and XI of the reports which contrast the NASA culture with other high-reliability cultures. And there's much to learn from this. And we expect in the course of these hearings to try to distill what's the best lessons that the DOE should learn from that.

Thank you particularly for taking the time to do this because I know that you're running toward the end of your commission on the Columbia Board, and your time's valuable, and I'm glad you chose to spend it with us. Thank you.

CHAIRMAN CONWAY: Jim, anything?

MR. McCONNELL: No, nothing.

CHAIRMAN CONWAY: Okay, General?

MAJ. GEN. BARRY: Okay. Well, good morning Mr. Chairman, and ladies and gentlemen. It is indeed an honor to be here today. My intent here is to go through some introductory remarks, and then I'm going to show some slides, and then we'll open it up for questions and answers as you see fit.

I would like to also just state at the very beginning here that what I think I'll be able to present here is a summary of about nine months of work by some very dedicated Americans in trying to come to the root cause of what caused the Columbia accident. You'll find that we have basically arrived at two causes, a technical and an organizational cause. The technical cause, particularly for this group, I think, will be of interest.

But probably the most compelling element will be the organizational, culture, and managerial elements, because the lessons learned that we derived from that I think can be applied not only to public but also to private organizations. But this is unique because this is a very complex organization that had a failure. And I think we can all learn considerably from that.

Let me begin by just saying that at the end of the report you will notice, if you had a chance to look at it, that we have a patch that memorializes the three human space flight accidents. And we include Apollo 1 in there in 1967, the Challenger mishap in 1986, and of course Columbia. And on the back it says, "To the stars despite adversity, always explore." And that's kind of the context that the board took when it first took its charter and moved on.

Now, President Bush on February 4, just three days after -- the mishap, of course, occurred on February 1 -- he said, "The cause of exploration and discovery is not an option we choose, it is desire in the human heart. We find the best among us, send them forth into unmapped darkness, and pray they will return. They go in peace for all mankind, and all mankind is in their debt." And it's with that kind of focus on that legacy, particularly for the seven great explorers who lost their lives on February 1, that we began our investigation.

And we all know that 2003 started as a great year, certainly for the celebration of 100 years of flight with the Wright Brothers. But unfortunately on February 1, the year began on a note of sudden and profound loss. As the Columbia Accident Investigation Board formed, from day one we felt that we were laboring in a great legacy of the 107 crew: Rick Husband, Willie McCool, Mike Anderson, Dave Brown, K.C. Chawla, Laurel Clark, and Ilan Ramon.

The Board owes a lot of thanks to a lot of people because it was a staff of about 120 that reviewed 30,000 documents, over 200 interviews, more than 3,000 inputs. And about 400 NASA engineers were involved, and 25,000-plus debris searchers on the ground from every state, local government, Federal Emergency Management Agency [FEMA], Forest Service, Boy Scouts. So a lot of great effort by a number of great Americans.

Our view stated from the outset is the space shuttle is not inherently unsafe. Now it's still a development vehicle with inherent risks, and we would have said it was unsafe if we felt it to be that way. We were under no pressure to keep it operating, and the International Space Station [ISS] was not a factor in our deliberations. However, it can be operated a lot more safely, and that's what we concluded, and it will not last forever.

As I mentioned to the Board earlier in our conversations this morning, we are entering an era of something we've never been before. We are entering an era of a reusable space vehicle that is aging in an R&D [Research and Development] environment. We've never had that before. Of course, with Mercury and Gemini and Apollo, they were one-time-use vehicles. So with that realization, I think, there's a lot that we can gain, not only from aviation but from the nuclear industry, DOE, and certainly at NASA.

We looked into technical, organizational, and cultural aspects to truly lessen the chance of another accident. Most of you realize that when an investigation usually starts and something goes wrong, you'll find the widget that broke, find the person closest to the widget, you'll either fire or replace that person, and move on. We didn't want to make that mistake by only leaving at that point. We wanted to make sure that we got down into the organizational elements and made sure that we didn't have a repeat of Challenger, because we did see a lot of echoes with Challenger in 1986.

The Board was independent. We were reporting to numerous constituencies: the American people, the White House, Congress, the Astronaut Corps, their families, and the rest of the NASA family. And we just didn't look into the Columbia accident for the space shuttle program, but we looked at it as a whole.

We examined physical failures, weaknesses from history and evident in NASA's organization, and other significant observations that might cause a future accident. Now, let me state from the outset, NASA is an outstanding organization. I could spend days, if not weeks, talking about the profound accomplishments, and outstanding history, and great number of people that we have in NASA. The mission is unique. It's stunning in its technological accomplishments and a source of pride and inspiration without equal in the United States. However, Columbia did happen. It was a turning point in a lot of ways.

We've called for renewed debate in manned space flight, and a renewed commitment to human space flight.

Space flight is far from routine. It involves substantial elements of risk and needs to be recognized for those risks. And we can never take it for granted. And we owe this to the legacy of the Columbia and her crew to get to the heart of the matter.

Now, there are causes in any mishap, and we found two main ones: technical cause, a physical cause, and an organizational cause. Let me stand up now, if I may, and we'll start the presentation on the PowerPoint slides. I have some more to say about that. Next slide, please.

This is what I'll cover, a little bit about the causes, and summary, and the formulation, but basically the two parts. This is the technical, and this is the organizational element, and a look ahead, and a little bit about recommendations. We'll go through that. Next slide.

First of all technical cause. Frankly stated, the foam did it. The foam came off, hit the left wing, we had a perforation, a crack in there on launch. And then, of course, on reentry, superheated air entered the left wing and ended up in the catastrophic loss of the orbiter. Effectively what happened on the launch on January 16, 81 seconds after launch, is when the foam hit the left wing. We'll talk more about that. Next slide.

Organizational causes. Much more compelling in the sense that it was harder to get our hands around it. We wanted to make sure, again, we just didn't focus on the technical elements. But there were issues of culture, organization, and management that we found to be causal in this mishap. We treated the technical cause and this cause as equals.

Reliance on past success, organizational barriers, lack of integrated management, informal chain of command, communication problems, all of those are things that we arrived at, and we'll talk a little bit more in detail as we go through the brief. Next slide.

Of course this is the crew. Seven dedicated explorers. Six of the seven are in the military. The only one that wasn't in the military was K.C. And of course Ilan was from Israel. Next slide.

