# April 23, 2003
# Houston, Texas

***COLUMBIA* ACCIDENT INVESTIGATION BOARD PUBLIC HEARING**
*WEDNESDAY, APRIL 23, 2003*

9:00 a.m.
Hilton Hotel
3000 NASA Road 1
Houston, Texas

**BOARD MEMBERS PRESENT:**

Admiral Hal Gehman
Rear Admiral Stephen Turcotte
Major General John Barry
Dr. John Logsdon
Dr. Jim Hallock
Dr. Sheila Widnall

**WITNESSES TESTIFYING:**

Dr. Milton Silveira
Mr. George Jeffs
Mr. Owen Morris
Mr. Aaron Cohen
Mr. Robert F. Thompson

**ADM. GEHMAN:** Good morning. The Columbia Accident Investigation Board public hearing is in session. Today and this afternoon, we're going to deal with various types of risks. We're going to listen to a number of experts and talk about their view of risk management and risk mitigation and how risk is looked at from about five different angles, particularly as it applies to manned space flight and the Shuttle Program.

This morning we're going to look at risk as it applies to the original design and construction of the STS. Later this afternoon, we're going to look at risk from the point of view of experts on aging aircraft. We have a couple of experts going to testify and talk to us about how risk migrates over a period of time as aircraft are used. Then later in the day, we'll have Professor Diane Vaughan who will talk about organizations and how organizations deal with risky enterprises.

For this morning, the Board is very fortunate to have a wonderful panel with years and years, maybe decades and decades of experience in this particular enterprise, the STS system. The *Columbia* Accident Investigation Board would like to thank the NASA Alumni League for organizing this panel -- and a very special thanks to Norm Chaffee, the president of the Johnson Space Center chapter of the league -- for helping us to arrange this panel that we have in front of us.

What I'm going to ask, Panel Members, is if you would, first of all, go right down the row in some order or another and introduce yourselves and including in your introduction, if you would, say a word or two about the official position you had when you were involved in either the Johnson Space Center or the STS or Shuttle Program when you were actively engaged in running it. Then when you're finished with that, I would invite you all to make any kind of an opening statement that you would like to make; and then we'll proceed into questions.

So if I could ask you to start at one end or another there, and maybe with Aaron there, and introduce yourself, including a little background of your involvement in the Space Transportation System.

**AARON COHEN, ROBERT THOMPSON, GEORGE JEFFS, OWEN MORRIS and MILTON SILVEIRA testified as follows:**

**MR. COHEN:** Good morning. Thank you. My name is Aaron Cohen and I was the first NASA Space Shuttle Orbiter Project Manager from 1972 to 1982. This period of time encompassed the design, development, and the first four flights of *Columbia*. I retired as the Johnson Space Center Director in 1993 and I taught at the Texas A&M University from 1993 until 2001. I am now Professor Emeritus of Engineering at Texas A&M.

During this period of 1972 to 1982, there were many design challenges on the various subsystems and the integration of the subsystems into the basic vehicle. This included the structure system, the life support system, the environmental control system, the Thermal Protection System, which were the tiles and the carbon material, the thermal seals, the avionics system, the auxilliary propulsion system, the hydraulic system, and the many mechanical systems such as doors, actuators, and tires.

I would like to say that we have a very good documentation of this activity, and it was prepared in 1993. It was a compilation of papers presented at a conference held at the Johnson Space Center in June 28th to 30th of 1993. This documents the design challenges of all the Shuttle systems. The papers were prepared by the NASA and contractors' subsystem managers, and the subsystem managers were the backbone of the Shuttle design.

This is my introduction statement. I will be happy to answer your questions in the hopes that we will be able to return the Shuttle soon to safe flight.

**ADM. GEHMAN:** Thank you very much.

Mr. Thompson.

**MR. THOMPSON:** Okay. My name is Bob Thompson. My principal reason for being here today, I was the Shuttle Program Manager from 1970 to 1981. That encompasses a time that we started into what we called Phase B, the very early design activities on the Shuttle; and I remained the Program Manager through the first Orbiter flight, at which time I retired and went to work in industry.

I'll be happy to answer any questions. I think certainly the subject of risk management, I think we all recognize that any vehicle that can fly to and from earth orbit is going to be a risky vehicle by definition. So you're going to have to deal with risk. I don't care how you design it. Of course, the way you determine that you want to design it really sets in the family problems you're going to have to deal with; and it's very important in the early design phase to pick the set of problems you're going to want to have to live with. I think we were extremely conscious of that when we picked the configuration that we picked, and we knew we had a lot of problems to deal with. As long as we continue to fly the Shuttle, we'll have to have problems to deal with. So I'll be happy to answer any of your questions as we go on through the morning.

**MR. JEFFS:** I'm George Jeffs. I've spent since the Sixties in the space business, most of it with NASA, a lot of it with the Air Force also. I was at one time the Chief Engineer of the Apollo Program, the Program Manager of the Apollo Program. I was the Apollo Program Manager and the Shuttle Program Manager at the same time for a while. I ran the space division that also had the global positioning satellites. The Rocketdyne division reported to me. The energy activities reported to me at Rockwell. I ended up running that part of Rockwell that was sold to Boeing.

I've enjoyed working on the space program with the NASA because we have thought alike. We have been after the basic cause of problems rather than Band-Aiding problems. We've left no rock unturned to try and get the right answer to these things, mutually. We may have missed a few, but they were unknown to us or we would have fixed them. All those years I have spent in the middle but between NASA and industry and making those teams work because the teams are just as important a part of making these big programs happen as the hardware itself. I find myself again in the middle here, with NASA fine people on both sides of me, a thorn amongst roses; but at any rate, I will try and also answer any of the questions you might have that we may recall the answers to. We're all very proud of the hardware and its performance. Some of the best memories that I have are the astronauts telling us, after flights, what beautiful hardware it was to operate. Thank you.

**ADM. GEHMAN:** Thank you, sir.

**MR. MORRIS:** My name is Owen Morris. I was with NASA throughout the Apollo Program and worked on the Space Shuttle from 1972 to 1980. Initially I worked with Aaron as his assistant Orbiter manager, and then later I was in charge of systems integration at the Level 2 of the program. I worked with Bob Thompson there from late 1972 to 1980, retired in 1980, and then formed a company of my own for the next 15 years, working on conceptual design. I'm very happy to be here and look forward to answering your questions.

**ADM. GEHMAN:** Thank you, sir.

**DR. SILVEIRA:** Hi. I'm Milton Silveira. I first became involved with the Shuttle in March of '69, before we landed on the moon. I was involved in Phase A studies; but even prior to that, I was involved in the design of the systems, support systems on Mercury, Gemini, and Apollo. I went through the Phase B studies; and when we started into the hardware studies, I moved from running a Shuttle office in engineering and development over to become Aaron's deputy as Orbiter Project Manager.

I was involved with the Shuttle up until about '80, when I moved to headquarters to become NASA Chief Engineer. I retired from NASA in '87, after 36 years with NASA.

I currently serve as a technical adviser to Lieutenant General Ron Kadish in the Missile Defense Agency. I'm glad to be here and hope we can help you.

**ADM. GEHMAN:** Thank you very much. Did you all get to make any opening statements that you would like to make before? Okay. That's fine.

Okay. What we'll do is start a round of questioning here and I'll go first and then I'll open to any one of my panel members.

I'll address my question -- and all of us will follow this procedure. We'll address our question to somebody, but I hope that any of you who wants to piggyback on the reply or elaborate or anything will please feel free. We would love to have two or three answers to the same question because you all approach this thing from slightly different angles. Some of you were more intermittently involved with systems and some of you were more Project Manager and integration related. So I'll start the first question.

Mr. Thompson -- and others, too -- I notice that in addition to being involved in the STS system in the Seventies, which was in the program design definition phase, that you had previous experience in Gemini and Apollo also. Could you in any way contrast the engineering development, the Project Managership, the rules under which you operated of those two systems? Is it possible to draw for us any differences or similarities between those two systems? And then I would invite anybody else that would like to comment on that.

**MR. THOMPSON:** Well, I would give you a broad, general, off-the-top answer. I think the processes and procedures and the management approaches and techniques were better in Shuttle than they were in either of the two programs previously, mainly because we in government and we in industry had matured a good deal by working through those programs. For example, all through Mercury, Gemini, Apollo, Skylab, we kept a "Lessons Learned" document. 8086 or something. I can't remember the number. I think it was the 8086 document, and we made the 8086 document an applicable document on the Shuttle Program.

Let me pick a specific example. We lost a main propulsion test article during the Shuttle development period because we used the wrong weld wire in a critical weld joint. That wrong weld wire came about because the vendor had mixed two metals on the weld wire reel. We had learned in an earlier program that, in any critical welds, you ought to test the weld wire you're actually using before you make the critical weld. We missed that early in the Shuttle Program. We came back and corrected it, but that lesson learned came out of the previous programs and fed on into the later programs.

So that's just one of many, many, many examples I could cite and I think, frankly, both the government management team and the contractor management team was more experienced and probably was able to take on the Shuttle design and development job and in many respects the Shuttle design and development job was considerably more difficult than Mercury and Gemini and probably more difficult than any single element of the Apollo Program. So I think I would say that we were better prepared to manage and develop a critical risk program in Shuttle than we were previously.

**MR. COHEN:** I'd like to add my comment. It's almost the same as Bob's but maybe a little different emphasis. I was on the Apollo Program. I wound up being the manager of the command and service module on Apollo. The heritage we had from Apollo was a very strong subsystem manager concept, both at the government and at the contractor. It turned out to be a very, very good system. Our subsystem managers, in all honesty, were not peak ticketed, so to speak, to the program office. They actually worked for the head of the engineering directorate, which was Max Faget at the time, but the subsystem managers essentially did do their daily work for the project office and there was a very good check and balance. They had a very good relationship with their counterparts at Rockwell or at Grumman or in the Apollo Program, but in the Shuttle Program at Rockwell.

There was just a very good check and balance in the system. I felt very comfortable with that because if there was a disagreement, the subsystem manager could always go to Max and Max could then go to Chris, who was the Center Director, or Bob, and we could resolve the issue. So I felt that that was a heritage from the Apollo Program that made it very good.

**MR. THOMPSON:** While we're on this subject, let me make another point that I would like to call to the Board's attention. At the time we were moving into Phase B on the Space Shuttle Program, we still had not decided what configuration to build. So the Phase B management was still led out of Washington with almost identical management roles at Johnson Space Center and the Marshall Space Center because it had not developed exactly what vehicle we were going to build. Once we got to the end of Phase B and it became apparent the vehicle we were going to build, we went into a somewhat new management structure for NASA, which set up a Program Manager at what we called Level 2.

If you aren't aware of it you need to understand what Level 1 was in Shuttle, what Level 2 was, and what Level 3 was. The agency, NASA, and within the manned space flight, decided to set up a Level 2 Program Manager having agency-wide responsibility for the design, development of the vehicle but to locate that individual institutionally at the Johnson Space Center so that he could take advantage of all the institutional resources. But he did not have any program per se responsibility to Center Director. He had, of course, a desire to keep the Center Director informed, but he did not responsibly report to the Center Director. He reported directly to Level 1 in Washington; but in working in Houston, then you had to work across two other centers to work the other project elements.

In addition to the subsystem managers that were set up within the project elements, one of the key things that I feel that we set up to manage across the Program were what I call ten key technical panels. We picked a key NASA individual to chair those panels, and we made those ten key technical panels all report into Owen Morris' office that was part of my Level 2 program office. Those key technical panels then had membership put on those panels of experts all around the country at other NASA centers, within contractors, within universities; and those technical panels worked specific technical issues that cut across the total vehicle. They reported in to Owen and then any issues came from there to my control board and I had the responsibility to sign off or approve or implement the things that came out of that integration process.

If that process has been allowed to weaken, I would be very concerned because that's the heart and soul of working issues across the vehicle of a technical nature. For example, if insulation is coming off the Tank, the Tank Project Manager cannot approve that. He cannot allow that to happen. That violates a systems-level spec. He has to come to the Program Manager at Level 2 and ask the Program Manager to approve a bunch of insulation coming off the Tank. If the system isn't working that way and if the Problem Report and Corrective Action procedure is not working and if the program is not bringing the collective intelligence to deal with those kind of problems that you do if you work through the system properly, then you've got a problem in the program and you need to fix it.

**ADM. GEHMAN:** Let me follow up on that. I don't want to hog the microphone here. So I'll let my panel get a word in here edgewise. For me to understand the chain of command, did any of you work for the Chief Engineer at JSC?

**DR. SILVEIRA:** For the Chief Engineer at JSC? In reality, although he did not have that title, Max Faget, who ran engineering and development, was basically our chef engineer; and, yes, I was on his staff during the Apollo Program.

**ADM. GEHMAN:** During the Apollo Program. What about the STS?

**DR. SILVEIRA:** During the Shuttle Program, we started out that same way, yes, sir, until I became Aaron's deputy. Yes, sir.

**ADM. GEHMAN:** To get to Mr. Thompson's point then, as I understand this -- and I'm beyond my level of expertise here. If you were trying to resolve an engineering program -- of course, that's all you did for ten years was resolve engineering problems -- but the engineering section or the engineering division, would you describe for me the checks and balances between a fix, an engineering solution that Mr. Faget had responsibility for, versus either the Shuttle Integration Office or the Shuttle Program Manager?

**DR. SILVEIRA:** Well, probably our biggest disputes were always between operations and engineering as to what operations wanted and what engineering was capable of doing. I think, in general, the thing is, you know, we as a team had been working all through the Apollo Program together and I think as a team we realized that we were all friends, we knew each other, we knew who to go to, and we knew how to resolve any issues we had. And we usually, you know, came to a compatible solution as a result, without having to be dictated to as far as what approach we ought to use.

**ADM. GEHMAN:** The point I'm trying to get at -- and thank you for that answer. The point I'm trying to get at is: Would it be incorrect for me to characterize Mr. Max Faget's role as being essentially an equal to the Program Manager?

**DR. SILVEIRA:** Yes, sir.

**ADM. GEHMAN:** That is correct.

**MR. THOMPSON:** I don't understand why you would use the word "equal." No, Max Faget could not make a within-the-program decision.

**ADM. GEHMAN:** I understand that.

**MR. THOMPSON:** He could come to me and make his wishes known. He could come to my control board and argue until we got to midnight, pro and con. If he did not like what I did, he could go to the Center Director, who could go to my boss in Washington and straighten me out; but when it came time to decide who made the decision, there was no doubt who made the decision and who was responsible for it.

**DR. SILVEIRA:** But there were few decisions that went that far.

**MR. JEFFS:** You need to put this in the right perspective, too. The majority of people worked for the contractor. We had 40,000 people on Apollo. We worked for these guys, but those guys worked for us. On Shuttle we had up to 20,000 people. So you've got a whole engineering structure, both in the contractors' level and the different contractors with the subcontractors. So those technical issues were being massaged with great care, and they were being interfaced with the NASA so that we had a team working. But the drawings came out of the contractor. The detailed decisions on how to do things on change control within the contract were done with the contractor. So you've got to look at both these things together to see who's making the decisions and how they're made.

**MR. THOMPSON:** And you have to really be a little more specific. Ask us any detail you want and we can tell you how that would be managed and handled. For example, if it was a stress-level issue down in designing what an allowable stress somewhere internal to a wing, you'd have to go deep into the contractor organization and check that work to really find out whether it was pro or con. And the subsystem managers in the government actually checked that work, not number by number, but looked at the procedures used, looked at the decisions made, looked at the allowables and the materials and this sort of thing. But now if you ask who's responsible for not having an abort system on the vehicle, you have to ask me that question. You cannot ask George Jeff or you cannot ask Milt Silveira that question.

**MR. JEFFS:** But if you would ask who, why it didn't work, then you can ask George Jeffs. (Laughter)

**MR. THOMPSON:** Well, if it didn't work, it's a combination of the government and the contractors.

**MR. MORRIS:** Yeah, I think, getting back to how decisions were made, we probably ought to talk about the Change Board that Bob Thompson chaired. That board was made up of all of the element managers. The Orbiter was Aaron Cohen. The Tank, the Boosters, the Engine. Reliability. Max Faget sat in on that board. He was a bona fide member of the Board. Operations was a member of the Board. And there was no significant decision made that that board did not understand. Now, as one of the Program Managers in Apollo once said, you know, "The Board is here and this is a democratic organization but I have 51 percent of the vote."

**MR. THOMPSON:** But there was never a significant decision made in the Shuttle Program that Max Faget didn't have plenty of opportunity to sit in my board while we were discussing it, make his wishes known as many times as he wanted to, and he knew exactly why I made the decision I made. Whether I agreed with him or not, he knew why and he knew and by the next day I had signed off on the decision and written up why it was made.

**MR. COHEN:** Let me hitchhike on one more thing. The Orbiter also had a Change Control Board, and on that board we had Rockwell sit in on the Board, we had a contractor sit in on the Board, and we had each directorate, like Gene Krantz from Flight Operations, George Eddie from Flight Crew, Max, and R&QA and so forth. So we also had a board. Now, if it went outside our envelope boundary, then we would take it to Level 2; but if it was inside, then we make the decision.

**MR. THOMPSON:** And you can say the same thing for the other project elements -- the Tank or the Engine or the SRBs.

**MR. JEFFS:** As Bob says, the other elements, whether it's the SSMEs or the Orbiters, these are engineering focus operations. The engineering is the head of the snake. So engineering had a key voice in almost every decision that was made down the line on these programs. And a free voice.

**DR. SILVEIRA:** And I think, importantly, the heritage of the organization, most of us came out of the Langley Research Center and we moved to the Manned Spacecraft Center when it came down to Houston. So we had a heritage of working together. We knew each other, and we respected each other. Once we arrived at a decision, everybody supported it. There was no hassling afterwards. We were sort of really, in looking at a lot of organizations today, we were sort of unique in that regard, in being able to work together and make decisions together.

**MR. THOMPSON:** You never strive for 100 percent agreement. If you get 100 percent agreement, there's something wrong.

**ADM. GEHMAN:** Right, you're missing something.

**MR. JEFFS:** I'd like to add one more thing I mentioned earlier, and that is the issue of organization and developing organizations. I was fortunate to have, with the Apollo Program, a source of great depth of capability of people, experienced people. They came from the aircraft areas. They came from P-51s. They came from SMJs. They came from across the Board on how to build aircraft. A great base.

That base was trimmed and kind of honed during the Apollo Program. That same base fortunately was maintained on the Shuttle Program. Trimmed and maintained. So we had not only the same kind of people but the same people, the same procedures had been smoothed. The knowledge of what each element could do and couldn't do within the organization and between ourselves and NASA was understood. That doesn't exist to the same extent, as I see it, in these different companies today, probably because a lot of those people are gone and you can't put everything in the database. You've got to have with the people. So there you go.

**MR. THOMPSON:** George just read part of his proposal for the contract.

**DR. LOGSDON:** I want to go back to the period of '69 through January of '72. At the policy level, the decision whether to approve the Shuttle was being debated; and you folks at the engineering and management level were getting, I think, changing signals of what kind of Shuttle was going to be politically acceptable. I guess the question is, Bob, you said you started as Shuttle Program Manager in '70 and, Milt, you said you were involved in the Phase A studies. Phase A studies produced a particular concept, a fully-reusable straight-wing Shuttle. So first question: Did that first design have the large payload bay, the 15 by 65 payload bay?

**MR. THOMPSON:** The answer to that is yes; and the answer to what came out of Phase A, what came out of Phase A, those of us that were given the responsibility to go implement the Program felt that that was a very dumb way to go about it. The two-stage fully-reusable system, as we looked at it in detail about going to build it, a lot of people argued that politics made us change it; that is absolutely not correct. We changed from that vehicle because we found, as we dug into it, that was not a very smart way to go about the job, for many, many reasons. I could spend half a day here explaining it all to you, but the concept that politically we wanted to build a two-stage fully-reusable vehicle but couldn't afford it, that is not correct. The vehicle we built is the vehicle that the NASA people that came into the program starting in Phase B that had the responsibility for building it, we built the vehicle that we wanted to build, not the one that the politicians told us we had to build.

**DR. LOGSDON:** Fair enough. In 1970, a new set of requirements, I believe, appeared in terms of what was required to get Department of Defense support for the Program -- with additional cross-range, I guess, being the most important of those new requirements. Tell me if I'm wrong, that that had a link to shift from a straight-wing to a delta-wing configuration.

**MR. THOMPSON:** You want me to answer that?

**DR. SILVEIRA:** Let me make some comments on that, John.

Of course, you know, a few of us got cleared on what the Air Force programs were; and once we understood what the Air Force requirements were, then we understood how that affected the design and changed over to meet those requirements.

**MR. THOMPSON:** I'm not sure I would agree with that. I think the myth that the straight-wing two-stage fully-reusable Orbiter was a good system to build is strictly a myth. You don't want any wing on the Orbiter while you launch it, and the only benefit of the straight wing is in the terminal approach and landing phase. The fact that what Max was proposing was to hold that straight-wing vehicle up above the stall level all the way down to 10,000 feet above the runway, then whip it over and land it on the runway and to carry those straight wings all the way to orbit and back, and to have a fly-back booster, that whole system crumbled when you began to look at it.

NASA did not put cross-range in the vehicle because the Air Force forced us to. NASA put cross-range in the vehicle because we thought that was the right way to build the vehicle and it just happened to give the Air Force some capability they wanted. But we wanted it for abort capability during the launch and we wanted to start flying the vehicle right at entry. We didn't want to keep the thing above stall all the way down to landing area and then flip it around. So the myth that the Air Force made us do something we didn't want to do is absolutely a myth.

**DR. LOGSDON:** So the implications of that design for thermal protection came along with the NASA engineering decisions.

**MR. THOMPSON:** We got the same thermal protection the way we fly the Shuttle that we were going to get with the straight wing. The straight wing was not any benefit thermally at all.

I guess it's awfully interesting to me, look back over 20, 25 years, the myths that have grown up and where they have come from. But I'll go on the record today saying NASA built exactly the vehicle it wanted to build.

**DR. LOGSDON:** I guess the final thing I'd like to talk about a little bit is the cost estimates for development and operation that were provided, again, to the political level of decision-making. OMB gave you a budget ceiling, I believe, in May of '71 that said you had to build the system with a five billion-dollar development cost; and the ultimate presentation, at least to the White House level, said you could do that, or 5.5 billion, with an operating cost of $118 a pound. I'm curious where those numbers came from, particularly the operating cost.

**MR. THOMPSON:** Well, I'm not going to answer just the operating cost; I'm going to answer the whole question.

**DR. LOGSDON:** Good.

**MR. THOMPSON:** Again, one of the big myths on the Shuttle is that it was way over budget. That's an absolute myth. In December of '71, when Jim Fletcher and George Low went to San Clemente to present the final recommendation to President Nixon, we prepared a letter that George and Jim took with them, a one-page letter. That letter said that we felt we could build the configuration that you now know as the Shuttle for a total cost of $5.15 billion in the purchasing power of the 1971 dollar but that it would take another billion dollars of contingency funding over and above that to handle the contingencies that always develop in a program like this. So you need to budget 6.15 billion in the purchasing power of the '71 dollar and that we could build it and fly it by 1979 if everything went perfectly, but the $1 billion and 18 months ought to be planned in the program because that's probably what will really happen and we'll probably fly it in early '81. That was in the document.

Jim Fletcher and George Low went to San Clemente, had a little model of the Shuttle. President Nixon approved it. He came back into the agency at NASA. Bill Lilly, who was the Comptroller of the agency at that time, took that letter and started his negotiations with OMB. When he finally got around to getting it through the OMB cycle, they took the letter and said we'll take the 5.15 billion, but we won't give you the one billion because we never budget contingencies. We'll hold you to the 1979 launch date because we never launch budget contingencies there, and we'll put it in the '73 budget at those numbers.

So we lost two years of inflation in that little maneuver in OMB. I went back and talked to Bill Lilly. He said, "Shut up. You got your program. Go on about your business." So we did. During those years of the Shuttle development, inflation got as high as, what, 20 percent, 18 to 20 percent some years. We would usually get maybe two thirds of that out of the Congress. Also, the Shuttle was picked as a program to be monitored by OMB and they actually put five or six people out of the OMB into my office level here at the Johnson Space Center and they monitored for several or probably two years exactly where all the spending was to try to keep an accountability in the Program.

One of the fellows who worked for me in the financial area, named Hum Mandell, kept a very accurate level of the spending in the Shuttle Program. When we finished the program, his record showed that the Orbiter actually under-ran our original budget, including the one billion dollar contingency and the 18-month schedule. Our schedule was right on. The other elements of the program were slightly over. The total cost of the program, when you account for inflation, account for the under-commitment of the '71 to '73, you account for the deliberate schedule that OMB asked to us do with their funding. He came to me after the first flight and says, "Here. We can prove you met your cost and schedule goals." I called John Yardley in Washington and John says, "Hell, why don't you put it in a filing cabinet. No one's interested in that." So we put it in a filing cabinet. Hum took it and got a Ph.D. thesis on it at the University of Colorado. So you can get his thesis and read it if you're really interested in the true funding.

Now, one more thing. I remember being called on television at the time, not knowing that Jules Bergman was going to be on. After they introduced me, Jules Bergman says, "Hey, Mr. Thompson, you said you could build this thing for $5 billion. You've already spent 8.5 billion. That's a terrible overrun. What the hell you going to do about it?" Inflation doesn't mean a thing to the people who write in the papers, and it's a pretty complex job to keep up with the true cost of a development program like the Shuttle. In fact, after three years, OMB quit and went home. So the myth that the Shuttle was way over budget is another myth.

**DR. LOGSDON:** Bob, you didn't answer the question about operating costs.

**MR. THOMPSON:** All right. Operating costs. (Laughter) I had a better answer for development costs.

At the time we were selling the program at the start of Phase B, the people in Washington, Charlie Donlan, some of them got a company called Mathematica to come in and do an analysis of operating costs. Mathematica sat down and attempted to do some work on operating costs, and they discovered something. They discovered the more you flew, the cheaper it got per flight. (Laughter) Fabulous.

So they added as many flights as they could. They got up to, what, 40 to 50 flights a year. Hell, anyone reasonably knew you weren't going to fly 50 times a year. The most capability we ever put in the program is when we built the facilities for the Tank at Michoud, we left growth capability to where you could get up to 24 flights a year by producing Tanks, if you really wanted to get that high. We never thought you'd ever get above 10 or 12 flights a year. So when you want to say could you fly it for X million dollars, some of the charts of the document I sent you last night look ridiculous in today's world. Go back 30 years to purchasing power of the '71 dollar and those costs per flight were not the cost of ownership, they were only the costs between vehicle design that were critical to the design, because that's what we were trying to make a decision on. If they didn't matter -- you have to have a control center over here whether you've got a two-stage fully-reusable vehicle or a stage-and-a-half vehicle. So we didn't try to throw the cost of ownership into that. It would have made it look much bigger. So that's where those very low cost-per-flight numbers came from. They were never real.

Let me make one other comment. In my judgment -- and no one can either agree with this or disapprove it -- in my judgment, it would have cost more per flight to operate the two-stage fully-reusable system than the one we built, even though the cost analysis didn't show that. When you get two complex vehicles like that and all one vehicle does is help you get up to staging velocity -- and the staging velocity is 12,000 feet per second -- when you build a booster that does nothing but fly up to 12,000 feet per second, you've built something wrong. I think that's what the two-stage fully-reusable system was; and I think, had the agency tried to build it, we wouldn't have a Shuttle Program today. My feelings.

**ADM. TURCOTTE:** You've largely described what could be in today's, I guess, modern management vernacular as a matrix organization as it existed back in the Sixties and Seventies, et cetera. You also described some complex relationships between both contractors and the different Center Directors and the Program Manager, element managers, subsystem managers, et cetera.

**MR. THOMPSON:** There were no complications on the program management channels. They were very clear.

**ADM. TURCOTTE:** Okay. Could you explain the difference, as you see the organization today, in its relationships, its matrix structure today, and compare and contrast it to the Sixties, Seventies, and up to, say, the middle Eighties.

**MR. THOMPSON:** I could not, because I'm not in detail familiar with what they're doing today.

**MR. COHEN:** I don't think I can either. I knew that question was going to be asked, but I really don't know enough about what they're doing today. I understand the system very well. You described it as a matrixed system. It was. It may appear to be complicated, but it was really very well defined. I mean, the people, when they came to work every day, they knew what they had to do; and both at the contractor and at NASA, they knew what they had to do and they knew what their role was.

**MR. THOMPSON:** I want to try and make another comment. A lot of the people at NASA had come from working in a research center back at Langley, through Mercury, Gemini, Apollo, Skylab; and when we got to Shuttle and set up the matrix organization for Shuttle, it was clear to me then and it's clear to me now that the primary responsibility for integrating that program was the government's responsibility. So when we wrote the RFP for the contract that Rockwell ultimately won, we asked for them to build us an Orbiter and to provide major systems engineering support. We did not say you're responsible for systems engineering across the Program and we didn't say you're responsible for integrating the program, because they had no contract leverage over any other part of the program. They had no responsibility for the Tank or the Booster Rocket and so forth, no direct responsibility. So it was the government's responsibility to integrate the program.

