Professor Sheila Widnall.

We are really lucky that she is able to come and talk to us today.

She has been here at MIT since 1964 as a professor and then as provost, but she didn't serve very long as provost because she was assigned to go to Washington by the President to be the Secretary of the Air Force, which she did for almost five years, I guess.

Four years.

Then came back here.

And she is now an institute professor which basically means you can do anything you want, right, including come and talk to our class.

In particular, Professor Widnall was on the Columbia Accident Investigation Board.

And that specifically is what she's going to talk to us about today, along with just general comments about how this relates back to systems engineering, the design, operation of the Shuttle, and basically anything else that you would like to say because it is your time.

So thanks for being with us, Sheila.

OK.

Well, thank you, Jeff.

As I understand the schedule.

It is two hours.

And if I don't finish, we still take a break.

And then we come back and finish, is that right?

Generally, the way we've run the classes is that we encourage students to ask questions while you're talking.

Absolutely.

That will probably slow me down a little bit.

Up to you.

Anyway, two hours, we'll just take it as it comes.

OK.

Well, I am going to focus on the Columbia Accident Investigation.

I must say, and I'm sure I will say many times as I go through it, that it was an incredible experience to be a member of that board.

02:00 I get chills up my back when I see that.

The reason I show this is for two reasons.

First of all, I mean it was, in fact, an incredible event.

I am sure that all of you can remember where you were that morning when that happened.

I also show it because of the expression on the face of the principal mission controller, Leroy Cain, when he realized that the Shuttle was lost.

And if the Shuttle doesn't make it to Cape Kennedy, more or less on schedule, there is no engine at that point, you've got a problem.

And so he was in a windowless box in Houston.

And so he had no kind of external, although all the citizens of Texas knew what had happened, the guys in the windowless box did not.

So it was really an incredible emotional experience for all of NASA as an agency.

But then what happens after that?

Well, fortunately the Challenger Commission had anticipated the need for a method to call an accident board into being if there should be another Shuttle accident.

And so there were individuals who were more or less ex-officio by rank or title waiting to be called.

So, the fact of the matter is, that on Saturday, when this all happened, the Accident Investigation Board was pretty much called into being at that point.

Now, who were the Accident Investigation Board at that point?

Well, they were primarily government employees.

Not so much NASA employees.

That clearly would have been unacceptable.

But they were military.

Three Air Force generals, the head of Air Force Safety, a general from Space Command and a general from Material Command who had actually served as an executive staff to the Challenger Commission.

That would be General Barry.

So, they had some very good experience.

The board was chaired by Admiral Hal Gehman who had been the Vice Chief of Naval Operations.

He had also been the Chairman of the Cole Investigation.

I don't remember how many of you remember the Cole Investigation, but there was a big explosion.

It is in the Middle East.

I don't remember.

Where was it?

Yemen.

It was probably Yemen killing 19 people.

And there were other government employees.

Somebody from the National Transportation Safety Board.

Jim Hallock who is across the street here at the Department of Transportation, the head of NASA Ames and the head of Navy Safety, Admiral Turcotte.

It was a smaller board than it ultimately ended up being.

05:30 And I'm blanking on names because I am at that sort of age, but we had a Nobel Prize physicist from

Stanford.

You have to have a Nobel Prize physicist on a Shuttle investigation.

Also, somebody who had been looking into issues of policy and history with respect to the Shuttle Program.

And I am not getting any of these names right so I'm not even going to try.

Pardon?

The class has met John Logsdon.

John Logsdon, right.

Thank you, John Logsdon.

Doug Osheroff was the Stanford physicist.

He was kind of a kick because at the beginning he was very media shy.

He just wouldn't talk to the media, but then he really got into it and he went way outside the box, which was kind of interesting to see how that all happened.

In any case, we were all pulled together and we were chartered to uncover the facts, as well as the actual or probable cause of the Shuttle mishap and recommend preventative and other appropriate actions to preclude the recurrence of a similar mishap.

Yes?

Professor Widnall, before you and Sally Ride came on there were no females?

That's right, no women.

[AUDIENCE QUESTION] I'm not sure.

Maybe a little bit.

But, actually, the day of the accident, of course everybody was saying what happened?

That's not what I was saying.

I was saying I wonder who is going to be on the board.

I actually had a strong sense that I, in fact, would be on the board.

Think about it.

Gene Covert had been on the Challenger.

I think, like you have to have Nobel Prize physicist from Stanford, you have to have an aeronautical engineer from MIT.

I think the other thing was, as Secretary of the Air Force, I was really in charge of accident investigation.

All accident investigations reported to me.

Well, you guys don't know a lot about accident investigations in the military.

But there are two accident investigations in the military.

One called a safety investigation, which is privileged, and you take testimony and you seal it.

And I will talk about that later because we tried to replicate some of that on the Columbia investigation.

You have that one and then you have the public investigation which you take testimony, people can be court-martialed.

There is an Accident Investigation procedure that goes on in the Air Force, and I had really been in charge of that.

In addition to be an aerodynamicist, which is always good, I was the aerodynamicist on the commission, I was a faculty member at MIT, I had been Secretary of the Air Force, I had been in charge of accidents.

Also, I had spent my last five years really being interested in space, safety and mission assurance in space.

I mean all these things kind of came together.

Sally Ride was obvious.

She was an astronaut.

And she had been a member of the Challenger investigation board.

She brought that historic knowledge.

I don't think that was the primary thing, but it is probably good to have a balanced group. See, I actually did come on board pretty much February 18th.

That was when I came.

I think that one of the early issues that we faced was our relationship with NASA.

I think at the very beginning NASA had this image that we would work for them.

That was one thing.

And the second thing was that we would find the widget that failed and then we would leave leaving them to carry on.

Not with this group of people you don't do that, and not in this situation.

We very clearly and fairly early established our independence.

We removed a number of senior NASA people from inline responsibility for the investigation like Ralph Rowe.

Again, I'm blanking on these names, but the people who had been in charge of the program.

Of course, some of them quit even before we got there.

Linda Ham was right in the middle of things.

And we just said look, we're not questioning your integrity but you just cannot investigate yourself so we need to move you aside.

Go back to your normal responsibilities and bring in independent people who had not been so deeply involved.

And they will be the primary interface between the Accident Investigation Board and NASA because we really needed to use NASA.

I basically had very strong interactions with the NASA aerodynamics division.

And you will see the reasons why as we proceed.

But at the end of my interaction with them, which occurred at the end of June, and they presented their 450 page report to me with all the calculations and studies and things that they had done at my direction, I basically looked to the group and said well, I think I could probably give 22 PhDs at this point to this group.

Because we had really pressed the envelope in terms of improving the methodology that we used to analyze some of the details of kind of what I'm going to talk about.

But, in any case, the issue of independence was extremely important.

And I recall a lot of meetings with a lot of banging on the table and yelling and screaming before we finally got this all straightened out.

Admiral Gehman was an incredible leader.

He really just did such good work.

He had a sense of where to press and where to stay on pad and how to interact.

He really was a marvelous chairman.

Incidentally, he recently served on the BRAC Commission so he is somebody who is deeply involved in public service.

And I know, from my conversations with him, that he is a person who refuses to serve on any board of directors that has anything to do with the Department of Defense because he does not want to give the appearance of a conflict of interest.

And he is just a man of incredible integrity.

Obviously, I am a big fan.

In any case, we proceeded then to wrap our group together and begin our interactions with NASA.

12:30 And I will show that a couple of times.

And this happened in about 81 seconds, two seconds after launch.

I don't remember the mach number, but I think it was something like 2, 2.5, something like that.

This is the video.

And you see the piece coming off and smashing.

And I will show it again.

That video was pretty much available the weekend of the launch.

There was an understanding among senior program managers that there could be a problem.

Now, what did we know about it?

Well, there were video cameras at the site.

There was a video camera located here, a video camera located here.

A rather shallow angle to try to do any triangulation.

But, obviously, you use what you have.