107; This was the 113th flight for the

space shuttle. This was the 28th mission for Columbia. And remember, Columbia was the first space shuttle. It was launched April, 1981. And this was a 16-day mission that started on January 16.

Now just real quickly, we'll go ahead and hit on "Shuttle 101." A lot of you are familiar with this, I know, but the point to be made is I'd like to just show this for the solid rocket booster and the external tank. The external tank is as tall as the Washington Monument. We sometimes lose that perspective. And that whole external tank, as it appears to be golden here, is entirely covered with foam. The entire thing is covered with foam. And if you remember the launches that we saw with Apollo, Mercury, and Gemini, pieces of ice falling off. Well, the capsule was on top. Unfortunately this time, with this design, the shuttle was on the side. So this foam is built there to prevent ice formulation, which has a lot more density than foam does, to prevent that from formulating and then coming off on launch. So I want to bring that to your attention as we talk about it.

All right. Let's talk about, next slide. We're going to talk about the formulation of the Board real quickly. A very distinguished group. I don't know how they picked a fighter pilot to be part of this, but I managed to get on there. Of course Admiral Gehman, a retired four-star Navy admiral, was our Chairman - did an outstanding job on leadership and bringing the Board together.

We have Sally Ride that you know. We have Dr. Osheroff, who is a Nobel Prize winner. We have representatives from the Army, from the Navy and Air Force represented there. Sheila Widnall, former Secretary of the Air Force, as a case in point. Scott Hubbard, who runs Ames [NASA Ames Research Center]. Then we've got Roger Tetrault that some of you may know from DOE. He was the chairman of McDermott [International].

So, a group that really brought a lot of diversity and certainly a tremendous amount of knowledge. Next slide.

All right. We call this the Gehman test. But now I'm going to talk about the technical issue. But what we wanted to make sure, if we were going to arrive at a cause on the technical side, we wanted to be able to stand with some authority and say, okay, this is what we thought the cause would be. You notice in our causal statement on the technical side, we didn't say, "Probable cause;" "Most likely cause;"

we said, "The cause."

And the reason we were able to come to that conclusion was it passed all of these tests and arrived at the same point. And the point was that the foam caused the issue. So we looked at aerodynamics, thermodynamics, timeline, imagery, debris. All of it led us to the same conclusion. I'm talking about the technical cause now. Next slide.

So let's talk about that in more detail. Next. All right. This launch occurred, and I'm going to show you where the culprit is. The culprit is this bipod foam. And I'm going to show where exactly that is located here in just a minute.

This foam is about this high. [The speaker held his hand at his waist height, approximately 45" from the floor.] It weighs about 2.6 pounds. It is covering a very complicated geometric connection point from the external tank to the orbiter. And this is the piece that fell off that caused the mishap. So go ahead, and let me show you exactly where that is now.

This is the launch sequence. You'll notice the information on the top. It's got Mach number and speed and height. Well, here we're going three, four, five thousand feet. Of course, the external tank is feeding the orbiter with liquid fuel, but the solid rocket boosters there are solid fuel. At about 81 seconds you'll see this is the culprit right here. Bipod foam. And this is what comes off at 81 seconds. It occurs at about 2.4 Mach at about 65,000 feet, and it hits the left wing right about here. This is the main landing gear door on the left side.

The piece comes off, and it comes off in actually three chunks, one larger and two smaller. The two smaller do not hit the wing. The larger piece does. We think that was about a 1.6 pound piece of foam. It hits it at about 500-plus miles per hour. And what that amounts to in foot pounds of pressure is about 8,000. Hits it, and this is just a translucent element just to demonstrate it. Okay, we can stop there. All right, so this is 65,000 feet, Mach 2.4 - 2.5.

Okay. I want to show you some video, real-life video. Here is the launch. From here it goes over the water. About right here is when the foam comes off at about 81 seconds. Okay, right there. We only had two cameras. Unfortunately, NASA was not maintaining the quality control on their cameras as much as we would have liked. We didn't get the quality that we wanted. We had the experts in the nation come together to try to enhance it to the best of their ability and this is the best that we could come up with. Go ahead and show.

Now it comes off the left side, of course. And this is just a recurrence over and over and over again of the foam coming off. But you can see it's a pretty dynamic hit. And immediately, they arrived at the conclusion that it didn't go over the wing, it went under the wing. So they unfortunately arrived at a conclusion it didn't hit the leading edge, it hit the bottom of the left wing, when in truth of fact it did hit the leading edge and at a pretty good velocity. So that's one view. Next slide.

Now let me give you the other view from this camera down further south. This one was really out of focus and didn't give us a whole lot of help. But if you look very carefully you can see the foam coming off and hitting the left wing. There it is, and it comes in, hits the left wing. There's no apparent damage, certainly with lack of quality on this film, to be able to arrive at the conclusion that this thing really did cause damage. But I will show you how we arrived at a final determination that it was, in fact, the cause.

Okay, we'll take a look at, next slide. All right, so there's the culprit. There's where it's located. And this is what that foam covers, a very complicated geometric connecting point. Okay, let's go through the bipod. I want to show you in appreciation of how that is formulated, what's underneath it. There's the bipod connecting point. Remember there's some connecting points on the bottom port, but this is up at the top. And this is what's underneath that foam. And then there's some ablated material that actually we concluded didn't serve any real function but had always been there, so they never removed it. But this is the connecting point from the external tank to the orbiter.

All right, I want to show you how this is prepared. Go ahead and link on this. It's interesting. Imagine the external tank sitting in Michoud, which is near New Orleans, and all they do is they spray it. They don't build it and then glue it on it. They actually spray it on, this foam. And they do it in a very controlled climactic environment, temperature, and humidity. And it takes them about a week to do all of this.

But what they do is they spray it over there in a very, again, geometrically challenging area. So you can imagine how hard it is to get foam under all the little crevices. And then they spend the next week carving it out. It's like an architect trying to -- they've got specific angles, and specific distances, but every one of them is unique. None of them are exactly the same. And I'll show you how we determined that to be a fact, too. This is the end result on how they put it together. But this is the piece of foam that killed the astronauts.

All right, well, here's the trajectory, roughly the size, and came at it about 500 miles an hour. And trajectory you can see. Not the whole piece came off, we just think a part of the piece came off. But it was 1.6 of the 2.6 pounds of foam. Next slide.