Now, we used all of the hardware development contractors in a very heavy support role. A lot of the ICDs were actually prepared on assignment by Rockwell in Downey, but those ICDs came into Owen's office for review. They went across the total program for review and came to me for signature, and I had the full control of those ICDs.

Aaron couldn't change anything that impacted the Tank. The Tank couldn't change anything that impacted the Orbiter without coming back to me at the systems level. So it was no doubt but what the government had the program management and the programs systems engineering integration responsibility, but we plugged the contractors in in a way to use their talent as effectively as we could.

**GEN. BARRY:** I've really got two questions, if I may. One has to do with history, and one has to do with design. On the history element, could you please give us maybe a characterization of what I'm going to say here -- and correct me if I'm wrong in any of it. It has to do with compromises.

Now, after, of course, when Apollo was coming to the end and Jim Fletcher was Administrator, there were plans, originally, to put stations on the moon. Then that was backed off by the administration and there was a space station design with a Shuttle. Then that was given up in place of the Space Shuttle as we know it today, which was a bit of a compromise to try to put a space station capability payload to orbit, get down to hopefully $1,000 per pound eventually at some future point, depending on how many times you flew per year. The historical question I'd like to ask is: What compromises were made on the structure development on the Shuttle in that time period? Then I'll ask my design question here.

**MR. THOMPSON:** I hate to keep hogging the thing here, but you're asking history and I guess I'm the oldest person here. To answer your question, I've got to take you to 1968 or '69 -- I can't remember which year -- and the Space Council. Do you know what the Space Council is?

**GEN. BARRY:** The Vice President.

**MR. THOMPSON:** In 1969, driven by the fact that the government works on five-year budget plans, it was then incumbent on NASA to put some dollars into the out years for where they wanted to go post Apollo. So the nation then came to a fork in the road or what are you going to do with manned space flight, in 1969, because you could see the end of the Apollo Program. We had already decided what to do with the residual hardware in what became known as the Skylab Program. If something wasn't done, we were going to go out of the manned space flight business. That simple.

So the Vice President at the time, Spiro Agnew -- and this thing never really got advertised very much maybe because of that -- in any event, he chaired the Space Council and they worked for about six months and they looked at where this nation should go post Apollo, so-called post-Apollo planning. I'm sure those are in the records and you can go back and get them.

That Space Council looked finally at four major options. They looked at a manned Mars expedition, they looked at a follow-on lunar program, they looked at a low earth orbital infrastructure program, and they looked at getting out of the business. They looked at those four things.

They made the decision to have a low earth orbital infrastructure program. It wasn't we'll build a Shuttle or we'll build a space station, you know. We will have a low earth orbital infrastructure program. It never got announced like Kennedy announced the Lunar Program, but that decision was made by the President on the advice of the Space Council.

Now, up until that time there had been a lot of debate in this country about whether space station should be a great, big, artificial-gravity rotating wheel launched on Nova-class boosters or whether it was to be a zero-G station built on orbit in modular form with something like the Space Shuttle. The desire for a zero-gravity, modular space station prevailed at that time. It was a commonsense, logical thing to do; but before you can go that way, you obviously have to have something called a Space Shuttle. You have to have a truck and a personnel carrier and a work machine to go up there and do that work.

Also, at the time the President was giving the head of NASA instructions to come down off the 3.5 percent spending that we had peaked at in Apollo, down to about one percent spending for the agency. As Jim Fletcher looked under his one percent spending -- with Apollo ongoing, with Skylab ongoing -- he felt that he couldn't have but one billion dollar annual funding expended on low earth orbital infrastructure development.

We then undertook obviously to build the Shuttle first and then the modular, zero-gravity space station second; and the low earth orbital infrastructure gave the nation a capability to operate from the surface of the earth up to 600 nautical miles, operating Shuttles and space stations and interim upper stages that would take payloads from that low earth orbital up to geosynchronous orbit. As the thing evolved, we started with the Shuttle; and the requirements for the Shuttle were driven 99 percent by what we wanted to do to support the space station. It also happened to give the Air Force the kind of payload volume and the kind of capability they wanted, although they really wanted to be at higher orbits for their work.

So the Air Force came in and said we will plan to use the Shuttle and we will also take on the task of building the interim upper stage, which was part of the low earth orbital infrastructure. So NASA embarked on the Shuttle. It wasn't necessary to commit to a space station at that time because the Shuttle had to be built and operational before you commit to space station, and the President at that time, Nixon, had other things on his mind. He didn't get up and make a great, big speech about low earth orbital infrastructure.

So now a lot of myths have grown up about we stumbled between space station and the Orbiter and we wanted to do an Orbiter this way and an Orbiter that way. That's not the way it happened at all. It was pretty orderly planning. It was a decision to go to the low earth orbital infrastructure. Let's have a Shuttle, then let's have a modular zero-gravity space station.

Once the *Challenger* accident occurred, the Air Force got off of the ship and stuck with their original vehicles, which I think was probably the right decision for them all along because the nature of their missions don't fit the Shuttle quite that well but they could have done some of their work. But they actually developed the interim upper stage and they built a bunch of launch facilities at the West Coast that we ultimately phased out.

**GEN. BARRY:** Let me ask the following question based on a historical perspective. Can you give us an understanding of the design specifications for the Orbiter to take debris hits? When you finally settled on the design after going through these ramifications of alternatives and finally settled on, as we know, the Space Shuttle system to be today, our question from the Board repeatedly is: Was the Space Shuttle designed to accept debris hits from foam, either at the RCC or at the belly with the tiles?

**MR. THOMPSON:** The answer to that is no. The spec for the Tank is that nothing would come off the Tank forward of the 2058 ring frame and it was never designed to withstand a three pound mass hitting at 700 feet per second. That was never considered to be a design requirement.

**MR. COHEN:** You've got to recognize, when we first started flights, we were concerned about ice coming off the Tank. That really was our big concern, was ice going to come off the Tank, because we knew ice would do very serious damage.

**MR. THOMPSON:** But usually ice under insulation was our principal concern where you would get a crack in the insulation, you had cryo-pumping under there, you'd get ice formed up under it, and a chunk of ice and insulation come off. We must have had -- Owen, you can estimate – 15, we had so many meetings on trying to make sure we didn't have ice, we called them the ice follies meetings.

**MR. COHEN:** And we still have an ice team today that goes out and inspects the vehicle before every flight.

**MR. THOMPSON:** I don't know what they're doing today. It was my understanding -- and you can correct me, Owen -- I was pretty sure we did ultrasonic testing on the Tank foam insulation, looking for any voids. We carefully did visual inspection. We put together a very comprehensive ice team that walked up and down the vehicle just before liftoff. We put the beanie cap on top of the Tank to capture the cold exhaust gas to make sure no frost or ice built up there. We even talked one time about building a great, big damn building around the whole thing and environmentally control it, but we decided that really probably wasn't necessary.

We paid an awful lot of attention to making sure nothing came off, because we knew if we fractured the carbon-carbon on the leading edge of the Orbiter, it was a lost day. We could take a fair amount of damage on the silica tiles and still be all right, but it was a maintenance problem. So we worked very hard to make sure we did not have any foreign object debris.

**DR. SILVEIRA:** You have to understand the exterior of the vehicle of the Orbiter is glass. I mean, the coating on the tile is a silicate glass, and you have to treat it like that. So, yeah, impacts are not allowed.

**MR. JEFFS:** Let me hitchhike on that briefly, too. That is that it's kind of incongruous, when you look at the overall picture, the RCC panels are -- the bottom line, for example -- the rear of the panels is not completely true. There's a little waviness in it which is just due to the way it comes off the tool and spring-back and so on; but when the tiles are matched to it, the tiles are delicately matched to mix those interfaces all the way along. With a graphite epoxy, the coefficients of expansion are such that you can maintain those shapes just right. Then we stand back and think, gee, there we go to great pains to kind of hand-tailor all of this stuff and then all of a sudden we're hitting it with debris. It just is two different worlds.

**MR. THOMPSON:** Well, let me comment. The silica tiles that are on the Orbiter behind the carbon-carbon, in the damage testing and the testing we did on that during the program, in most cases the type of damage you would expect to get on those is not the kind of damage that kills you. Most of the time when you hit those tiles hard with something, they were fragile enough that you knocked the outer layer off but the inner layer where it's been densified against the two glue joints and the strain isolation plate, just a portion of the silica, the two glue joints and the strain isolation plate gives you enough thermal protection to make an entry. So people have gotten locked up on the fragile nature of the silica tiles. The silica tiles are fragile to damage, but they're actually pretty forgiving. You can take a lot of damage right there. You cannot take any damage that knocks a hole in the carbon-carbon leading edges.

**MR. JEFFS:** Well, let me add one thing to that. That is that they're a robust system from what they're designed to do, and that's to take the heat loads. They are a little delicate here and there when it comes to like the coatings because the coatings are part of the radiating heat transfer. So the coatings are meant to be there, and it's also pretty critical on the front edges of that system so that you don't trip the boundary layer. You certainly don't want to trip the boundary layer on the front end of that thing.

So, as Bob says, those tiles along the interface to the RCCs are also densified. So they're a higher density than the tiles further aft. So they're stronger. You do that, taking with it the higher thermal conductivity through the thing, and still maintain the bond line temperatures. So they are more rugged and they will, as he says, give you assurance you're going to get through even if you have some missing, but you don't want to do that and you don't want to nick them on that front end.

**MR. COHEN:** We were concerned early in the program whether you could damage a tile and that tile damage at the bond line and that the heating then would cause what we call an unzippering effect where you actually damage the bond line and a lot of tiles would come off. That would be the case we were concerned about. But as Bob said, the tile is actually pretty forgiving with reasonable types of hits. But you can't take large hits that really cause you damage that would destroy the boundary layer.

**MR. THOMPSON:** Let me take you back on this and tell one story. We were doing some thermal testing of the silica tiles in a thermal wind tunnel out at Ames. We heated the air stream with some carbon heating elements. And there was a test panel with several silica tiles put on it that would be put downstream and then you would hit it with this heat pulse in the aerodynamic wind tunnel there. We ran the tests on the silica tiles. Lockheed, which was the subsystem manager for the silica tiles, ran these tests out at Ames, and the heating elements, the copper heating elements in the tunnel failed and they put a whole bunch of carbon shotgun-like particles in the air-stream. They actually blew off probably 70 percent of the silica tiles, just like you would shoot it with a shotgun. They brought that to my office to show me what happened on that. I said, "Well, okay, that's fine but what happened to the temperature of the aluminum behind it for the re-entry heating pulse?"

They said, "Well, instead of 200 that we were looking for, it got up to 3 or 4 hundred degrees, but it didn't structurally fail."

I said, "Hell, that's the best test I've seen in a long time."

**MR. JEFFS:** Just a couple of notes on it. When you look at that wing after flight, it's fascinating to see where the transitions occur. You can see from the heating patterns under the bottom wing. You can see how far back that transition is. So you're laminar a long way back, which is very reassuring. Even if you had a nick along the front edge locally, it doesn't necessarily transition the boundary layer throughout the total wing. It could be just in the local air of the wing, and it would be probably be survivable. So we weren't really concerned with the zipper effect. Fletcher was really worried about that, but we didn't think that would occur.

**MR. THOMPSON:** Well, you don't want to leave the impression that if you trip the boundary layer, you would lose the vehicle.

**MR. JEFFS:** No, but I didn't say that. I said you could locally trip it and you could have higher heat transfer coefficients in that region but you're not going to necessarily lose the wing in those circumstances.

**MR. COHEN:** Let me ask you a question. You may be more familiar. Have you gone back and looked at Volume 10 now? Do they have a requirement in there for the size of debris?

**GEN. BARRY:** Volume 10.

**MR. COHEN:** Volume 10 would be the design specification --

**DR. SILVEIRA:** That's a Level 2.

**MR. COHEN:** Do they have a criterion in there?

**GEN. BARRY:** They do have a criterion, and it's like .006 foot pounds per hit. It's very, very small. It's almost minuscule to the point where it can't take hits, just like Dr. Silveira mentioned. So that's the puzzling aspect because, in reality, as you trace the hits on the Orbiter from the very beginning, from the very first mission, they've averaged, you know, as high as 700 on STS-27 to 300 on STS-87 and almost every Orbiter has averaged about 50 to 100 hits. So it's interesting to see that the design specification really was not to allow for any hits, although the reality has been it's been pretty durable for most of that; but the design specification is contrary to the reality.

**MR. JEFFS:** Weren't the majority of those coming off the runway?

**DR. WIDNALL:** What runway?

**MR. JEFFS:** Landing the thing. You get a lot on the runway. That runway is coarse.

**MR. THOMPSON:** Here again, Aaron was talking about a document that was called the 07700 series of documents. Those are the Level 2 documents that I controlled to put the specs across the program. Volume 10 was one of those specs, and that was where the 2058 ring frame came from. In any practical problem, it would be nice to meet all of your specs. In the real world, though, you know, I will sit here and let you shoot at me with a pop gun that's got a little cork in it that won't come halfway over here all you want to; but if you pick up a .45 and shoot at me, I'm going to get the hell out of here. So you've got to have some judgment when you're operating a vehicle of this nature of what you're willing to live with and what you aren't willing to live with. And that's hard to write in a specific spec and it's hard to live in an ideal spec world because you run into practical problems like popcorning of insulation.

**MR. JEFFS:** Let me say one more thing. I might have left the wrong impression here, too. That is, you know, first off with the RCC. We were always concerned about the RCC and the loads on the RCC. We spent extra money and extra time to go to the woven cloth, for example. We didn't go to the single filament stuff to take advantage of the load direction and all this jazz. We really went overboard to make that as strong as possible.

We went through the whole litany with McDonald on the problems they were having on trying to make a graphite tail for the F-15 or F-18. I don't know which one it was. They had a lot of problems with it relative to how you weave in the middle interfacing elements of the carbon-carbon. You can't just drill holes in carbon-carbon. So you've got to weave in the interfacing metal elements in order to attach it to the air frame. So they had special techniques that they had gone to to wrap it in like you tape-wrap a swollen ankle or something like that, to really get those pieces in there right. Went through all that stuff with them. So we really had a rugged RCC. That RCC, the Q alphas are, I don't know, 900 to 1100 something like that, pounds per foot. So they're taking a pretty damn good load up in that front end. So they're not wussies, that's for sure.

**MR. THOMPSON:** Well, they are strong; but they're still a ceramic. What you don't do is hit a ceramic with a real sharp, high-energy, low-time blow. Anything going 700 feet per second, even if it's a soft piece of insulation, if you look at the force-time curve that we put onto that insulation, we didn't do a dead-chicken test on it. We knew well you could knock it off if you hit it with enough potential energy, or kinetic energy.

**MR. JEFFS:** You guys mentioned the holes have been mentioned on the RCC. When I looked at the first flight back, up at Edwards, I was looking at boundary layer transitions pattern and stuff. I noticed on the underside of the wing that I could see occasionally a few holes. They looked almost like a circular hole. Completely circular. Almost like a hole that would be popped out of your porridge when a steam bubble come up out of a porridge, you know. I couldn't figure what those things were. I thought maybe we might have trapped water in the zip or something and we had gotten over the boiling temperature of water, which is like 160 or something like that at the altitude, and that we were building ourselves a little steam engine there and that might be accounting for the tiles occasionally popping off, which we couldn't figure out why they would occasionally come off. But we ran some tests and they ran some tests lately at Langley and they haven't verified that that's any condition at all. I noticed you said there some round holes on the RCC, or somebody was saying that there were some holes. We just don't know what the nature of those holes are. We had never seen those before. We didn't see any of those at testing.

**GEN. HESS:** One of the issues that's often discussed in the back rooms of the Board is this thing about whether or not the Shuttle is an operational vehicle. We wonder if y'all could share your opinions on that versus being an R&D vehicle.

**MR. JEFFS:** I've got a lot of heartburn that I can share with you on that. You know Beggs wanted to declare the Shuttle operational after about five or six flights. That was one of the reasons for the SPC. It was one of the reasons for the Shuttle processing contract being given at the Cape. Our arguments or my arguments were that we were still learning about the machine and we still had a number of things to really sweat out before we completely understood it and all the characteristics and, therefore, the development contractor should be maintained strongly in that act.

**MR. THOMPSON:** George, you need to ask him what an operational vehicle is. Define it. A vehicle that flies to earth orbit will never be operational in a sense a 747 is operational, if that's your definition of an operational vehicle.

**MR. JEFFS:** So we were as operational as we ever had a space machine, I guess, because we had flown it that many times.

**MR. THOMPSON:** But it will always be a risky endeavor.

**MR. JEFFS:** Well, we're still learning about these machines. It's a machine that doesn't have the same wear and tear as an aircraft. I mean, we're not landing it ten times a day or what have you. It does take heavy loads on launch. It takes thermal loads on re-entry. So it's different. It doesn't do much on orbit. It's pretty easy for it on orbit. But it is not a hard-driven machine from an operational point of view, and it's more like a helicopter.

**MR. THOMPSON:** You're still hitting it with four million pounds of thrust.

**MR. JEFFS:** Well, you only do it every once in a while. You only do it twice a year rather than ten times a day. I wanted to add one more thing to it, though. That is, further, it's like a helicopter, and even more so, in that when you get it to the ground, you can do anything you want to it. You can re-examine it. You can change, add to the tiles, fix the tile problems and so on. So you're rebuilding the machine between flights.

**MR. COHEN:** No matter what you say, the hardware, the process, whatever, needs to take -- you need to have tender, loving care of it.

**MR. THOMPSON:** You need a development mentality organization managing it.

**MR. COHEN:** It's a hostile environment you go into and return to.

**MR. JEFFS:** With all respect to Beggs, though, he wanted to -- the other side of that argument, the flip side obviously, is that if you're the development contractor, you're continually making changes to it. So stop making changes, guys, to make it better all the time. That's where Beggs was coming from.

**MR. THOMPSON:** I've heard that all my life: "Don't make changes." If it's about to break, you better change it.

**MR. JEFFS:** You've got to have those kind of eyes looking at it so they can see ahead of time before it's about to break.

**ADM. GEHMAN:** I'd like to ask Mr. Morris and Mr. Silveira if you'd comment on this, whether it's an operational or a developmental vehicle.

**MR. MORRIS:** Well, I would go back to Bob's question. How do you define operational? I think, in my experience, any high-performance aircraft is continually being inspected, is continually being modified. They're being updated with glass cockpits and other things that are systems upgrades. But any high-performance vehicle is continually being modified. I think the Shuttle, although I haven't been involved with it for many years now, has been modified more than most operational aircraft, things you call operational; but I don't think there's a difference in the amount of changes made. I don't think there's any difference in the philosophy of the way you manage the Program or operate the vehicle. I think a high-performance vehicle, be it in space or in the air, continues to be something you are developing and you're learning more about as you operate it.

**MR. THOMPSON:** I think it's also somewhat delusionary to think you can start with a new sheet of paper and build a new vehicle and it won't have any problems and it will be easy to operate and it will be cheap to operate and everything will be fine. That's always what you come out of Phase A with; but once you build it -- and particularly if it's going to sit on the surface of the earth and then accelerate to 18,000 miles an hour, stand re-entry heating, land on a runway -- you're going to have to give it a lot of attention.

**MR. JEFFS:** As you say in the aircraft business, it's operational on condition. It's an on-conditional airplane, but you've got to have the right eyes looking at it to know when that on-condition time occurs.

**ADM. GEHMAN:** Mr. Silveira, you want to comment on that?

**DR. SILVEIRA:** You know, like with any vehicle, you have to continue to scrutinize the results of every flight. You know, we had many thousand hours on 737s when we had to go back and modify the actuator and the rudders because it didn't really work the way we thought it did on that. I think that's the thing you have to continually do with any aircraft.

Now, as the aircraft gets more mature, of course, you can back off some on the scrutiny; but where the Shuttles have actually very, very limited amount of flight time, then you've really got to pay a lot of attention to it. You say: Are they operational? To a certain extent, yes, but you still need an awful lot of engineering scrutiny to examine what the results were of the last flight.

**MR. THOMPSON:** You have to also recognize that a rocket engine, you're essentially building a very hot fire in a cardboard box; and you have to do it very carefully. If you get a little bit off on your cooling paths and so forth, you burn up your box.

**MR. JEFFS:** We've come a long way. We didn't really know that much about the regen system with the SSMEs. As a matter of fact, we had a lot of trouble going through the gates to get the engine started. The guy I worked for at the time that ran Rockwell used to say, "How in the world are you ever going to get three engines started at the same time if you can't start one?" That was a very good question. We've come a long way and we've learned a lot about the engines. Where we found shortfalls -- or not shortfalls -- but marginal conditions and we were operating with low margins, those are things that have been worked on. Changed. Addressed. The pumps and so on.

**MR. THOMPSON:** And the digital controller.

**MR. JEFFS:** And that's the kind of whole process that should go right along with the evolution of the whole system. Someday it will be even more on-condition in total, but it will still have those things in it that we learn from the operation of a system like this in space, which is new. We don't have the aircraft background that we had.

**DR. HALLOCK:** You mentioned Volume 10. I've had some many sleepless nights looking at it, trying to understand what was going on, and looking at this evolution over time. You also mentioned that one of the criteria you had was that you didn't want to have any strikes, foam strikes, is the way we were talking about it at that time. But how about the ambient environment itself? I mean, things like what you might expect in that when you get up into orbit, such as space debris and micrometeorites and other types of things that could also cause damage to the craft?

**MR. THOMPSON:** I would comment that we did not know enough about the orbital environment to practically say what kind of impacts you should take from orbit. So, frankly, we did not spend a lot of time trying to design the Orbiter to take hits while on orbit from unidentified objects.

**MR. COHEN:** We did have a criteria -- and I believe I'm right -- the criteria in the Orbiter that you could have a penetration or an opening of a half an inch or so diameter and have makeup volume, makeup gas.

**MR. THOMPSON:** You're talking about the environmental control system.

**MR. COHEN:** Yeah, the environmental control system. So the crew could get their suits on and do a de-orbit. But that was not for space debris. That was just for a penetration.

**MR. JEFFS:** We did have the specs on particle size impingement on windows and what have you. So the windows are all designed for that.

**MR. THOMPSON:** For a certain particle size. But you could certainly get above that.

**MR. COHEN:** As Bob said, I don't recall orbital debris being discussed very much.

**MR. THOMPSON:** I don't think you would really know enough today to put a good spec on a system flying in earth orbit.

**MR. JEFFS:** We had some data from Apollo that we used.

**MR. THOMPSON:** It's going to have to be a judgment call for someone.

**DR. HALLOCK:** One of the things you hear a lot of discussions going on at this point is: Is there someway that one could make a repair on orbit? Were those kinds of issues addressed back in those times?

**MR. THOMPSON:** They were discussed. They were never addressed in a serious way.

**MR. JEFFS:** Well, we were pretty serious about trying to figure out how the heck you might replace a tile. There's a young lady in the bowels of NASA named Bonnie Dunbar -- or Donnie Bunbar or whatever they called Bonnie -- and she's a Ph.D. in ceramics. She was right in the middle of the tile operations. She worked for us a while up at Palmdale. We often discussed how in the heck if we look at the detailed process of what the guys had to go through just to get a tile on and how you would do that with gloves, you know, in an EVA situation. And it's not easy. I'll tell you, it's not easy. You know, you've got to pull-test it and you've got to do lots of things with it to verify that you've got -- you might take some shortcuts if you just had to make a repair in orbit, I suppose. I suppose it's doable, but it's very tough. Now, how you replace an RCC panel? That's something else.

**MR. THOMPSON:** First of all, I noticed in the paper a lot of conversation about looking at the Shuttle while on orbit. We did look at the Shuttle while on orbit for the first Shuttle flight, using the Air Force resources. It was more from a we would just like to know ahead of time whether we've got some potential problem in front of us, not because we had any ability to go inside and do very much about it.

**MR. COHEN:** Those things are documented. I don't recall. But the real issue is going EVA and trying to get to the various parts of the vehicle. Even if you had a kit, it's very difficult. With the space station there, it may be another thing.

**MR. THOMPSON:** You could do some things like that. It's a matter of whether that's a good expenditure of your resources with the probability of what you can really do that's practical.

**GEN. HESS:** I'm kind of curious if you would characterize for me the role of the safety organization in the structure that you had back in the Sixties and Seventies in terms of how it integrated itself with the system development.

**MR. COHEN:** Let me say a little bit from the Orbiter point of view on the changes. In our Change Board and my daily meetings, SR&QA had a person sit in on every one of our meetings; and I think that was the same thing at Rockwell, also, from the Orbiter point of view. Somebody was there. Again, very much as the engineer was a check and balance, SR&QA was a check and balance because in that case I believe Marty Raines was the head of SR&QA and he reported to Chris Kraft. So again, if SR&QA had an issue with what we were doing, just as engineering or operations, there was a check and balance at my level.

**MR. THOMPSON:** Well, I think I'd comment this way. Within the Program, there was a very active Safety, Reliability & Quality Assurance presence and activity. We did all the usual failure mode and effects analysis. We did all the development of critical items list. I signed off on probably several hundred critical items, recognizing if that item failed, we'd lose the vehicle. Safety was spread throughout. Safety, Reliability & Quality Assurance was spread throughout the entire Program.

We looked very carefully at whether we wanted to do what we called the nines business, whether we wanted to attempt to do statistical quality assurance kind of things. In looking at the spectrum across the Shuttle systems, the part of the system where the nines kind of approach made sense in avionics and things like that was a relatively small part of the overall system. So we did not go into a formal statistical qualification program where we could get nines that had some meaning to tell us which part of the system was relatively good and which part wasn't. We tried that on Apollo and gave up on it, more or less. A lot of consideration was given to what we called the formal or statistical safety and quality analysis, and we decided it was not worthwhile to try to lay that on the Program.

How you put the statistical number to an O-ring failing is pretty hard to come by; and if you have a lot of garbage in, you get a lot of garbage out. So I think you have to be very careful. If you're building television sets by the thousands and taking data on this resistor and that resistor and it tells you which resistor is causing your televisions to quit, it probably has some value; but when you look at most of the systems on the Shuttle, you cannot do the kind of numerical numbers of tests to give you, under a properly controlled condition, any kind of valid input data. And once the people get those nines, they really maneuver them, whether they have any real meaning or not.

Owen, you may want to comment on this.

**MR. MORRIS:** You know, if you take this and go to the structures, which is really kind of where we're interested today, we did use fracture mechanics, fracture analysis. We did have margins in the vehicle; and that's the way, again, aircraft are designed. Structure has to be qualified to the level of the margin, and then it has a reliability of one in your nines approach.

**MR. JEFFS:** Structure is tough, but we also have redundant load paths. So if we had one failure, we had a second path in order to take the load.

**MR. THOMPSON:** In some parts of the system.

**MR. JEFFS:** Wherever we could.

**MR. THOMPSON:** For example, we went to safety factor of two on the Solid Rocket Boosters. Typically the Air Force in their ballistic programs were using either 1.25 or 1.4. We went to a safety factors of two on these SRBs in the amount of insulation we put in, in the structure, design allowables, and so forth, which is relatively high for these kinds of systems; but we did it because we didn't have a backup for the SRB. If the SRB failed, you lost a system and we knew that. We didn't get there by nines; we got there by safety factors, as best we could.

**MR. COHEN:** Design philosophy, at least. Margin in the design, whether it be electronics or it be structures, is important. Redundancy and margin. I would say margins first and then redundancy. If the redundancy adds to the margin, then it's good. If the redundancy doesn't have margin, then it's not very good. So that's what we really looked for was margin in your design, the deterministic type of analysis rather than probabilistic analysis.

**MR. JEFFS:** The tiles in the design was considered for 100 missions with a factor of four. So a factor of four was on top of that 100 or so. That was considered in the design. The Orbiters were built by MCRs. The MCR is a Master Change Records. I signed every Master Change Record, and I looked for lots of things in those MCRs and one of then was safety. But we had organizations that were tuned and they came out of the Apollo Program. They were looking for the what-ifs. They were looking for failure modes and how to recover from failure modes. So therefore, in the design, how do you put something in when you don't have those failure modes? So we had a very sensitive organization to that; and that was partially schooled into them from interfacing with the Mission Control, for example, in the Apollo stuff, on how to respond and react to in-flight emergencies. So a lot of that basic background was in the fundamental design as best we could put.

**MR. THOMPSON:** We haven't mentioned sneak circuits. We did all the typical sneak circuit analysis work. We did all of the kinds of things we had learned to do in the previous programs to prevent the rocket going off when you hooked the battery up and that sort of thing.

**MR. JEFFS:** All the golden chute relays and everything.

**ADM. GEHMAN:** All right. We have a lot more questions and we're going to go on for at least another 90 minutes, but we're going to take about a 10 minute break here so we can all pay attention and be in comfort while we're doing this.

(Recess taken)

**ADM. GEHMAN:** All right. Ladies and gentlemen, we're ready to resume.

Gentlemen, thank you very much for your very forthcoming answers to our questions. We appreciate it.

Dr. Widnall, if you're ready, go ahead.