And so, as a result of triangulated these two video cameras, we were able to make an estimate.

It's probably also worth mentioning that there were other video cameras but they were out of order.

Right.

And I was going to talk about that with respect to our recommendations.

One of our recommendations was that working video cameras were an absolute necessity for launch.

In other words, you do not launch if you don't have a reasonable set of video cameras.

And, by the way, you don't launch at night because then, obviously, the video cameras would not be any good.

That was one of our recommendations, what I would call a near term recommendation, return to flight recommendation.

Yes?

[AUDIENCE QUESTION] I don't know the answer to that.

Maybe you know the answer to that.

It is very interesting because I have been doing a lot of mission assurance and space accident stuff.

You almost always have a picture of a space accident mostly because they occur on launch.

So, in the case of the Challenger, we had excellent video.

We could see the little hole in the Challenger.

We could see the stuff coming out.

In this case, we had reasonable video of potential impact.

You can launch with an 8000 foot ceiling.

In which case we would not have seen the Challenger.

Yeah, at that point.

I don't think it's true now.

And I don't know how they followed up on that, but there is also a possibility of using aircraft if they cannot get the video.

In any case, it turns out to be an important issue.

And we made recommendations.

What we knew about the impact was we figured -- Of course you guys all know exactly what this is.

This is the left wing underside.

This is where the curvature changes, and so it was kind of right in here some place, what we refer to as panel seven, panel eight, panel nine of the underside of the composite material that surrounds the leading edge.

Now, I don't know if you guys have studied that composite material.

It is a truly marvelous material.

And I may say a little bit more about it.

So, we sort of knew where the impact had occurred.

Obviously, we were hampered by the shallow angle of the video but this was our best estimate.

The velocity was estimated to be roughly 800 feet per second.

And that was obtained from several different methods.

One was a computational fluid dynamics calculation of how would the airstream accelerate a piece of foam of that particular shape weighing two pounds and having it hit?

And the other thing was from the video itself.

We had pretty good correlation between the estimates based on the video and the estimates based on calculations using computational fluid dynamics, so we felt pretty comfortable about this velocity.

What did we know?

When I joined the board what did we know?

What kind of data did we have?

Well, this particular vehicle had some telemetry of some sensors in the wing and in other places.

At this point in the investigation, we had not recovered the flight data recorder.

The other thing that is interesting is that this is the only vehicle with a flight data recorder.

This is the vehicle that was considered to be a research and development vehicle.

All the other vehicles were operational.

They did not equip them with flight data recorders.

Now, I will get back to this point when I talk about the criticisms that we had of the agency.

But we took strong exception to the notion that the Shuttle had be declared to be operational.

And, therefore, there was no need to continue to study it as a research and development vehicle.

It was just like a piper cub or a 747.

That takeoff was a routine event and was not, in fact, a major event.

And even in this system, if a sensor failed in the flight data recorder it was not replaced.

So what we had on the Columbia was a wasting asset, but at least we had an asset.

We had a flight data recorder.

At this point we had not found it.

Where were these sensors located?

Well, there were a lot of sensors in the wheel well.

There were some temperature sensors in this region of the leading edge.

There were some temperature sensors back in here and different places.

Now, one thing that is significant about this is that these temperature sensors were connected to two different boxes.

Actually, it looks like three but what I'm going to focus on are these wires.

Some of the temperature sensors were connected to wires that were basically in this region and running along the wheel well.

19:30 That's one of the reasons why that was important and kind of how we began to hypothesize what had gone wrong.

Now, you see the time was sort of 8:44.

That is Eastern Standard, I think.

I was shopping, actually, at the time.

Between 8:44 and 9:00 is when all of this took place, so we're talking about 15 minutes of problems.

At 8:44 everything was fine and at 9:00 the vehicle had crashes.

20:30 Why did these sensors fail first?

It was because the wire that controls these sensors is located here in this sort of critical area, so that was the wire cutting.

Yes?

You said the other orbiters don't have flight data recorders.

Right.

[AUDIENCE QUESTION] Commercial, that's a whole different mindset.

Yeah.

I mean those carry people and it is an FAA regulation.

21:30 That the wires were being cut.

And so we could follow the failure of these sensors right up to the point when the vehicle, we had loss of signal which was at about 8:59.

This whole thing happened fairly rapidly, of course, and this was the trajectory of the vehicle.

I will show another picture, but the whole problem sort of started off Hawaii and then the vehicle began to break up here in Texas.

This was kind of what we knew on roughly February 18th.

In fact, that's all we knew really.

I mean the temperature increases were not particularly dramatic, you know, 50 degrees, 30 degrees.

That's not really interesting.

What was interesting is the wires were cut.

That was more interesting.

OK.

We began to look for the debris.

We had people essentially marching over the State of Texas about that far apart.

It was an extremely expensive thing, but we recovered about 40% of the material that came from Columbia.

And, of course, it is all these little pieces of stuff that fell on the ground.

Fortunately, it fell in a fairly rural area.

Nobody was hurt.

I don't think there was any damage to structures or anything like that.

And we were able to recover a great deal of it.

A lot of it, because I actually looked at the weather radar, was very small particles that actually floated into the Gulf of Mexico.

I mean you could see it on the weather radar, the NEXRAD system.

You guys all know what the weather radar is.

But you could see the particles streaming into the Gulf of Mexico.

I think a lot of it was just sort of vaporized.

And there is a footprint of the debris.

And we did a lot of searching in that area.

We tried to search upstream.

We were really trying to find the earliest pieces of debris, but these fell down onesies and twosies in really strange places like in mountains in Utah and stuff like that.

So we were never really successful, although some of these had been tracked on radar by the FAA.

And there is the debris collection, a hanger down at Kennedy.

This is pretty standard stuff for a commercial aircraft, I think you all know that.

When you have an accident, what you try to do is recover the debris and reconstruct the vehicle.

This debris was particularly interesting.

And I don't know if I have a graph later, but let me talk a little bit about the temperatures involved.

We're talking about reentry of a damaged vehicle at mach 25.

Now, of course, that is the course that I tried to get out of when I was a graduate student, was that high temperature stuff where the gas begins to ionize and dissociate and, you know, all that enthalpy stuff.

I really tried to avoid that, so I got paid back.

Anyway, that is the subject of high-speed gas dynamics.

And so I had to take a refresher course.

And Judd Barren, one of our faculty members, was extremely helpful.

I used to go over to his house on Saturdays and he would give me references.

But, roughly speaking, if the gas didn't dissociate, the temperatures on reentry at the leading edge of this vehicle would give off 50,000 degrees Fahrenheit, which is really pretty hot.

The fact that the gas does dissociate -- Ionization at this mach number is not that important.

It interferes with the radio signals but does not, in fact, absorb a lot of energy.

The gas is slightly ionized 1%, something like that, 2%, but not enough to be a big energy issue.

But the dissociation of oxygen, dissociation of nitrogen is an extremely important phenomenon.

And, because of that, the gas temperature is roughly 10,000 degrees Fahrenheit which is a lot better than 50,000 degrees Fahrenheit.

So that makes a big difference.

Let's talk about the leading edge material.

The leading edge material is, in fact, an incredible material.

It is a carbon-carbon composite material.

It is about a quarter of an inch thick and it can withstand a temperature of 3200 degrees Fahrenheit.

And the Shuttle was conceived in, what are we talking about here, '70?

Yeah, '69, '70.

We don't have much better materials today.

We might be able to go to 3400 degrees Fahrenheit instead of 3200 degrees Fahrenheit, so we've made some progress, but this is a marvelous material.

Now, how in the world, with the gas temperature of 10,000 degrees Fahrenheit, can you use a material of 3200 degrees Fahrenheit?

Well, that's the other part that I tried to avoid as a graduate student.

It is called radiation.

And what is it?

The Stefen-Boltzmann Law of Radiation, T to the fourth.

And you could write it down on the back of an envelope and you can calculate it.