All right. Well, if that was the doer, what was the receiver on this hit? And that's the left wing. This left wing is a very unique and amazing piece of technical capability that dates back to `70s technology. I will tell you a question I asked the astronauts we had talked, after we learned this, and I didn't know this before the mishap of course. But I asked them how thick do you think the leading edge is. And if you look at this picture here, it kind of implies that it's pretty thick. In truth of fact it's a quarter of an inch thick. A quarter of an inch thick. And it's an amazing piece of technology.

Now there are 22 of these panels, numbered 1 through 22 on each side of the wing. And they cost $850,000 a piece, and almost take about six months to make per panel. So very sophisticated. Remember, this is not ablative material that we saw during the early launch of the capsules. I mean, this is reusable as we go along here. But it's only a quarter of an inch thick. Okay, next slide.

So, impact location we think was panel number 8 which is right on the curvature with a shock-shock interface on the wing, for those of you who are aerodynamic experts, and about 500-plus in miles an hour. Next slide.

And it kind of came across. We did the best we could in enhancing the photography, but there's no evidence there that there's any damage to the left wing after the hit. So what do we do to try to arrive at a conclusion? Next slide.

What we did was, it turns out that we did have a sensor, and this is an interesting story. This is the MADS [Modular Auxiliary Data System] recorder. Bottom line, this is a recorder that you cannot get your hands on until after the shuttle comes back. It is not a black box. A black box in an airliner is meant to be built to withstand high pressures and explosions and all this other stuff. This was just encased in a regular old metal case. It was like the old reel-to-reel recorders that some of us remember from music in the `70s. And it is unbelievable that we recovered this.

Now this orbiter has 4,000 sensors that have telemetry down to the ground. There are a lot of sensors that go into this MADS recorder that are not telemetry down to the ground. So if we did not recover this recorder, we would have been hurting.

Now here's the story. The engineers were able to predict based on other debris we picked up around it from the ground where this thing was on the ground. They were so confident, they sent a team out and said, "Look here." The team went out, couldn't find it. Again they were so confident it had to be in that area they sent them out again, and darned if they didn't find it under a bunch of brush. It was in pristine condition. It was a marvel that it landed up-side, it didn't land in the water, and it didn't have any serious damage. Because of that, we were able to get some data. This is the key one.

This is where the location of that sensor was behind panel number 8. Remember I said panel number 8 was where the hit [occurred]. But panel number 9, I'm sorry, panel number 9 is where the sensor was. And this is where it's located behind about where the spar is. Well, what it did tell us? Next slide.

What it told us was the temperature increase of about seven degrees on launch. Now this is, each one of these colors represents a different launch. I draw your attention to the black one. This is Columbia on the mishap. Most of these others on launch will go down and go up one bit. One bit is about two degrees. Columbia went up three bits, which arrived at about seven degrees. That allowed us to arrive at a conclusion that it was damaged, and there was some kind of a problem with the left leading edge on assent. Because we needed some kind of evidence to prove that it wasn't a micro-meteorite or something like that. And we did conclude that on launch there was a problem. Next slide.

Now, jump forward. We have now launched into space. It is now the second day. What we did was after the mishap, and that's a key point, after the mishap, we went to the Air Force, and we said please look at all of your radar, any photography that you've got to give us any clue.

What they did was they looked at over 3,000 optical and radar observations. And what they discovered was on the second day, there was something that was paralleling the orbiter and that eventually re-entered the atmosphere and burned up in about two days. And we wanted to try to figure out what that was, especially as we developed our hypothesis on the technical cause. So go ahead and hit there, Matt.

Now this is an example on one of the radars. This happens to be up in Massachusetts. But we have an Eglin, Beale, Navy. This is at Cape Cod and Kirkland. That helped us get some information. The information we got was -- next slide.

It took us two days to track this piece, but something was paralleling the orbiter, and it eventually re-entered. Now some of you know this, some of you don't. But most of the time the orbiter is flying upside down in regards to the Earth, and it's flying backwards. Because if it takes a meteorite hit, if it hits the engines it's no big deal because they've already used the engines. They're not going to use those anymore. Now they do use retro-rockets to maneuver the shuttle in space, but they don't need the engine back there.

So anyway it's flying backwards. And then about the second day, our radar in the Air Force determined that something was flying parallel. We don't know exactly where it came because of the radar cross section distinctions, but we know something came off of it. And what we ended up doing was, we surmised it came from this area. But we took every single possible item that we could think of that could have come off, from blankets to pieces to parts to parts of the wing, and we sent it to Wright-Patterson Air Force Base and did two things. We looked at the ballistics, and we looked at the radar cross section. There was only one piece that solved the problem, that matched the radar cross section and the ballistic reentry and the burn cycle on a piece. And that happened to be a part of the reinforced carbon-carbon, in other words, the leading edge.

So it helped reinforce for us that something was wrong with that leading edge, and something came off of it on the second day. Couldn't completely conclude that that was absolute, but it helped us in our analysis. Okay, let's go back.

So now, next slide, I want to jump to the reentry sequence. So now we've gone through the launch. We've gone through 16 days in flight. And now they're coming back. Now remember, nobody knows there's a problem. I'll go into a little bit about the analysis, but they saw the foam hit after the second day reviewing the film. They've done their analysis at NASA. They've concluded that it is not a safety-of-flight issue. Okay, and we'll talk a little more about that when we get to the organizational causes.

I do want to show you the reentry hit. This is 8:44. We lose the orbiter on the hour. So at about 16 more minutes, we're going to lose the orbiter. So here's the reentry sequence. Some of you know this. Here is Florida. On the other side of the planet is when they start this reentry. And what they do is what I call in fighter pilot terms a split-S, but much more complicated than that. But here they are over Australia. Again, you'll see Mach number, and speed and altitude. So here we are at 820,000 feet.

You'll notice that the left wing is opaque. We did that for demonstration purposes. All of those little green points on the left wing are sensors that are either telemetry to the ground or to that MADS recorder. You'll notice that everything is normal. They come in about a 40-degree angle of attack in penetrating the atmosphere. They're starting to heat up.

The entry interface doesn't really start until they get to 400,000 feet, so about right now is when the entry interface starts at 44 minutes past the hour. We've got a high speed here. Green is good, and blue is bad. So we'll start there; it's a little different. Something is wrong with the left wing. Again, they don't know it on the ground, they don't know it in the cockpit, but we know from telemetry now, as well as from our sensor, that something is eating at that left wing.