**DR. WIDNALL:** I'm going to ask an engineering question. Given that at that period of time that composite materials were sort of new -- in fact, not to make a pun of it, they sort of were at the leading edge -- I sort of would like to understand what kind of testing was done on the RCC panels. For example, was there a lot of fatigue testing done? Did you have in-flight unsteady pressure loads data that you could use for fatigue testing? Did you cycle the panels through a vibratory environment followed by heating and ultraviolet or whatever-else-is-up-there environment? Did you rip them apart? Did you impact them with small pellets? What kind of testing was done on the RCC? It's clearly an important issue for the design of the vehicle.

**MR. JEFFS:** Let me tell you what little I know, and a lot of things I don't know the details of. First off, the RCC panels, I'm sure, in the process, were subject to all the rigors of qualification of everything else on the program; and that included structural testing of all major elements. So the RCC panel was certainly a major element. The interface of the RCC panel to the wing structure itself was kind of a critical area. The whole issue of water in graphite epoxy and how it might play in the game. The whole issue of the specs re salt water, et cetera. Now, whether they vibrated the panels or not, I don't know, and I don't have the documentation to identify it, but I would be very surprised if there weren't detailed documentation of the structural testing of those panels and the load interfaces to the wing. I don't remember anything in the way of impacting those panels with high-velocity particles or something like that. I don't remember that, but the rest of it I do recall that there was some of those.

**DR. WIDNALL:** What about testing to destruction? I think one of the issues that we are amused by is that the RCC panels seem to have broken right along the center line of the leading edge. So were the panel destruct-tested by putting loads on them to see where, in fact, they would break?

**MR. COHEN:** Testing we did on the panels. On the RCC panels.

**MR. JEFFS:** I'm surprised that it would break in that area.

**DR. WIDNALL:** I know. I was surprised. I have no explanation for this.

**MR. JEFFS:** As I said, that cloth is woven cloth.

**DR. WIDNALL:** No, right along the leading edge, they broke. I have no explanation for that, but I wondered whether structural tests had been done.

**DR. SILVEIRA:** I don't recall.

**DR. WIDNALL:** I know they're very expensive panels. So obviously...

**MR. JEFFS:** Yeah, what we could test, we tested; and we tested to know what kind of margins we had. We tested them certainly up to yield; and whether we went to ultimate on those panels, I don't know. But I'm sure that the Boeing guys would have that in their files.

**ADM. GEHMAN:** Anyone else want to make a comment?

**DR. SILVEIRA:** Don Curry was subsystem manager on the RCC, would be familiar with what testing we did. But as I recall, we took a number of panels to destruction. I don't remember seeing a failure like that, at least in the stuff that he showed me.

**MR. JEFFS:** We had material we could work with. You know, there was a long process that they went through at Vaught to develop the panels because the panels were pyrolyzed, as you know, and you build them on this tool that has to go in the oven with the panel, and then we would get spring-back. So they went through a lot of steps before they got the right spring-back in those panels. So they had panels to work with; and Vaught, in general, did a very good job on those panels overall. So I'm sure that they tested those.

**MR. COHEN:** I'll refer to this document.

**DR. WIDNALL:** Thanks a lot, Aaron.

**MR. COHEN:** It does talk about -- this is the Space Shuttle technical conference and Don Curry --

**DR. WIDNALL:** I would love to get a copy of that.

**MR. COHEN:** It does talk about the early design challenges, the leading edge. Of course, one of the big issues was the coating, the coating and the degradation of the coating and how the panels degraded with the degradation of the coating. Now, it doesn't go into a tremendous amount of detail in here, but it does give you an overall view. This was written by Don Curry, and Don Curry is the subsystem manager. I don't have the data in front of me, but I'm almost sure we did take the panels to do some structural testing on the panels. I don't have it here but --

**DR. SILVEIRA:** The RCC was really a big technical challenge, as far as building the panels. You know, when we started doing it, John Yardley made a comment to me one day. He said, "If I ever hear about delamination, it's going to be your job." Well, LTV actually did, I think, a superior job in putting it together. They really did. You had to pack the panels in carbon retorched to form and the like and there were very, very few quality problems that we experienced during the development of the panels.

**MR. COHEN:** They did Eddy current testing and sonic testing of the panels in the manufacturing process.

**MR. THOMPSON:** There was never any thought, though, that those panels would withstand a 20,000 foot pound kinetic energy strike. They were not designed for that. The whole intent was to not let it happen. You could not set out and design -- I wouldn't know how to design the leading edge of that wing to take a 20,000 foot pound kinetic energy strike.

**DR. SILVEIRA:** Not many airplanes are designed that way.

**MR. THOMPSON:** I think we may have had to abandon the program, had that been a requirement.

**GEN. BARRY:** I'd like to address the issue of the design of the Space Shuttle itself insofar as lifespan is concerned. Right now in our readings, of course, the original design was to fly 100 times in 10 years. So that's ten times a year per Shuttle. Here we are at 2003. We know the *Columbia* was on its 28th flight, not 100, and certainly not within 10 years. So we've entered an era that the Board has pretty well identified as an era of reusable vehicles in an aging space platform in a R&D or development based environment. So let's say aging spacecraft in an R&D environment, for practical purposes. I'd like to get your perspective on how long you anticipated in the original design on how long the Shuttle would last, in light of the fact that NASA has announced now that the Shuttle will fly until 2020. Can I get a perspective on lifespan for the Space Shuttle?

**MR. THOMPSON:** Let me comment. Then I'd like to have some of the other people talk. We debated a lot about what kind of a number to put in the spec for that. Frankly, we could never find very much that was sensitive to that number in the kind of application we were talking about for Shuttle.

You know, 100 times would be a minor load for an airplane or airplane structure or fuselage and so forth. We put it in there to help ferret out any problems that people might come back and say, "Hey, it won't go 100 times." I don't remember anyone coming back and saying that was a constraint for anything.

I would think, with reasonable attention and oversight and proper upgrading of subsystems and replacement of subsystems as appropriate, I don't see any reason why the Shuttle couldn't last many, many years. You know we have B-52s out there flying after 30 or 40 years. We've got some T-38s out at Ellington that have got how many years on them. So that 100 number we put in there was never much of a driver to us on the Program. We didn't quite understand what we were trying to control with it in the first place very thoroughly, and it was more put in there to see if it drove anything out. And I don't ever remember anyone coming and asking for an option on the 100-cycle lifetime.

Owen, you may want to add more to this.

**MR. MORRIS:** I don't think, in my memory at least, that we ever really addressed any issue that said we have to have five more pounds or we have to do something to be able to reach 100 missions. I keep going back to aircraft; but, again, if you look at T-38s, yeah, they're still flying. They're flying okay. Now, they've had some wing problems. There have been cracks. The cracks are carefully monitored on a per-flight basis or every 10 flights, whatever the spec is on that, and you continue to operate. You know, I think you can do the Shuttle the same way.

**MR. JEFFS:** Let me say a couple of things about it. What we did on both Apollo and Shuttle, we did have age life critical item identification. So we identified all the items that we knew about in the system that were age life critical. For example, all the rings, the N204 and all those seals were on that age life list. There are all the pyros. The pyros were also bootstrapped so that you fire pyros every six years from the same lot to see that, in fact, you still had life in that pyro which could change.

I think the specs for the review of the Orbiter after every so many years, there are certain items called out to look at specifically in those; and some of those were kind of age-related in the thinking when they went into that review spec. It's kind of like the 3,000-hour turbine engine or something like that. They're in that overhaul spec requirement.

I think the rest of it, as you say, it was a development item. We didn't know everything, too, that might have some characteristics re aging. So a lot of that is as required as we go through and look at the spacecraft. Certainly, you know, I think about this oft-times at night because I own and fly helicopters a long way and what I do in those helicopters is far less than what we do on that Shuttle in the way of looking at it very carefully to see what is aging as we go through the process, particularly on the Thermal Protection System.

**MR. COHEN:** The real issue on extending the life would be the obsolescence of the subsystems, the replacement of parts, and the computers and this type of thing. Of course, we did upgrade the cockpit; and really obsolescence of hardware and replacement of hardware is probably one of the biggest issues, I would think.

**MR. JEFFS:** Let me say another thing. One thing that worried me was the screed. The screed worried me on the wing. I was worried about screed from the point of view of were we introducing something here that could, in fact, be sort of a zipper kind of effect. So I specifically went after that through the years; and the guys convinced me that there was no aging identifiable, that we had a true, solid bond in the screed on that wing. So that's one of the kinds of things you look at from an aging point of view.

**ADM. GEHMAN:** If I could follow up on that, some things age by how many times they've been used, like cycling an aircraft, but then there's also some things that chronologically age. Carbon-reinforced panels and things like that age by stress, but they also age chronologically. If you had an RCC panel and you left it out in the breezes of the Atlantic Ocean and you never flew it, it would deteriorate. But wiring ages and wiring insulation ages. And you mentioned seals and things like that. They obviously age. But there are a number of critical items on the Shuttle which, when you get to the 20th anniversary and you're thinking about flying it another 20 years, even if they've been properly maintained, it does occur to us that there are a number of critical systems that have to be looked at very, very carefully. Wiring comes to my mind. Wiring insulation.

**MR. THOMPSON:** Then again, you still have to ask yourself am I safer to continue to do that or do I embark on building a new vehicle, which one puts me into more risk. Frankly, the vehicle you have experience on, if you're looking at it at that level and watching those kinds of things, you may be safer sticking with the B-52.

**MR. JEFFS:** Let me say something about wiring. After the Apollo fire, we redesigned the Apollo; and the wiring in that Apollo was superb. I mean, it's better than any airplane I've ever seen, by far. That same wiring, all those wiring specs and so on, were carried over into the Orbiter. So it's not just a matter of redundancy in the wiring and separate routing of the wiring; it's the detailed quality of the wiring itself and the combing of the wiring and the ties of the wiring and the curvatures and everything else that are all carried over directly into that Shuttle. So there may be wiring problems there in the insulation, for example, in certain areas and it should be looked at, but in general you're starting out with a wiring set that is far superior to most of those that you're normally familiar with.

**ADM. GEHMAN:** Let me ask a question.

**MR. JEFFS:** May I say one more thing there?

**ADM. GEHMAN:** Absolutely.

**MR. JEFFS:** On the panels, the RCC panels. We were always worried about water in the RCC panels because, you know, graphite epoxy is sensitive to water. You get water in it and you're going to lose properties of the graphite epoxy -- and it is graphite epoxy, after all. So it always worried me that we should take a special look at those panels, and I think the guys were doing that. For example, in the *Columbia* I think those had just gone through a recycling back at the plant, as I understood it. I was always worried in that hashed-up field that we've got between those bodies that we might get some occasional buffeting on those panels and might be working the RCC panels at the interface to the structure itself. I don't know whether that's true or not. There's no way to tell, you know; but it is one of those kind of things that would contribute to aging in that you get a lot of cycles on that joint.

**ADM. GEHMAN:** That's a line that we're curious about. For example, the RCC is a pretty tough piece of structure but one wonders, after it's been heated to 2000 degrees two dozen times or three dozen times, what are the changes in its properties. That's one of the things we would like to look at.

**MR. JEFFS:** You've got some RCC panels back, didn't you?

**ADM. GEHMAN:** Oh, yes.

**MR. JEFFS:** They went through kind of an unusual environment, but you might get some information along those lines.

**ADM. GEHMAN:** We're going to do things like shoot foam at them and things like that at 700 feet per second.

Let me change the subject here a little bit and go back to the original design here again, the Seventies again, and talk about weight. Weight was one of the issues that you all wrestled with in order that you could get enough payload up to make it worthwhile. The history of the program shows a lot of concern about weight -- the weight of the vehicle, the weight of the payload, and a number of steps which were taken to lighten the vehicle and to thereby increase what it could carry.

Certainly, as a layman, one of the things that struck my attention was the decision to stop painting the ET because you could save 375 pounds worth of paint. So you get the impression that the concerns about the weight of the vehicle as it developed and the weight of the payload it could deliver into orbit was always on your mind as you were watching weight at all times. Could you describe the history of that process and, am I correct, was this a big concern that you were watching all the time?

**MR. THOMPSON:** Well, let me comment on that. Anyone who designs a vehicle to go to orbit will have to be careful about weight. Getting 99 percent of the weight to orbit isn't acceptable. So one of the things we struggled with was how to, first of all, select the weight targets and how to allocate the weight among the elements, what kind of weight to hold in reserve at the Level 2 or the Program Manager's level, and how to manage weight over the lifetime of the program like this.

As we got underway in the development program, we intentionally phased the startup of different elements based on several considerations; but weight affected some of this. We started the rocket engines for the Orbiter first because we felt that was the most difficult development cycle. Several months or almost a year later, we started the Orbiter development; and, of course, all during that time we were doing the systems engineering level things, doing the wind tunnel tests of the total system, doing the overall early design things that begins to see how much a design, as it matures, might meet the weight target you put in it to start with.

We deliberately delayed the start of the External Tank until we were pretty far along on the Engine and the Orbiter so that we could then size the Tank, because the amount of propellant and the ISP of the propellant tells you what you can take to orbit. We then started the SRBs last, and we actually left some growth. If you look at the SRBs today, unless someone's done something I haven't heard about, there's about two feet on the front end of the SRBs where you could add more SRB propellant if you really had to. Now, you only get a one for eight gain on the SRBs; but there was still that kind of consideration as we got into weight.

Now, once you have gotten into the program well enough to where you then can have pretty good confidence on your allocations to the different project elements, you still keep a certain amount of weight reserve at Level 2. Then if one of the element managers begins to complain that he's got a problem he'd like to fix but there's a weight constraint -- I can remember in one of our ice follies tests the Tank Project Manager wanted me to give him relief from ice forming on the LOX line because it was going to take too much weight to fix it and a little bit of ice isn't going to hurt you. I said, "No, you cannot have any ice on the LOX line and I'll give you 500 pounds to go fix it." And he went and fixed it.

Now, did weight make us do anything dumb? I don't think so. Did we have to manage weight from day one? Absolutely. The 65,000 pounds, 100 nautical miles due east, when we got to the point where we had to trade a little bit off late in the development program, we did; but then we got it back. Fairly early in the program, we went to the fusion-bonded titanium thrust structure in the Orbiter because we picked up a good block of weight and we thought it was a good thing to do, not because we were in so much trouble we had to do it. But we had to do it -- I mean, we did it to pick up that weight.

As far as I know, they quit painting the Tank after I left the Program. Painting the Tank gives you a little bit of advantage to the external surface, but the number that I remembered was 700 pounds of paint on the Tank. As far as I know, they quit painting the Tank more to save money and it wasn't really necessary rather than that they were in any kind of critical weight bind.

We put moderately tight but reasonable weight targets, and I cannot excuse a single dumb thing we did on weight.

Owen, you maybe want to comment on it at a systems level.

**MR. MORRIS:** Actually I think you're right, Bob. We did have a weight margin all the way through. As I remember, the Tank decision to take the paint off the Tank -- and this was after I left, but I was associated with it peripherally a little bit -- I think at the same time we quit machining the Tank after we sprayed it. Initially there was a machine job; you actually machined the foam. This left a much more porous surface. At the time that it was decided not to machine it anymore, you then had a hard finish on the outside of the foam; and the paint was no longer needed. And the Tank guys at that time, I think, had some weight problem and that was a good trade-off to trade that.

**MR. THOMPSON:** I do remember one time in discussing with J. Bob Thompson, the Engine Program Manager, some concerns he was having. I asked him specifically. I said, "J. R., if I give you another 1,000 pounds of weight, is there anything you want to do differently?"

He said, "No, I don't want another 1,000 pounds of weight. I don't need it. I don't want it."

**MR. JEFFS:** Let me add a couple of things. One of the reasons that the aircraft falls through as far it does on landing is the short forward landing gear. One of the reasons for that is to make sure that the weight was minimum of that landing gear. So we looked for saving weight everyplace we could on this machine. It's characteristic of all the space programs, as Bob said. On the MCRs that I talked about, which are thousands of them, every one of them has a place on it for how much weight this change adds to the system and which drawings carry them. So it was pervasive, and it was designed that way to be sensitive of the weight.

**MR. COHEN:** From day one in the Orbiter project, we were concerned about weight and we had a weight problem, but as Bob said and George said, I don't recall doing anything that was irresponsible because of weight.

Of course, that heritage came from the Apollo Program. You talk about a weight program. Owen was the aluminum module Program Manager, and we didn't get off the lunar surface unless we get to some real fancy footwork on reducing the weight of the lunar module. On the command module we had to take weight out because of the parachute hang weights. So we had weight problems on every program, but I don't think it caused us to do anything that was irresponsible.

**MR. JEFFS:** As far as Bob's comment on the weight side, the element of the system that has worried a lot of us from the beginning the most is, of course, the engines, the SSMEs. We're always been concerned that that was probably the place that if we ever had any problems, that's where we might have them. Of course, we had years of development of engines at the bottom of flame pits and so on, as we went through that development, to understand how sensitive and how critical that element was.

One day Sam Phillips and I were sitting together at a meeting at Rocketdyne and they were talking about the weights on every individual component of the engine. We thought that was the right thing to do as far as the requirements were concerned; but we thought, gosh, if we had to allocate the weights, we would probably add a little bit more to the engine side somewhere here, guys. But that's the only area of weight allocation that I could see. We didn't have any problems with embracing that concept on the Orbiter itself.

**ADM. GEHMAN:** Thank you. Another design parameter that historians have written about is the requirement for reusability. For example, as you are well aware, re-entry vehicles prior to this had had, for example, ablator-type coatings on them which were, of course, gone when they came back but --

**MR. JEFFS:** Not true. They weren't gone. Some of it was gone.

**ADM. GEHMAN:** They were used.

**MR. JEFFS:** They were used. I spent a lot of time trying to convince NASA to shave off those ablators to fly again. They were over-thick.

**ADM. GEHMAN:** They were well used when they came back. But the reusability parameters drove a number of things. Well, I'll let you describe for me what kinds of things it drove, but the history tells us that it drove such things as TPS systems which could be taken apart in little sections so you only had to rework little sections at a time and things like that. I don't know if that was driven by reusability or not. You can correct me on that. Again, going back in your experience, how was the reusability requirement characterized in your decision-making and your engineering design work?

**MR. THOMPSON:** Well, again, let me start off. At the systems level when we got into the early Phase A part of the program, full reusability was leveled on the program as a program requirement, under a perception that that would make it a more cost-effective program, particularly in the cost-per-flight regime. Of course, that was coming into a space business where staging and expendability had been a fundamental part of flying to space. One of the reasons the early system could go to space was because you could stage. You'd go part of the way and throw off weight. That even helped them explore the South Pole when they went down there.

So we accepted reusability during Phase A and came up, as I talked earlier, with the two-stage fully-reusable vehicle. But as we got into Phase B and particularly began to look at the details, when you've quit cartooning and gotten down to the specifics of designing and building and basing your reputation on something, then you begin to ask the question, does it really make sense to do it that way? I used to make a kind of simplistic argument that if expendability didn't make sense, there wouldn't be any Dixie cups around. You know, everyone would wash their cups and reuse them.

So there are systems that are more cost effective if you throw part of the system away. Particularly as we looked at putting the cryogenic propellants inside these vehicles and you had to think about insulating those Tanks, making a good thermos bottle inside that Tank and accommodating a minus 430-degree liquid that's going to shrink that Tank. I've got to shrink that Tank six or eight inches and it's still part of my structure.

Putting cryogenic Tankage within the aerodynamic envelope of the vehicle is an extremely difficult job. I don't think we've even done it to this day. So it began to make a lot of sense, at least to me and lots of others when we got into Phase B, to look at throwing part of the system away. The first thing we did was take the LOX out of the Orbiter and then we took the hydrogen out of the Orbiter and then we looked at, well, if we did that, we got the Orbiter down to a size where we didn't need this kind of booster and this kind of booster had a hell of a lot of complexity to it and maybe if we want to meet the national funding level, this is a better way to go than that way and might even be better if we had all the money in the world.

So reusability had a significant impact at the broad systems level and the fact that we put the propellant in an External Tank and threw it away, in my opinion, was probably the best -- and I would even defend today -- the best overall systems level decision we made. I think even if you were starting a system today with today's technology, you might come to the same conclusion.

Now, reusability, once we decided to partially reuse the

Boosters by fishing them out of the ocean and cleaning them out and so forth, brought some concerns to us, particularly as it affected the gimbaling of the nozzles on the SRBs. You have to worry about the APU and the gimbaling systems and so forth after you parachute them into the ocean. So that reusability was a concern; but the fact that you got them and looked at the O-rings and things of that nature were some pluses.

Reusability on the Orbiter? I never remember the fact that we were going to use the Orbiter over and over gave us any unique set of problems that we could have avoided by throwing something away. Throwing the Tank away, I think, was a great thing. Partially reusing the SRBs made a lot of sense; and reusing the Orbiter, particularly with the three expensive engines in the back end, made a hell of a lot of sense.

**MR. COHEN:** Well, if your question is, if we didn't have reusability on the Orbiter whether we could have come up with a different Thermal Protection System. I think that's where you were going with it. I don't know the answer to that, but I do know that if you had tried to use something like an ablator, it would be very, very heavy. You know, just to give you an example, if I recall correctly, the Apollo ablator was something like 100 pounds per cubic foot and the tile is something like 9 pounds per cubic foot, 20 pounds per cubic foot. So if you tried to use an ablator on the Orbiter, although we have ablators now that are much lighter, you would probably never get off the pad. But I don't think that you would have come up with a different Thermal Protection System.

**MR. JEFFS:** The whole beauty of the system is the reusability. I mean, you get the spacecraft back. That's the first time we got a spacecraft back really to speak of, unless you got some pieces of it back on parachute or something for other reasons. It's the first time we got the engines back. Usually the engine guys bury their sins in the Atlantic Ocean out there. That's what ELVs are. We don't do that; we get it back.

If you try to minimize cost to orbit, you get your airplane back, get your hardware back. So these guys got as much of the hardware back as they possibly could; and the Orbiter, bless its heart, is the most beautiful example of reusability. That whole reusability was facilitated by that radiated heat shield to get it back. And getting the engine back was an added bonus. So you want to get your avionics back which are expensive, your engines back which are expensive --

**MR. COHEN:** Fuel cells.

**MR. JEFFS:** -- your air frame back. And the heat shield makes that possible.

**MR. THOMPSON:** But had we made you put all of that cryogenic propellant internal to the Orbiter, you'd have had a hell of a bunch of different problems.

**MR. JEFFS:** Much more difficult.

**ADM. GEHMAN:** Thank you. But tell me something. I mean, I understand what you're saying, the fact that we have this wonderful reusable machine is a work of art and a work of engineering. It's an engineering feat. But you are trading some things. For example, you are lifting three 8,000-pound engines into orbit for no good reason other than reusability.

**MR. THOMPSON:** You've got to go to orbit with three 8,000-pound engines, no matter what you do. You can't get there without those engines. Now, you can throw them away or you can bring them back. Now, the Orbiter has to have some capability to bring 8,000-pound engines that wouldn't be there; but you've got to go to orbit with those engines.

**ADM. GEHMAN:** Just as you have to have the ET to supply the engines with fuel.

**MR. COHEN:** Right.

**ADM. GEHMAN:** The ET doesn't go to orbit.

**MR. THOMPSON:** Well, it goes, for all practical purposes, within a foot per second to orbit. Then you use the OMS to kick it on into it. We did that so we could put it in the Indian Ocean where it didn't bother people.

**ADM. GEHMAN:** I'm not in any way diminishing the engineering feat of building the Orbiter, but there are design trades that were made in here. For example, if you decided you wanted to reuse the engines or for some reason it was a requirement of the system that the engines be part of the reusable cycle, you now are in the position of having to lift the engines and bring the engines back. It makes the mass of the Orbiter higher on re-entry by 10 percent or something like that.

**MR. JEFFS:** That's the price of a two-way airplane.

**ADM. GEHMAN:** That's correct. I assumed that this was all debated and there were people that had positions on both sides.

**MR. THOMPSON:** It's still being debated.

**DR. SILVEIRA:** I think involved in that, of course, was the operational cost of the Shuttle in itself and then what you want to do is to return the high-dollar cost components like the engine and the avionics and the like. So as a result, you place the main engines in the Orbiter. You know, no doubt reusability shaped the Thermal Protection System because the two that we really gave serious thought to were high-temperature metals as well as surface insulator. Surface insulator, we thought, was a considerable weight saving.

When we started the program, we actually took on three major developments. One was the main engine, which was the only thing that made Shuttle possible. The other thing was a TPS, which was a major development. You know, we ended up with 6-inch tiles because the guys kept coming to me after tests and said, "Milt, the 12-inch ones keep cracking in half," and I said, "Well, why don't we make them 6 inches." That's what we settled on. I mean, simple as that. Then, of course, the other was the integrated avionics which, you know, is very complicated because, again, when you decided to take the engines to orbit, this gave an airplane with a very aft CG and as a result you had to go to a control-configured system to be able to fly it back.

**MR. THOMPSON:** Well, you would have had to do that anyway, Milt.

**DR. SILVEIRA:** Not necessarily. I think you could have flown it back without it if you had a proper CG on the airplane.

**GEN. BARRY:** I'd like to address another topic, if I may. Another topic would be managing risk, if I could get your perspective on this. We have clearly a system of systems integration element here with the STS. We are trying to address, as a board, providing substantive recommendations that might allow the Shuttle System Program to be strengthened. So, in light of the way you managed risk at the beginning of the Program, I'd like to maybe call on that knowledge base to just comment on a few things.

I know from the readings -- and, of course, my experience at NASA during the *Challenger* when Milt and I were there at NASA Headquarters -- that with the CIL listing, you clearly had a focus -- and you've already brought it up a number of times -- that a concern was with the SSME. Then we have a failure on a simpler, less-complex part of the Shuttle; and that is, of course, the O-ring on the Solid Rocket Booster.

Now, we jump 17 years later and you look at the CIL list again and, lo and behold, at the top of the CIL list is a clear focus on the SSME and we have a problem with, of course, the tragedy on *Columbia* and it is part of the simpler part of this system of systems. It's foam on the External Tank as the leading candidate, as the Board has been working here and trying to determine what the cause.

So the question that we have really got is: How do you manage risk in a system of systems, complex environment that certainly we have here, when you clearly have a good focus on some of the complex elements -- and the SSME is a case in point -- but we miss listening to the material that is talking to us, insofar as an O-ring in one case and maybe some foam in this case?

**MR. THOMPSON:** Let me start with that and then y'all jump in. What you say certainly was the emphasis on -- if you had asked me when we started this program what would be the first thing that would fail that would cause us to lose a system, I would have probably talked to you about a failure in the Liquid Engines in the Orbiter, number one. I might have talked to you about some failure on the Thermal Protection System. I would have been a long time probably before I got down to an O-ring on the SRB; but independent of that, any flight anomaly should be put on a PRACA, Problem Report and Corrective Action list. And the discipline in the system ought to be such that that PRACA is properly evaluated, in the sense that it's very clear whether it's a life-threatening issue or is not a life-threatening issue and who can sign off on that PRACA.

Now, the O-ring, I could argue whether that would be something that the SRB project could handle alone because you could argue that's internal; but when it's squirting hot gas toward the Tank, it's not internal. It's a Level 2 PRACA. Both of those items should have been entered on a Problem Report and Corrective Action. It should have been listed as something that could destroy the system and it should have come to the Level 2 Program Manager for full discussion and full disposition and full willingness to accept it on the next flight. And at the Flight Readiness Review, the Program Manager should have signed off on both of those PRACAs, saying, "I understand what the failure is, I understand the consequences of it, and I'm willing to fly." Now, if the system's working, that's the way you manage risk; and you should manage it whether it's an O-ring or TPS or a turbine blade in a Main Engine. It should be no difference.

**MR. JEFFS:** Let me make a suggestion here. I spent some time on this broad area of management review operation with Sheila and others on the Deltas. I think it gets down to the depth of what was stated here by Bob, and that's attention to detail and to every last detail. Every last detail. It's hard to just wrap your arms around something and corral that whole thing.

One thing that I have found useful in the past and suggest on big programs to look at where some of these details need further scrutiny are the MRs. The MRs are Material Reviews. They are identifying little voices that you should listen to. In the space business or in airplanes or anything, you've got to listen to the little voices because that may be the last thing you hear.

**MR. THOMPSON:** And you have to hear the little voices.

**MR. JEFFS:** Yeah. You've got to hear them, and you've got to do something about them. What I suggested doing with the MRs is what I call -- it's kind of a parallel to what Krantz and NASA and others have done down here on the what-if processes pre-flight -- and that's to review each MR. If I have an accident, I'm going to go look at the MRs among other things, first thing anyhow. So look at the MRs and do a pre-accident investigation. Just like it was an accident. Go through all those MRs. They are at least an identifier of where some of those voices are listening to be heard.

So how to answer your question any further than that, I don't know. It's get to the details and get to the right details, and that means you have to look at all the details.

