imagery, or do you think the well has run dry?

MR. HILL: No, sir, I think for the most part the well has run dry. Again, most people contacted us right away. We had most of the video in hand within a week. Overall, the support from the public has just flat been overwhelming. So I would expect not to get any more in.

Now, there have been two isolated cases out west of two individuals who strung us along for several weeks before it finally became apparent to us that they must have been under the impression they were going to collect on the *Columbia* gravy train. And it did take us a while to figure out while they trickled an individual image to us or an individual video to us that is, in fact, what was going on. They must have discovered this was their 15 minutes, but they are huge exceptions to the rule. The overwhelming support has just been fantastic, and I think we have it all.

GEN. DEAL: In the early days when the Admiral took us to Nacogdoches, there was talk about everywhere from offering a bounty money incentive for people turning in parts, you know, going out in fields and looking for parts, to certificates from NASA to thank them. Are any of those still under consideration, or are we just in a debris collection mode?

MR. HILL: To my knowledge, we are not planning on offering any rewards to people to incentivize them to come forward if they have not already. I can tell you the folks here that are doing work have every intention, when the dust settles, to come up with some formal recognition. We have various folks we want to recognize. In my team's case, we definitely want to recognize the people that took these images for us and made all this possible; and there are various things that, at the working level, we are kicking around that we would like to do. Now, I'm sure the Program will do something when this is all over.

GEN. DEAL: Great. Thank you.

One more for Doug. You gave us an excellent tracing of all the sensory. You've had plenty of time now to do some reflections on it and some lessons learned. Anything that you've already considered that we ought to be thinking about as far as sensor wiring, sensor location or junction boxes and how they're constructed?

MR. WHITE: I'd have to say no. It's probably too soon to speculate on any type of redesign that we might want to do with our instrumentation. As you know, the instrumentation wasn't designed to have flow inside of the wing; and so it probably failed in the way we would have expected it to. So as of yet, we have not considered any sort of internal redesign to better protect that instrumentation or even make more instrumentation available.

ADM. GEHMAN: Gentlemen, on behalf of the Board, we want to thank you for appearing today; but I hope you will also take back to your working groups, of which I know you are the tip of an iceberg of literally hundreds of people that are working with extreme zeal and professionalism to try and solve this riddle – because many of us have visited your working groups and we know how many people are working on this – please pass on to all of them our deepest gratitude and our deepest respect for the work that you all have done and will continue to do. We appreciate it very much. We haven't solved this thing yet, but someplace in your work we'll find the answer and we appreciate it very much. Thank you for appearing here today. We appreciate it.

(Hearing concluded at 4:24 p.m.)

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