And it turns out that the gas coming in does heat the leading edge up, but then the leading edge radiates out the right amount of energy to basically have an equilibrium temperature of the order of magnitude of, say, 2800 degrees or maybe 3000 degrees.

It is comfortable below its maximum temperature, but this is obviously a very dangerous situation.

In the early days of the Shuttle Program they made some tests of this material, its ability to withstand impact.

They shot BBs at it and made quarter inch holes in it.

And then I'm a little fuzzy on this part.

They may have tested those quarter inch holes in an arc jet to see would they ablate, how would they behave and would they grow?

And I think at that point they felt comfortable that they could withstand the impact of a BB and not be destroyed.

So that is an important set of issues.

I guess the other thing I want to point out is if you have a good solid continuous edge you can support a temperature of 3200 degrees because of radiation.

But if you get a hole in that leading edge then the gas that goes into the cavity behind the leading edge is your old friend 10,000 degrees.

But there is no radiation balance to bring you back down to 3200 degrees so you have a 7000 to 10,000 degree arc jet coming through any major size hole in the leading edge of the shuttle.

And that is, of course, exactly what happened.

And, to remind people, 10,000 degrees is the surface temperature of the sun.

Oh, it's very hot.

Yes.

There is no material that will withstand this.

And this happens routinely in shuttle operations is that the shuttle reenters at mach 25 and the temperatures of the gas surrounding the shuttle are about 10,000 degrees.

And we've successfully gone through how many shuttle flights in total?

114.

It's a sporty course.

Now, I want to talk about something else we knew before we found the flight data recorder.

And this was of great interest to me for lots of different reasons, but one of the things we were able to do is infer the aerodynamics of the damaged vehicle by looking at what the Flight Control System had to do in order to keep the Shuttle perfectly on its pre-assigned flight path.

In other words, until very late in the flight the Shuttle was doing exactly what it was programmed to do.

But it was working a lot harder and in very off nominal ways.

And we had to back this out.

Now, this is almost like a zero over zero calculation so it's a little sensitive, a little hard to do, but this was something the aerodynamics group did.

And I worked really closely with these guys.

I have great admiration for them.

They were able to back out the off nominal roll moments and the off nominal yaw moments of the Shuttle during this final reentry.

And I made this little schematic of kind of where were they when some of these things happened in terms of the Coast of California and their flight over New Mexico and down to loss of control over Texas.

Before I do that, let me just add to my previous remark that you almost always have a picture of a space accident.

Now, normally that's because space accidents occur on launch.

This is a remarkable photo of a space accident.

This photo was taken by modestly my guys at Kirtland Air Force Base.

And basically they had been working with optics.

That is basically their business.

And so Saturday morning IBM personal computer, fooling around with some little telescope that they had been developing for tracking things.

32:00 Yeah, this is interesting.

This is a bulge at the leading edge showing some distortion of the shock shape due to vehicle damage.

And I obviously consider this photo to be extremely probative.

And also there is a small amount of debris that has got some optical signature to it that is sort of streaming out of that general area indicating -- I mean there are all sorts of things going on in this vehicle, but one of the things that was going on was the melting of aluminum, the vaporization of aluminum and the combustion of aluminum because aluminum will burn.

I don't know how many of you know it but aluminum is something you add to rocket engines in order to get higher temperatures.

It burns when it gets hot enough.

It can be a very dangerous material.

In any case, we suspect there was a lot of aluminum combustion going on while this thing was happening.

Had there been, for reference, any similar photographs?

No.

So we didn't have a nominal baseline.

No, as far as I know.

I actually don't know the answer to that question.

I know, because I know the guys who took the photo and I know their boss, that they were doing it for a very specific reason that had nothing to do with anything they had done in the past.

They were trying to develop a little telescope to track things because that's what they do at Kirtland, is they work with optics.

But I don't know whether anybody has tried to do it.

I suspect their level of precision is a little greater than the average citizen trying to take a picture of the Shuttle coming in.

But this was not a really high powered telescope.

I mean they had some really high powered telescope at Kirtland.

This was just a small one.

Anyway, I don't know the answer to that.

Well, I think what we're looking at here is the glowing of this 10,000 degree envelope that surrounds the Shuttle.

That is what we're looking at, is we're looking at the radiation, basically, from the gas surrounding the Shuttle.

It was normal.

But, of course, this was 8:50 in the morning Boston time.

This is February so it probably was dark in New Mexico.

That is kind of the picture that we go, which I think is really neat.

This is the trajectory, but this is the backing out of the off nominal moments.

Now, let me talk about the yaw moments just to give you a feeling for what does all this mean.

I contend that off nominal aerodynamic forces are an indication of external damage to the

vehicle. That is basically what it is.

The vehicle was flying because its reaction jets were moving and doing all sorts of things.

The aerodynamic surfaces were virtually useless at these dynamic pressures.

This was a reaction jet controlled vehicle, but we knew how much force the reaction jets were putting out so we could do the vehicle aerodynamics.

Let me talk about the yaw moment.

What we have here is that as the accident began the yaw moment became negative, kind of flattened out for a little while and then became very strongly negative.

What is yaw moment?

Yaw moment is the force turning the vehicle this way.

If I have a damaged left wing, what is my yaw moment going to be and why?

Well, I'm going to have increased drag on this wing because I've got a big chunk out of the leading edge, I've got a disturbed shock, I've got all sorts of stagnation pressure in this region where in normal circumstances it would be smoothly flowing.

I've got increased drag on this wing, and so that's going to drive me this way which is exactly what you see.

That is off nominal yaw moment.

Roll moment is a little stranger.

Basically, as the drag increases, and you probably lose lift so your roll moment begins to go like that, you have decreasing roll moment.

This was a bit of a mystery because basically what it said is you lose roll moment, but then all of a sudden your roll moment increases.

That is a problem that only an aeroelastician could solve.

I happened to be an aeroelastician.

Do you know what I'm talking about?

If you stick your hand out of the car window and you turn it slightly what happens?

It goes up.

And it may also turn some more.

In other words, if you lose the leading edge spar of a wing, you lose its resistance to torsion.

Now, we don't have all the data we need to prove that that's what was going on.

But I believe a strong hypothesis that we lost the strength in the leading edge spar and the leading edge spar tipped up.

And obviously the lift would increase because the angle-of-attack was increasing.

But this was a very, very puzzling and very interesting phenomenon.

But, in any case, what happened is that both the roll moments and the yaw moments got too strong for the control system of the vehicle which, again, was just the reaction control jets that are on the area around the vertical tail.

Then, ultimately, the thing went into a spin, lost control and then, of course, the vehicle was lost, began to break apart.

This was a very interesting set of data.

And, as I say, when we started, this was pretty much all we had.

There was a pivotal moment, and it occurred sort of at the end of March, about March 27th.

Remember, the accident occurred February 1st.

We found the flight data recorder.

And we found it by these guys walking across the field looking for stuff.

And the flight data recorder was found.

And it was in pretty good condition considering it had done a reentry at mach 25.

We were able to recover the data from the flight data recorder.

I think we pretty much got it all.

At that point we had hundreds and hundreds of data points.

And I would say, at this point, NASA's attitude changed.

I think up until this point there had been a certain level of denial about the accident, about what caused it.

Maybe it was a micro meteorite.

Maybe it was some unexplained system failure.

They were not really sure that we were pursuing the right road until the flight data recorder was found.

And I think maybe that's to NASA's credit.

NASA is data driven.

And when they began to see the data and they began to see how well the data correlated with the hypothesis and the models then they hopped right onboard and did a tremendous amount of work to try to help us unscramble all of this and come to a hypothesis.

What kind of data did we have?

Well, this is a picture of the leading edge spar, this big thing here.

And this is a picture of the hypothesis sort of about a piece of foam taking out a fairly large piece of this carbon-carbon fiber and allowing hot gas to enter into the region behind the leading edge.

This leading edge region is, as you can see by the picture, sort of hollow.

There isn't anything back there.