**MR. THOMPSON:** But these two items that have caused the accidents in Shuttle are clearly Problem Reporting and Corrective Action items. Clearly. And if the PRACA system is working, if they're properly identified and they're brought to the right level and the right people discuss it and they make a decision, right or wrong, that's the way the system works. You've got to get them discussed with the right information and the right people and make the right decisions.

**ADM. GEHMAN:** Let me follow up on that. I think we all kind of agree with that. But some management arrangements migrate over the years. For example, the experience base of you and your team having wrestled with Gemini and Apollo issues, when you had to make engineering decisions or engineering evaluations in the Shuttle Program, you all came with a rich history of being able to sense when you were operating too near the edge of margins and you had the dirty-fingernail basis for understanding that you really did have to give that guy a 500 pound budget, you had to increase his weight budget and he really did need that 500 pounds to do that.

Over the years, management styles have changed. Management organizations have changed. A number of things have happened. For example, the role of the U.S. government person has migrated up and been filled in behind by contractors such that we don't have government people -- not that they're any better than contractors, but they have a different reward system. The experience level of these managers didn't get the same experience that you had because they didn't have all of these projects to experiment on and grow up in and they just don't have this rich background that you all have. They're just as smart and just as dedicated, but they just don't have the same background that you all have.

You have such managerial twists as this Max Faget and his engineering department has been morphed over the years now to where the programs have to pay his bills or he loses his employees. In other words, he's not independently funded anymore. That's a gross exaggeration; they are, but not to the extent that they were independent back in your days. There are a whole number of managerial trends that have taken place, driven by style and budgets and things like that.

So now we get to this meeting in which we're going to properly process an IFA or properly process a waiver or properly process some kind of a PRACA or something like that, but the machinery has changed now. The mechanisms have all changed. Based on good principles, based on first principles that you all have indicated, how do we balance this thing so that these good, proper sign-offs can be made by people who are qualified and understand the system, when the things are not the same as they were in your day and they can't be made the same? I mean, we can't go back and find people with the same kind of experience you had. It's not possible because NASA doesn't have, you know, four or five different space exploration projects going on in sequence in which to build the people with your experience. So somehow we've got to replace that.

What I've heard from you and what I've written down are what I would call first principles, and the first principles are you have to have knowledgeable people with experience and they have to have the authority and they have to have the richness of engineering horsepower behind them in order to make this case. And there has to be some checks and balances. Three or four of you have indicated checks and balances, not single-point failures in the management system.

Could you give me your views on today how you accomplish the things that you've said, when the dynamics of the management system have changed so much?

**MR. THOMPSON:** Well, you've asked kind of a complicated question for some discussion there. Let me comment this way. I think clearly, over whatever period of time you want to talk about, you have to maintain the internal procedural disciplines. You have to maintain the PRACA system and you have to maintain the forcing function that that puts in the Program because that's a discipline that makes you look at anything that's off-nominal whether it's in the worrisome engine or in the not-so-worrisome SRB. So you have to deal with PRACA. You have to deal with it in a formalized way through a Flight Readiness Review or whatever technique you want to use. So you have to maintain those systems.

Then you have to maintain enough high-quality well-trained people to make good judgments with those decisions. Neither one of these accidents that we've had on Shuttle require Ph.D.s in physics to understand. In fact, they barely exceed high school physics to understand. Erosion rates on an O-ring when there should be no erosion is an obvious thing. Kinetic energy of a 2.5 or three pound hunk of tile when it's traveling 700 feet per second, that's high school physics. There should not be anyone in a key management position in a Shuttle Program who doesn't understand those things in considerably more depth than it would take to make a good decision on them.

Now, why those things didn't happen is the kernel of your question. It appears to me that the agency needs to, number one, make damn sure that the procedures that bring the Problem Report and Corrective Action to the right discussion forum and then the right people are dealing with them in a timely manner.

Now, having said all that, there may still be some actions that occur in the Shuttle that those systems don't catch; but there's certainly no excuse not to have those systems in place and have reasonably good people dealing with them.

**MR. COHEN:** I think George Jeffs probably said it the best and the simplest. I think the people involved need to pay attention to detail, need to bring issues forward, that they need to pay attention to detail.

**MR. THOMPSON:** And they need to understand them. It's one thing to pay attention; it's something else to know what's going on.

**MR. COHEN:** I'll tell you a story, if I may. We were getting ready to go to the moon on Apollo 11. The initial measurement unit on the lunar module was perfect, no drift rate. All of a sudden it started drifting high but not out of spec. We, the Draper Labs or the MIT Instrumentation Lab and the subsystem managers, all went to George Low and told him he did not have to change the IMU out on the lunar module. Very risky. The lunar module was made out of Reynolds wrap almost. And George Low looked at us. He said, “You may be right, but I’m going to change it out.” It was telling a message. It was telling a message that it was drifting -- not out of spec but it started doing something different. I’ll remember that as long as I live as a thing that you need to think about.

**MR. JEFFS:** Well, you’ve got to make sure that you get people in the right places that qualify in three categories. One, they’ve got to be intelligent. They’ve got to be dynamic, and they’ve got to care. They’ve got to care. If you lose any one of those three, you’ve got a miss. So you’ve got to make sure at least the leadership has those qualities. That’s for the near term.

For the longer term, though, it’s a bigger problem because we in industry are losing our capabilities in these areas and our backgrounds; and you in government are doing the same darn thing. I don’t know what the answer to it is. Apollo was a stretch. Apollo stretched us technically, and it brought to bear a lot of interest and a lot of people in science and engineering. In the broader sense, we probably need something like that in the future to be able to attract our young people to science and engineering.

**DR. LOGSDON:** This is really kind of a follow-on to the discussion we were just having. I mean, the five of you represent the first generation of people that learned how to do things in space in this country. As Bob Thompson has said, putting people in orbit and getting them back safely is one of the hardest things that humans do. Most difficult. Most challenging. You are all here under the auspices of the NASA Alumni League, which should indicate that you have continued some involvement with the agency. Are you willing to give us your impressions of the NASA of 2003 as an organization? Is it up to the job that faces it? And if not, what sort of things you’ve suggested in the past few minutes are needed to fix it?

**MR. THOMPSON:** John, I would personally dodge that question because I left NASA 20 years ago. I do not think that manned space flight is beyond the technical capability of this nation by any stretch of the imagination. I think the young generation, in many respects, is smarter than we are by far, better trained. So I think that what we’re talking about here is easily achievable. There’s no reason the NASA today can’t function well and operate the Shuttle safely, whatever that means, and take on whatever future things you want to do in manned space flight. So I haven’t lost faith in the agency.

Now, I do think you have to be extremely careful when you draw the interface between government and industry. I’ve been on both sides of those fences. The people on both sides are just as honest, just as dedicated; but they’re driven by different things. If you’re in industry, you’ve got a different set of constraints on you if you run the program than you are when you’re in the government. I think the NASA of today ought to be very careful in drawing back so far and saying that contractor’s responsible, when he really doesn’t have the ability to be responsible if he doesn’t control the subs or doesn’t control the associates or he’s not in a position to make all the right kind of balance judgments, don’t put the muscle on him. I mean, don’t put the monkey on his back if he doesn’t have the muscle. So my only comment is I don’t believe NASA is serving itself well if it pulls back too far in feeling an overall technical management responsibility for ongoing programs.

**MR. COHEN:** I cannot answer your question directly either because I’ve been away from years. But I have had the opportunity since I’ve been gone to teach at Texas A&M. Seniors. I can guarantee you that those young men and women that are coming through the class, I would hate to compete with them. They are truly outstanding. Many of them, whether they get their advanced degrees and go to MIT or whether they go to Purdue or whatever, most of them want to go to work for NASA or their contractors.

So good students are very interested in the space program and a lot of my students did come to work at the Johnson Space Center and other space centers. So, you know, I think the people are there and the people are good. I mean, the students today, as you know, are just outstanding.

**DR. SILVEIRA:** John, if I may. You know, there’s no doubt in my mind that the kids today are better educated than we are. I have two kids that work in the Program, and they’re both smarter than I am. The thing I get paid for, at least, is to try to go out and find out what’s going on in industry that we don’t get the product we used to get out of them.

I think some of it comes about because we have started to train a lot of paper engineers rather than hardware engineers. Kids are not looking at the hardware enough to really understand what’s going on and, anytime there’s a little discrepancy in it, really get to understand what is happening. The hardware’s trying to tell us something, and we don’t carry it to a point where we really go and understand it and fix it.

You know, recently we had a PDR of one of our programs, you know, and the contractor was proud: “We have spent 3,000 man-years on documentation.” I can’t imagine a program demanding that kind of paper to keep it going. I think the thing we need to do is to get kids out from behind the computers and get them to go out and walk the factory floor and really see what hardware’s all about.

**MR. JEFFS:** I’ll say three things from the industry side. I won’t try and reorganize the NASA. That takes a little longer. But I think that, as Bob mentioned, we march to different drummers, in a way; but when I ran the space and energy operations for Rockwell, I was also a corporate vice-president of Rockwell. So I had a lot of pressure that didn’t have a thing to do with the space program, but it didn’t keep me from applying the right kind of people on the problems at the right time in the right way. And I think these guys will all attest that they didn't see anything in the results of what happened with the industry on their hardware that was influenced in any negative way by profit motives or otherwise in getting those problems solved.

Number two, there are a lot of smart people out there in industry. They can be assigned. There are talents available to the people that run these companies. I think it takes their focus also to get the right kind of people in the right place at the right time on the space program and to look at their priorities.

The third thing is that one of the things that made Apollo and Shuttle happen was an excellent working relationship between industry and government. That working relationship was criticized in many ways by being too close and what have you; but I assure you, when it came to solving the technical problems, it wasn't. I also assure you when it came to getting any money out of these guys, it also didn't manifest itself in the way of excess profit. So I think that encouraging the good working relationship on mutual utilization of each other's capabilities is an excellent additive to making these big programs happen properly and on time.

**MR. MORRIS:** I'd like to follow up on that just a little bit. I think one of the things that over the last 10, 20 years has happened in this process of NASA going up and being backed by contractors is a lack of sufficient check and balance. The one thing we had in the Apollo Program, in the Shuttle Program, during the design phase, was parallelism between the government and the contractor. Both were very good, but they also were checks and balances. When you turn all the responsibility either to the government or all the responsibility to the contractor, you lose some of that check and balance.

I think the process that you have to look at things like the O-ring or like the foam, you need to make sure the process you have asks the second question, not what did that cause on the last flight but what else could it affect. I think in both cases the second question was not asked properly. I think that's the thing that can be fixed with a system. The system that assures the right checks and balances and the right questions are asked.

**DR. WIDNALL:** Not including the space program, what are the other major scientific and technical challenges faced by our nation that have the power to motivate our young people?

**MR. THOMPSON:** I think, frankly, the Defense Department is one of the greatest motivators of our young people. I think maintaining a very strong and very active military or defense capability or offense capability, either way you want to talk about it, is a very important contribution to our society. We in NASA often take a lot of credit for technology advancement. I'm not so sure in the same number of years the technology advancement wasn't stimulated more by the Defense Department than NASA. The fact that you have to solve the kinds of problems that the military solves on a routine basis drives technology certainly as much as the space program. Obviously medical research. So I could list eight or ten things, but certainly we benefitted to a great extent in the NASA space program by what was going on in the Defense Department in similar activities -- be it rocket science, be it structures, be it flight control systems.

For example, at the same time we were putting the control-configured flight control system on the Shuttle, DOD was doing the same thing with the F-16. And we visited their research laboratories and they visited ours. We took some things, learned from them. They took some things and learned from us. Both systems are working today, 35 years later, quite well. So I would like to see us maintain an extremely strong national defense capability, if for no other reason, to drive the kind of thing you're asking about.

**MR. COHEN:** I think in my observation, being in academia for a while, is that there is a lack of funds for students that want to get their advanced degrees, to go on to get their Master's degrees and Ph.D.s. I think that could be a big stimulus to producing more graduate students and actually enhance our engineering capability in this country.

**MR. JEFFS:** They had a session not too long ago that George Abby pulled together at Rice that addressed the subject in part; and it seemed to me that to attract the young people, it's going to have to take something that has duration long time. Most of the military programs, albeit some of them are changing now, are lesser duration. It needs something that people can address and assign their life to, youngsters, and enthusiastically do that. I think that the NASA has that within its grasp if they better structured and articulated the total space program, the unmanned systems and the manned systems. And I think manned systems have to be an element because they have the aura. They have the thing that brings the young people into it more than the unmanned programs do. But the unmanned programs and the manned programs go together. So a better articulation of the total program. The targeting of something like a Mars stretch or something such as that, like the Rumsfeld approach, get out in front of the pitch, go out --

**DR. WIDNALL:** George, I specifically ruled out the space program.

**MR. JEFFS:** Oh, you did.

**DR. WIDNALL:** Yeah, I did. I really wanted to talk more comprehensively about our whole society, science and technology and our young people. I think obviously I think we all understand the power of space.

**DR. SILVEIRA:** As you know, the President has charged Missile Defense Agency with a deployment capability into '04, beginning of '05. That's a pretty big technical challenge.

**ADM. GEHMAN:** Let me ask a question that I think is related. Once again, going back to your experience in

Gemini and Apollo and Spacelab. These programs were not exactly heel-and-toe programs. There was a little overlap among those programs and people migrated and people learned and people worked their way up through the process.

In your judgment, what's a generation in a space vehicle? In other words, how long do you think that we should stay with a space vehicle and how big a leap do you need to make to have its replacement come along? Is 20 years, 25 years, 40 years, a generation? And should we have a replacement program already have been started? What's the time frame here and what are the indications or the characteristics of when it's time to say that's a generation? You've all heard of Moore's law that a generation in computing power is 18 months. Well, what's a generation in a space vehicle?

**MR. THOMPSON:** Let me make a jump at that because I've thought about this a little bit in my own career. In my working career, I spent the first 11 years in basic research at a research laboratory and, frankly, I was beginning to not get burned out but I was ready for a change. The space program came along. I got in the space program; and we did Mercury in about four years, as I recall, from the time we started talking about it until we had finished it. Before we finished that, we took on Gemini; and we finished that in maybe five. Let me just pick a number. Five or six years. Before we finished that, we had Apollo. We did Apollo in ten years. We then bootstrapped Skylab in there for three or four years, using the residual Apollo hardware. So during that 20 years, you know, I never spent more than ten years in any one focused area -- sometimes as few as four, sometimes as many as ten.

When we took on the Shuttle, Skylab and Apollo/Soyuz were the only things in town, and we had a gap of activity of three or four years, five years where we didn't fly anything from Soyuz until we flew the first Shuttle. But that ten years was a very strong development cycle. So for people at least like myself, there was an interesting activity every four to ten years that lasted anywhere from four to ten years. So you could jump from one to the other and grow as you jumped.

Now, if the country does not take on those kind of programs and you say stick with the Shuttle for 50 years, then you have to find some way, internal to that, to keep people excited. Maybe you do it somewhat like the military does, by rotating them every three years or rotating them every --

**MR. JEFFS:** Two months.

**MR. THOMPSON:** Again, the military found out in the R&D program it didn't want to rotate them as much because they lost the technical competence. So if it's not possible for the nation to throw an exciting new program out there every five years, then you have to look for some other motivation below there. I would say ten years in any one kind of an assignment is probably enough for most people and they need to go do something either more complex or something different. But that's just a wild guess.

**MR. JEFFS:** These programs cost a lot of money; and therefore when you start them, you better darn well make sure you've figured out what you want to do with them and what you're trying to do with the programs. That's kind of item number one.

The other thing is that these programs are often paced not by money and talent but they're also paced by technology. So there's no point in taking off on a single stage to orbit if you don't have an engine that can perform that kind of mission. So we go charging off and we all get together and say, "Let's go single stage to orbit." Then say, "Well, that's great but how do we get there? Oars?"

So therefore you've got to look at the technology base as it permits you to make decisions for the next generation. So I think, like Bob, it seems like it's five years, Gemini; 10, 15 on Apollo; 15, 20, maybe 25 on Shuttle. The next one is going to be longer than that. But it's going to have to have the technology behind it that enables you to commit that kind of funding and that duration of lifetime of people to it.

**MR. COHEN:** I think there are things you can do. In fact, things have been thought of that you can do is to in some way combine the talents of the human exploration program and the robotic program for Mars exploration and bring the human element of the program involved in that. I think those are things I think you could do.

I mean, one time we looked at a Mars sample return mission, JSC working hand in hand with JPL to do a Mars sample return. It never did come to fruition, but I think things like that would really create the interest and keep the people sharp and keep people very interested.

**DR. SILVEIRA:** When you consider that the Shuttle is a first-generation vehicle, first of its kind, you would think -- and I know a lot of the mistakes we made in the design initially that we have found out as a result of flying the vehicle. You would think within a 20-year time period that we would be coming up with a better design, seeing it's going to take another ten years to build a vehicle. I think it's far overdue that we should be into a second-generation vehicle similar to Shuttle.

**MR. JEFFS:** If you know what you want to do with it.

**ADM. GEHMAN:** My question, at least what I had in mind, was more along the programmatic and technology angle than it is the human resource angle. I appreciate what you say, and I agree with what you say. You've got to challenge people if want to keep good people working on these things. But it does seem to me that a generation in space vehicles -- I mean, I can't put a number on it, but I can tell you that it's not zero and I can also tell you that it's not 40. A generation is someplace in between there; and if it's some number less than 40 and it takes seven, eight, nine, ten years to produce this thing, I'm wondering how urgent it is that we get on with this.

**MR. JEFFS:** You know, I would like to add one thing to the previous statement. There are lots of opportunities that can be identified; and some of them have some very interesting possibilities, I think. I would commend the agencies and others from initiating the nuclear engine programs. I think this is a whole new avenue that's going to open up a lot of possibilities. I think that the idea of coming up with some engine that will essentially be unto itself, a turbojet or engine, a rocket and the whole schmeer in one swoop is an excellent kind of focus if there's feasibility basis behind it.

Those are the kinds of things that will offer the opportunity to identify these kinds of program. If I were going to try and build a new Orbiter today, I would do a few things differently, but I don't think the machine would be a heck of a lot different than before. It might have titanium in it instead of aluminum, for example. It might have a different, more rugged tile system, even though the one we've got is adequate. There might be a lot of things that we could do with it that would make it a better racehorse, but it would be in the thoroughbreds instead of the claimers or something. You know, it's not going to be that big of a step forward. But those other kinds of things like the engines and so on, nuclear engines and so on, those are the things that are going to offer the opportunities for us.

**ADM. GEHMAN:** Thank you for that. Assuming that if we could cast off to the side, for example -- this is argumentative, so you just have to make an assumption with me here -- if we could cast off to the side that the next step that we make in space has to be a leap -- I mean, why can't it be a tiny step? You know, aircraft developed by evolution. We didn't go from the Wright flyer to the 747. We went in many, many, many evolutionary steps.

So I hear this all the time that, well, you've got to stay with the Shuttle because the next giant leap is not there in front of us. I don't find that to be completely compelling. The President has already said that man is going to continue his journey in and out of space. Is there any reason why we can't do that journey in an evolutionary way, that we have to have some big, giant leap in technology to do it?

**MR. JEFFS:** No, but it has to be enticing enough for the new generation of people coming along to want to dedicate their lives to it. We're already losing our capabilities now on the one we've got. It's not sexy enough. It's not exciting enough.

**MR. THOMPSON:** Well, let me argue with that a little bit. I tried to allude to this before. When Nixon made the decision, the so-called low earth orbital infrastructure decision that I spoke about earlier, there was no big national-level discussion of it or national-level announcement of it or national-level description of it. So a lot of attention was not drawn to it. Part of the reason, politically, you were proposing to do something that was considerably less expenditure, less effort, less glamorous than the Apollo Program. So compared to what Kennedy did with the Apollo Program, announcing a low earth orbital infrastructure wasn't nearly that sexy, so to speak. Plus, the personality of the man, he wasn't that interested in space. So he didn't make a big to-do about it.

There is plenty about what we're doing today and what we will do in the next 10, 15 years that should excite a lot of capable people to work on it, even though it's not exploring Mars. I frankly think it will be a long time before you can convince any Congress to spend the money to embark on a properly thought-out Mars exploration mission because it's going to be extremely costly and there's going to be a hell of an argument about whether it's worth that cost as compared to putting the cost somewhere else.

So I think what is needed is a little more attention to explaining. For example, the space station, I think, is a very exciting program. The thought somewhere in the future of direct solar conversion to electrical energy with a solar power station in orbit. The kinds of things you can do in a low earth orbit with Shuttle and space station-type vehicles could be made into a very exciting program.

Part of the problem is that people want to throw that aside and go to Mars for some reason, and we've got to put the defense in that because I think where the nation's going to spend its money for the next several years in manned space flight is going to be in low earth orbit and we'd better start explaining the beauty of it and I don't think you're going to have any trouble getting plenty of people to work on it, good people, if you'll talk about it and explain it properly.

**MR. JEFFS:** The only addition to that is that Apollo dragged with it a lot of technology. A lot of technology came out of Apollo. A lot of new businesses came out of Apollo. It was a stretch and it was an exciting kind of thing. And if you don't have a stretch, you're not good to drag the technology. And I think that dragging the technology, forcing it into the forefront is the thing that's best not only for the space program but for the nation.

**MR. COHEN:** In order to do what you say, though, I think some group or some body, some body of people need to establish the need for doing it, what is the need, what are you really trying to accomplish, before you can really move forward to the next step, I think.

**ADM. GEHMAN:** Let me close this by asking the last question, which is a complicated one. My understanding of the glorious history of space exploration in which you all play an important role is that over the years the role of the NASA engineer has migrated in a sense. You read in popular literature that in the original program that Werner von Braun was accused of wasting money because when he received components from contractors, he had his engineers take them apart and put them back together again. I don't even know if that's true or not. In any case, those engineers, even though they didn't build this thing, they now got dirty-fingernails experience; and as you went through the Gemini Program and Apollo Program, a lot of that was in-house work. There was a certain amount of basic research and basic engineering that was done in-house and some of it was done by contractors and some of it that was done by contractors was checked by in-house engineers. Then as we migrate away, more and more of this work is being done by contractors and less and less of this work is being done by NASA employees.

So my two-part question. Is this management by subs -- let me get to my bottom line. Then I'll ask the question.

One of the possible outcomes of this Board's work may be some comment about some kind of a system qualification or a system recertification that if you were to really fly these Orbiters from one decade, two decades, into their third decade that, just like a 747 or something, if you're going to extend the service life of it, you ought to do some kind of a system qualification or system certification. Well, if there's nobody at NASA that has that hands-on engineering experience, then you've got to have contractors do it.

Now, does that get us into a boxed canyon here? Does that trouble you, or would you think that the style that you all grew up on in which NASA engineers also had hands-on engineering experience by some way is either critical or not critical? A lot of people have said it's not necessary to do that. How do you feel about that? Particularly in light of a possible outcome where it's possible that we might have to in some way formally recertify the three remaining Orbiters or requalify, do we have to do it system by system and who does it?

**MR. COHEN:** Well, I know when I was Center Director of the Johnson Space Center I always liked to have at least one or two projects, in-house projects where the engineering talent at the Johnson Space Center was doing the work. I think that was carried on. I think they went pretty far with one of the crew rescue vehicles they were designing here at the Johnson Space Center. They went pretty far with that. So I think in-house NASA projects or in-house projects at NASA that they can actually, as Milt said, get their hands dirty on is very worthwhile; and I think it does teach them an awful lot. Now, that takes money, it takes emphasis, but I think some type of steady, continuing having of in-house projects, I think, is very important. That would answer, I think, part of your question.

**MR. JEFFS:** I'd like to make sure the picture is not painted in some strange fashion here. The NASA guys are the guys that set the requirements and check the product as it meets the requirements. Industry is the one that puts the product together. The drawings are all prepared by industry and all the specs are prepared, all the list of materials, everything is built and tested, all the tools are made by industry. Industry does the job.

Now, if you're going to recertify the vehicle, industry, with NASA's overview, would be the one that puts together the details of what that recertification process should constitute and consist of. So it's not like NASA is doing all the job. NASA is a supervisor and an overviewer. Industry is the one that does the job.

I'd also like to say that you made some comment earlier about testing and checking. On occasion we've had to check NASA tests. Every once in a while NASA runs some pretty strange tests, too. So we've had to straighten that out. So it's both sides.

**ADM. GEHMAN:** It is both sides, but it is healthy.

**MR. THOMPSON:** You do, though, need to have -- what George says is exactly correct. Nowhere in our manned space flight experience, except extremely early in the Mercury Program, did NASA sit down and do the drawings and build in NASA shops a spacecraft. The first spacecraft we flew in Mercury, we actually designed with civil servants in the Langley Research Center. We built it in the Langley Research Center shops with civil service people and we took it down with the support of the Air Force and launched it on an Air Force rocket at the Cape and got our early Mercury data off of a thing called Big Joe. From that point onward, the people who do the drawings, the people who do the detailed internal stress analysis, the people who do the certification, formal certifications at all level, that is industry's job. That's what you contract with them.

My point I would like to make is you need to contract with them in such a way that they can bring their talents to the program effectively, but you have to leave the government in a proper control mode in that contracting format. If you contract in such a way that it isolates the government from some feeling of responsibility or some feeling to need what's going on or some reason to make critical decisions, then you've backed the government out too far. For example, if you take all of the contractors working on Shuttle and assign them under one integration contractor and give him all those contracts to run, that's fine; but you haven't gone down to one contractor. You've gone from 80 to 81 contractors, and you then have to back the government off to let that contractor assume a certain level. Otherwise, you might as well stick with the government and 80 contractors if you're going to still penetrate to where you are. But you also have to set up the contracting channels properly and the responsibilities properly.

I personally favor something much more like we had in Shuttle where, for example, no contractor in Shuttle had the leverage over the other contractors. Rockwell could not go tell Martin to do anything from the Orbiter to the Tank. It had to come through a government channel to get something done, and the government then was in a very knowledgeable and in a very controlled position to do it that way. It puts a responsibility upon the government that you've got to be prepared to fulfill, but I think it keeps you involved in a much more meaningful way.

Typically, in my judgment, in the earlier years, NASA penetrated the program probably a notch lower than the military DOD typically penetrated their programs. The NASA that I knew did not need the aerospace support to the same level that the Air Force needed aerospace support on the ballistic missile program. Either way, you can make it work; but you ought to decide which way you're doing it and make sure you make it perfectly clear. And I would very much like to see NASA retain a capability to penetrate the programs relatively deeply.

**MR. JEFFS:** I'd like to make a comment on one other statement that you made. That was about hands-on. I think hands-on is a fundamental need for the engineers on both sides of the fence, both the NASA and industry. One of the classic examples was to take thermodynamics people down and show them the hardware that they were actually influencing, changing, and controlling the configuration of. It's a revelation to those. You find the aerodynamics guys, aerothermal guys, thermo guys and so on tend to get remote from the program and work with just paper. Get them out and show them the hardware and it gives you a better project, a better person that's working on it engineering-wise, and he has greater accountability and responsibility for it. So that's true on both sides.

**MR. MORRIS:** I'd like to build on that a little bit, if I could. I think NASA in particular needs to be very careful that they retain smart management. I think, to do that, they have to come up through the ranks with a few dirty fingernails, maybe even greasy fingers. One of the things that really upset me was the cancellation of the X-38 project, the recovery vehicle that Aaron was talking about. This was a chance for the people working for NASA to actually understand how you go make something happen. By doing that, they then become much smarter managers.

I think at the time NASA pulled away from management in detail -- and there were a lot of good reasons to do that -- there was then at the same time a promise made that research and development internal would be increased, and increased materially. I don't think that's happened. Therefore I think the NASA personnel have lost out both ways over a period of time. They no longer are managing in detail and they are not backing up, in research and prototype development, the experience level within the organization that they really need.

**ADM. GEHMAN:** Well, thank you very much, Mr. Silveira, Mr. Morris, Mr. Jeffs, Mr. Thompson, Mr. Cohen. We thank you very much for joining us here today. We thank you very much for your open and candid discussions of all these issues.

As you can see, the Board has a fairly wide aperture about what we are going to write in our report. They include such matters as you have discussed with us today; and your background knowledge is still valuable, still of great benefit to the nation. I thank you very much for agreeing to contribute it here in such an open forum. We really appreciate it very much, and we wish you all the best of luck. Thanks very much.

We will reconvene at 1:00.

(Luncheon recess, 12:14 p.m.)

**COLUMBIA ACCIDENT INVESTIGATION BOARD PUBLIC HEARING**
*WEDNESDAY, APRIL 23, 2003*

1:00 p.m.
Hilton Hotel
3000 NASA Road 1
Houston, Texas

**BOARD MEMBERS PRESENT:**

Admiral Hal Gehman
Rear Admiral Stephen Turcotte
Major General John Barry
Dr. John Logsdon
Dr. Sheila Widnall
Mr. G. Scott Hubbard
Mr. Steven Wallace

**WITNESSES TESTIFYING:**

Dr. Jean Gebman
Mr. Robert P. Ernst
Dr. Diane Vaughan

**ADM. GEHMAN:** Good afternoon. The afternoon session of the Columbia Accident Investigation Board public hearing is in session. This afternoon we're going to hear from two experts on the subject of aircraft aging, which is another risk element in the Shuttle program which wasn't originally foreseen -- at least I don't think it was. The Shuttles were originally designed to last 10 years and now we're passing 20 and headed toward 30. And the Shuttle vehicle then is facing issues which need to be looked at to determine whether or not the shuttle can operate safely. We're very pleased to have you two gentlemen join us.