It finally burns through at 48 minutes past the hour, burns through the leading edge, and super-heated air is getting in there. Not plasma as some of us have used the term before, but it's super-heated air. It is now 49 minutes past the hour, 249,000 feet. The orbiter makes a right-hand kind of bank slice turn, helping getting us through the atmosphere. This is normal. It's all being flown by the autopilot. The crew is in the cockpit putting on their gloves, you know, drinking water, getting ready for landing at Kennedy.

So now we're at 240,000 feet. You can see

Mach 24. Now look at, those of you who know knots and airspeed, 74 knots. So if you didn't have the heat, and you stuck your hand out the window so to speak, which you can't do obviously, it would be about driving your car at 74 miles an hour, 74 knots. Obviously the heat is the issue. But there's not a whole lot of molecules of oxygen.

This is at night still, in the early parts of the morning, so it's still dark. Here's the coast of California that's coming up. They're in a right-slicing turn. You'll notice at about 56 minutes past the hour they go into a left bank turn which is, you know there's a little bit of yaw so they're not going to quite get to Florida if they don't come back a little bit. Nothing's unusual. But however right now we're starting to see super-heated air burn through the spar. So now it's getting into the wing in its entirety.

Again, no indications on telemetry to the ground or in the cockpit that there's a problem here. You'll see some sensors that are reading off-nominal here because some of the air flow, and there is some there, oxygen, not much, but the temperatures are reading different than they had normally been. So we started seeing that.

Now debris is coming off. As soon as it crossed the coast of California, amateur photographers were taking videos of it. And we were able to get all that. But debris is coming off, and probably a lot earlier than California. We don't know that because we didn't have anybody taking film. But we asked the American citizens to donate their film, and they were great, and we were able to -- I'll show you some of that here in just a little bit.

Here we are at 220,000 feet. Debris is coming off. Cockpit doesn't know it. NASA doesn't know it on the ground. Super-heated air is now getting ready to enter the left main gear. We're crossing the coast of New Mexico, and approaching Texas. Here's the sun. The sun's coming up, so it's getting lighter. And there is some serious disruption. At 56 minutes it goes into its normal program, everything looks nominal, left-hand bank turn. Again, at 40 degrees angle of attack, not much yaw. Okay, speed is about 13,000 miles an hour. And then Mach is still about Mach 20.

Again, we lose the orbiter on the hour. So now 57 [minutes past the hour]. Communications are now going on that, hey, we're getting a reading of some bad temperatures in the sensors in the left main landing gear. Not too unusual. Sensors have gone bad before. Communications go from the cockpit. It's acknowledged by Colonel Husband [Commander of Columbia Shuttle Flight STS-107], and that's the last transmission that he makes. Remember, we lose the orbiter on the hour.

You're going to notice that the retro-rockets here fire. And this shuttle is working real hard to maintain this attitude. And, fortunately, all four retro-rockets fire, never seen before, never really normal, trying to stay there, just before we lose signal, and she disrupts. So here we are approaching loss of signal. Four retro-rockets fire, and that's what happened, and then we lost the orbiter after that.

All right, let me go back to some slides here. This is at 44 minutes past the hour. Everything, remember green in this case is good, blue is bad, and everything is normal. I will draw your attention to the wiring. We started seeing some off-nominal readings of sensors back here, but that's not where the heat was. The heat was here. And what happened was it burned through the wiring here.

So let me start at 44 minutes past the hour, everything looks good. Next slide. Well, at 48 minutes past the hour, we have confirmation from sensors that the super-heated air does burn through the leading edge -- remember, I said it was only a quarter of an inch thick. By the way, this quarter of an inch thick is protecting 3,000 degrees of temperature. But there's a boundary layer even at that altitude that's about six inches in front of it that has 8,000 to 10,000 degrees. So this quarter of an inch of reinforced carbon-carbon [RCC] is absolutely a marvel. Well, it failed here because of the impact of the foam on assent. And at 48 minutes temperature is getting in there. Next slide.

We know that from the sensors. This is the back part of the spar. Okay, so this is about right there, where that sensor is on the back side. At 51 minutes past the hour, we [about] know burn-through through the spar now; it's going to get into the left wing because of sensor readings. Next slide.

And super-heated air starts going up and down the left wing. And the wire bundles -- remember when I pointed out to you -- this is what it looked like. This is an actual picture of Columbia. And the burn-through starts on this wiring. Next slide.

Here we are at 52 minutes past the hour, and these sensors are starting to go offline because this wire has gotten burned. And the first indication to Mission Control was about 52 minutes, when they see four elevon-actuated temperature sensors that are starting to go off-nominal. Next slide.

Well, the super-heated air finally makes its way into the left main landing gear at 56 minutes past the hour. Next slide. And this is when we lose signal. Blue is bad, so all these sensors have gone offline. All right, this is where we're located, about over Texas. It was in a left-hand bank turn, and at about 18 seconds past the hour is when we had catastrophic break-up. Next slide.

All right. I mean to spend a little time on debris reconstruction. An amazing amount of Americans did some incredible work in trying to pull the pieces back. We actually recovered about 38 percent of the weight in the orbiter, which is pretty phenomenal. We'll probably have hunters and hikers, you know, for the next 10 or 15 years bringing pieces of the shuttle. But we were able to get that much back. Next slide.

Here is the debris pattern. You can see from Dallas, it's located here in Nacogdoces. What we know is there's parts and pieces up here, but this is much more mountainous region, and we weren't able to get [to it]. But this is all pretty populous. It's an absolute godsend that on Saturday morning when this occurred that nobody was hurt, nobody was injured, and nothing was really damaged by all those pieces and parts coming out of the shuttle. Next slide.

Oh, I'm sorry, let's go to the amateur video. I'm going to show you a couple of demonstrations. Again, this isn't professionally done. These are all amateur videos, but there's two sequences I want to show you. One is debris number 6. This is Venus, actually. And the shuttle you can see, you're going to have a flash here in a minute of debris coming off, right there. And even the guy who was taking the photograph didn't see it until after we collected it. But it gave us a good time location continuum to position this correctly.

So there was a number of them. There were like 16 of them that we clearly saw debris, and then toward the end, I'll show you this last one where you see the break-up. There happened to be an Army helicopter flown by a Dutch and a Belgian in training at Fort Hood. And they were able to pick this thing up on their infrared scope. And this is the final seconds of the Columbia. And you can see it breaking up. Leading parts were the three engines, and then other parts of the orbiter as it broke up. Pretty sobering.