There is a layer of insulation covering this, but that is because of the radiation.

In other words, because this, in fact, is 3200 degrees.

It radiates in both directions.

And so there is a layer of insulation here to protect against radiation.

But that insulation will not protect against the equivalent of an arc jet.

That is just, again, burrowing and blasting it.

It was fairly quickly that this gas just blew a hole through the leading edge spar.

How did we know that?

Well, it's kind of interesting.

Let's look at one of these.

We had all these wires back here.

And we had these temperature sensors.

Let's just pick one temperature sensor.

I didn't even know where it was located, but it was not located in this region.

It was located back someplace else.

So we looked at the temperature sensor and compared it with earlier flights where the earlier flights would show this behavior and this temperature sensor kind of did this.

It began to go up and then all of a sudden we lost it.

What happened?

42:00 The picture begins to emerge of wire bundles being cut, of gas entering here, of this wire bundle being cut to the sensor of this, in fact, entire region beginning to sort of fill up with extremely hot gas, 7000 degrees roughly, eventually entering the wheel well, although, that was later in the flight.

We did have some indication of the gas in the wheel well because of the temperatures and the loss of sensors.

Because of this the focus turned to the question of this what we call RCC, which is this composite material that surrounds the leading edge.

And where did we find it?

And we found a lot of it.

I mean we found it all along in Texas.

The other thing we were able to look at, with respect to the RCC, is its pattern of erosion.

I mean this RCC was kind of flopping out in the breeze here at roughly 7000 to 10,000 degrees.

And so it was a material that was being effectively subject to an arc jet.

And, if you took a material like that and stuck it in an arc jet, it probably would ablate and it would maybe sharpen up and you'd have maybe little pointy edges where it had ablated.

And so we looked at the part that was particularly eroded.

And that would be the yellow stuff.

And we found that upstream of the stuff that was more put together, the rest of the RCC from the wing.

And, from the right wing, we found the right wing downstream of the left wing which means that the left wing came off first.

Now, the image that emerges from this is hole in the leading edge, material coming off, but gas flow going down this what some people called the "chunnel." I never liked that term, but it's a big open cavity.

Gas flowing down this open cavity and simply destroying all the fittings that held the RCC onto the wing.

I mean the screws and the brackets and all of that.

And, again, gas is coming in.

And the wing just unzips.

All this stuff just kind of unzips and falls off.

And, of course, that is where we find it, just lying on the ground.

It all unzipped and fell off.

What did we actually find?

45:30 What we had to do, however, is to construct analysis using a whole lot of different disciplines.

And we had to be able to analyze, according to the rules of that discipline, and line them all up for consistency.

And I would say that we never found a theoretical or experimental result that was in conflict with our basic hypothesis.

And that everything sort of lined up.

I was more or less in charge of the aerodynamic analysis, as well as my favorite subject thermodynamic analysis.

I never liked that part either, but the whole question of heat transfer and how fast these materials would melt, I was pretty much involved in that.

I may have another picture later, but let me just show you some pictures that we had.

There is a hypersonic wind tunnel down at Langley.

And we did a lot of tests in that wind tunnel.

One of the things we did was we had a score of wind tunnel models.

They were about this big.

But we took chunks out of their leading edge.

We have our wind tunnel model which was the nominal shuttle.

And then we'd have a nominal shuttle with panel six missing and then a nominal shuttle with panel seven missing and a nominal shuttle with panel eight missing.

47:30 And then you see the green.

That is probably a little intermediate temperature.

And then you see the blue.

That is probably lower.

But, if you look at this, being an aerodynamicist, I can tell you where that vehicle gets hot.

It gets hot near stagnation points and near leading edges.

And especially at the stagnation point on the vehicle.

You can put a wind tunnel model like that in a hypersonic tunnel painted with this special paint, and you can take pictures of it and you can get that temperature distribution.

Here is my little figure of aerodynamic forces.

We had all sorts of data from both the flight data recorder and the telemetry that gave us a pretty good indication of the timeline.

If any of you ever want to come into my office, I have this enormous poster.

It's like ten feet long which basically shows the timeline of the Shuttle reentry with all kinds of the individual data bits, the temperature distributions and all the things that kind of we could fit on this enormous poster.

That is kind of what we were trying to do.

We looked at the debris.

We looked at forensic analysis of the debris.

Where was it ablated?

What was its chemical composition?

Did we see melted Incanol?

I mean we saw all these things and were able to figure it out.

Well, we knew what temperature Incanol melts at so, therefore, the temperature on this particular piece was, I don't know what the temperature of Incanol is, but let me say 1200 degrees.

It would be that kind of material.

49:30 And you don't replace this material.

This material is the same material that was used on the original shuttles.

Every time it flies it loses a little bit of stuff through vaporization.

And so then they kind of tried to paint it again, but I think our hypothesis is it just gets weaker and weaker as it is being used.

And the problem is it is hardly being made anymore.

It is material that was all made at the beginning of the program.

It is not being made anymore.

It is very expensive.

It is not a material that is easy to get.

And, in fact, that became an issue for us because one of the things I will show is we wanted to do a full scale mockup of the leading edge and we wanted to test it with a piece of foam going 800 feet per second.

Now, why would we want to do that?

Well, that is exactly the test conditions that we wanted to simulate.

Well, that is not only expensive but this material just doesn't exist.

I don't remember where we got the material.

We probably took it off of Endeavor or something like that.

But, I mean, this was a big deal that we should run this test because the material is very precious.

But, anyway, we banged on the table and said that we were going to do this and that they had to support us.

We did the wind tunnel test.

I have a question about that test.

Yes?

My reaction, as an outsider, when they published the pictures of the holes on that test was wow.

Wow.

That was my reaction, too.

Yeah, my reaction was wow.

51:30 Anyway, we did the tests and we studied timelines, we conducted arc jet tests, we did forensic analysis of debris, both chemical and sort of physical.

We did a lot of different in-depth analysis.

The test itself, in addition to being expensive and working with material that was really hard to pull together enough of this material to run the test was also emotional.

It was also an emotional event for the people involved.

And just very late in the game NASA said we are prepared to accept that the foam put a hole in the leading edge so don't run the test.

And we said well, you may be prepared to accept his but somewhere down in your organization is someone who doesn't believe that, and this test is for him.

I actually met that guy.

I mean there are people in NASA who do not believe this.

So maybe what makes sense is let me show the movies and then we will have our break.

Here is the wow.

Can I hear it from the class?

Wow.

And this really was.

I mean the guy who developed this material, and, as I say, I have great respect for that material.

53:30 Let me go inside.

This is inside.

They had a camera mounted inside.

That is kind of gee whiz thing because you can see the deformation before it breaks.

Was this done in the wind tunnel?

No, this was a full scale mockup that was done at Southwest Research Institute.

We had a big mockup of the vehicle.

It was done outside.

Southwest Research has been involved in the Shuttle Program for quite a while.

They have a foam gun that they have used to shoot foam primarily at the underbody tiles.

The concern has always been on the strength of the tiles.

Do you guys know what the tiles are?

The sort of foam stuff that is underneath the vehicle.

They have done a lot of tests on foam.

Not big pieces of foam but sort of small pieces of foam.

Never tested the leading edge because it is damn expensive to test this leading edge material.

And the only tests I am aware of were these BBs that were shot.

This was really the first time this test was done.

Now, let me make a profound comment about space systems.

There is a fundamental principle in the development of space systems, test-as-you-fly.

You all know that.

I hope you all know that.

This test should have been done at the beginning of the Shuttle Program.

It was not done.

And the reason it wasn't done is because there was a requirement in the Shuttle Program that foam shouldn't come off the orbiter or off, whatever that thing is, the tank.

It was a requirement that foam shouldn't come off the tank so, therefore, why do the test if it's a requirement that foam not come off?

Well, the fact of the matter is foam has come off on every single shuttle flight, as far as we know.

So this was a violation of the test-as-you-fly principle.