Dr. Jean Gebman is a senior engineer at the Rand Corporation; and Mr. Robert Ernst is the head of the Aging Aircraft Program at the Naval Air Systems Command, Patuxent River. We're glad to have you both with us.

I would invite you to introduce yourselves and say a little bit about your present job and your background; and then if you have an opening statement or a presentation, please go ahead and proceed. Why don't you both introduce yourselves first, and then we'll go ahead with the presentation.

**JEAN GEBMAN and ROBERT ERNST testified as follows:**

**DR. GEBMAN:** Thank you, Mr. Chairman. I'm Jean Gebman, senior engineer at Rand, working on the Aging Aircraft Project. My educational background is in aerospace. My doctoral work majored in structural dynamics with minors in fluids and control engineering.

**MR. ERNST:** I'm Bob Ernst, the head of the Nav Air Aging Aircraft Program and also representing the Joint

Council on Aging Aircraft, which is a DOD, FAA, NASA, and industry consortium trying to work on age issues. I don't have the storied credentials and degrees that my counterpart here has, but I've got a lot of years of experience working on old platforms and rust and corrosion and obsolescence and some of those types of things.

**ADM. GEHMAN:** Thank you very much. Go ahead and proceed.

**DR. GEBMAN:** Thank you, Mr. Chair. Bob and I are going to present two briefings that are very complementary. I'm going to talk about some technical details to give you a somewhat hurried survey of the landscape technically, and then Bob's presentation is going to deal with some of the cultural and programmatic matters.

Next chart, please. This is simply a bit of background. In the interest of time, we'll just press on ahead. Next chart, please.

The examples that I've selected do have a methodology behind them, and this chart is an attempt to try to capture the essence of that. We're going to focus on the top set of items, although aging aircraft do involve all of the functional areas that are listed on the left-hand side of the chart.

Next chart, please. So this is going to be the focus.

Next chart. Whether or not this focus proves helpful to you is, of course, a matter to be determined as your investigation moves forward. So my purpose here today is more to share with you some areas where the aging aircraft experience might prove helpful as you move down the road.

Next chart, please. You all have seen the various diagrams of the Shuttle. I'm going to focus on the left side.

Next chart. And simply make a couple of points. We have four main spars that go through; and when we talk about structures and structural dynamics, one of the things we often quickly look at is the wing route where the spars go through. That's just simply one area that one is always interested in.

Next chart. Another area that's of interest and will be touched on by one of my examples subsequently has to do with the aluminum honeycomb. This is simply a cross-section showing at the top there the interior face sheet, which is aluminum; the corrugation, which is aluminum; and the adhesive bond between the corrugation and the exterior face sheet; and then, of course, the Thermal Protection System underneath. A very sophisticated system. And one of the things we will be talking about later is the matter of adhesion as a method of joining structural materials together.

Next chart, please. This is a list of the samplers. Let's get right to it.

Next chart. B-52. A very interesting story. This often is pointed to as here is why it is possible to maintain a fleet for a very long period of time. We need, though, to be cautious and acknowledge how it was we got to that situation, because you may note that the G model and the D model have long since gone to the boneyard. Corrosion was the principal culprit. The basing at Guam was about the worst base you could be at for an Air Force aircraft from a corrosion standpoint.

Next chart. Even the H model, to get it to where it is today, has been significantly rebuilt in many areas, as these various shaded areas demonstrate. Moreover, it has been based at a location that is relatively benign from a corrosion hazard standpoint, and the maintenance people learned a good lesson from the experience of the G model; and there has literally been a zero tolerance for corrosion. If they see corrosion, it must be removed.

When we visited the depot about six years ago, we looked B-52 and the KC-135s. I was challenging the technicians on the B-52, "Show me the corrosion."

They said, "Dr. Gebman, there is none."

I said, "Folks, it's an old airplane. We know there must be corrosion."

Finally, they were able to show me a detail at the back of the airplane and they acknowledged, we ground out a little bit back here, but this is not even significant.

This airplane is very different from the 135. Next chart, please.

**ADM. GEHMAN:** Could I ask you to go back a second. In that first bullet, what is a full-scale fatigue test, what's a damage tolerance analysis, and what's a tear-down inspection?

**THE WITNESS:** The full-scale fatigue test is where you take an article that could be flown in flight and, instead of doing that, you set it up to be loaded cyclically by attaching various jacks and an enormous hydraulic contraption and typically you will try to simulate two -- in the old days, four -- equivalent lifetimes to identify where the fatigue vulnerabilities are so that they can be addressed during production and/or during maintenance.

**ADM. GEHMAN:** And I assume also recognize -- I mean, in other words if you have a fatigue indicator like a crack or something like that, the idea is that you would then be able to recognize that if that were to happen in a service vehicle.

**DR. GEBMAN:** One of the most important things you learn from the test is where the cracks are taking place and so that you can set up a maintenance program or do a modification so you don't have to set up a maintenance program. The damage tolerance analysis is a method of studying the growth of fatigue cracks and their significance, giving you further information that you can use for fleet management and modification purposes.

The tear-down inspection took place in the 1990s, largely to identify places where corrosion was going on in areas that could not otherwise be seen. When we do heavy maintenance, we don't take the airplane totally apart. The notion of a tear-down inspection is to take a high-time airplane which you're prepared to sacrifice and literally take every part, open it up, and see where you have challenges.

**MR. WALLACE:** Is the concept of damage tolerance that you will be able to detect cracks and things and also make predictions as to their growth rates in such a way that you can easily detect them before they become critical?

**DR. GEBMAN:** Yes. And I would encourage, if I might, that we try to speed through the examples because you will have an opportunity to see illustrations of some of these specific points.

With the board's permission. Next chart, please. Moving on to the 135, corrosion is the principal challenge with that fleet.

Next chart. This is an example of a tear-down inspection. What you're looking at is a drawing of the top view of the full fuselage. Each square is an area that they took the structure apart, opened it up, looked at it sometimes under a microscope. If you see color in the square, it means they found at least light corrosion present. Just about every square that they did a detailed examination of, they found some indications of corrosion with that fleet. That is a result of the materials that were selected, the environment in which it is operated, and the maintenance program which it had through its lifetime.

Next chart, please. Similar view. This time it's the wing structure.

Next chart, please. As a consequence, over time when these airplanes go in for heavy maintenance now on a five-year cycle, it can take a year to do the complete job.

Next chart, please. This chart shows declining labor hours required. We are now at a point where the labor hours to do that heavy work is eight times what it was the first time it was done when the airplane was about eight years old.

Next chart, please. Until very recently it was the Air Force's intent to keep all KC-135s to the year 2040 or thereabouts, at which point the fleet would be 80 years of age. Recently the senior leadership has decided that the older airplanes, the E models of which there are somewhat more than 100, need to be retired sooner than that; and they are now looking at leasing perhaps a 767 to fill this particular function. So one's perspective about life can change significantly as you learn more and more about the growing burdens before you.

Next chart, please. Moving on now to a new decade. Next chart. I share this example with you to illustrate some of the complexities and depth and breadth of endeavor one can get into when dealing with life issues. Now, the irony is that this is dealing with the new C-5A in the early Seventies. It had a very unfortunate experience in its full-scale fatigue tests. Fatigue cracks throughout the airplane, especially in the area of the wing.

The Air Force Scientific Advisory Panel convened a study in 1970 for the Air Force, made some recommendations. The following year, a major engineering effort was launched. The independent review team. One hundred people worked for one year, going through the results of the full scale fatigue tests, looking at the different options that the Air Force might consider, analyzing Options A through H, and presenting them to the leadership. Ultimately Option H, wing redesign and replacement, was selected. Once you open up the area of structures, the number of things that you can end up having to examine can be considerable. That's the lesson from this particular example.

Next chart, please. This example is a little bit different. We're focusing on a specific technical issue. It's honeycomb composite material, and it proved, in those few areas where it's used on the F-15, to be quite challenging.

Next chart. These are some of the methods in which the water and the corrosion and cracking and durability issues arose with that particular fleet. To the extent that this proves of interest, the area of honeycomb composites, this particular fleet -- and there are some other examples -- might be worth looking at.

**GEN. BARRY:** One comment on that. This is also the leading edge of a lot of the wing forms in the F-15s, particularly in the tail as a point. So might be of interest in the board.

**DR. GEBMAN:** Yes, sir. Thank you.

Next chart. Moving on to the Seventies, here we have two examples dealing with the loads that actually occurred, exceeding what the designers thought the loads would be.

Next chart. This is a classic. The F-16 was designed for both air-to-air and air-to-ground work; and it turned out that in the air-to-ground mission area, the loads that the structure encountered very quickly exceeded the capacity of the structure as it was designed. This illustrates the importance of really monitoring your loads through your life cycle so that you can take that load information and update your expectations as regards fatigue cracking.

Next chart, please. This is the process. This is the durability and damage tolerance analysis process and I'm certainly not going to lecture on this today, but this is a summary that you might find useful as your work moves forward. When I look at this, I look at it from not only a structures viewpoint but also from a systems viewpoint. You can literally go through that chart and change its orientation from fatigue, which it was designed for, to corrosion or other kinds of things that affect an aircraft as it ages. Indeed, today people are working on the development of what's called a functional integrity program approach, which mirrors this aircraft structural integrity kind of program.

Next chart, please. The B-1 example is a little bit different. Here we were dealing with acoustic fatigue, which is a dynamic phenomenon and it's a bit like the tuning fork. If you hit the tuning fork, it will vibrate at a natural frequency. Well, aircraft structures, if excited at their natural frequency, will engage in vibration, and this can greatly accelerate the propagation of fatigue cracks. That's the essence of that particular story. It's an interesting one from your all's perspective to an extent because it involved both thermal, aerodynamic, and structural dynamics. It turns out that the designers deliberately had hot exhaust from the engines going over the control systems at low-speed flight to increase the control authority of the control surfaces.

Next chart, please. Now for our final example. Next chart. This is an airplane that served quite long in terms of landings. It was designed for 75,000, and in flight hours it was not all that high. It was designed actually for 50,000. This example illustrates the three things listed on the chart.

Next chart, please. Imagine yourself flying over the Pacific in this particular airplane. You're in Row No. 5. You have the seat next to the window, and over your left-hand shoulder there's a fatigue crack. From the NTSB's excellent work, it appears that the sequence we're going to talk about started at the fastener hole indicated here. What's important to focus on here is the length of the fatigue crack. The blue is supposed to depict the sky. From the outside of the airplane that crack was only a tenth of an inch long, and yet it contributed to a sequence of events that we're going to look through in the subsequent charts.

Next chart, please. Part of the problem is that it wasn't just one crack at that fastener. There was one on the opposite side, as well. It was only .11 inches. So from a detection standpoint, this would have been a bit of a challenge to be detected visually just from a casual walk-around kind of inspection. From a fracture mechanics standpoint, though, the crack is really a half inch long because when you look at the stress intensity at the tip of the crack, what it depends upon is that total length, that .53 inches. And fatigue cracks, we now know, grow at a rate that is a function of how long they are. So the longer the crack, the more rapidly it will grow as that part of the structure goes through its next cycle of loading up and down.

Next chart, please. Not only was Fastener Hole 5 cracked on both sides, but there were also adjoining fastener holes numbered 3 through 9 that also had these kinds of cracks.

Next chart, please. Consequently, Fastener Holes 3 through 9 simply zipped across one afternoon when the loads hit a particular level; and this particular sheet of metal separated from its counterpart.

Next chart, please. The problem is -- and I must apologize, this chart didn't quite make the translation from Macintosh to PC the way I had hoped -- this chart is intended to illustrate two pieces of skin with an adhesive material between the skins. You see, the fasteners were never designed to carry the load. The load was supposed to be carried by the adhesive. The adhesive broke down. There was corrosion that took place. So we have a combination of adhesion failure and corrosion going on, destroying the primary joining mechanism. The fasteners picked up the load, but cracks developed very quickly because they really weren't intended to carry the load for very long.

Next chart, please. The failure next was supposed to be stopped by what's called a fail-safe strap. These are spaced every couple of feet. But it also was glued, if you will, to this skin. The glue had eroded over time. Corrosion was taking place. So when the load came zipping down to the fail-safe strap, it too broke.

Next chart, please. Indeed, all of the fail-safe straps broke between the two major bulkheads that define the boundaries of this particular failure. Fortunately, there was only one fatality, although there were a number of other injuries. The silver lining to this particular cloud is it caught the attention of the aerospace community, and since then there have been a whole series of efforts that really were stimulated by this and some subsequent events.

Next chart, please. One of the matters you all will be talking about later, I think, might be somewhat related to this chart. This was not a matter that was brand new in 1988. The first signs of it were back in 1970, and the bullets in this chart sort of trace some of that history.

Next chart, please. So in closing, two more charts. Next chart. In looking back at the life cycle management of fleets over time, there are some things that seem to serve us well, and they're highlighted here. We talked about the durability and damage tolerance analysis, the full-scale fatigue tests, tear-down inspections, updating the damage tolerance analysis with new loads data because loading environments change over time with flight vehicles, and maintaining high levels of system integrity.

Next chart, please. In closing, many fleets have flown way beyond the traditional points of retirement. In studying these fleets, each seems to have its own unique story in terms of the challenges it had and how those challenges were dealt with. We hope, we at Rand on the Aging Aircraft Team, that this quick survey of the landscape may prove of some aid to the board as you continue your important work.

Thank you.

**ADM. GEHMAN:** Thank you very much.

**MR. ERNST:** I'm hoping to see a slide here in a minute that comes up.

I want to thank you for the opportunity to talk to you a bit more about the cultural issues. Dr. Gebman and I compared slides for the first time about two hours ago, and you'll see some tie-ins to his slides that is more by coincidence in our mutual experience than by any preplanned coordination.

One of the things I want to focus on is cultural, and it goes back to part of the problems that I saw in Dr. McDonald's Shuttle Independent Assessment Team back in 1999 and some changes that I think need to be made in the aerospace industry.

Next slide, please. I also want to offer the apologies of Colonel Mike Carpenter, my counterpart in the Air Force Aging Aircraft Program, who was still stuck at Wright-Patterson. You'll see these slides we kind of do interchangeably on here. This one's a little dated, but it shows the growth of the age, the average age of our fleets over the last 10 or 12 years, most of it in the DOD side from a procurement holiday. When you're talking about aircraft reaching 20 years of age, that's an average age. You've got some like the B-52 and the KC-135, H-46, they're getting up in the late 30s.

We are in unprecedented areas in dealing with aging aircraft. It's not like we can go back and find the predecessor of the B-52 and see how it did in its 45th year. There isn't that data. As you can see from Dr. Gebman's presentation, there are a lot of complex issues. I use the phrase, "This isn't rocket science," but it really is a complex issue, an age type of rocket science in there. Even though we have a lot of very, very talented individuals working on these issues, we're kind of a one-of-one type of scenario. We're out in new areas in there.

I also want to show that the systems, even that are old, it doesn't mean they can't be effective. I think all we have to do is look to the recent aircraft performance in Operation Iraqi Freedom to see that our legacy platforms, when they're put in the hands of qualified operators and maintainers that are dedicated to their jobs, can do a tremendous job and do a great performance. But sometimes those aircraft, when they get up in age, we have new issues that we have to handle in there.

The challenge we need to do is balance when can we recapitalize. There's no idiot light that just sits here and goes, ding, "Replace this aircraft and buy new aircraft." We have to look at a variety of factors, things such as fatigue tests, tear-down inspections, load surveys, complex issues. And frankly, they aren't very sexy. When you talk about I want you to go study corrosion and rust propagation in aircraft, that's not the thing that the young kid out of school necessarily wants to focus on. So there are some challenges there.

Next slide, please. One of my other hats that I put on to cover my bald head is part of the Joint Council on Aging Aircraft. I wanted to explain a little bit about this. This was a grassroots group that got together a little less than two years ago because we all realized in the Air Force and the Navy and the Army and Coast Guard and DLA and NASA that we did not have enough resources. You can read resources as people, money, and time to be able to handle all the issues adequately but we said, you know, we're taxpayers and every April 15th I look at my tax statement and say, gee, I'd like to see if I can reduce that tax burden somehow. So we decided to cooperate and graduate and see if we could share things together and work together on certain issues in here. This group met in about August of 2001, the Joint Aeronautical Commanders group said, "Hey, what are you doing on aging? Let's get together and formally charter this group."

Next slide, please. So if you know anything about the Joint Aeronautical Commanders Group, the service three stars, at the systems command that report to the Joint Logistics Commanders group in there. They have a series of boards, and we were adopted by them and became one of their boards.

Click it again for me and bring up my next pretty picture. There's the people we have from the leadership of the different aging aircraft communities. And we are a board and what we're trying to do now is bring the attention of aging aircraft issues up to the other members of the board and to try to get things changed.

For example, training. We went around and we found out that sometimes our maintenance training wasn't up to snuff in certain areas. So we went back and said, "Hey, how does that training curriculum that was done when the S-3 that Admiral Turcotte flew was delivered in 1974, how should that change?" And we went through and looked at seeing some of those things because aging is going to change some of your core functions and logistics and engineering and supply support and those issues and our job is to bring focus to those.

Click it again for me, please. Next slide, please. What is the mission of the JCA? Twofold really. One is to identify and investigate issues. But we're not just a think tank. We're not going to put a pretty little report that says you really need to go, you know, build this or you need to do this. We're also serving as program managers that are fielding products, especially in the transition area, taking a lot of the new technologies that are out there and look really good, putting them on aircraft and making sure what application they work. That's our focus. And that's one of the biggest pitfalls we have on an aging side is taking all that really neat stuff out there, all those science fair projects, and putting them on platforms.

Next slide, please. Ironically, I sat in the airplane late last night and said what are some of the characteristics of a robust, good successful program; and you'll see a lot of similarities to what Dr. Gebman presented. The first thing we have to do is understand how all of the components, whether it be an O-ring, a structure, an ejection seat in a fighter aircraft, whatever you need, how does that age. If you look at the way we classically develop air vehicles, we spend a lot of time focusing on the development side, getting it up to initial operational capability, and then we've qualified all those issues, they're good, we just kind of do some monitoring of our data but we really don't know all the interdependencies of all those different materials and how they age as a function of time, how they age as a function of changes in environmental regulations, how the load changes, the pilots are going to fly the airplanes differently. We have mission changes on there and we now want to be able to do this or do this or drop this bomb. You can look at all the DOD airplanes over time and see the mission changes. So we have to understand how each of those subsystems are effective in the system of systems.

The next thing is monitoring our fleet usage data. You give a pilot an aircraft, and he's going to find unique ways to be able to fly that airplane in an environment, especially with new mission growths that we've got to counter. The way you do a fatigue test is you go and you estimate how many 1G, 1 1/2, 2G maneuvers, how many landings, how many takeoffs, how many pressurization cycles, and you put it all in there and you literally, you know, bend this thing like it's a piece of silly putty to see where a crack's going in. But you're guessing how that airplane is going to be used 20 and 25 years in advance. And one of the changes that we've seen is we need to go and monitor that fleet usage, collect that data, and then update that fatigue testing because, you know, I guarantee things are going to be different ten years from now, just as they were ten years ago.

You need to utilize that fleet data to go back and not just collect it in some big data morgue but go back and say: How are your original calculations? Are you using up your service life earlier? You know, the Navy went and bought some F-16s for their adversary squadrons, and we used them up in about four years because they were all doing the shooting down their watch type of stuff very quickly in there. The mission changes, the requirements change, and we have to be able to make sure our original predictions -- they're not wrong, but they've got to be validated. It's kind of like me taking my two thumbs and going like this and saying, yeah, I can figure out and calculate how I'm going to go to the moon. You've got a lot of mid-course corrections you have to do.

The last issue which was brought up before, I found it amusing to hear the previous panel talk about the daily reporting systems in PRACA. We need to collect good data, but we need to have that data resident at the subject matter expert's fingertips, not in some type of huge data base in the sky that nobody can get to. And all those elements need to be in there. It's more than just neat technology. You have to have all these elements and, folks, this ain't sexy but this is the core that allows you to manage a fleet effectively.

Next slide, please. The Joint Council on Aging Aircraft, working together, try to run their own programs and share this data together, is trying to make process recommendations and not just field issues. Microcircuit obsolescence was brought up today. What data do we need to buy in our acquisition programs to make sure that we can support the rapid changeover in technology, because we're not going to drive it in Department of Defense or NASA anymore. When we have to get with the industry and figure out what data we need, what's the best approach, that's going to require some acquisition changes, some process changes -- again, not just technology -- but yet we will take those technologies, evaluate them, and say these are the ones we need to select.

I once told a group that I was walking along the beach and picked up a pretty seashell and out ran three guys selling corrosion solutions. I mean, there literally are hundreds of technologies; and I think I broke my corrosion lead's pencil when he got up to about 84 different areas. I said let's get six out there and be successful. We like good ideas. That's what fuels the reduction of our problems with aging aircraft, but we need to also make sure that we are pushing not all of them but we are pushing the top couple of them.

We are facilitating the transition, making sure that we are prototyping them on the aircraft. We do not fly what we have not tested; and I can show you story after story after story when we did a prototype test, something else happened, either we had a sealant or we had a compound, or wash cleaning fluid that interacted and we need to be able to evaluate those issues.

Of course, we're promoting knowledge management. What is the cost of aging? Where is that big idiot light that says: "Buy more F-18EFs and retire S-3s for tankers"? Where is that point that we can make the right economical decision? And there's a paucity of data on those issues and it's kind of like everybody has their own way of calculating it and we're working with Rand, trying to get all those groups together.

So we're working together on a variety of issues from process to technology to acquisition to knowledge management type of solutions.

Next slide, please. That's what I do on my part-time job.

We've been tasked by the Aeronautical Commanders Group to try to foster a national strategy, working DOD, NASA, FAA, and industry. What do we need to do? A lot of our effort, about 80 percent of our time, is on what I call tactical initiatives, what is the best way of inspecting wire, what is the best corrosion compound, yada, yada. About 15 percent of our time or more is strategic areas. What do we need to do to handle diminishing manufacturing sources and obsolescence? About 5 percent of our time is on things like what is the right amount of sustaining engineering that we need to have on our team. How much emphasis do we need to have on our data systems? What data do we need to collect?

Next slide, please. We just recently partnered with NDIA and AIA, two industry consortiums, so that we can get feedback from industry, because I'm not going to say that I'm clairvoyant and have all the answers. I've made enough mistakes, I have nine lives based on my mistakes, but I want to get from industry that partnership of where do they think we need to change. Do we need to change our process for buying, for supporting? What amount of balance is there in the government and industry team?

Next slide. You purposely can't read this. I don't want anybody to read this because it's an early version. But we've actually gone to doing road maps where we've surveyed -- and this is from wiring -- from both a technology point of view, an acquisition, a logistics, a training, all those areas, all the different programs that are out there. When you see those pretty little red things, well, green is good, yellow is ehhh, and red is real bad. You see where we need to build a strategy, and we're trying to make sure that all of our funding and resources, they're not joint but they're at least lined up and all pointing in the same direction and we're pulling in the same way.

Next slide. What are some of the successful models of teams that we've stood up. Too often we have a hearing like this and we go in there and Congress passes a new law and we anoint a new person to be the czar of something and he comes out, or she, and puts out lots of mandates. And maybe I'm a cynic -- well, I know I'm a cynic -- maybe I'll admit it -- but that doesn't always work.

One example I want to point out is what we did with the JCAA corrosion steering group. The reason it was successful is we took the materials experts in each of the sites and married them up with the program teams, put in logistics people for publications and training, a cross-functional IDT, and said, "You guys tell us what to do." My role now becomes less of a manager and more of a barrier-removal expert. At least that's what I call myself. They call me something, other things, but we can't say those in public. So we need to build those from the bottoms up and not just create something from the top down that puts more unfunded mandates on us.

Next slide, please. Summary. I think our aging aircraft problem's a serious threat. I think it's something that requires an infusion of resources, an infusion of capital, and a national strategy to be done. At the Joint Council on Aging Aircraft, we're trying to coordinate those different areas. You can come back and judge whether we're successful or not. I think the industry cooperation is critical. We're not going to say that this is a government-only issue, but we're listening for the best possible practices. I will steal from anybody and any group and, as Winston Churchill said, he would even say a kind word for the devil in the House of Commons if he would help him against the Nazis. I'll even partner with the devil if he'll help us with our aging aircraft strategies, and I think we need a strategic process that requires that collaboration. And the last time I checked, we need NASA's involvement in there. Their involvement's increasing, but we need to remind NASA that one of those A's stands for aeronautics and we need them and their expertise. That's all I have, thank you.

**ADM. GEHMAN:** Thank you very much.

**MR. WALLACE:** I think the focus has been mostly on structures, although Mr. Ernst did talk about avionics and wiring. I know that in the civil sector where I came from, after Aloha we launched, of course, a very extensive aging airplane program. I feel like the structural part, at least perhaps in the less challenging field of civil aircraft operations, is reasonably well handled or at least that we currently feel that the aging systems challenge is greater -- and wiring in particular.

I wondered if you have any sort of conceptual thoughts on aging systems, wiring, and whether or not there's a different approach. You talked about the need for accurate reporting and that sort of thing. But in many respects those seem to be some of the more difficult challenges.

**MR. ERNST:** You could pick any subsystem that you want and the process that was set in place -- from analysis, technology, investments, prototyping, data collection -- that Dr. Gebman showed, needs to be followed through. And I believe that the FAA's wiring non-structural program follows some of those classic issues. In having been part of it and actually teaming with the FAA on some of those areas in wiring, you can see that it follows the same type of elements in there.

Wiring is a major issue. We made some mistakes when we selected the wire types in some of our vehicles in the Eighties. We did some qualification testing on it, and it had some very adverse characteristics. I'm trying to be nice. We now need to make sure that we're developing things that are not just saying, yeah, throw that one away, build all new aircraft, but can inspect it to make sure the bad characteristics, i.e., the arc tracking that was associated with aromatic polyimide insulation is not prevalent. But all those elements require smart people working together and the success story is -- I'm not sure you're aware of this, but the FAA has spent a fair amount of money really investigating the different types of inspection technologies, whether it be frequency domain reflectometry, time domain reflectometry, scanning wave ratio, and a whole bunch of things that make my brain hurt. And the Navy is actually doing some of the transition and manufacturing of those systems and buying and fielding them initially in our depots and our organizational-level troops. The Air Force is doing the same thing. We're working together on these issues and eventually we're going to get products that the commercial industry can take back in on. So you see the FAA do the early R&D, the Navy and the Air Force do some of the tech transition of prototyping and measuring and quantifying what percentage of wire chafing is now degraded that you have to replace it -- what are those red, yellow, green thresholds -- and then the commercial aircraft industry can pick up and procure those things without having to develop all those issues. The process is pretty much the same, but we need to make sure we have a robust area in all those issues. Wiring is in pretty good shape. Corrosion in structures is in pretty good shape. If you want to talk about helicopters and all those rotating machinery, it's a pocket of poverty.

**MR. WALLACE:** Well, following up on one of your points about the type of detailed inspections required, I mean, can you speak to the issue which I know was very much discussed sort of in the post-Aloha inspection implementations of just sort of numbingly monotonous maintenance tasks and the human factors associated with that?

**MR. ERNST:** I like the choice of words. One thing that when I got a chance to sit inside or look at the internal bay, cargo bay of the Columbia in '99 was at Palmdale and there were wiring issues, the primary method of inspection of wiring was the Mark 1 motto, eyeball in a mirror. And I sat there with the Air Force wiring technologist on a team, George Zelinski, a very detailed, knowledgeable individual, and I tried to see if I could find those myself because I'm an engineer. I've been around wiring enough times. I couldn't see those issues that they were required to pick up. And we had a system then that was mind-numbing, that required a lot of expertise and experience and there's technology out there that can do that better and, more importantly, can do that as a precursor to failure. You don't have to wait until you see insulation to say, yes, it's through. What we need to get to is a prognostic system where we can check non-intrusively, not pulling bundles apart, but we can check those wiring bundles and say aha, I'm starting to get some breakdown whether it be due to hydrolysis, whether it be to chafe, vibration, wear, gremlins, whatever, and say now I've got 80 percent through. At 20 percent I now ought to go on a scheduled maintenance procedure and put that together. And that's where we need to go and that's part of a holistic wiring strategy that I believe we have right now. We just have to get it funded and implemented.

**MR. HUBBARD:** I have a question for Mr. Ernst. You made a passing reference to NASA's PRACA problem-reporting system. Could you characterize for us what you think are the best characteristics of the kind of accurate problem-reporting system you referred to in your slides?