All right, with that understanding, I want to move to the next point. Here is left is red, and right wing is blue. And as supported our hypothesis, the left wing obviously disintegrated before the right. So we can see that from the debris pattern. Next slide.

And we reassembled this at the floor of the hangar in Kennedy Space Center. Here's the nose. The left wing is actually -- think of the orbiter as upside down. The left wing is over here. So we're looking at the bottom part of the orbiter from the view you have now. Next slide.

But here's the left side, and here's the right side. We didn't get as much from the left side as we did from the right side, and that kind of makes sense. And what we were able to do -- next slide -- it's absolutely amazing what the technicians and engineers were able to do. They could identify every part almost without exception and try to put it back on the orbiter. And we did it with a three-dimensional re-enhancement.

And you can see the left wing here again in support of the hypothesis that there was a burn-through here in RCC. And we didn't quite recover these pieces, but that made sense to us too. But it really helped our analysis. Next slide.

All right. I want to talk about the doer and the receiver, in my words. The doer of course was the foam, and the receiver was the left wing. Let's talk about the foam again. Unfortunately there were six previous occurrences of this particular piece of foam that came off. And you look at the dates -- '83 -- '90, '92, '92, '94, and look at this one. October, a year ago. Just before the January launch, a big piece came off.

Now, NASA wasn't aware of all of these. They had seen four. We found two more in our analysis. And this is only the ones we could see, that weren't flown at night, and that weren't flown in the weather. So on average, about 10 percent of the time this piece came off. So there's probably three or four more out there that we didn't see.

On all of these, none of these caused any problems insofar as damage to the orbiter. This piece came off and didn't hit the orbiter, it hit the left solid rocket motor skirt. And it came off at 31 seconds and not 81 seconds. So it didn't quite have the force that the one that hit Columbia. But there were messages. There were signals. Next slide.

What other people don't really know is that the orbiter has been taking hits from day one. Unfortunately, the space shuttle was designed not to take hits. In fact, if you look at the specifications in the book, it says that it can take a 0.006 foot/pound of hit. That is a number 2 pencil dropped from about here. [The speaker held his hand at shoulder height, approximately 60" from the floor.] Remember I told you that this piece of foam hit it at 500 miles an hour, 8,000 foot-pounds. That's not 0.006.

Unfortunately, it's been taking hits, mostly on the belly of the orbiter at the tile level, and not the leading edge. But they had some really bad ones here. This is when a piece came off the solid rocket motor at the nose cone. And as late as 1996, STS-87 [Columbia Shuttle flight commencing November 19, 1997] had some. And most of the foam coming off was the external tank. But there is some debris on launch that spits up, that gets counted. But every time they came back, we'll talk about normalization of deviance, but hits were taken and it got accepted as normal business, cost of business of doing this. Next slide.

Well, pretty dynamic area. This is exactly when the foam came off on Columbia. It was Mach 2.46 at about an angle of attack of two degrees. We did with the computational flow dynamics a reconstruction. You can see this is a very challenging area. Lot of pressure this way, against that. But by itself, we concluded that the foam was structured not to come off. So something else had to contribute to it. Next slide.

Well, what we found out is that we had a whole bunch of external tanks down in Michoud in New Orleans that were already built. The bipod foam had been prepared and already made. So they're sitting there. And we said okay, we'd like to dig into those. So we cut into and dissected it. And we found all sorts of interesting things. We checked the right side and the left side, and we found problems. Next slide.

We found voids and rollover and de-bonds, de-laminations, and all sorts of challenging things. As you remember, he's spraying the thing, and it's kind of hard to get foam under every little piece and crevice, and pretty geometrically challenging area. Please.

DR. MANSFIELD: Does that foam survive the reentry into the water?

MAJ. GEN. BARRY: Well, remember the solid rocket booster separates at two minutes, and the external tank separates at eight and one-half minutes. So the answer is no. The external tank burns up on reentry.

So the only proof that we have is they do have separation cameras that take pictures. Unfortunately on this one the angle was not, you know you can never predict exactly how it's going to roll off, and it was not able to give us a clear picture to let us see what was there. But this is how we dissected and found out that we have manufacturing challenges and original design defects. Next.

Okay, let me go to the RCC again. This is the reinforced carbon-carbon leading edge, quarter of an inch thick. It doesn't look like quarter of an inch, but think of it as a wraparound. But this thing is just a quarter of an inch all the way around. Pretty blank area there. Some insulation. Here's the spar. It will eventually burn through the leading edge and burn through the spar. Next slide.

This thing is a quarter of an inch thick. It's made up of silicone carbide, which is like glass, carbon-carbon reinforced, as some of you are familiar with, and then silicone carbide. It's an amazing piece of technological achievement. It radiates the heat, it doesn't absorb it. And it certainly doesn't ablate it. Okay, let's go back.

Okay. I just want to mention, then I'm going to show you some impact testing. The aero-thermal analysis we went through at Langley, and put this thing in a different modes and try to figure out what the aerodynamics was. We looked at burn-throughs and wirings and forensic testing. All of this led to this technical conclusion. Next slide.

So using the Gehman test again, aerodynamic, thermal, timeline, imagery, debris evidence, all of us concluded that the cause was the foam coming off and hitting the left wing. Next slide.

And we have proof and evidence, and this is examples of breach in panel 8, and wind tunnel tests, and temperature increases, and the panel's launch imagery and left wing. So all of those, that's just examples that allowed us to arrive at what we thought was conclusive evidence that this was the technical cause. Next slide.

DR. MANSFIELD: The knife-edge erosion on panel 8, the significance I think it means that the knife edge was exposed because of the break during --

MAJ. GEN. BARRY: Right. The debris talks to, and it's really unbelievable what the technicians can go. But we could see the heat pattern that was generated by different debris that we were able to recover. We could see the splash of the materials that were recovered, that, you know, aluminum burns at a certain rate. And then we have different parts and pieces that burn. So all those things allowed us. But that knife-edging element showed us the burn patterns that, again, reinforced the conclusion that it was panel number 8 where it went from there. Next slide.