That is, I would say, the number one principle in the development of space systems is test-as-you-fly.

It is the most important thing.

Anyway, we can take our break now.

And remember JR Thompson's remarks about testing to failure, which they did on the main engine, didn't do on the SRBs, and they clearly didn't do here.

OK, a quick two minute, you know the drill.

What you see is sort of an aluminum frame.

I mean what you have here is really what would be called a full scale mockup.

It is an aluminum frame that holds the tile in the right position.

And I suppose holds it with fittings of the right strength.

In other words, what you're trying to do is replicate with what would be called a full scale mockup the structural conditions of the leading edge.

You would have fittings holding the panels and then you would have it angled properly to the foam gun, which is over here some place, and then you fire the foam at 800 feet per second.

So that's basically the test.

And, as I say, it was done outdoors.

It was quite spectacular.

A big audience, you know, there was the media and NASA.

A big audience.

It was quite an event.

As a result of this, the committee felt pretty confident that we had identified the technical cause of the accident.

When we started this, we didn't know how sure we would be so we had all these words like probably, more likely than not, conceivably.

Because we needed to think about describing our certainty whether we knew, in fact, what had happened.

But by the time we finished all of this, because everything had lined up so well, we felt pretty confident that we knew, in fact, what had happened.

And so we all sat down around the table and argued about these words.

This was a committee consensus.

We voted on every word.

Well, not every word.

Some of the words are obvious.

But we basically came to consensus on every single important word in this statement of technical cause.

I will just sort of let you read it because it took us a long time to write.

I should mention that one of the things.

And I think this was from the flight data recorder.

I really have not given you as much data about the flight data recorder.

But one of the things we had from the flight data recorder is an indication of conditions on assent relative to earlier flights.

And if you look at the conditions on assent, you can make a pretty good case that there was a hole in the leading edge on assent after the foam had hit.

Because you see increased temperatures on the sensor right behind that region of the leading edge.

And so you can make a pretty good case that the hole was there on assent after mach 2.5 or whatever the mach number was.

But that was data from the data recorder?

I believe it was from the flight data recorder.

They didn't get that on telemetry?

They did not have that from telemetry.

I'm pretty sure about that but I'm not absolutely sure.

Yes?

[AUDIENCE QUESTION] Oh, they knew that weekend.

Oh, in fact, I'm going to talk about that because that's part of the organizational and cultural issues.

Finishing the technical cause, this was our final statement about the cause of the accident.

But we didn't stop there.

Not this group of people.

Yes? I was going to ask how soon did you arrive at the hypothesis that the hole led to the gases that led to the [OVERLAPPING VOICES]?

I think pretty quickly?

Yeah, I would say it was pretty quickly.

Now, there was a little pushback from NASA on that.

But I described my appearance on February 18th on the board and the fact that we had the wire cutting sensor information, that we had the video of the foam hitting the Shuttle and exploding.

In other words, there was a shattering of the foam.

And we had the aerodynamic forces which indicated damage to the vehicle which were consistent with the wing leading edge.

We have a picture from Kirtland of some bulging around the wing leading edge.

I would think by sort of the third week in February that's where we were headed.

Now, you don't want to get blindsided.

Sure, we don't want to get blindsided.

We got lots of inputs from the public, as well as from the scientific community.

And there was an input we felt we had to take seriously.

And I can sort of say what it was.

We got an input from sort of solar physicists who said that on that day there was a violent sun episode that would have sent a shower of solar radiation to the earth on that particular day.

And that it was possible that this could have created some kind of shockwave in the vicinity of the Shuttle and done some damage.

I mean it was a credible hypothesis.

I called the Air Force.

Out at Hanscom we have these guys who do basically radiation physics, radiation weather, space weather.

And Jim Hallock from DOT kind of shepherded that part of the project, but Jim is a physicist.

He has a PhD from MIT and works at the Department of Transportation.

And so the two of us go together and said we have to take this seriously.

We have to put an expert team together and completely examine this hypothesis.

So we did that.

And we had data from all over the world of this radiation coming in, and so it was very exhaustive.

It turned out that this radiation didn't reach the earth until 3:00 PM on that day, but we took it seriously.

I think that was probably one of the most credible things.

We obviously got a lot of junk stuff that it was an Israeli plot or something like that.

I cannot even remember those things.

And then I think there was always this suggestion that it was just a micro meteorite, but I think because of the magnitude of the damage and the fact that, I think this is general knowledge, the Air Force watches space junk.

They have a catalog of everything that is lying up there, and there wasn't really a piece up there large enough to do that kind of damage so that was eliminated.

There were a number of hypotheses.

But, again, when we did the data, we didn't go in with a hypothesis.

We went in to see what the data told us.

That was a bit of independence with respect to the data and the analysis.

Yes?

[AUDIENCE QUESTION] No, it is melting.

No, the temperatures.

See, it's aluminum.

[AUDIENCE QUESTION] Eventually.

Well, I think heat was the main culprit.

The dynamic pressures, and I am sorry I didn't bring the graph, in this regime were not that large.

I am thinking they were less than 100 pounds per square foot because you're really up at very high altitude.

And, even though you're going very fast, the dynamic pressures are not that high.

I actually have a graph of dynamic pressures.

In fact, come into my office and you will see the dynamic pressure as a function.

I would think the way to think about it is that the important parts melted.

See, we know from observations, and I didn't show all of these, but people were recording, I don't remember what we called them, but big pieces of the Shuttle were coming off.

You saw the video with all these pieces flying in, but we have pieces coming off as early as California.

And I think we hypothesized at one point that the upper wing came off.

In other words, the upper surface of the wing just lifted off.

And the reason it did is not so much from pressure is that all this gas is in there.

Aluminum melts at 700 degrees Fahrenheit or some ridiculously low number.

We're talking 7000 degrees Fahrenheit so we're talking about destruction primarily by arc

jet. You have to think of the atmosphere as a big arc jet.

And eventually the vehicle became uncontrollable, unflyable because the aerodynamics were so off nominal and the vehicle couldn't be controlled.

But, again, I think the dynamic pressures didn't get larger than 200 pounds per square foot.

I don't think.

Which is about what I am doing right here.

That is about 200 pounds per square foot.

Yes?

What happened to the crew?

[AUDIENCE QUESTION] I probably don't want to talk about that.

We have some information.

Well, let me say what I can say.

The vehicle itself stayed intact through a large part of the reentry and got into what would be called the fighter pilot's regime, you know, 50,000 feet.

The actual cause of the death of the crew was what any fighter pilot would experience if he lost his vehicle at 50,000 feet.

It's blunt force trauma.

That is what it was.

And we found a lot of the cockpit.

Reentry is really interesting.

There is something called ballistic coefficient.

Do you know about ballistic coefficient?

We found briefcases, pillows.

Ballistic coefficient, people talk about it in two different ways, and one is the reciprocal of the other.

I always get confused about that.

But if you have a low ballistic coefficient and you drop a pillow at mach 25 at 400,000 feet, it would probably make it to the earth because it will slow down and then it will just gradually float down to earth.

We found a lot of the crew compartment, a lot of pillows, chairs, all the stuff that was really light just reentered without burning up because of ballistic coefficient.

There was a lot there.

69:00 And so that gets into some of your questions having to do with when did they know.

And, of course, the big why question.

Let me go to that.

Now I'm going to go off into the second part of our investigation.

And we consider this to be as important, if not more important than our technical investigation.

We talked a little bit about the history of the Shuttle Program.

And I am sure that is something that you have been through in terms of the budgets, the margins, what we believe is a mischaracterization of the vehicle as a mature operational system.

And we think that there is a story here to be told, and so we looked into this.

Now, I have to say that I was not as much a part of this as some other members because I was busy on the aerodynamics part of it.

But you had John Logsdon, we had quite a number of the Air Force people, and Admiral Gehman were more deeply involved in pulling together the sort of history of how this happened, the cultural issues.

I am sort of reporting on behalf of my fellow board members what our conclusions were and the data that we gathered together to put this together.