**MR. ERNST:** A system has to be real-time. It cannot be a system that takes 18 months to collect data. It's got to be something that is easy for the operator or maintainer to input. The Navy system, years ago, was a paper system where the poor guy, after working a lot of hours fixing the aircraft, would fill out the paperwork and, because of that, there were inaccuracies once in a while -- not in Admiral Turcotte's squadron, of course -- but there were inaccuracies every once in a while we went back and looked at those types of things.

**MR. WALLACE:** Are you trying to sell him something?

**MR. ERNST:** I could tell stories, but I won't.

**ADM. TURCOTTE:** We go back.

**MR. ERNST:** It has to be a system that is easy, simple, robust, and it has to be something that tells you something about the failure, not bug-in-the-cockpit type of issue and then say, "I removed the bug." You need to go in there and say, "Hey, I had some failure issue," and it needs to tie back in from the operator what his perception of the failure, because he's going to describe it, "Hey, this didn't work." He's not going to say that you had a corrosion on Pin 5 of your connector which stopped your data flow. That's going to be the engineer, and it has to tie those systems together with some software that can easily do some trend analysis. And another point we have to do is we have to keep the data long enough to do trend analysis. And there has been a push to throw systems and data away after 18 months and we need to go back five or six or seven or eight or ten years to get a statistical sample size. So those are some of the characteristics, and we're working to get some of those systems implemented now.

**MR. HUBBARD:** On the report that my predecessor Harry McDonald did, one of the shortcomings that he found was that the PRACA system did not appear to have all of these characteristics you just mentioned.

**MR. ERNST:** Harry called it the data morgue.

**MR. HUBBARD:** Data morgue. Yes. One of the things that you commented on just a few minutes ago was getting the material to the subject matter experts at their fingertips. Can you expand on that a little bit?

**MR. ERNST:** Sure. Let's switch to an avionics box failure. We need to not only have it so that a data expert who knows the system can write trend reports but the information if we get a failure back, let's say, on an INS system that failed, that individual who's cognizant of that system needs to go in there and say, "Have I had other failures on this system? Can I find some trending? Is it just recently or periodic? Can I go in and find out if memory chips or whatever type of chip is failing in other systems?" He needs to be able to do that research, that forensic science at his computer terminal and a lot of times our data systems will give us great reports on how many maintenance manhours we spent, three months late. And when we get a mishap in, when we get a box that's been failed, we need to understand and have that information right there at our fingertips.

**MR. HUBBARD:** It would be as if you only got a report on your checking account every three or four months.

**MR. ERNST:** Yes, sir.

**MR. HUBBARD:** Thank you.

**ADM. GEHMAN:** Mr. Gebman, in one of your viewgraphs that you presented on the heavy maintenance work days per depot for KC-135s and also in the heavy maintenance workload ratio which showed how much depot-level maintenance is required, how it's grown over the years, in your experience -- and I'll ask both of you this -- is that an accurate indicator that there's something else working below the system that you need to go look at? Is just keeping track of how much depot-level maintenance is required and how it's growing, how does that relate to characterization of aging?

**DR. GEBMAN:** Excellent question.

**ADM. GEHMAN:** Or is it just interesting?

**DR. GEBMAN:** Excellent question. We have studied now all of the Air Force's fleets and have compiled the statistics for, in particular, the labor hour growth over time; and it seems that once you get beyond 15 years, you're almost certainly facing a future of climbing work to be done -- some fleets that will start a bit sooner, the fighters tend to start sooner, their lives being somewhat shorter than the larger aircraft. It just seems to be a feature of aging. It might well be somewhat analogous to people. In the older years, we find ourselves going to the doctors somewhat more often than in our teenage years.

So if you want to have a sense of the age of a fleet, one measure that you might look at is, well, how is the maintenance workload changing over time. And when you see that steep part of the curve, like the presidential transport, the old 707 known as the VC-137 in Air Force nomenclature, that one literally exploded over a couple-year period and those airplanes are no longer with us.

So it's certainly something to watch. We've tried regression analysis, various statistical methods to try to correlate the rate of rise, the characteristics of fleets. We're making some progress in that area, but this is an area where there's a lot that's not known.

**MR. ERNST:** You want to mention the cost-of-aging study?

**ADM. GEHMAN:** Go ahead.

**MR. ERNST:** One of the issues is I had seen the Rand data almost when I started in the aging aircraft program about four years ago and we've shared back and forth and just recently the Joint Aeronautical Commanders Group Aviation Logistics Board has kicked off an effort that we're part of to look at what are these factors, can we translate the KC-135 experience to other Navy aircraft and other Air Force and Army helos and try to understand what are those factors so we can get a better idea of what's causing it and what the trend lines are. Just having information that says my cost is going up is not sufficient to be able to correct the problem. You need to then drill down and say, okay, but why. You know, I think on the KC-135 they have a pretty good idea of that. But that's what you need to do is not just look and say, yes, it's going up by 7 percent but you need to understand why is it going up 7 percent and what can you do to try to mitigate that curve.

**ADM. GEHMAN:** So my understanding is that, unlike the Dow Jones Industrial Average, the fact that older aircraft require more maintenance is not remarkable in and of itself and is not an indicator that anything's breaking or anything's going wrong. You've got to have much, much better indices at the system, subsystem component level in order to determine it.

**MR. ERNST:** And it's not just age. I'll give you an example. We were talking this cost of aging. I don't remember the numbers off the top of my head but one of the folks at Tinker said it's costing them X number of hours to paint a KC-135 now and it cost them a lot less ten years ago. And they said we're not adding one more ounce of paint. The problem is that you've had different changes in environmental regulations over those years, and you've got to make sure you're accounting for things properly. I mean, those environmental regulations aren't bad, but we've decided that this hurts Bambi and Flipper and those types of things and we want to take them off and it requires different steps and you've got to factor that in there. A lot of the cost growth you're seeing is due to things that are not age, either environmental or fleet usage. Yes, they're going to go up, but they may go up in a certain time to a manageable point and then where that curve breaks, that's what we have to figure out.

**DR. GEBMAN:** I'd just like to hasten to add that Bob is absolutely right. You need to look at the underlying mechanism. If the workload is climbing because you now have to tend more to corrosion and you're satisfied that you're able to see the corrosion and tend to it, that's manageable. In the area of fatigue cracking, you have to be a little bit more careful. Rising workload may indicate that you're getting more and more cracks closer and closer together, and one of the very important assumptions that we make in managing fatigue cracks is that the neighborhood is healthy. So as the population density of cracks starts to get too high, you run into a situation where you might have thought you were fail-safe but, in point of fact, the neighboring structure can't carry the load.

**DR. WIDNALL:** I'm sort of sensitive to this issue of aging aircraft because I worked on the B-52G when I was a freshman and I worked on the KC-135 when I was a sophomore. So my friends are still out there.

What I want to talk about is composite materials. I was a little sorry that you sort of excluded that from your chart, but I'd like to get a sense from you about some of the challenges associated with these composite materials. How well do we really understand their fatigue properties? Do we really understand their properties as well as we understand metals? What about their exposure to UV radiation and high temperatures and corrosive chemicals and all those sorts of issues? And I know we're using these more and more in our aircraft fleets in general and in particular on the Shuttle. They're obviously a key part of it. And it's just not composite materials but other kinds of brittle materials, sort of what I would call nonstandard materials.

**DR. GEBMAN:** Thank you for asking this question because when I was thinking about what to talk about today, I really struggled with do I talk about the areas where we have depth of knowledge that might be useful to your investigation or do I talk equally across the areas even though the depth of knowledge is shallow. Clearly, with metals there's a lot that we know, especially on fatigue, and we're learning rapidly on corrosion.

In the area of composites, I think that Charlie Harris from NASA Langley at the conference earlier this month of the AIAA, American Institute of Aeronautics and Astronautics, this big gathering, 780 people, 525 papers, Charlie gave a talk about the progress in composites and he was very positive and upbeat about all the good technical work going on. And that was all appropriate. But then he shared with the group a round robin exercise where they sent problems around to people, the same problem to work on, and people came back with different answers. And then they did another exercise where they even told people what the problem was and they still came back with different answers in terms of the methods and the assessments.

So the whole area of composite materials is one that might be analogous to where we were with metals back in the 1950s. Back in the 1950s, we had the alloy-of-the-month club; and that's where the B-52 and the KC-135 came from. The young engineers were finding out better ways to do the chemistry to get strength, but they didn't have time to understand the durability, the fatigue properties, and the corrosion properties. I'm somewhat sensing that, with composites, we're still inventing cleverer ways to get strength but we don't yet understand the long-term durability characteristics. The science is far more complicated because with metals it's homogeneous, it's the same material, with composites you've got fibers and glues or resins and it's a very complex interaction to try to model and we're not good at it yet. So anything that is made of composite requires even more circumspection and attention than probably the metals.

**DR. WIDNALL:** I was afraid of that.

**GEN. BARRY:** Excellent presentations by both of you and raises a lot of questions. As you know, the board has taken a very serious approach to aging spacecraft in this what we call R&D development test, however you want to call it, environment.

A couple of comments. Your references to the Air Force, as obviously I'm familiar with, where we are older than we've ever been before. We've never been in this era in the United States Air Force -- as is the Navy. We're approaching ages where the average age of our platforms of 6,000 is 22 years old. So even within the data experience base that we have flying airplanes, we're approaching new environments.

Now, let's translate that over to spacecraft. We are entering a new era in spacecraft, with reusable vehicles in an environment of aging. We've never been there before. So we've got two parallel efforts going on that certainly can kind of cooperate and graduate, as we've seen evidenced by the Navy and the Air Force here.

I've got a couple of quick questions and then a rather larger one. First question is: Is NASA involved in any of this Joint Council on Aircraft Aging, as far as you know?

**MR. ERNST:** Yes, sir. NASA has been involved in the aging aircraft effort since Aloha, prior to me being in it. The efforts at Langley in structures and corrosion NDI have been solid. Just recently, Christmas timeframe, before Columbia, they said, hey, we recognize we need to help you in that national strategy; and they're getting more involved. We need even more. I need to fill in gaps.

**GEN. BARRY:** On your side as well as the space side? I mean, are they translating lessons learned to both aero and space?

**MR. ERNST:** Yes. I'm not going to tell you it's even and homogeneous throughout, but I know that in wiring, the Shuttle folks at Kennedy are in lockstep with my guys and the FAA and I know the aerospace side and structures are working real well together. We're trying to see where the gaps are and plug them in there. We need more involvement, but they have been involved.

**GEN. BARRY:** All right. Let me ask this. Two things. Let's just talk about corrosion and let's talk about fatigue cracking that, Jean, you mentioned earlier. Right now we have capabilities within our aircraft to do stress-testing that you mentioned as an example. We have programs that are not only based in the United States -- Australia has an excellent one on how do this. I think we all recognize that who are in the industry. What can we do insofar as spacecraft are concerned because obviously they are larger and we translate that to our larger aircraft insofar as dynamic testing is concerned, because I don't think it's unfair to say that managing aging spacecraft in NASA, for the large part, is done by inspection. So how do we translate that, what we've learned in aircraft, over into NASA as a possible recommendation?

**MR. ERNST:** I think you need to break it down into the subsystem component areas. For example, we had this discussion on the McDonald's team three years ago now, on the SIAT team on wiring, where we had totally different environments but we could take the Air Force and Navy's experience with aromatic polyimide insulation and say here's what we saw under these load conditions. Now, under a probably higher vibration, higher thermal but shorter duration environment, how is that going to translate? We know how that fatigue, so to speak, environment can translate and run a new model to see what it should do with the Shuttle program.

That's the kind of transformation that could be done, but only if you know how each of those subsystems and the materials of those subsystems is going to behave as a function of time and age and environment over a number of years. The problem is a lot of times we don't know that information. So we know how it works here, we know the loads are different, but we don't know how the age is going to translate as those factors are translated, if that makes sense to you. I don't think it's hard to do that, but you have to invest in some age-related studies and that's not necessarily the top of the list.

**GEN. BARRY:** One of the concerns we have is to be able to analyze how the Orbiters have been shaken, rattled, and rolled over these many years, especially when we take into consideration that this was a spacecraft that was designed to be flown 100 times in ten years and now we're multiple years, decades past that and we are still only at the 20s and 30s. A question then is, you know, how do we maybe translate some of the lessons learned on how the spacecraft are flown within spec but, you know, after a while, get some kind of stress loads on them that can be accumulated over time and measured. Now, translate, if you could, the lessons learned that we've developed on aircraft that might be able to be translated over to NASA.

**DR. GEBMAN:** Could I have Chart No. 24, please.

**MR. ERNST:** You guys are going to learn this chart, because he wanted to show this to you.

**DR. WIDNALL:** He's ready for you.

**DR. GEBMAN:** This is a really tough question. Obviously, with the Shuttle we don't have the luxury of a full-scale fatigue test. Obviously doing a tear-down, if this was an aircraft fleet and when we had hundreds or even tens, we'd consider taking the oldest one and tear it apart and see what ails it and then use that to guide future work. When you're down to three, that's not an option.

So then you ask yourself, well, what might we do? And when you look at this diagram, on the top row, the matter of force tracking data and loads analysis, there may be some things you could do in terms of assuring that NASA has developed all of the effort that it can, evaluating the strain gauge recordings and pressure recordings from prior flights, and that you really have as excellent a record, historically, of the loads that have been imposed on the structure as you can possibly get.

The next thing you then could consider doing is, given the best loads data, to go back and, using more current finite element analysis methods which have improved greatly over the decades, to go in and do some spot checks on your stress computations to make sure that you've got the best that we can do in terms of estimating stresses from the given loads and then take it the next step and go in for the fatigue part to check on the crack growth calculations, the fracture toughness issues, and to make sure that the engineering community has really been resourced and tasked to do everything that we can to understand the health analytically of the fleet.

Then the final thing you might consider doing, from the debris that you do have, in effect, you have already a partial tear-down circumstance and to go in there at some point and literally take apart that which is still connected together and really check for like adhesion on honeycomb, how is that, that waffle still adhering to the face plates, and just get as much mileage as you can out of your debris in terms of understanding what the health of the remaining fleet may be.

**MR. ERNST:** Slice up your poles, your joints, rivet holes, things like that. That's what we do routinely.

To follow on with the chart that Dr. Gebman put up, you'll notice a couple of things. One, do a mid-life assessment of the loads. You know, the Columbia originally was kind of a flight-test bird and I believe had some several hundred pounds of instrumentation and sensors in there to measure its fleet loads. To give you an example, the P-3 and S-3 program just recently completed mid-life fatigue testing at Lockheed, and we found drastic changes to both loads from what they were anticipating. The maneuvers were a little different. The theoretical issues, the early introduction issues slowly change over time. You know, it's like boiling a pot of water. It doesn't boil all at once. And I think you need to go back and really do those load surveys.

You also need to do some type of tear-down. You can't cut up, you know, the Atlantis and make it a series of razor blades and fractographic analysis and stuff; but the Columbia, when they had wiring problems in '99, NASA did go and remove certain wire segments. You can go in without cutting the whole thing up and remove certain panels, remove tiles to see adhesion, remove subsystems. When a part's going through an overhaul, take this part on overhaul and do those types of things. So there are things that you can do; but again, you've got to have a proper program to get that environment and see how we're doing.

The S-3 example in fatigue tests, we had 12 points that we considered life-limiting on the aircraft. Four of those they knew in the original fatigue tests and the odds were out of there. We found an additional eight points that were due to the loads, and due to the tear-downs that we saw microscopic cracks. We were able to go in and cold-work fastener holes in that aircraft and give it fatigue life back. Real simple operation, real cheap, and not have the 305-inch wing cracks we had in the P-3. So you're able to do some of those things if you invest in the time and the resource and have a robust program.

**DR. GEBMAN:** If I might, I'd just like to follow up. Could I have Chart No. 7, please. There's an important aspect that I neglected in my answer, and that is that we're dealing with a spacecraft. And I apologize. Obviously with something like the Shuttle, you have thermodynamics acting as well as structural dynamics; and in addition to getting a solid characterization of the historical loads, you also want to get a solid characterization of the historical thermodynamic exposure because -- take a spar cap, any one of those four spar caps that are identified with the arrows. If, in the course of the history of a particular spar cap, it has been exposed to temperatures different than the other spar caps, then the loads in that part of the structure are going to be different by virtue of the thermal expansion of the material. So this is a very complex thermal as well as structural dynamic circumstance.

**ADM. GEHMAN:** Let me follow up on that before I call on another board member. Do I understand that you are suggesting that it's useful in the study of aging aircraft to establish some measurements of what I would call stress cycles or something like that? We understand age. We understand landings and takeoffs. But there are other events which cyclically stress the aircraft, particularly in the case of the Shuttle. And it's useful to keep track of those, in addition to the obvious ones like landings and takeoffs and how many months, hours and all those kind of obvious things.

**DR. GEBMAN:** These things with aircraft are tracked routinely. Exceedance curves are developed which are a statistical way of representing even the small variations.

My most recent comment suggests that we should also construct a thermal exceedance spectrum, as best we can from the historical data, so that to the extent that we've got differential thermal expansion of structure going on, we can factor that into the loads that the members receive.

You see, there's two load levels. One is the aerodynamic load and the inertial loads applied to the gross structure. The other issue of load is, for a particular structural member, what load does it see over its lifetime; and that can be driven by thermal expansion issues, just as it can be driven by the aerodynamics. And given the historical records of the temperatures, the engineers should be able to construct and may already have done thermal exceedance curves to go along with load exceedance curves.

**MR. ERNST:** I think you need to look at every environmental factor and see if there is a similar type of a correlation in there. We've done a good job of fatigue tracking. We're tracking a lot more parts than we used to. The models are a hundred times more detailed than they used to be. We can calculate things a lot finer, but I think you need to look at all the different loads in environments that any vehicle goes on and say, okay, what's changing, what's the effect of that over time.

**ADM. TURCOTTE:** For both. Kind of the 3Cs in aging -- you know, Kapton, Koropon, and corrosion -- which go back a long time in finding problems with Kapton wiring, with Koropon bonding, de-bonding, heat translation, all of those things. That's Part 1 of the question. Could you, kind of both of you, talk a little bit about major lessons learned from both fleet usage, commercial usage, and your knowledge to the extent of findings on the Shuttle, both, you know, galvanic or intergranular types of corrosion.

Part 2 question. If you were king for a day with your knowledge of the PRACA data base, what would you do to improve it?

**MR. ERNST:** You're going to get me in trouble. I was very nonpolitically correct about the PRACA data base in 1999. And I have not seen it since then but I think if you go back and you read the Shuttle Independent Assessment Team report, you will find that the comments of the group were less than favorable on PRACA. I'm not saying that the Navy and the Air Force and the Army's data systems are perfect, but we're taking steps in the right direction. So I really can't comment on what they're doing today. I know they made some improvements, but it was pretty abysmal back in 1999 and, I think, masked some of the issues that feed into your risk equation that we saw back then. I think that was a mistake.

As far as handling some of the materials and some of the issues with Kapton, aromatic polyimide insulation manufactured under the Dupont trade name Kapton -- get that correct -- we didn't do a good job on establishing realistic life cycle testing for that material when it was introduced. Kapton has a lot of good properties. I don't believe I said that, but it has a lot of good properties. It's very, very tough. It has some very adverse characteristics that we never tested for. But I think you can go through several other tests and I know there's been arguments with the FAA on the flammability tests, whether that's applicable, and there's lots of different tests and we didn't do a good job of running a qualification test and an aging test that's run on a short period of time that's trying to cover 20 or 40 years. So we made some mistakes on that.

The other issue is once we had problems with the wiring insulation, I don't think we developed realistic scenarios. If you look at the cost of replacing and rewiring a whole aircraft, it's several million dollars. Well, do I really need to do it? Do I need to do it in all areas? Which platforms do I need to do first? And what we have done now is develop a bouquet of options. Whatever color of flowers you want and whatever kind of room, it goes together. Because what my wiring options on the F-14 Tomcats, which are going to be retired in the next four or five years, is totally different than what I would do on earlier production F-18s or P-3s that are going to be around a little longer. So you have to develop options based on risk so that you can do things quickly, cheaply, easily, and get it done and not just give one option is all.

So I think two issues. One, we didn't do a good qualification testing and we need to continue, just like the life cycle testing, just like the fatigue tracking where you update it and you get better; and the second issue is we didn't develop any options.

**DR. GEBMAN:** On the matter of wiring, the Air Force in the case of the KC-135 embarked on a major rewiring program about five years ago; and that is going to probably continue for the next four to five years, at which point they will have substantially replaced the wiring on the 135. The basis for this was an accumulation of maintenance actions that was becoming increasingly costly to exercise and a concern for flight safety, and those two factors together seemed to have driven the train on that fleet.

Unfortunately, our ability to predict life, we don't have the engineering tools that we have with fatigue cracks, either with composites yet or, for sure, with wiring, which makes those areas very difficult to feel comfortable about with an aging fleet.

**ADM. GEHMAN:** How comfortable would you feel with the study of the aging characteristics of a main engine that's fueled by liquid hydrogen and burns a thousand gallons a second and produces a million pounds of thrust? How's our data base on how that baby ages?

**DR. GEBMAN:** Well, on my chart I did include a line that said propulsion; and it didn't get extremely high grades for data or methods or people that really understand life issues in that area. So you've hit another excellent nail squarely on the head. For those areas, going back to General Casey's comments about understanding margins and managing to margins, you really have to worry that as time goes by, you're eating into those design margins and at some point the ice becomes thinner than what you're comfortable with. And that's a technical judgment probably more than an engineering calculation.

**MR. ERNST:** Follow up. One of the successful programs that the Air Force and the Navy has is on aircraft engines. And they've realized that you've got a lot of moving parts, a lot of high temperatures, a lot of complex interactions in there. And they have what they call CIP, Component Improvement Program, where they go back in and they test and they see where their problem areas are and they incrementally try to infuse newer technologies and fixes in the early parts of the service.

Again, that's one of those that's always fighting to try to get resources adequately in there, but if we follow what the commercial industry does, we can really improve the reliability and we can have a pretty good idea and almost get to a scheduled maintenance type of inspection so we're not flying and say, yeah, lost an engine or had a shutdown but, okay, now at 7, 8 hundred hours I have an 8,000-hour interval period and know exactly what to replace. So that's another example where we've taken the methodology that Dr. Gebman talked about on structures and we've transferred over to the engines, and I think both the commercial and the military have very good experience in that being successful.

**DR. GEBMAN:** I certainly wouldn't quarrel with my distinguished colleague, but I would hasten to add that the commercial engine and even the military engine circumstance with aircraft is far different than the circumstance we're talking about here.

**DR. LOGSDON:** This is all very far away from the experience of a Washington policy wonk. So excuse me if these are really naive questions. What does the fleet size of three do to the ability to do the sorts of things that you think ought to be done?

And the second question, I think it's really for Mr. Ernst, coming out of his independent assessment experience. Is NASA routinely collecting the kind of data that would feed into the kinds of trend analyses? You know, outside of faults, PRACA and that, is there a data base that you could apply some of these methodologies to?

**MR. ERNST:** Well, I think all the agencies and commercial are collecting a fair amount of data.

**DR. LOGSDON:** On Shuttle.

**MR. ERNST:** On Shuttle? I mean, you look at the Navy programs and Air Force programs. We're collecting 80 percent of what we need. I still think we need to do more -- the cause of failures.

For example, if I went into the Navy's data base on wiring chafing, there is no failure code for chafe right now. What's the primary failure mode for wiring? We're fixing that, by the way, so I can say that. But that's one of the issues. I mean, we're not recording the right type of information in all cases. We're about 80 percent there.

My beef with PRACA at the time was you couldn't go in there easily and extract anything to make decisions. I at least can go into some of the services' data bases and pull some information and get a pretty good idea and then at some point I have to play archeologist or forensic scientist and go back through and do some more digging. But we're collecting about 80 percent. There need to be some other changes; and, unfortunately, data is the one thing that everybody wants to cut in the budget crunch. We don't want to pay for that data.

**DR. LOGSDON:** If I understand PRACA correctly, you have to have a problem or perceive a problem to even get in the system. I'm saying is the Shuttle even instrumented to capture the kind of data that you would like to have to measure various elements of its aging.

**MR. ERNST:** Not in all cases, but I think you can probably do some work-arounds with that and be able to check things. I mean, you don't have to do everything in flight. You can do engine run-up cycle times and check temperature rise in there, check component issues, and test stands. Things like that. You can capture that information if you need to.

You need the maintenance-reporting information, which PRACA primarily did. You need to trend analysis like if I get to this certain load level, this is going to impact my fatigue life. And then you need to be able to do periodic instrumentation at times. And it doesn't always mean a full-scale in-flight test. It means capturing some of the data. And that data was available. You could get that. Was it easily, readily available? No, it wasn't readily available.

**DR. GEBMAN:** Putting my engineering hat on relative to your data question, given that the instrumentation and wiring in the Shuttle and the systems were designed in an earlier era in terms of electronics, it might well be worthwhile rethinking the matter of what are we interested in observing during future flights in order that we might create a more complete record of environment and loads so that we can better manage the remaining lives of the fleet.

**MR. ERNST:** Health management, health monitoring for the system.

**DR. GEBMAN:** And regarding your observation of the number three, what does it mean to have three in a fleet? From an operational perspective, one of the early lessons I learned at Rand was that whenever you visit a unit, you always expect -- and Admiral Turcotte will appreciate this -- you always expect at least the Nth airplane to be a source of supply for the others, if you're lucky. Sometimes it's more than just the Nth airplane. So if you have a fleet of three, from an operational perspective, one of the three is needed to support the operation of the remaining two. And to have an operating fleet with just two means that you only have one backup and that's very thin.

**MR. ERNST:** And I think it makes your correlation. A lot of times when you have how many hundred F-15s and F-16s, you can start looking at the gross number of failures and say aha, I need to look at something. When you have three, you can't rely on that. You have to take a little bit different systems approach to be able to capture your data.

The Navy flies some type model series, you know, that are 12. Twelve EP-3s. And each one of them is a slightly different configuration. But you can capture that information. It just requires a little different approach, and sometimes it's not as robust, predictive, leading edge because you don't have that significant sample size.

**MR. WALLACE:** Were you suggesting, Dr. Gebman, that sort of the fleet leader concept; or were you suggesting cannibalizing parts? I wasn't entirely clear.

**DR. GEBMAN:** No matter how good your supply system is in terms of providing parts, you always end up in a circumstance where you have a first-time demand for a part and the last airplane of the unit then becomes the offer of that replacement part. I think that if you talk to the NASA folks regarding the matter that's referred to commonly as cannibalization, it's borrowing a part from one aircraft or spacecraft in order to be able to launch one that's scheduled to go.

**MR. WALLACE:** Another question. This is jumping subjects a bit. Should the goal of an aging aircraft program grow beyond maintaining the aircraft to be as good as new? What I mean by that is: Should it meld in with sort of obsolescence issues, issues where the technology has simply gotten to be so far behind the state of the art that it either makes sense for economic or safety reasons to upgrade or even reasons of simply maintainability?

**DR. GEBMAN:** You're raising the issue of replacement, fleet replacement; and we have struggled at Rand with the Air Force long and hard on that matter because, for example, the tanker fleet. It's a very important fleet. Without the tankers, the Air Force doesn't go places. They don't have aircraft carriers to carry their airplanes. So they're very dependent on their tankers; and to have almost all of your tanker fleet wrapped up in one type of aircraft that's 40 years old now and to be planning to do so for another 40 really raises questions.

The first thing we looked at, well, is there a case on economic grounds for replacing the fleet. There was an economic service life study done and it shows rising costs, but it doesn't show the rising cost by themselves being a sufficient basis for justifying a new fleet, whereupon then you start asking questions along the line of obsolescence issues, foregone capability improvements that you can't have without substantial investment in an aging fleet. So this whole question about when is it wise to replace a fleet is one for which we still don't have a good methodology for dealing with.

**MR. WALLACE:** I really didn't intend to ask that question about replacement. Well, it was a good answer. But about replacing the fleet as opposed to simply upgrading, particularly, I mean, fleet replacement, you know, lots of smart bean-counters with spreadsheets do that for the civil aircraft industry but I think there's a whole different set of different issues with next-generation spacecraft. My question really is more about upgrades.

**MR. ERNST:** To address that -- and you picked on obsolescence. When you get to the microcircuit obsolescence issue, which has become a science fair, pet rock project of mine over the last 10 or 12 years, there are lots of different options and right now we have some system incentivized to just find this chip to put in this box in a lot of cases. We found about a third of the time that doesn't make sense because not only is that part obsolete but the three around it are going terminal and the whole board's wearing out because we keep replacing it so many times because of poor reliability. So it's probably better at that time to take the whole thing, take the cards out, and make it a lobster trap somewhere and then put a new system in there. That really happens about a third of the time. But we need to again, I think, balance some of the different pots and stovepipes of money that are available, especially in DOD, to be able to optimize those issues and have the best understanding of the age effects, where they're going to be two years from now, because I may make a replacement today and I've got three more downstream. I need to look where I'm going to be three years from now and say this is time to replace this 1988 Tercel that I had with 189,000 miles and go buy something new because this is just the tip of the iceberg. And I don't think we're doing a real good job of that but's one of the challenges of not just maintaining status quo but looking and saying what capabilities, what mission growth areas, where am I going in some reliability issues and balance all of those into like a triangle of a decision matrix.