Well, to nail this thing shut, the final thing we wanted to do was shoot foam at the RCC leading edge. Now what we did was we reconstructed the left wing and shot foam at it. And this is at the right velocity. It had the density that we think, 1.6 pounds worth of foam. And hit at the right angle, the correct angle, and put a significant hole in the left leading edge. We're still getting push-back from NASA that foam is not going to damage a leading edge. Well, obviously it did here.

On the day of Columbia, on the launch of January 16, it could not have made that kind of a hole, because on reentry it never would have made it to Texas. It would have broken up. But it did cause some damage.

Let me show you the inside of it. Remember I said on day two there was a debris that came loose? We don't know exactly, but what you can see here is the look from inside on this test. Pretty compelling. And big pieces that could easily have separated on day two, maybe not that large, but certainly some piece could have. But pretty violent, and pretty damaging. Okay, let's go back Matt.

All right, now I've spent quite a bit on the technical issues, and go ahead, next slide. We're going to now move, well let me just mention areas that weren't a factor. You know, it's important to study what you conclude not to have been contributory. So we looked at everything, wiring to fuel spills to the depo work, and sabotage, and micro-meteorites, and foreign objects. None of them had any evidence that would allow us to conclude that they were causal in this mishap for the technical side. Next slide.

And then we go to the accident occurrence. There was a story that we got from the one of the books that we reviewed. We had a number of seminars with safety experts. The story goes something like this. There were two Canadian brothers who were responsible for chlorinating a well in Canada. And unfortunately they had a lot of cattle, and feces were getting into the water, and they did not do it correctly. People got sick, and a few people died. Big investigation. Long end result was they found the brothers didn't do their job right.

Well, when they started digging into the investigation, remember I said the widget breaks, they find the guy closest to the widget, and you either fire or replace them, and then you end your investigation. They did not choose to end it there. They went further, and they found out there were a lot of compelling organizational, cultural, and managerial problems that dated all the way back to the Parliament in Canada. Under-funding, lack of training, bureaucracy, down-sizing, out-sourcing, all of these things that we kind of saw in this.

It gave us proof positive that we just didn't want to stop at the technical cause. So we move into the organizational elements for history, decision-making, and on. Organizational system effects. Next slide.

Well, there's a lot of history on the Challenger mishap that was echoes. There were a lot of compromises made on the original design of the shuttle, not unlike the original compromises that were made in the nuclear industry. Budget cuts. You can see the significant leveling off. NASA was working on about $3.5 billion. Seven billion of their 15 is devoted to manned space flight, the space station, and the shuttle. About 3.5 of the seven is shuttle. But workforce reduced by 40 percent. And a mature and reliable system.

I'm going to hit on this a little bit in the sense that NASA declared in the early `80s that the shuttle was operational. When you declare anything operational, your mindset changes. Let me give you an example. The Air Force has not declared the F/A-22 operational yet, and it has over 17,000 sorties under its belt. This is 113.

But the decision was made to call it operational, and in the early `90s, with the out-sourcing efforts, a lot of decisions were made to out-source more to the contractor. That's going to pay some problematic, unintended consequences. And the unintended consequences that the expertise, technical expertise for the civilian government engineers went down.

I'll give you an example. In 1990, there were 48,000 government mandatory inspection points. In 2003, there were 8,500. So it has gone down that much on the out-sourcing and the privatization elements. Next slide.

Also as part of this, from Challenger to Columbia, replacement of the orbiter was supposed to be -- this orbiter was designed to fly 10 years and 100 flights. It did not fly for 10 years, it flew for 22 years. And it didn't get 100 flights, on Columbia it got 28 flights. So it was an aging spacecraft that had gone longer. But they kept pushing out the replacement. The board was a little disappointed that there really was nothing on the books at the time of the mishap for a replacement orbiter.

Fluctuating attitude towards investing, space flight culture, how do we do things here. There's a little arrogance that was evident. Perfect place. Challenger occurred in 1986, but we have now 87 flights under our belts since then. We've been there, we done that, we got the t-shirt. Next slide.

Decision-making at NASA was also problematic. Remember, here's the bipod foam. It had come off. They weren't listening as well to the signals. It's great to have perfect hindsight when you do these things and say, well, how could that happen?

But as I mentioned to the Board earlier, just in a little defense of NASA, there are over 1,600 single points of failure on this system. What that means is they have a critical item list, and critical item list number 1, if any one of those 16 items fail, that will be loss of orbiter or crew or both. This was listed as one of the critical item lists, but they had already waived it, and they had looked at it, and they had gone to what we call normalization of deviance. If something goes wrong, and you notice it, and you say okay, fine. Something goes wrong again, you notice it, but still no damage, no occurrence, and it just becomes a normal way of business, you accept it as normal business. And Diane Vaughan, who had written a book on Challenger, first coined the term "normalization of deviance".

Not a whole lot of good trend analysis or hazard analysis reviews. And there was some scheduling pressure. It wasn't as problematic as Challenger was, but it was incestuous a little bit. And what they were focusing on was node 2 of the space station. Node 2, my terms, like a tinker toy. You're going to have that one piece before you start branching it out. And this was February '04. They were all driving to that. And that's one of the things that was there. And it was evident in our interviews that we had with a lot of the workers, particularly at Kennedy. Next slide.

Decision-making again. We have problems with the team. Interesting insight. Maybe because of Challenger, if you have 10 units of energy on launch, orbit, and reentry, 8 was used on launch, to get off the planet. Very difficult thing to do. Another one maybe for orbit, and then -- that was the kind of division of energy levels.

The other thing that went along with that is prior to launch, we saw evidence that the general focus was: "Prove to me there is no problem," which is a healthy attitude in an R&D environment. After launch, it was: "Prove to me there is a problem." Little different focus. And the mission management team kind of went to that.

So we found that particularly in the requests for photo. The engineers wanted second confirmation, but the basic sense was, "Let's do the analysis and see if there is a problem, and then we'll go ask for photos." Well, they did the analysis, concluded there wasn't a problem, and they never did ask for the photos in an official capacity. A lot of consternation. You've probably read some of the reports on that.

Here's what's of interest. On the analysis that was done, they used a tool called Crater. Crater was designed in the Apollo era. It is a semi-empirical formula that you take the entry parameters of airspeed, and angle, and velocity, and you take the density and apply it against the material, and you conclude whether there's a safety-of-flight issue.

This analysis was done by a young engineer that had been trained over video teleconferencing (VTC), had two practical looks, and he was the one and only one that had really done this Crater. They just moved the expertise from Huntington Beach to Johnson Space Center. So there was movement going on. And this was the first time that Johnson was responsible for this kind of analysis. Before it had been done at Huntington Beach.