The things that were pointed out are that there was this fundamental uncertainty in the Shuttle Program and that led to a sort of fluctuating attitude towards investing in upgrades and infrastructure.

The nation didn't really know where it was going.

And I hope you won't take offense at this.

I worked for NASA.

You worked for NASA.

We found them to be an extremely insular organization.

And I think, actually, they still are.

They don't take advice from the outside.

And I will be prepared to admit that they are the only organization that does human spaceflight, at least in our nation, but they are not the only organization that handles risky technologies.

And they have a lot to learn from other organizations.

And they have not been a part of that conversation with the type of people like the nuclear navy and some of the commercial industries that use extremely risky technologies.

They have not been a part of that dialogue.

And that is where we have criticized them.

As I say, they are insular.

They think that they cannot learn anything from anybody else.

That they know how to do all these things and that they don't need to accept any external suggestions.

That is a very dangerous line of reasoning for an organization, really, no matter how good you are.

So we felt that the people at NASA, that leadership clearly believed these things and the people in the engineering workforce were under tremendous pressure to go along, in some sense, with these basic attitudes.

And we saw that in our investigation of kind of the what went on during the flight.

I mentioned before that there is this history of foam.

And let me introduce the word anomaly.

Have you talked about anomaly?

Not directly.

OK.

Anomaly is one of the most important words in space systems.

Anomaly means that something happened that shouldn't happen.

Anomaly should bring your organization to a standstill while you figure out what happened and why it happened.

Anomaly is a violation of requirements.

Sometimes I think it's a euphemism for failure.

Well, yeah.

Hopefully you catch it before failure.

Anomaly is a clue that something may even worse happen down the road.

It is something to be taken extremely seriously.

Foam shedding off the tank was an anomaly.

It didn't destroy the vehicle but it is a violation of requirements.

And, in the early days, it was really put on a list of problems to be worked.

I mean NASA didn't completely ignore it, but they put it on a list of the other 5000 problems that needed to be worked.

And they just kept flying until foam shedding really became a normal expectation that all the flights would have foam shedding and that nothing serious would ever happen.

It was treated as a maintenance turnaround problem, you know, when the vehicle gets back we can fix it.

And that was true in this case, too.

They said something like well, if foam hits the Shuttle, we'll fix it when it gets back.

I mean that was the stance.

Now, I think what's interesting about this, if you think about this, is that the anomaly of foam shedding without hurting the Shuttle was treated as if it were a planned engineering test.

In other words, it was a test that was planned to see if foam could hurt the Shuttle.

And the fact that foam didn't hurt the Shuttle was treated as confirmation that foam couldn't hurt the Shuttle.

Now, I think that's kind of a fundamental.

I like that particular phrase.

There was enormous schedule pressure on NASA.

They had already slipped a couple of times because of other what I would call strong signals.

We use the word strong signals.

When something really dramatic is identified NASA shuts down.

And I don't remember the issues.

There was something about a connector that didn't seem to work properly and it just grounded the Shuttle fleet for three months or something.

And there was some other problem that was a strong signal and they simply shut it down.

The foam we put in the category of a weak signal.

It is something that while you're fighting all the strong signals it is hard to justify shutting the organization down for what you perceive as a weak signal.

So they had used up almost all of their margin to complete the Space Station.

And they were under tremendous pressure.

Sean O'Keefe was obviously sent to NASA to put the house in order, put the schedule and the budget in shape and get this Space Station finished by February 19th.

Ooh, we've already passed that one.

We will talk a little bit about what happened on the ground while the vehicle was in the air.

I mentioned before that in the military we do two investigations.

We do a safety investigation where the testimony is privileged and we do an investigation which is public.

And our group was kind of doing both.

In other words, we were obviously doing a public investigation.

We had press conferences every week and the media would come and we'd share everything with them.

But, because we did have so many military people who understood the importance of accident investigation, we also had, I don't know, an annex, I guess you'd call it, a way to take testimony and keep it privileged.

And we did that.

We took testimony from individual people at NASA.

It was privileged testimony.

And they felt free to share with us their participation and what happened and who said what when and all of that.

And we had the damnedest trouble keeping this from Congress.

I mean it really was.

And anything that's written down is accessible to Congress, at least that's the way they look at it, but we really held very firm and we would not allow this privileged testimony to be accessed.

And I think the compromise we made was that a staffer could come over to where we were located, he could read the testimony and take no notes.

Well, they soon tired of that so the fact of the matter is they didn't come.

But we had a lot of privileged testimony that allowed us to put this picture together with employees not being too concerned about the implications of sharing with us.

So, the weekend that the flight went up, NASA knew that there was a potential problem.

And they put in place something called the "debris assessment team" which is supposed to look at all the data that they had and decide whether or not there was a problem.

Now, I've chaired a lot of committees, not only here at MIT but other places.

And I understand how important it is for a committee to have a clear charter and a clear line of reporting and to have a certain level of independence from their home organization.

For example, if I were chairing a committee here at MIT on an important research issue or important policy issue and members of my committee were getting pressure from their department heads, I would blow the whistle.

I would say that is not the way a committee works.

A committee has a charter.

It has independence.

It is not subject to outside influence from the people to whom these people report in their normal way of life.

So, with respect to the debris assessment team, I would make two comments.

First of all, they had a very unclear charter.

It wasn't clear kind of who they reported to or what their authority was.

And they, as individuals, were getting pressure from their home organization, both NASA and the companies, the USA, Lockheed, Boeing, because those guys were getting pressure from NASA.

It was just an enormous amount of pressure being applied to various people in what I considered to be a totally inappropriate way.

In any case, this team, I admire them.

I mean I think they were doing a good job.

They wanted to get on-orbit pictures to see whether or not using national assets we could take pictures of the Shuttle.

And so, who do you contact when you want something like that?

You talk to the Air Force.

And the Air Force is, of course, like a great collie dog just waiting to show what they can do.

You know?

I mean oh, great, we've got this wonderful opportunity to take these pictures.

It's really going to be fun.

We're going to show what we can do.

They are very enthusiastic about responding to that kind of request, but NASA didn't want the pictures.

I mean the senior managers of NASA didn't want the pictures.

The debris assessment team did want the pictures.

And they tried to make these requests of different parts of the organization.

And every time they would make a request it would get slapped down by senior managers.

Well, I guess we have it.

This is a highly classified area, but let me just say there were eight separate opportunities where we could have gotten some significant information about the state of the Shuttle and we didn't do it.

We didn't do it because every time there was a flurry of activity around there NASA said they didn't need it.

They'd fix the Shuttle when it got back.

If the damage had been discovered what do you think would have been done?

Well, I can talk to that issue.

I mean this is as good a time as any.

We actually asked NASA to do some studies about what could have been done.

This is a nation that will save a whale that is trapped in the Arctic or Baby Jessica in the well.

I mean if we find that there is a crisis we will mobilize.

There is no question about it.

It would be a very chancy situation.

We know the vehicle is destroyed.

The vehicle is lost.

There is no question about that the vehicle cannot reenter safely with the people.

So what was the best option?

I mean we looked at the possibility of stuffing the hole with things, you know, old sleeping bags and suitcases and stuff.

There wasn't anything onboard that could have withstood the temperatures.

And, of course, one of our recommendations was that there should be some capability for in-flight repair.

That has been a big issue.

But the only other thing you could do is to sort of go into life support mode.

Stop doing the science.

Jettison the module, I guess, which would make the vehicle lighter and then maybe the reentry would be a little more successful.

Conserve electricity.

Conserve water.

Conserve food.

Try to stay in orbit for an additional, I don't remember the number, 15, 16 days, something like that so that you could send up a second shuttle.

I think it was Atlantis.

They could get Atlantis ready and send it up.

It was sort of by chance, but it just happened that in this mission they did have the possibility of doing a rescue.

Right.

It's a gutsy move, but I have a feeling that if we actually had that information that we could have put that together.