**DR. GEBMAN:** There's a fleet that we're looking at now that has the potential for receiving an upgrade to its aviation electronics to give it capabilities to continue its military relevance. And there are also a series of mods being considered to upgrade the engine so that its flight safety features remain appropriate. And similarly with the airframe. And as we're going through the arithmetic on this particular fleet, one of the things that we're seeing is that by the time you're done making whichever of the three mods or all three of them to the fleet, the years remaining becomes very significant to your choice. And when you go to the operator and you ask the operator, well, how long do you want to retain this fleet, well, they're really not sure. So this question is almost as difficult as the fleet replacement question.

**MR. ERNST:** And you look at the mission changes in the Department of Defense in the last couple of years where we've gone from a Cold War scenario to more of a small conflict and now global war on terrorism and it changes. We have planes that, to pick on Admiral Turcotte's S-3, that were designed to hunt subs that were doing surveillance and tanking and dropping weapons and doing, you know, partridge in a pear tree and everything else. And you need to look at those mission changes as a function of age too and say, you know, I may be able to keep this aircraft doing what it did five years ago but you know I need to replace it. I need to go over here. And we don't always balance those issues.

I know the Air Force is really trying to look at that decision and set up a fleet viability board to weigh the aging factors in these mission scenarios. I'm monitoring that for the Navy to see what they do; and then after they get all the kinks worked out, we'll steal it. But that's kind of the approach. I think that answers it that it's not a simple answer but that's what needs to be looked at. I think the Shuttle has the same issue: Where does it need to be ten years from now?

**MR. HUBBARD:** I heard one of you mention or whisper the term "vehicle health monitoring," I think. The notion of a fleet of three. I'd just like you to think out loud for a minute or two about how vehicle health monitoring would apply in this case along three lines. One, what would a systems approach be to that, given that we have a fleet of three? Second, realtime versus recorded measurements? Third, what other measurements could you imagine? I mean, we've got a Thermal Protection System, for example, that is pretty unique to the Orbiter versus the military aircraft you mentioned. We've got pressure, strain, and temperature. Can you imagine, in this kind of systematic approach to vehicle health monitoring, what one might do?

**MR. ERNST:** Let me answer in reverse order. I don't want to bad-mouth technology. And I've talked about some cultural issues but there's some real technology advancements. I know some of the DOE labs have now started looking at electronic signature analysis for failures in motors, predicting when motors are going to fail. There are all kinds of things. I mean, you can literally go around to the different areas and find better ways that people can get precursors to failures if they measure data and give you good information. That would help us understand from an overhaul interview, it would let us know if you had a degraded flight mode issue so that we're not having, yes, that system failed, we have to do something else. It would really help you manage your redundancy a lot better, too. So there are a lot of new technologies beyond the strain gauges that I learned about in college that need to do.

I think the real-time versus recorded is something you need to use a system engineering approach in analyzing. There are certain oil analysis systems that I remember we had a vapor cycle system and by the time you got oil in the filter, you had basically eaten the whole system; it was too late. So putting an oil analysis system that you measure it every ten hours wasn't doing any good. It needed to be real-time.

Not everything needs to be real-time and any information at all, whether it be on one unit or on three units, is a lot more than no information and I think that having some health monitoring systems on any fleet -- Shuttle, the F-18, the S-3, or whatever, F-15 -- gives you information if you use a good systems engineering approach, not just collect data for data's sake but see what are you trying to do with the data and then drive what you need to collect to get data or what technology best does that, I think, is helpful.

**DR. GEBMAN:** I would like to speak both as a proponent and also share a word of caution. The engineering in me would prompt me to want to put strain gauges and instrumentation in many places. Probably too many. There's a trade-off between the disease and the cure, and it's possible to overdo a good thing. We need to remember that, with this instrumentation, comes wires; and we've already been talking about the vulnerability that wiring can introduce into the system. So what I would think might be helpful is to try to understand what are the critical issues that we're concerned about or we should be concerned about and then ask, for those critical issues, what initially at least modest amount of additional instrumentation might be appropriate and try to really focus on the core vulnerabilities and not to go too quickly too far overboard.

**MR. ERNST:** We can't be kids in the candy shop. I agree.

**ADM. GEHMAN:** Thank you, sir. I'm going to ask the last question myself; and, hopefully, it's a brief one. I think probably, Mr. Gebman, your Chart No. 3 answers this question; but I want to allow us to listen to it for a second. Would you list the aircraft aging areas of examination as to which of them appear to be mature technologies and which of them appear to be not so mature? Obviously the detection of corrosion, of course, is obviously a big one and I suspect we probably know a lot about that.

**DR. GEBMAN:** Probably the quickest answer to the question would be to focus on the first column and the last three columns. In the last three columns, we have my subjective assessment of where we stand in terms of data, methods, and people. The metals area for structure, we're in very good comparative shape to the others.

In corrosion, our data and our methods are still somewhat embryonic but now, thanks to the various laboratories really engaging the last several years in a more aggressive way, we're building a core of people that are knowledgeable in the area.

The business of adhesion, we haven't paid much attention to it. And my sense is that our data and methods are below low and even the number of people really knowledgeable in that area is not great.

Moving down to the composites, there's a lot of people out there. There's a fair number of people doing excellent, promising research; but the fruits of that research in terms of data and methods is still forthcoming.

In the area of propulsion, the general area strikes me, especially when we're thinking about Shuttle types of applications, as not particularly high. The whole area of high-cycle fatigue is still a challenge for the engine community, even for commercial aircraft.

Then the "Other" category. This is the one that worries me most because it's oftentimes the one that's not getting the attention that's the one that bites you the hardest. Functional systems, pumps, motors. The TWA 800 killed more people than metal structures in recent times, and that may well have been down in this "Other" category, either the wiring or the functional systems.

So as the board moves forward with its good work, attention to all of the technical areas. And all that I've tried to accomplish here today is to bring forward that there are some areas where the aging aircraft community really has depth. If that proves to be relevant or of interest, the community is certainly prepared to help. In the others, it's going to be more challenging.

**ADM. GEHMAN:** Well, thank you very much. On behalf of the board, I would like to express our appreciation for your attendance here today and your complete and helpful replies to our questions and the information that you've given. You're obviously great experts and we've learned a lot and we hope that we can apply it to this problem. We appreciate your attendance.

We're going to take about a ten-minute break while we seat the next panel, and we'll be right back.

(Recess taken)

**ADM. GEHMAN:** All right. We're ready to begin our last session of the day.

It's a privilege for the board to recognize Dr. Diane Vaughan from Boston College. Dr. Vaughan has written an influential and well-read book on the Challenger accident. We are continuing our look into the business of risk assessment and risk management. This is one of the classic studies on the Challenger accident. Most of the board members have at least read parts of your book, Professor Vaughan; and we're delighted to have you here.

**DR. VAUGHAN:** Thank you.

**GEN. BARRY:** And we're ready for a test.

**ADM. GEHMAN:** I would like you to please, if you would, before we get started, introduce yourself by telling us a little bit about your background; and then if you would like to say something to get us started, we would be delighted to hear it.

**DIANE VAUGHAN testified as follows:**

**DR. VAUGHAN:** Thank you. I'm a sociologist. I received all of my education at Ohio State University, getting my Ph.D. in 1979. After that, I had a post-doctoral fellowship at Yale; and I began teaching at Boston College in 1984, where I am currently a full professor.

My research interest is organizations. I'm, in particular, interested in how organizational systems affect the actions and understandings of the people who work in them. So it's what we call, in my trade, making the macro-micro connection, how do you understand the importance and effect of being in an organization as it guides the actions of individuals. My research methods are typically what we would call qualitative, which are interviews, archival documents, and ethnographic observations. So using these methods, I have written three books, the last of which was The Challenger Launch Decision, which was published in 1996.

**ADM. GEHMAN:** Thank you very much. You may proceed.

**DR. VAUGHAN:** All right. I want to start from the point of view of Sally Ride's now famous statement. She hears echoes of Challenger in Columbia. The question is: What do these echoes mean? When you have problems that persist over time, in spite of the change in personnel, it means that something systematic is going on in the organizations where these people work.

This is an O-ring -- not The O-ring, but it is an O-ring. I want to make the point that, in fact, Challenger was not just an O-ring failure but it was the failure of the organizational system. What the echoes mean is that the problems that existed at the time of Challenger have not been fixed, despite all the resources and all the insights the presidential commission found, that these problems have still remained.

So one of the things that we need to think about is when an organizational system creates problems, the strategies to make the changes have to, in fact, address the causes in the system. If you don't do that, then the problems repeat; and I believe that's what's happened with Columbia.

What I would like to do is begin by looking at what were the causes of Challenger, based on my research, to point out how the organizational system affected the decisions that were made, and then make some comparisons with Columbia and then think about what it might mean, taking that information, to make changes in an organization to reduce the probability that this happens.

One of the things that we have learned in organizational --

**ADM. GEHMAN:** Excuse me for interrupting. If I may ask a question while we're still on this subject. On your first viewgraph, the first bullet, you said when you find patterns that repeat over time despite changes in personnel, something systemic is going on in the organization. There are no negative connotations in that sentence. You didn't say something wrong is going on in the organization. I assume the obverse is also true. If patterns repeat over time and you keep changing people and you keep getting good results, then it's the system --

**DR. VAUGHAN:** The system is working. Right. It's the fact that there is a bad outcome that we're looking at here. Thank you.

**ADM. GEHMAN:** Thank you. Sorry for the interruption.

**DR. VAUGHAN:** I wanted to begin and go back over just really briefly what happened in Challenger. First, the presidential commission reported that there was a controversial eve-of-the-launch teleconference during which worried engineers at Morton Thiokol, the solid rocket booster contractor in Utah, had then objected to the launch, given that there was going to be an unprecedented cold temperature at launch time the next day.

Marshall management, however, went ahead and launched, overriding the protests of these engineers. Not only did the commission discover that but also the fact that they discovered that NASA had been flying with known flaws on the Solid Rocket Boosters' O-rings since early in the Shuttle program, that these flaws were known, and known to everybody within the NASA system.

May I have the next slide, please. What happened was what I called an incremental descent into poor judgment. This was a design from which there were predicted to be no problems with the O-rings, no damage. An anomaly occurred early in flights of the Shuttle, and they accepted that anomaly and then they continued to have anomalies and accepted more and more. This was not just blind acceptance, but they analyzed them thoroughly and on the basis of their engineering analysis and their tests, they concluded that it was not a threat to flight safety. It's important to understand, then, that this history was a background in which they made decisions on the eve of the teleconference. And that was one more step in which they again gradually had expanded the bounds of acceptable risk.

Next slide, please. One of the things that's critical with Challenger, and also now, is the fact that we tend to look at bad outcomes and look backwards and we're able then to put in line all of the bad decisions and apparently foolish moves that led up to it. It becomes very important to look at the problems as they were unfolding and how people saw them at the time and try to reconstruct their definition of the situation based on the information they had when they made their choices.

Next slide, please. The Challenger launch decision was, in fact, a failure of the organizational system. And I hope, by going through the explanation, it will show why it was not groupthink; it was not incompetent engineers, unethical or incompetent managers.

Next slide, please. So what happened? Richard Feynman called it Russian roulette, which implies that there is a knowing risk-taking going on. The result of my research, I called it something else, the normalization of deviance. And I want to use the organizational system perspective to explain how this happened.

The idea of an organizational system is that there are different levels at which you have to do your investigation. So the first is the people doing the work, their interactions, and what they see; the second level is the organization itself; and the third level has to do with the environment outside the organization and the other players that affect what's going on internally.

So let's start with the bottom layer, the people doing the interaction. First, it's important to know that they were making decisions against a backdrop where problems were expected. Because the shuttle was designed to be reusable, they knew it was going to come back from outer space with damage; and so there was damage on every mission. So simply an environment like that, to have a problem is itself normal. So what to us in hindsight seemed to be clear signals of danger that should have been heeded -- that is, the number of flaws and O-ring erosion that had happened prior to Challenger -- looked different to them. The next slide will show how they looked as the problem unfolded.

What we saw as signals of danger, they saw as mixed signals. They would have a problem flight. It would be followed with a flight for which there was no problem. They would have weak signals. Something that in retrospect seemed to us to be a flight-stopper, to them was interpreted differently at the time. For example, cold, which was a problem with the Challenger flight, was not a clear problem and not a clear cause on an earlier launch. Finally, what we saw as signals of danger came to be routine. In the year before Challenger, they were having O-ring erosion on 7 out of 9 flights. At this time it became a routine signal, not a warning sign.

The next slide, please. That's what's going on on the ground floor. So the question is then how does the organizational system in which they're working affect what they're doing and how they're interpreting this information and how their decisions move forward. This is what I call the trickle-down effect. Congress and the White House were major players in making decisions, and their policy decisions affected how people were making decisions in the project.

The budget, the problem of Challenger starting out with insufficient resources, meant that the only way the program got going was by Challenger, by the Shuttle program being responsible in part for its own livelihood. That is, it would carry payloads. The number of payloads it would get paid for annually were expected to contribute to its budget.

So early on, the Space Shuttle project was converted from what during the Apollo era had been an R&D organization into a business. Contracting out and regulation both had altered the Shuttle program so that it was much more bureaucratic. There was lots of paperwork. A lot of people who had been in pure engineering positions were reversed in the sense that they became more administrative. They were put in oversight positions, and they had a lot of desk work to do.

Finally, when the program was announced, it was announced that it would be routine to fly Shuttles into space. It would operate like a bus. So the expectation that it would be routine also had an effect in the workplace. The effect was to transform really a culture that had been pure R&D, with emphasis only on the technological discovery, into one that had to operate more like a business in that cost was a problem, production pressures were a problem.

The notion of bureaucratic accountability made the agency what some people told me was bureau-pathological. That is, there were so many rules, there were so many forms to be filled out that these kinds of tasks deflected attention from the main job of cutting-edge engineering. It wasn't that the original technical culture died but that, in fact, it was harder to follow it through with these other influences on the shuttle program.

How did these actually play out on the ground? Next slide. The original technical culture called for rigorous scientific and quantitative engineering, real solid data in the form of numbers to back up all engineering arguments; and that was still true. However, also with the original technical culture, there was a lot of deference to engineering and engineering expertise based on the opinions, valued opinions, of the people who were doing the hands-on work.

The latter was harder to achieve within a bureaucratic organization where hierarchy dominated. The schedule became a problem interfering with the decisions by compelling turn-arounds in time to meet the schedule, so that expected research on hardware problems sometimes continued past the next launch. So they were still getting more information while a new launch was in process.

It also affected them in that the engineers and managers truly followed all the rules. In the midst of a system that many people at the time said was about to come down under its own weight before Challenger, what was happening was the fact that they followed all the rules in terms of having the numbers, in terms of procedures, gave them a kind of belief that it was safe to fly. Engineering concerns had to be backed up with hard data or there couldn't be money set aside to do a correction to the program. Hunch and intuition and concern were not enough.

Next slide, please. The third part is to say, well, there was a long incubation period here. Why didn't someone notice the trend that was going on with the Solid Rocket Booster project in terms of O-ring flaws and intervene? This is where the organization's structure was at that time a problem. The safety system had been weakened. One safety unit had been completely dissolved, and staffing had been cut back. Top administrators, because of extra work in an expanding program, were no longer able to maintain what in the Apollo program was known as the dirty-hands approach -- that is, keeping in touch with the technology, the problems, and the riskiness of it.

And the anomaly tracking system, which was another way that you could get warning signs, made it very difficult for administrators to isolate serious problems. At one time under their Criticality 1 category, which is the most serious label that you can give to a technical problem, they had 978 items on it. So how, of those, do you sort out which are the most serious?

Next slide, please. With this as an outline, I'd like to move to some comparisons, the echoes that Sally Ride talked about. First, here I'm drawing analogies. I spent nine years on the Challenger book and I haven't done this on this case, and your investigation is still under way. So where I'm able easily to identify the similarities, it's harder to define the differences; and what we see now as similarities are yet to be proved. So my goal here is just to maybe point you in some ways to look, and not come to any conclusions.

First, in both circumstances, Columbia and Challenger, a crisis -- well, let's say it was a crisis of uncertainty. Circumstances happened for which they had no background experience. They came to this condition of high uncertainty with a belief in acceptable risk -- that is, based on all the Flight Readiness Review decisions that had preceded, they believed they were flying with a vehicle that did not have a problem that was related to, in Challenger, O-rings and, in Columbia, the foam problem. They believed in their own analysis. That was this background, and they had engineering reasons for believing that.

Second, in each of those cases, Challenger and Columbia, there had been an event in the recent past that had some import for their decision-making that night. For Challenger, the year before the launch, STS 51B was launched in January. The condition that the engineers on the eve of the Challenger launch were concerned about was the cold temperature, which for the next day was predicted to be at an all-time launch-time low. The STS 51B, which was launched in January of 1985, was launched where also cold temperature mattered but not on the launch pad. The cold temperature had been the three previous nights when the vehicle was sitting on the launch pad and the temperature was down 19 to 22 degrees at that time.

The foam strike in Atlantis. There had been several foam strikes preceding the Columbia launch. The Atlantis foam strike, which happened in October of 2002, was the most recent. The history in the foam strikes was that they had problems with imagery, that they couldn't see so much the location of the strikes and so on. So that was part of the history which led to the fact that that night they didn't have or that -- when they discovered the foam strike, that they didn't have good data.

For the cold temperature on 51B, there was a similar effect. At the time when they did the analysis, the engineer who went to the Cape and looked at the vehicle when it was disassembled and looked at the Solid Rocket Boosters was alarmed because he saw that in the base of the putty in the groove in which the O-rings lay, the grease was charred black like charcoal; and he believed that this was significant. But when they came forth after that with their analysis of 51B for the next Flight Readiness Review, their analysis showed them that it was still safe to fly. They had had damage of the O-ring, they had serious O-ring erosion, and they had had for the first time hot gases that had gone beyond the primary O-ring to its backup, the secondary O-ring, and their analysis told them that in a worst-case scenario, it would still work. It would still work.

Where does cold come into this? The engineer who saw the charcoaled grease had this feeling that, intuitively, this was bad. So when he argued that cold should be a serious concern, they had at that point had many things happening with O-rings. The smallest thing could cause damage. So, for example, a piece of lint in the bed of putty in which an

O-ring lay could cause erosion. Each time something different had happened. They believed that there was no generic problem because they were not having damage on every ring on every mission. Sometimes they would not have any. So that he could not prove that cold was a correlation with the O-ring damage.

They decided at that point that they should get some cold temperature data; but they didn't scramble to get it, as this engineer said. The reason they didn't was they believed it was a unique incident, that the chance of overnight temperatures of that low for three nights running in Florida was, in his words, the equivalent of having a 100-year storm two years in a row. So there was no scramble to get temperature data. They did some resiliency tests, but they did not have systematic temperature data. So in both circumstances, when the condition of high uncertainty came up for both Columbia and Challenger, they did not have a lot of supporting data, they didn't have the best data available to them and this, it turned out, mattered.

The third point is that the organization's structure interfered with good communication, and it interfered in several ways in which there seem to be parallels across cases. There were, in this case, missing signals. People who had information, if that information had been relayed up the hierarchy, might have made a difference. People in the Challenger evening teleconference were in three different locations, and they were in telephone communication but not video. People were in different locations who did not speak up, so their message didn't get across on the main teleconference line.

Why didn't they speak up? Some people felt that that was their specialization, they hadn't worked on it recently, and therefore though they had some input and they had some information, they didn't know what the most recent data was. Some people didn't speak up because it simply wasn't their specialization. Other people didn't speak up because they trusted in the hierarchy, they trusted in the key people who were running the teleconference to guide it in the right direction, they trusted the engineers at Thiokol to do the analysis. Those were some of the reasons.

One of the parallels with Columbia comes up in the accounts of the e-mails that were circulated from approximately the 21st on, worries of concerned engineers. From newspaper accounts that I've been able to conclude and the e-mails themselves, that in a sense they were marginal to the process, they had not been brought in early on, this was a conversation they were having among themselves. They were also specialized and felt that perhaps they didn't have the same information that other people had. There was a trust in the hierarchy; and, as one of them said after a press conference early in your investigation, "We didn't have the data." That is, they were concerned they didn't have any hard numbers.

One of the characteristics of the conversion from the Apollo-era culture to the Challenger-era culture was that intuition and hunch didn't carry any weight. They carried weight in everyday, daily decision-making and batting around ideas, but when it came to formal decisions like the Flight Readiness Review, it was hard data, it was numbers that were required. And in this case it was significant to me that he said we didn't have the data and therefore, not having the data, they didn't feel empowered to speak up in these e-mails and carry them upward farther.

There is evidence of production pressure in the Challenger case that I haven't seen yet in Columbia. In Challenger, there was a deadline for the engineers to make their preparation for their eve-of-the-launch teleconference engineering recommendation about the relationship between the cold temperature and O-ring erosion and what they expected, what they were recommending in terms of launch. They scrambled to put their analysis together, dividing up the work, and began faxing their charts over the telecon line without having the time to look through them, and if they had taken that time, they might have noticed ahead of time -- if they had collectively looked through them, they might have noticed ahead of time that they didn't have a strong correlational argument. So as a consequence, it was a weak argument in terms of the engineering culture at NASA. The hard numbers didn't hold together. They couldn't prove that there was a cold temperature correlation with O-ring damage.

At one point the key engineer said, "You know, I can't prove it. I just know it's away from goodness in our data base." But in that culture, that was considered an emotional argument, a subjective argument, it was not considered a strong quantitative data argument in keeping with the technical tradition at the time.

So far there isn't any evidence of engineering concerns during the history of the foam problem like there was with Challenger either. Afterwards, there had surfaced some memos in Challenger, the previous year in particular, as engineers at Thiokol were trying to get through the bureaucratic rigmarole in order to get the help they needed to try to analyze the problem; and they were working on a fix at the time.

The other point I wanted to make was about bureaucratic accountability. What was obvious with Challenger was that on the eve of the launch that the concerns of the engineers were not prioritized. It also seems to be the case in the requests for the imagery from Columbia that concerned engineers discovering the foam strike at this point described it as it was large. There was nothing in their experience like this. It was the size of a Coke cooler. This was unique. They met, a team of approximately 37 engineers, and made a request for better visuals than the ones that they had from ground camera; but somebody up the hierarchy canceled the request. In a condition of high uncertainty. One of the comments that I read in the newspaper -- and I don't claim to have all information on this -- was that the request had not gone through proper channels, which points to me the significance of rules and hierarchy over deference to technical expertise in this particular case.

There are many conclusions we can think about from this, but one of them is that in both of these situations, following the normal rules and procedures seemed to take precedence; and we know that, in fact, in conditions of uncertainty, people do follow habits and routines. However, under these circumstances where you have something without precedent, it would seem that this would be a time not for hierarchical decision-making but for a more collective, collaborative, what does everybody think, let's open the floodgates and not pull on the usual people but especially what are the concerns of our engineers and also to let up on the idea that you have to have hard data. Engineering hunches and intuitions are not what you want to launch a mission with; but when you have a problem that occurs that's a crisis and you don't have adequate information, this is a reverse of the pro-launch situation, in which engineering hunches and intuitions ought to be enough to cause concerns, without asking for hard data.

So what's to be done if it turns out in this investigation that you do, in fact, find a failure of the organizational system? Could I have the next slide, please.

Typically in the results of an accident investigation, two things happen. One is that the technical culprit is found, and a technical fix is recommended and achieved; and second, that key decision-makers are identified who had important roles where they might have prevented a bad outcome but didn't. More typically, the organizational system goes untouched. It is, in fact, more difficult to identify the flaws in the organizational system. It's harder to pin it down and it's more challenging to try to correct it. In fact, there are many people who are experts in how to build high-reliability systems and what are the problems with systems from an organizational system that might help in advice in circumstances like this.

Next slide, please. Just looking at the model that I put up earlier where we looked at the trickle-down effect, it leaves three levels at which you might target changes. First, the beauty of operator error is that it deflects attention from key policy decisions made in the past that have affected a program and affected the daily operations. Policy leaders need to be concerned and aware of their responsibility with risky systems and be aware of how their choices affect the hands-on work. They also are responsible and implicated.

Cultures, for example, are hard to change, but leaders must try to change them -- even if they weren't the ones who created them. It's important that they remain in touch with the hazards of the workplace. Whereas in the modern NASA it may be more difficult for administrators to stay in touch with the hazards of the workplace and the dirty-hands approach cannot be carried out like it was in the time of Apollo, still it's important to stay in touch with those.

For example, prior to Challenger, the Shuttle was declared as an operational system. As a result of that and the belief and the expectation it would be routine, citizens were allowed to be taken on for rides. The people at the top of the organization apparently believed that it was not a risky technology and therefore it was safe to take along ordinary citizens. The engineers who were doing the daily work did not believe that it was -- I mean, they were aware of all the problems in the system on a day-to-day basis. They were the ones who had the dirty hands. They were not the ones who made the decision to put a teacher on the Space Shuttle.

Another aspect of concern for top leaders is changes are often made in an organization's structure for budgetary reasons, for better coordination, without thinking about how that might affect the people who are having to make decisions at the bottom. What does it mean, for example, when you have an International Space Station and NASA is now dividing up the work so that there are two combined structures and projects in which decisions have to be made? How are these priorities getting sorted out? Does that affect what's going on in the program?

Contracting-out had a serious effect on the work of people making technical risk analyses. We know hospitals, when they have mergers, often let people go, and it loses the institutional memory and there are startup costs in people getting going again. These kinds of changes should not be made without looking at their implications.

Second. Please, next slide. Target culture. You can't really make assumptions about your culture. We think we understand our cultures, but they act invisibly on us, and so we cannot really identify what their effects are. In one of the comments post-Columbia concerning the e-mails, "We have a safety culture and we strongly encourage everyone to speak up at every opportunity." And I'm sure that they believe that. But when you look at the chronology of events, even in skeletal form in which I'm aware of them, the fact that these what-ifs didn't percolate up the hierarchy, the fact that the engineering requests did not get fulfilled indicates that there are some things that suppress or that are acting to suppress information.

It's also significant, I think, in terms of culture to understand the power of rules. The things that we put in organizations that do good also can have a dark side. It is really important at NASA, because of the complexity of the agency and its projects, to have rules. You couldn't run it without rules. It's impossible. But then there are times when maybe the normal rules don't apply. So how do you train people to recognize circumstances when you have to expedite matters without going through the hierarchy, and how do you empower engineers to get their requests filled?

Finally, targeting signals. Missing signals are obvious in both cases. What does it mean to try to reduce missing signals? One is to truly create a system in which engineers have more visibility, their concerns have more visibility on a formal and informal basis. Second, the safety system. The parallel with Challenger and the reduction of safety personnel is also a parallel with Columbia. When you reduce a safety system, you reduce the possibility that other people are going to be able to identify something that insiders have seen and normalized the technical deviation. And the slippery slope. When you're working in a situation where problems are expected, you have problems every day, and people are busy with daily engineering decisions, it becomes very difficult to identify and stay in touch with the big picture.

How do you identify the trend so that people are aware when they are gradually increasing the bounds of acceptable risk? It is certainly true, based on what we know about organizations and accidents in the social sciences that this is a risky system and what we know is the greater the complexity of the organization, the greater the possibility of a failure.

The same is true of organizations. Organizations are also complex systems. The greater the complexity of the organizational system, also the greater the possibility of a failure. When you have a complex organization working a complex technology, you're never going to be able to completely prevent accidents, but the idea is to be more fully aware of the connection between the two so that you can reduce the probability that a failure would occur.

That's it. Your turn.

**ADM. GEHMAN:** All right. Well, that's a bucket full.

Since you studied the Challenger decision so carefully, and even though we're talking about Columbia here, let me ask a Challenger question, even though it's loaded because it has Columbia implications. Several things you said struck me, and they're related to each other. One is that you can't change the behavior unless you change the organization. You can change the people, but you're going to get the same outcome if the organization doesn't change. Yet in another place up there, you said beware of changing organizations, because of the law of unintended consequences. You've got to be really careful when you change organizations.

What do you make of the post-Challenger organizational changes that took place, particularly in the area of more centralization and program management oversight? What do you make of all of that?

**DR. VAUGHAN:** The changes that I am most familiar with are the ones related to launch decisions. That is that immediately following, they put an astronaut, former astronaut in charge of the final "go" outcome of the Flight Readiness Review procedure and they tried to integrate engineers, working engineers, into the flight readiness process more. I'd say that there is always a problem in organizations in providing the stability and the centralization needed to make decisions and make sure information gets to the top and providing the flexibility to respond to immediate demands; and without, you know, really studying this, I would say that what we know about Columbia is that flexibility, at least in a couple of circumstances, really wasn't there. That becomes interesting in thinking about the differences in the pre-launch decision-making structure and post-launch decision-making structure. That is, the post-launch decision-making structure is actually designed to create that kind of flexibility so that you could pull in people as you need it and so on.