They applied the analysis. They concluded there was no safety-of-flight. However, they did not conclude that it hit the leading edge. They concluded it hit the belly. So the angle of impact was a lot less than obviously hitting a curved piece of leading edge. So they think it just kind of glanced off like you would skip a rock off the water.

And interestingly enough, the conclusion was that Crater had concluded that there was enough damage to burn through and get to a point where it would have been a problem. But Crater had always been conservative. So Crater anticipated that it would penetrate eight inches, my terms. They found it to be two inches. So they subjectively looked at the analysis and concluded there was no safety-of-flight, even though Crater if applied told them they had a problem. But the problem was on the belly with the tiles, and not the leading edge. A lot of missed opportunities they didn't quite get a hold of. Next slide.

I do want to draw your attention to the issue. We didn't ask the question until two months into the investigation, but the question was: "Could you have done a rescue effort?" And could they have found, if they knew there was a problem. Maybe there was no one who knew there was a problem.

So we said okay, here's the entry parameters. Somehow on the third day of launch you are told you've got a problem with the left wing. Could you have gone out and looked at it? Yes, they could have. And they could have designed an EVA, extra-vehicular activity, outside. And they could have hooked themselves up to the payload door. And if you hook yourself on the payload door and stand in the wing, guess what panel you're standing on? Panel number 8. So they could have probably seen that they had a problem.

Next question was, okay, if you found out you had a problem, what could you have done about it? Next slide. Turns out Atlantis was on the vertical assembly building, ready to launch in about three and one-half weeks. Could they have rolled that out early and done a rescue, and done it?

Well, if they went through the process, they would have to have waived or looked through quickly on a lot of checks. If they had launched, the shuttle Columbia could have lasted for 30 days. The limiting factor is not oxygen, it's not water, it's not food, it's their ability to recycle carbon dioxide. But if they reduced their activities, slept more, did less movement, they probably could have lasted for 30 days.

Could they have gotten Atlantis out on the pad, launched it? Remember, if they launched it, they would have made a general risk that whatever caused Columbia's problem they really weren't sure what would happen to Atlantis. But they could have done a rescue if they did tethering, and launched with four astronauts, came back with seven for a total of 11. It would have been very crowded in the cockpit, so to speak, in the upper and the lower bays, but it might have been possible. Next slide.

And this shows the other question we asked them. Could you have repaired it if you knew there was a problem? Very difficult to arrive at a conclusion here, but if they could have stuffed things into the crack, or it might have given them a chance to survive. But highly unlikely, and very problematic. Okay, let's go back. Next slide.

All right. Then we looked at the organization. Now, there are two things, even though you are looking at the words, I'd like you to just concentrate a little bit on what I'm going to say here for a minute. Bottom line here is: this was a complex organization. Complex organizations fail in complex ways.

What we found here was there was a disconnect between balance of power and checks and balances. What do I mean by that? The program manager -- I want to date you back to 1986 and Challenger. A lot of stovepipes, a lot of culture, at

Marshall, and Kennedy, and Johnson, and Thiokol. They put a program manager in charge of all of it. Not a bad thing to do. He was responsible for all of the major elements for the program for the shuttle.

Here's where it was not good. The program manager was responsible for cost, schedule, launch, safety, waivers, technical assessment, and engineering to a large extent. When conflicts came up in time and schedule, you could make adjustments on waivers, and safety, and things were done on that order, unfortunately, over the course here. Nothing duplicitous that we saw. It was just a normal consequence of budget cuts, and you know now one person is doing three things instead of just one thing. And the normal consequences on that.

So the balance of power was not conducive to an R&D environment. Remember they had already made their determination they were operational. So when you're more operational, you can take chances like that a little bit more readily.

The checks and balances were not good because in the case of safety, I want you to imagine, my words again, the program manager is like a two-star general sitting at the table, and the safety person is sitting on the side and it's a young airman, or twostriper. Kind of hard for him to raise his hand, or her to raise her hand, and say I don't agree with that. The checks and balances weren't there.

The other thing that was problematic was the integration. They had an integration office. They called it integration, but it was not an integration office. It was more a technical expertise, particularly on launch for wind shears, and the software that was put in for launch. Very technical-oriented, but not really an integration office for the program.

So you've got stovepipes that weren't talking to each other, and a perfect case in point on that is when the foam came off one time that they saw in the bipod region. Remember I said it came off six times. They only knew about four. But one time it came off they assigned the resolution and investigation to the external tank. Stovepipe. Then another time it came off, and they assigned it to the orbiter. Stovepipe. Another time it came off, they didn't assign it to anybody. All right. They determined it not to be a safety-of-flight.

So those balance of power checks and balances weren't there. There wasn't someone to do the technical analysis that needed to be done if a waiver was required, or a technical specification needed to be put aside. There wasn't anybody independent to review that. You put it with the same organization that was responsible for cost and schedule and so forth.

Now one of the things we found, I'll go ahead and blow this up here, to show you the disconnect on balance of power and checks and balances. This blue is one person. And he had responsibilities to the program, to the headquarters, and to an intermediary. So how can you check yourself, you know. And a lot of that was typical down-sizing people, and one person's now required to do four things, but before they were only required to do one.

All right. They didn't demonstrate characteristics of a learning organization. And we studied two major theories, and that one was the normalization theory and high reliability organizations. And we found NASA not to be a learning organization in a lot of ways. What we found out in the case of Challenger is that the Navy had sent over 5,000 officers through training using the case study of Challenger to try and understand a complex organization that failed. NASA didn't do that to any of their major senior managers. It wasn't part of their culture to do this learning element. And unfortunately they didn't go to school on it, and we saw a lot of echoes. We call them "echoes of Challenger." Sally Ride coined that term one time in a press conference, and it absolutely was correct. In our Chapter VIII of the report we really show shuttle, Challenger/Columbia, Challenger/Columbia, and show a lot of significant common elements. Next slide.

Both accidents were failures of foresight and policy compromises. By the way, you'll see criticisms on both sides of Pennsylvania Avenue here. Remember I said it's not just the two guys that didn't chlorinate the well, you know, it dated back all the way to Parliament in Canada. We found that to be true for responsibilities for the White House, Congress, and NASA that dates back to multiple administrations.