It is interesting that when you read some of the stuff that is being talked about, like the Hubble and things like that, we did not recommend that a second shuttle be standing by.

But that seems to have been internalized at NASA as a potential safety measure.

That they will always want to have a second shuttle standing by if they send the shuttle up.

The problem with that is it's a bit of a "going out of business" strategy because there aren't that many left.

Yes?

[AUDIENCE QUESTION] We never looked at that option.

We simply didn't.

This particular vehicle was not in an orbit that could have reached the Space Station.

And that is another big issue, is whether you want to have the Space Station available for a safe house if you have an accident.

In this particular case, this vehicle could not have reached the Space Station.

Soyuz could not have reached this because Soyuz launches from 51 degrees.

This was in 28 degrees.

Also remember there were seven people aboard so you would have needed three Soyuzs.

The Russians just don't have them available.

It was either Atlantis or nothing.

Larry, you had a question.

Yeah, going back to the on-orbit photo.

It was alleged at the time that the NASA management thought that the quality of the photos was what it had been several years earlier and, therefore, would not have helped them.

Let me speak to that because I was going to mention that.

In the early days of the Shuttle Program there was, in fact, a good interaction between NASA and the national security apparatus that does this sort of work.

And people at NASA were cleared, to an appropriate level, to have this interaction.

That has atrophied.

The current people at NASA basically have no experience with that world, are not cleared to an appropriate level, have just not had an interaction and see it as a bigger deal than it really is.

It is not a big deal.

We do it all the time with my collie dog friend.

I mean it's just not a big deal.

So our recommendation was that there should be a better interaction between NASA and the national security apparatus.

And that the senior people at NASA should be cleared to an appropriate level to have that interaction.

And that this should be, in fact, routine that you always take pictures when the shuttle is in orbit.

And so I think that was basically one of our recommendations.

In any case, we were not pleased with the decision or the failure to take photos onboard.

86:00 It was called the "crater model".

Its fundamental purpose was to figure out whether foam would hurt the tiles.

It was developed as a result of the experiments done at Southwest Research Institute of shooting small pieces of foam at the tiles.

Not the leading edge but the tiles.

And it was sort of all things kind of rolling together.

The people who developed this model were in Huntington Beach, California when they transferred the operation to the Cape or to Houston, I don't remember.

The senior people in that group refused to move so they turned the tool over to junior people.

There was a loss of corporate memory, a loss of understanding, and so it just got worse and worse and worse.

And so finally the people who were applying these tools were not the same people who were in the development of the tool and really lacked understanding of what this tool was all about.

The tool predicted that you had a serious problem.

But they said, oh, well, the tool always over-predicts.

They ignored it and said there was no problem.

I mean it was just cascading of kind of bad things happening.

We talked a little bit about the organization of NASA.

And I don't know whether you talked to Aaron, but this would be a good question to ask Aaron Cohen.

I am setting him up here.

About an independent safety organization at NASA.

Yes?

[AUDIENCE QUESTION] As far as we can tell nothing until about one or two minutes before.

Actually, Mission Control had arranged for a press conference with the crew in orbit.

Right.

Are you going to mention that?

I will talk about that.

Because the crew new that some foam had come off, but they were told that it was no problem.

Yeah, but that's different than the crew knowing.

Right.

No, I think that is true.

That the crew was notified that there had been an incident on liftoff but there was no problem.

And the only reason they told them was because somebody from the press might ask them.

Yeah.

And I have had media training so I know exactly what they were thinking about.

The Shuttle lands, the astronauts get out, the microphone gets into the mouth and they say do you know?

And the astronauts would say of course, we knew, and we understood it was no problem.

I mean it was a pre-media sort of skull session for the astronauts, as opposed to a more responsible concern.

What we do know about the astronauts is we have the voice recording and stuff, and I think there was something from Mission Control to the astronauts saying we see a temperature anomaly in your wheel well.

The temperature was 50 degrees higher than would have normally been.

And this was literally just like I don't think any more than five minutes before the vehicle lost control.

Maybe even less than that.

I mean it's all in the timeline.

And that is probably all I want to say about it.

I think the evidence we have seems to indicate that the astronauts knew.

Obviously, when the vehicle went out of control they knew there was a problem, when it began spinning and stuff like that.

But, as far as we know, there was no indication prior to that.

Everything else was sort of nominal.

Yes?

After both shuttle accidents, you have investigation boards, but what happened after Apollo 1, for example?

[AUDIENCE QUESTION] I don't know the answer to that.

Well, actually, that's what Aaron did talk about, safety organization with respect to that and Apollo 13 and the fact that when it was set up, they did start out with a very strong independent safety organization which did not exist before Apollo 1.

90:30 Now, why did we say that?

Well, you're all engineers.

The idea behind an independent safety organization is that you should have engineers fighting.

How do engineers fight, in an ideal world?

They fight with data and analysis and hypothesis and testing.

In other words, if the program wants to waive a requirement, change a requirement then they have to present a case.

And if the safety organization feels that there is crossing the line then they present a case.

And the two organizations basically try to bring together the best analytical and experimental framework they can in order to determine what should be done.

And so that's the notion of an independent safety organization.

I guess the thing that I was somewhat gratified by, we will see how it all works out, is that we recommended, as a return to flight thing, that NASA present a plan for an independent safety organization with the idea that in the midterm they would actually begin such an organization.

Sean O'Keefe took the bit in his teeth, I guess is the way to say it, and he moved out much more strongly on that than I would have anticipated.

We met with him last December.

I guess it was December.

These years go by very quickly.

But he had actually put in place a structure, to get ready for the flight, that had outside experts from within NASA to sort of come together as an independent safety board to look at anomaly resolution.

I guess they didn't do too good on the foam.

But, in any case, as far as the structure goes, it was a stronger safety structure than had existed before.

That was something that we recommended.

It was very important that there be an independence in the safety organization and that this is, in fact, a characteristic of an organization that effectively manages high-risk.

And we would claim that there are several such organizations in our country.

And there is a lot to be learned and a lot to be shared.

We also looked at the comparisons between this accident and the Challenger accident.

And, in fact, found more similarity than you might have expected given that Challenger occurred on liftoff and this occurred, well, in reentry, but did occur on liftoff.

In terms of the role of engineers and technical managers, this notion of normalizing deviance.

Deviance is an anomaly.

It is a departure from the requirements.

And, if you normalize it, it means you accept it.

You accept it and, in fact, you try to profit from it by saying that it's proven that there is no danger.

So this phrase normalization of deviance is an important sort of technical phrase that our group used.

We had with us, actually, a faculty member from Boston College who had written a book on the Challenger investigation.

She is a social scientist, and she worked very closely with us to try to put, what I would call, the social science and organizational effects together.

That is Diane Vaughn.

You might bring her over some time.

She is a fascinating speaker.

But the thing that was interesting about Diane, not only was she a great colleague, she published her first book on the Challenger accident, is there's an in-depth analysis of the cultural flaws in the organization that led to the Challenger accident.

She published this book.

And she said well, you know, I got a lot of reaction from the book.

She said the Navy called, my old boyfriend called, the various industries called to have her come and talk about safety culture.

NASA never called.

NASA never indicated any interest in her analysis of the cultural flaws within the organization that led to the Challenger accident, which I think is another indication of the insularity.

That was, I think, an important input to our look at the organizational issues.

We got together as a result of all of this.

And, as I said, I wasn't deeply involved in, say, some of the privileged interviews having to do with the individuals.

But certainly as a board, we came to this organizational cause which we considered to be as important as the technical cause.

And the various words rooted in the Space Shuttle Program.

History and culture.

Original compromises that were required to gain approval.

The years of resource constraints.

The fluctuating priorities.

The scheduled pressures.

This mischaracterization of the Shuttle as operational rather than developmental.

Lack of agreed national vision for human space flight.

The cultural traits and organizational practices that were detrimental to safety that we're allowed to develop including reliance on past success as a substitute for sound engineering practices such as testing to understand why systems were not performing in accordance with requirements.

Organizational barriers that prevented effective communication of safety information and stifled professional differences of opinion.

Lack of integrated management across program elements and the evolution of an informal chain of command and decision-making process that operated outside the organization rules.

A bit of an old-boy network in some sense.

And we should mention the lack of an agreed national vision for human space flight has been the jumping off point for everything that has happened since with the new vision, which is presumably going to determine what we do in the next ten years, so I think it is great that all of you called attention to that.

Let me talk about our recommendations.

We made recommendations in basically three piles.

One of them are the near term recommendations which are the return to flight recommendations.

And these were monitored by a committee of 28 people.

It was enormous.

In any case, we asked them to present a plan for an independent safety organization.

I think they went a little further.

We asked that they develop a method to do onboard repair.

Now, there was a big discussion about onboard repair.

It is very clear that it is much easier to do onboard repair for all sorts of different reasons, including crew safety if you are going to the Space Station.

Because then you've got a safe house and all sorts of supplies.

It is like your recreation room.

If you're not going to the Space Station, it is considerably more dangerous, and that is the fundamental issue with respect to a Hubble mission.

Because a Hubble mission is incompatible with going to the Space Station.

If you take this recommendation seriously, you either have to develop an autonomous onboard repair, which is much more difficult than a Space Station onboard repair, or you cannot have any Hubble mission.

So, this is a bit of turmoil in the political issues surrounding missions.

The other impacts, as I mentioned, not our recommendation, but this notion of having a second shuttle standing by seems to have been internalized.

There were a number of other recommendations.

Our report is on the Web.

I mean more video cameras.

More onboard video that gets telemetered to the ground during the flight so you don't have to wait until the vehicle gets back to see the video.

External video cameras launched during day.

Keep your sensors up to date.

I mean there was just a whole lot of I think 25 recommendations of a return to flight.

And the Return to Flight Committee was in charge of monitoring all of those.

And they have recently issued a report.

Incidentally, I got a copy of the Return to Flight report and donated it to the AeroLibrary.

It should be in the AeroLibrary.

And there was a very interesting minority report that was submitted by like about five people which was just damming with respect to their observations about how NASA works the safety issues.

Take it as the opinion of these five people who were on the Return to Flight Committee.

It makes good reading.

But that is all in the AeroLibrary.

Our midterm recommendations.

In some sense, we made these recommendations assuming the Shuttle Program would continue.

And I think we had this recommendation for an independent safety organization.

And what I thought was one of our most important recommendations was that if you intend to fly the Shuttle past 2010, you should recertify it.

Now, certification is a very technical process where you have to go through every piece of equipment and, in some sense, revalidate that it will satisfy the requirements.

101:05 What better project for the Shuttle Program Office and the Independent Safety Organization than to recertify the Shuttle?

At least that was my vision.

That would really be an extremely useful thing to do, to work together, to recertify the Shuttle.

Now, unfortunately, evidently the Shuttle is not going to operate past 2010 so we will see.

I mean they won't recertify it.

Now, I think what's going to happen is they're going to get up to 2009 and are going to say oh, my gosh, we don't have any way to get to space.

There is going to be enormous pressure to keep the Shuttle operating past 2010.

And, of course, they will be late to need in terms of recertifying.

It is going to be a bit of a jump-all at that point.

It should be very interesting to watch.

Now, the long-term recommendation, of course, we made was that we need an agreed upon vision for further manned space flight.

And so, from my point of view, we skip the midterm and we went immediately to the long-term because with the President's new program that we have basically set this vision.

And, unfortunately, we have skipped some of the intermediate steps that would have strengthened NASA as an organization and its ability to carry out a new mission.

I stand back watching, as all of this develops, having had this incredible background of being a member of this Accident Investigation Board.

It looks like I landed the plane right on time.

Yes.

Incidentally, I brought this Halloween candy.

And I would really appreciate it if you guys would come and take it because it's not something that my husband and I need.

And if it doesn't get eaten, would somebody please take it down and put it with the graduate students downstairs?

Good.

Anyway, you had a question.

I am wondering if you think there might have been any effect on that if it was explicitly stated that this is why we want the recertification to happen.

I don't know.

You know, it is hard to micromanage a big organization.

I personally was disappointed because I believed very strongly in this.

And I felt that it would be a way to bring the organization together around this set of ideas.

So, that won't happen.

And we will see how they work with this "independent safety board" that they have put in place.

All of what we're doing is self-education.

It is organizational education.

It is self-education.

It is process education.

So, we will see how they will bring all that together.

The reason I asked that was because actually, in terms of reading this recommendation, I read it a little differently.

I thought it was kind of a push to move past the Shuttle to say that recertification is going to be too complicated.

Well, there might have been a little bit of that.

I mean it really was up to NASA to decide whether a process that was so resource-intensive was worth doing, I mean given the fact that the Shuttle is in the sort of sunset of its career.

I guess I felt that we should leave that to them but that they could not continue to operate the way they were operating.

I think that was really the message.

They had to make a decision.

Sheila, the board's recommendation of the number of 2010 has had enormous impact.

I know.

Of course it has.

Very negative from my point of view.

Say something about how you picked that number and how flexible it is?

Well, recall we did this in 2004.

We wanted to give NASA enough time to get back to flying.

And, of course, the whole definition of what recertification means is a bit unclear.

In other words, I would think that NASA could have gone in.

I think what we saw was we needed to get a couple of flights under our belt, but we needed to go back.

I think what we meant by recertification is a relook at the whole mission.

What is that thing called?

Mission rules?

No, not mission rules.

When they get together and decide whether they are going to fly.

Mission readiness review.

Flight readiness review.

We felt that the flight readiness review was broken and that part of the reason it was broken is that there were too many requirements that were silly like the Shuttle had only two wings instead of four because you'd need redundancy.

Wings are important, and if you really thought they were important you would have four instead of two.

And every time they did a flight readiness review you would have to go through these, what I would call silly requirements.

One issue about recertification was to try to narrow down to what were the key systems that needed reexamination in the light of technology and what we know about the Shuttle?

That, in and of itself, would have been a very useful process that would have helped this.

And so, I think what we saw is that there is a set of processes that need to be carried out after a couple of successful flights that would really position the organization to do its job.

107:00 They wasted a lot of time.

But suppose someone had come back to you, or members of the board and said well, life would be easier for us if we called it 2013?

Well, I would think if you're going to do that, that NASA should come forward with a plan at the minimum of how they're going to operate the Shuttle safely through 2013.

They have not even thought about doing that.

They are carrying on with "business as usual".

Flight, flight, flight.

And they are not thinking about this more fundamental issue which would, I think, be very useful for them as an organization of what are the critical issues if we wanted to operate the Shuttle to 2013?

They just kind of got off the hook by saying 2010, we can do that.

You know, pretty shallow.

Yes?

And this is going to have to be the last question, unfortunately.

Anyway, you're all invited to my office to see my big poster on the flight.

Your recommendation for not flying unless you have a safe house in orbit.

No, we didn't recommend that.

Oh, safe house in orbit.

OK.

If you would have said that at the beginning of the Shuttle Program, that would have cut out dozens of flights.

Sure.

But, you see, at the beginning of the program, NASA was committed to a system that met its requirements.

Once they backed off of a system that met it requirements, they left itself open to operating a risky system.

And so then you come in, after having two accidents, and say OK, how can we operate this system safety?

You've already demonstrated that you're willing to back off on requirements so how can we identify what some key issues are so that you get back to operating safely?

What we fundamentally recommended was that you should develop onboard repair capability.

And that's really all we said.

And we sort of left open how they would do that.

And so they investigated a lot of things and decided that it would be a heck of a lot easier if they could use the Space Station for a repair.

And so they themselves said OK, Space Station only.

That really was not our recommendation.

Although, we understood that it would be a lot easier to do Space Station repair.

OK.

Thank you very much.

[APPLAUSE]