NASA culture allowed flying with flaws when problems were defined. That's that normalization of deviance I talked about earlier. It appeared to be immersed in a concept of invincibility. They were the leading experts in the world. I mean, it's kind of hard for people to come in, do a study on them, and then people to accept it when you're viewing yourself as the expert. We've seen this in many other organizations, and I think that can be applied maybe to the nuclear industry too.

You have to be always careful about that. You have to encourage dissent points of view, and you have to ask for it. You have to welcome it. And unfortunately that wasn't being done. Next slide.

So organizational cause, history, decision-making, organizational structure, system effects, as well as all the words we've got here that I explained a little bit earlier. The Board has great confidence that the shuttle can get back to flying again in the short term. We had significant less confidence that the shuttle can be maintained because of organizational, managerial issues for the long term.

So we made some recommendations to try to put in place that would help. You know, after the tenth or fifteenth, they don't gravitate back like they did after Challenger to the issues of compromise, balance of power, checks and balances, safety, and so forth. Next slide.

So the history. We have a lot of compromises that were made in the original design of the shuttle. Decision-making: we see problems where people were saying, "Prove to me there is no problem, to prove to me there is a problem." Organizational structure, where we have balance of power, checks and balances, and safety are not sitting at the table right now. And system effects where structure and managerial emphasis. They were more concerned about who asked for the photo, rather than saying boy that's a darned good idea, why don't we get a second opinion, and prove to me there is no problem, rather than prove to me there is a problem.

Okay, we didn't want to just leave it to the point where we were guilty of just saying thank you very much, and looking backwards, which is typical of safety investigations. Here's the technical cause, looking backwards. Here's the organizational structure, looking backwards. We wanted to look forward with our recommendations and say, okay, what is it that we thought were absolutely essential for return-to-flight?

We came up with 29 recommendations. Fifteen were return-to-flight. In other words, those are recommendations that we said NASA has to do before they fly the next time. The other 14 were non-return-to-flight recommendations that go into the mid-term. Organizational recommendations I'll talk about in a minute, and re-certification of the orbiter.

We did call for re-certification of the orbiter. We found great discontinuity between specifications that were in books, like the 0.006 foot-pounds of pressure that could be taken by an impact to the reality it can take more than that. It probably can take 2, 3, 4 pounds of pressure depending on angle and density and all the necessary entry, but not 8,000 pounds. So make the reality of what is true to be what's in the books. So it requires re-certification of the orbiter.

It called for a national debate on manned space flight. And where Congress is going through a lot of hearings now. And then replacing the shuttle. We call for, and these are our exact words, replace the shuttle as soon as the possible as the main means of manned space flight getting into low-earth orbit.

And we didn't say tomorrow, or next year. We fully anticipate this is going to be an 8- to 10-year kind of project. But do it as soon as possible as the main means of getting man into low-earth orbit. Next slide.

Now the Board recommendations, I'm not going to go through all of them, but here we have return-to-flight in blue, and non-return-to-flight. In other words, mid-term to long-term. But we look at some of these subject areas. You know, wiring and bolt-catchers, and micro-meteorite and foreign object damage.

The big one for the mishap was the thermal protection. We had four for return-to-flight. That was everything from you've got to fix the foam coming off. They've done that. We'll never see that bipod foam again. They redesigned it. You've got to improve the debris that comes off. It's not just that bipod. There's other debris.

Then when it comes off, you've got to figure out how to see it with better cameras and analysis, and checking. And then after you see if there is a problem, then you've got to figure out how to repair it. And not just against the space station. The next 99 to 100 missions are going to the space station. That sounds good because if you're on the space station you figure well, I can do some repairs and really check it out. But you might have an abort to orbit and not get to the space station. So we have to have a autonomous capability to do repair.

And then if you do get to the space station you can use it as a sanctuary to maybe work repairs, or God forbid you can't repair it, and then you've got to bring up another orbiter. So there's a lot of issues in here that we spent a lot of time on. Next slide.

But the ones that I want to show you right now are the organizational recommendations here. Now this first one is clearly what I've already talked about. Separate the technical assessment capability from the program. And that's what this one says. A technical engineering authority that was independent.

So if the program manager wants to waive a specification or a requirement, he cannot do that on his own or her own. They have to go to a special technical assessment, they will do the analysis, detailed analysis, not PowerPoint briefing, detailed analysis to be able to conclude yes or no, we support this.

So be the sole waiver authority for technical standards, conduct integrated analysis, trend analysis, verify, and then should be funded directly from NASA headquarters independent from the program, not dependent upon the program. Next slide.

In the next recommendation we said this central safety. Again, relegate, bring safety back up to where it should be, put it more centrally from the headquarters. And organizations be independently resourced, not dependent on the program. Program safety before was funded by the program.

And reorganize the integration office. Get away from the stovepipes. Have a true integration function where you can go, the program manager can go and feel confident that they have got horizontal integration all the way up the line, and it's not going to be stovepiped and not done in a concrete and organized manner. Next slide.

Okay, next. Okay, we'll leave it here. In the end, last thing I just want to say here is the Board assumed and concluded that the U.S. wants to retain the human space flight program. Now the Board worked over seven months to get this report. We're really into the ninth month. On Tuesday of next week, we are going to release the remaining volumes, which are Volumes II through VI. These are all supporting the main document. We didn't accept everything in there, but it's a good reference material for people to understand what went into the conclusions that we finally got to.

But our Board worked to understand the causes, to minimize the risk for the future space program. And as President Bush said on February 1, "Mankind is led into the darkness beyond our world by the inspiration of discovery and the longing to understand. Our journey into space will go on."

Mr. Chairman, I'm prepared to answer any questions that you or the Board may have.

CHAIRMAN CONWAY: General, I thank you very, very much for a very, very excellent presentation here. And your report itself is an indication of a very good hard work by a lot of very experienced and very capable people.

I will say I'm hopeful that the Department of Energy and the work that it does for the safety of the nuclear weapons program will have learned from this because we see right today the Department of Energy has undertaken what we believe to be some major changes in the way they've operated in the past, and as they're proposing to upgrade in the future, that have this Board somewhat concerned.

I think there's a lot of lessons to be learned here. And we hope that the DOE will have learned from these studies that you and your associates have put together, and to keep them from making some major mistakes.

VICE CHAIRMAN EGGENBERGER: I'd like to discuss a little bit with you the engineering organization as you believe it should be. Let me talk