What's ironic about it is it looks as if had there been either a direct route for engineering concerns to get implemented to shortcut what really little bureaucracy there seemed to be in that process that that would have helped, that if, you know, that could have circumvented the kind of need for hierarchical requests for imaging. In terms of the overall impact on NASA, I really can't say that.

**ADM. GEHMAN:** From my understanding, though, one of the post-Challenger results has been a much more formal FRR process. As you are probably aware, no more telephone calls, it's all face-to-face, it's done at the Cape, and you've got to be there and they're done in big rooms like this with hundreds of people in the room with several different layers, everybody there, and then there's a whole lot of signing that goes on. People at several layers actually sign pieces of paper that say, of the thousands of things that I'm responsible for, they've all been done with the exception of A, B, C, D, and then they have to be waived or something like that. Then they go through a many, many hour process of making sure that everything's been taken care of and every waiver has been carefully analyzed and in front of lots of high-level people. So it's very meticulous, it's very formal, and it's an eyeball-to-eyeball commitment that my organization has done everything my organization is supposed to have done.

Is that the kind of an organization in which weak and mixed signals can emerge? I mean, is that the kind of organization which would recognize mixed and weak signals and routine signals? Is that compatible kind of with your -- I'm still talking Challenger -- with some of the principles you outlined here?

**DR. VAUGHAN:** That was fairly much the procedure that existed at the time of Challenger, where every layer of Flight Readiness Review had to sign off on it. The criticism at the time, post Challenger, was that what was happening was the engineers who were making the analyses and coming forward at the Level 4, the ground level of Flight Readiness Review, those were the people who were getting the mixed, weak, and routine signals; but when they came together, they had to come up with a consensus position for their project manager to carry forward. And once they agreed, then they began gathering the supportive data that this was an acceptable flight risk. And as their recommendation worked itself up through the hierarchy, the system was designed to criticize it, to bring in people with other specializations who could pick it apart, and the result of that was to make them go back to the desk and sometimes to do more engineering analysis. That engineering analysis tended always to support the initial recommendation. So by the time it came out the top of the process, it was something that might have been more amorphous on a day-to-day basis was dogma and very convincing, which is why, with a backdrop of having that kind of information, you have people who believe in acceptable risk, it's based on solid engineering and history, who need to be convinced by hard data that something different is happening this time.

The system is designed to review decisions that have been made, that if there is a mistake in the fundamental engineering analysis, they can criticize it, but they can't uncover it at the other layers, which would mean that you would need another kind of system to detect that, such as outsiders who bring fresh eyes to a project on a regular basis. The Aerospace Safety Advisory Panel was very effective during the years of Challenger, with the exception of the fact that their charter kept them coming for visits perhaps 30 times a year. So it was impossible for them to track all the problems; and at that point when Challenger happened, they were not aware of the O-ring erosion and the pattern that was going on.

**ADM. GEHMAN:** I'm still trying to understand the principles here. It seems to me that in a very, very large, complex organization like NASA is, with a very, very risky mission, some decisions have to be taken at middle-management levels. I mean, not every decision and not every problem can be raised up to the top, and there must be a process by which the Level 2, Level 3, and Level 4, that the decisions are taken, minority views are listened to, competent engineers weigh these things, and then they take a deep breath and say, okay, we've heard you, now we're going to move on. Then they report up that they've done their due diligence, you might say.

I'm struggling to find a model, an organizational model in my head, when you've got literally thousands and thousands of these decisions to make, that you can keep bumping them up higher in the organization with the expectation that people up higher in the organization are better positioned to make engineering decisions than the engineers. I mean, you said yourself, "Hindsight is perfect." We've got to be really careful about hindsight, and I'm trying to figure out what principles to apply.

We as a board are certainly skittish about making organizational changes to a very complex organization for fear of invoking the law of unintended consequences. So I need to understand the principles and I'm trying to figure out a way that I can apply your very useful analysis here and apply it to find a way to figure out what the principles are we ought to apply to this case. So the part that I'm hung up on right now is how else can you resolve literally thousands of engineering issues except in a hierarchical manner in which some manager, he has 125 of these and he's sorted through them and he reports to his boss that his 125 are under control. I don't know how to do that.

**DR. VAUGHAN:** Well, two things. First, somehow or other in the Shuttle program, there is a process by which, when a design doesn't predict an anomaly, it can be accepted. That seems to me to be a critical point, that if this is not supposed to be happening, why are we getting hundreds of debris hits, if it wasn't supposed to happen at all. It's certainly true that in a program where technical problems are normal, you have to set priorities; but if there is no design flaw predicted, then having a problem should itself be a warning sign, not something that is taken for granted.

The idea is to spot little mistakes so that they don't turn into big catastrophes, which means spotting them early on. Two things. And one I'm certain that NASA -- maybe both of them -- that NASA may be very aware of is the fact that engineers' concerns need to be dealt with. I can understand the requirement for hard data. But what about the more intuitive kinds of arguments? If people feel disempowered because they've got a hunch or an intuition and let somebody else handle it because they feel like they're going to be chastised for arguing on the basis of what at NASA is considered subjective information, then they're not going to speak up. So there need to be channels that assure that, even giving engineers special powers if that's what's necessary.

The other is the idea of giving more clout to the safety people to surface problems. So, for example, what if the safety people, instead of just having oversight, were producing data on their own, tracking problems to the projects for which they're assigned and, in fact, doing a trend analysis to keep people's eye on the big picture so that the slippery slope is avoided?

**ADM. GEHMAN:** Thank you for that.

**DR. VAUGHAN:** Let me add also that there are other models of organizations that deal with risky systems, and social scientists have been studying these. They have been, you know, analyzing aircraft carrier flight decks and nuclear operations and coal-mining disasters. There are all kinds of case studies out there and people who are working in policy to try to see what works and what doesn't work. Are there lessons from air traffic control that can be applied to the Space Shuttle program? What carries over? Is there any evidence that NASA has been looking at other models to see what might work with their own system?

I know that in air traffic control they use an organizational learning model. What we find out from this comparison between Columbia and Challenger is that NASA as an organization did not learn from its previous mistakes and it did not properly address all of the factors that the presidential commission identified. So they need to reach out and get more information and look at other models, as well.

Thinking about how you might restructure the post-launch decision-making process so that what appears to have happened in Columbia doesn't happen again, how can that be made more efficient, maybe something -- maybe it needs to look more like the pre-launch decision process. But is there any evidence that NASA has really played with alternative models? And my point about organization structure is as organizations grow and change, you have to change the structures, but don't do it without thinking about what the consequences might be on the ground.

**DR. LOGSDON:** Could I ask just a short follow-up to that. Diane, your book came out in 1996, I think, right, and was fairly widely reviewed. We at the board discovered in some of our briefings from outside folks that the submarine safety program uses your work as part of the training program for people who worry about keeping submarines safe. Have you had any interactions with NASA since the book came out?

**DR. VAUGHAN:** No.

**DR. LOGSDON:** Have you ever been invited to talk to a NASA training program or engage in any of the things that you just discussed might be brought to bear?

**DR. VAUGHAN:** No, though, in fact, as you said, the book did get quite a lot of publicity. I heard from many organizations that were concerned with reducing risk and reducing error and mistake. The U.S. Forest Service called, and I spoke to hotshots and smoke-jumpers. I went to a conference the physicians held, looking at errors in hospitals. I was called by people working in nuclear regulatory operations. Regular businesses, where it wasn't risky in the sense that human lives were at cost. Everybody called. My high school boyfriend called. But NASA never called.

(Laughter)

**ADM. GEHMAN:** Anybody want to comment on that?

**GEN. BARRY:** What was his name?

**ADM. GEHMAN:** Let me finish my thought here. Professor Vaughan, again we're back to this organizational issue which I'm trying to determine the principles that I can apply from your analytical work here. If the processes we're talking about in the case of NASA, if they didn't follow their own rules, would that alarm you? What I mean is if there were waivers or in-flight anomalies or systems that didn't work the way they were supposed to work and, in the fact that they didn't work the way they were supposed to work, somehow started migrating its way down lower in the message category to where it wasn't sending messages anymore and therefore it was technically violating their own rules because they're supposed to deal with these things, would that be a significant alarm for you?

**DR. VAUGHAN:** Well, I think that one of the things to think about here is that NASA is a system that operates by rules; and maybe one of the ways to fix the problem is to create rules to solve the problem. So what are the rules when engineers need images, for example? Can't they find a way where they have their own authority, without seeking other authority, to get the necessary images? So I think I read that someplace, where the harmony between the way the organization operates and thinks in the key aspects of the culture itself are something that you might want to build on.

**DR. WIDNALL:** Actually I'm starting to frame in my own mind that the problem is that there is, in fact, one underlying rule and it's a powerful rule and it's not stated and it's not stated as simply as this question of following your own procedural rules. But let me sort of get into that. I've certainly found your framework very helpful because I've mused over this issue of how an organization that states that safety is its No. 1 mission can apparently transition from a situation where it's necessary to prove that it's safe to fly, to one in which apparently you have to prove that it's not safe to fly. I think what's happening is, in fact, that engineers are following the rules but this underlying rule is that you have to have the numbers.

**DR. VAUGHAN:** Right.

**DR. WIDNALL:** That's not the rule you stated, which was you should follow the procedures and resolve all anomalies.

**DR. VAUGHAN:** This is a norm.

**DR. WIDNALL:** Those are these kind of rules. I'm talking about the really basic rule that says you have to have the numbers. So that basically means that every flight becomes data and that concern about an anomaly is not data. So a flight with an anomaly becomes data that says it's safe to fly. So the accumulation of that data, of those successful flights, puts the thumb on the scale that says it's safe to fly; and people who have concerns about situations in one of these uncertain situations that you talk about, they don't have the data.

So I think it may be getting at, in some sense, changing the rule to one that it is not okay to continue to operate with anomalies, that the underlying rule of just having data is not sufficient to run an organization that deals with risky technologies. Because otherwise you're just going to end up with a pile of data that says it's okay to fly, and you're not likely to get much data on the other side.

**ADM. GEHMAN:** Is that a question?

**DR. WIDNALL:** That's kind of a comment.

**DR. VAUGHAN:** I completely agree with you. One of the reasons I emphasized in an earlier slide that you need to understand your culture is that it works in ways that we don't really realize. So how many people there understand the effect of intuition and hunch, which are absolutely integral to good engineering, and how the kind of impression on numbers suppresses that kind of information in critical situations?

People are disempowered from speaking up, by the very norms of the organization. Things like language. For example, the term I've read in the paper, "That's in family." That's a real friendly way of talking about something that's not really supposed to be happening in the first place. In nuclear submarines, they don't talk about it as "in family"; they talk about it as a degradation of specification requirements, which has a negative feeling to it. These kinds of languages which we think of as habits of mind reflect attitudes that are invisible, but the language really shows.

So the question is, you know, how can you get back in touch with the importance of engineering intuition and hunch in formal decision-making. Usually it works in the informal decision. You know, I think that's why the NASA administrators believe that they've got a safety culture and that people are free to express whatever they think; but when it comes to a formal decision, they fall back into the formal rules and that expression of concern doesn't get expressed.

Even if you take something as simple as an engineering presentation, the fact that it's reduced to charts, which are systematic, gets all the emotion out of it. It begins to look even more routine. The engineer in Challenger who saw the burned grease, the black grease, was seriously alarmed. I asked him, you know, later, "Did they see this? What did they see? Did they get a photograph?" He said yes. I said, "How did it look in the photograph?" He said it did not look serious in the photograph. So emotion is keyed to some kind of a logic based in engineering experience, and it should be valued and a way found to express it.

**GEN. BARRY:** Diane, I'm going to ask you a short question, and then I'm going to ask a longer question, if I may. First, the short question, focusing on organizational failure. The Rogers Commission, did they fall short on institutional recommendations in the aftermath of Challenger, or were they good ones and they just weren't followed through by NASA?

**DR. VAUGHAN:** The Rogers Commission was very good at identifying what they called contributing causes and what I would call system causes. That is, they identified safety cuts, cuts in safety personnel. They identified the failure of NASA to respond to recommendations of the Aerospace Safety Advisory Panel. They identified the history of the program and the fact that it was a design that was built on budget compromises in the beginning. They identified production pressures. They identified all those kinds of outside sources that had impacted the decision-making and that were a part of NASA's history.

In the recommendations, they didn't come forward with anything that said give them more money, change the culture. They weren't sociologists. They weren't social scientists and not trained to think about how that might have actually worked. The way it looked like it worked was in the sense that there were pressures there and key managers, namely Lawrence Malloy, who was the project manager for the Solid Rocket Booster project at that time, was the operator who made the error. Once that happened and the key person was identified and people changed and new people came in, then the system problems remained.

They fixed the technology. They fixed the decision-making structure in ways I described earlier. But the organization didn't respond and neither did -- in keeping with my point earlier about top leaders being responsible -- the organization did not respond in terms of getting more money beyond what it took at that point to fix the technical problem. They got an initial boost, but they've been under budgetary constraints all along. The recommendations in the volume of the presidential commission were related strictly to internal NASA operations. They were not directed towards policy-making decisions that might have affected the program.

**GEN. BARRY:** Okay. Let me build on that a little bit and just carry it on and see if this resonates with you. Let's talk about a bunch of items here and see if this falls true with what you know to be from Challenger that might be able to be translated over to *Columbia*.

First of all, you stated that with Level 4 identifying problems and being able to try to communicate that up the institution, the organization kind of stymied that. So I would characterize that as needing to prove that there is a problem in the early stages of the FRR or before flight. I think post-Challenger, you know, there has been a fix on that and, remember, the Flight Readiness Review is supposed to prove not only launch but also en route, in orbit, and then of course on recovery. So it's the whole flight. It seems like they've solved the problem on trying to say is there a problem in proving it. To post launch. There's, some would argue, an attitude that you have to prove there is a problem. So we kind of fix it on the launch side; but after it's launched, we kind of relegate back to maybe the way it was prior to Challenger: Prove to me there is problem.

Now, if we try to look pre and post launch, pre-launch is very formal, as Admiral Gehman outlined earlier. You've even alluded to it in the book. Post-launch, it could be argued, less formal, more decentralization, more delegation certainly, okay, from what we see at the FRR prior to launch. Multi-centers are involved prior to launch. I mean, they all meet and they all sit at the same place, they're all eyeball-to-eyeball. Center directors are represented, program managers. Post-launch, again decentralized, it's mostly a JSC operation. Of course, KSC gets involved if they're going to land at Kennedy.

There's a tyranny of analysis pre-launch maybe and that is because you've got -- well, you have a long-term focus because you've had time. But post-launch, there's a tyranny of analysis, but it's in real time because you don't have as many hours and you've got to make decisions quicker and all that other stuff.

The real question -- if this resonates with you at all -- could it be argued that during Columbia, NASA had a "Prove there is no problem" prior to launch and post-launch it was "Prove to me there is a problem" and we have this formal and informal kind of focus. It seems to me after Challenger we fixed the prior to launch, certainly with having people appear in person and no VTCs or no over-the-phone. Everybody had to be there in person. And we have maybe a problem that we need to fix post-launch now with the MMT and the decentralization elements and maybe the delegation.

I certainly don't want to relegate it to a headquarters level, but there are some things that need maybe to be fixed there. So I would ask really your opinion that is there some kind of a delineation in your mind, from what you know to date, pre- and post-launch, that we might be able to help provide solid recommendations on to improve NASA?

**DR. VAUGHAN:** I'm wondering if the post-launch flexibility is such that you can, in fact, have similar things going on in two different parts of the process in which people are not in touch. So I understand that video requests really originated from two different points, and working engineers in two different locations, and that they didn't really know that the other had originated a request.

It certainly seems that the mentality of proving your point when you've got a timeline like you do and it's an unprecedented circumstance, as it was with Columbia, is wrong, of course, in retrospect. The question you're asking is how can we convert that into a process that prevents this from happening again.

No, a famous sociologist named Donald Cressey once told me when I was beginning the analysis of the Challenger launch, "It's all these numbers. It's all these numbers, and there are these debates about issues. Why don't you do it like they do it in the Air Force? You just should have a red button for stop and a green button for go." And there's a lot to be said for simplifying a complex system, whether it's decentralized or centralized, so that key people can respond quickly and shortcut the hierarchy. I don't know if that begins to answer your question. But there may be need to be some more rules created in the sense that --

**GEN. BARRY:** And this is really stretching it but --

**DR. VAUGHAN:** Maybe it needs to be more formal than it is and maybe it needs to be more like the pre-launch procedure in terms of the rigor of numbers of people from different parts who are looking at problems that crop up while a mission is in process instead of waiting just -- I mean, some sort of a formalized procedure where there's a constant ongoing analysis instead of you've got worried engineers in two different locations who are kind of independently running around, trying to get recognized and get attention to the problem.

**MR. WALLACE:** NASA's taken quite a pounding here today but I'm wondering what we can --

**DR. VAUGHAN:** I thought this morning they were coming off pretty good.

**MR. WALLACE:** I would just like to talk about what we can sort of learn about what they do well -- in other words, areas where we don't seem to have this normalization of deviance or success-based optimism. Like BSTRA balls and flow liner cracks and some of those fairly recent examples where there were serious problems detected with the equipment, in some cases detected because of extreme diligence by individual inspectors and really very aggressively and thoroughly fixed.

It seems to me that part of the problem of normalization of deviance is sometimes the level of visibility that an issue gets. How do you sort of bridge that gap between those things that get enough visibility or sense of urgency and those that somehow seem to slip below that threshold?

**DR. VAUGHAN:** Someone said after the book was first published -- and then again now I've been getting a lot of e-mails. Someone said at the time the book was published, "I bet if you took any component part of the Shuttle and traced it back, you would find this same thing going on." Perhaps doing a backward tracing on other parts of the Shuttle could show you two things. First, what are the circumstances in which they're able to locate an anomaly early and fix it so they stop it in its tracks and avoid an incremental descent into poor judgment? Are there other circumstances in which the same thing is happening? Can you find circumstances where you do have the normalization of deviance going on?

It's interesting in the history of the Solid Rocket Booster project that there was a point at which they stood down for maybe two months to fix a problem. How is that problem identified? What are its characteristics? I would bet that the more uncertain, the more complex the part and the more amorphous the indications, the more likely it is to project into a normalization-of-deviance problem, given the existing culture where flying with flaws is okay in the first place.

**MR. WALLACE:** Well, sort of following on. Earlier you said -- and good advice for this board -- that we should try to see problems as they saw them at the time and not engage in the hindsight fallacy or whatever that's called. I mean, I'm not sure you said this; but my assumption is that that's almost the only way you can learn to do better prospectively. I mean, do you have any other thoughts on that? In other words, to see the problem as they saw them at the time, to me, is almost a step toward the discipline of seeing the next one coming.

**DR. VAUGHAN:** Right. It's an experimental technology still; and every time they launch a vehicle, they've made changes. So they're never launching the same one, even though it bears the same name. This is a situation in which, like most engineering concerns where you're working with complex technologies, you're learning by mistake. So that's why post-flight analysis is so important. You learn by the things that go wrong. Every once in a while you're going to have a bad mistake.

**ADM. GEHMAN:** Did I understand the point that you made both in your book and in your presentation here is that the answer to perhaps Mr. Wallace's question lies in the theory of strong signals? In other words, if NASA gets a strong signal, they act on it. No problem. They very aggressively shut the program down and go fix it. The problem is in the weak, routine, or mixed signals. Those are the ones that seem to bite us. Of course, there are a lot of them; and they don't quite resonate with the organization. Is that a good analogy?

**DR. VAUGHAN:** It is. The idea of a trend analysis is that it could pick out stronger signals from lesser ones before it becomes, you know, an enormous problem; but the recognition of the pattern is important, bringing forth the pattern so that the people who are making decisions are constantly in touch with the history of decisions that they've gone through before.

I have to say with that, though, it's important that they have quantitative evidence to fly. Maybe the more qualitative evidence could be brought in in other ways further up the chain, that whereas in Flight Readiness Review, for example, they present everything on charts and they ask -- the purpose of Flight Readiness Review is to clean the hardware and get it ready to go. The purpose of it is to clear up the problems as it works its way through the Flight Readiness Review process. What happens, as I mentioned, is that the engineering argument tends to get tighter and tighter because they're constantly doing the work to investigate and respond to questions and, in a sense, defend what they've said or find out if there are flaws.

At the time of Challenger, I read thousands of engineering documents for all the Flight Readiness Reviews that they had had and I didn't see anyplace in the Flight Readiness Review process that would allow for the presentation of simply intuitions, hunches, and concerns, where qualitative evidence might be presented, like a clear image or even a vague image of a piece of debris the size of a Coke cooler, for example, rather than charts for an engineering analysis, you know, that there ought to be room in the process for alarm.

**ADM. GEHMAN:** In your experience, particularly with what I'm calling these weak signals or this muttering around the room that the O-rings can't take freezing temperatures but we're not really sure whether they can or cannot, I have in my mind a model that says that it's unfair or not reasonable to set as a standard for the organization to act on literally hundreds of these misgivings that the tens of thousands of people may have and that it's an unfair standard to require the people who have these doubts to prove that their doubt could cause the loss of the vehicle or the crew. But I have in my mind that it's a more reasonable standard that management should realize that the accumulation of signals from the process are cutting into their safety margins and that you can accumulate these things not in a measurable way but in a subjective way, particularly in a regime in which you have very thin safety margins to begin with, that you should be able to reasonably determine that you're narrowing your safety margins in a way that should concern management. Is that a reasonable characterization of the standard or the bar that we set here?

**DR. VAUGHAN:** I think that shows up in the problem of lack of data in both of these circumstances, that there were early warning signs and in neither case had those early warning signs been pursued and say, "Well, the imagery is bad. We know this is happening. We can't see exactly where it's hitting. Why don't we get this now?"

I mean the power of the e-mail exchange was that they really hadn't thought the possibility of failure through. There was no plan for what needed to happen if there was, in fact, a serious tile hit and damage to the wing, what would they do at re-entry and what would it mean to attempt a wheels-up landing at the landing site, and that failure to pursue the trajectory of having a problem that's repeating. Like if you think about cost, you think about cost maybe in terms of if that's a factor in making issues a priority at NASA, which obviously it is anyplace -- you can't fix everything -- think of the cost if you simply don't have the data you need, which is, I think, the most stunning thing about the comparison of the two cases. At the time when conditions were highly uncertain, in neither case did they have the data; and having that background data is important.

**ADM. GEHMAN:** In your review of the Challenger decision, did you personally come to the conclusion that the launch decision would have come out differently if the Morton Thiokol engineers' split decision -- because some of the Morton Thiokol engineers said it was safe to launch, but they were split on that -- and if the managers at Marshall had reported that there was a split decision, that the FRR would have come out differently? Did you have any evidence of that?

**DR. VAUGHAN:** The managers at Marshall did not know that there was a disagreement at Thiokol. That was one of the problems with them being in three locations. No one ever thought to poll the delegation. So no one on the teleconference knew really where anyone else stood. They knew what Thiokol's final recommendation was and they assumed that Thiokol had gone back and re-analyzed their data, seen the flaws in it, and been convinced it was safe to fly. So the fact that not everyone was heard from was critically important.

By the same token, Thiokol engineers didn't understand that they had support in the other places, that one of the NASA managers who was at the Cape was really sitting there making a list of people to call because he believed that the launch was going to be stopped. So that was truly a problem.

Now I've lost sight of your question.

**ADM. GEHMAN:** The question is: In your research about Marshall, did you come to the personal conclusion from talking to people that the fact that the cold temperature analysis at Morton Thiokol was a split decision, that that would have made any difference at Marshall? I mean, did anybody say, "If I had known that, I would have changed my mind"?

**DR. VAUGHAN:** Yes. However, the goal is for unanimity and here's again where numbers count, that in the instance where engineering opinion is divided, then they make what's known as a management risk decision, that the managers take over and the managers at Thiokol then, who knew that their engineers were split, made a management decision. In retrospect, that was the most horrendous example of failing to listen to your technical people who said, "You know, I can't prove it, but I know it's away from goodness in our data base."

**ADM. GEHMAN:** This principle that I'm following up on here is important because we do have to be careful of hindsight. And it may be that, even armed with what is admittedly a minority opinion of a bad outcome, it could be that these are judgment calls that are made in good faith with people doing the best they can and they make a mistake. I mean, they call it wrong. So the question is whether or not we can indict the system, based on these incidents.

**DR. VAUGHAN:** I think you have to analyze -- you have to do a social fault tree analysis and figure out what actually happened and what went on, how is information relayed. I'm sure that's work that's ongoing with you.

**ADM. GEHMAN:** That brings me to my next question -- and pardon me for monopolizing the time here. Another good writer on this subject, who I think is Nancy Leveson, in one of her models she suggested that we need to diagram these decision-making systems because, just as you say, it's not a person, it's a culture, it's an organization that's really driving these things. Are you aware that anybody's ever diagrammed the FRR or the waiver, in-flight anomaly disposition system? Has that ever been diagrammed, to your knowledge?

**DR. VAUGHAN:** Not that I know of. But what would be more interesting would be to look at the more informal decision processes because the rules are so strong for how information is addressed in Flight Readiness Review that that would probably turn out the same every time. What you would want to look at are the more informal processes and try to map them and understand where the information stopped and why it stopped.

**MR. WALLACE:** I'd like your thoughts on the concept of whether an organization, this one, can sort of become process-bound. You cannot fault the thoroughness of the processes. But, I mean, is there a point at which they can almost subvert other thinking processes, that people become so confident in the thoroughness of the processes and the fact that they're tested, they reach a comfort level with processes where they become the be-all and end-all?

**DR. VAUGHAN:** Well, that's one of my main concerns about NASA, that the fact that it is a very rule-guided organization and the fact that they do believe that when they follow all the rules that they have done their best and have confidence. That's why the rules tend to carry such heavy weight. Not only do they aid them with the process but then they have a cultural effect which builds confidence. If you're not in touch with the everyday engineering data itself, you can lose sight of the fact that it is still an experimental system. So it's the dark side of the organization. The same kinds of procedures that you implement to make it work better also can have an unanticipated consequence, and that's why keeping in touch with all the ambiguities in the engineering decision-making would be important.

Any other doubts and concerns? You know, by the time you get to the top of the Flight Readiness Review process, nobody's going to say that. One of the proposals from the presidential commission was that an engineer accompany his project manager at each level of the Flight Readiness Review tier, the feeling that because engineering concerns did not get carried up to the top prior to Challenger and in the eve-of-launch teleconference, they thought that would be a good idea. Rather than the engineers at Level 4 turning over all their information to their project manager and then the project manager carries it forward, let's integrate engineers into the process. But can you imagine some engineer in the top Level 1 Flight Readiness Review with 150 people, after all that's gone on, standing up and saying, "I don't feel good about this one"?

**ADM. GEHMAN:** Well, I agree with you. I agree with you. But I would compound that with an organizational scheme in which even though that engineer works in the engineering department and technically doesn't work in the program office but his position and his salary is funded by the program office and he wouldn't exist if the program office didn't pay him. In other words, we've wickered this thing to where the money flows down through the projects and they send money over to the engineering office to hire people. So now put yourself in the position of this guy who's going to contradict the officer who's paying his salary, and you don't have a very comfortable formula.

**DR. VAUGHAN:** I understand that. I think there's a parallel situation with safety people.

**ADM. GEHMAN:** Well, yes and no. There is a safety organization in the programs and in the projects and their positions depend upon the largesse of the project managers, but there's also an independent safety organization.

**DR. VAUGHAN:** I meant in terms of rank. Like independent authority and power based by where they come in the GS ranking system.

**ADM. GEHMAN:** Absolutely. That's a question I'm going to ask you after General Barry and Dr. Logsdon have a shot.

**DR. LOGSDON:** What I have is a comment that's as much directed at the board as it is at Professor Vaughan. It's just that the discussion made me think of this line of reasoning. We've been talking about the rigor of the pre-flight process for Flight Readiness Review, compared to a different structure for what goes on during a mission. There's almost a symbolic element here. The management of the launch is a Kennedy Space Center responsibility; and the moment that the Shuttle clears the launch tower, the control over the mission shifts to Johnson. Sean O'Keefe is trying to say that NASA is a single organization, but he's got a long way to go to achieve that goal. These are very proud organizations and, of those, Johnson is the very proudest of the proud because it's one of the only two places in the world that knows how to manage a space flight. There are now -- what's it, '61 -- so 42 years of experience of managing humans in space.

So we're beginning to talk about maybe we can examine the process of mission management and see whether it measures up to some standard of high-performance organizations, and I think that's what we have to do. But there's a lot of received wisdom and maybe it's ossified wisdom by this point in the process. So as we go towards that, I think we have to make sure that we don't have unintended consequences. So, as I said, that's just a comment, not a question.

**ADM. GEHMAN:** Would you like to comment on his comment?

**DR. VAUGHAN:** Well, he directed that to the board, as well.

**ADM. GEHMAN:** In the interest of time, I'll go on to General Barry.

**GEN. BARRY:** I'd just like to add one more thing to your parallel kind of discussion between Challenger and Columbia. Could you just see if there's anything you know of that you could add to this kind of construct? You know, there was a lot of organizational changes here in the last couple of years. We moved Palmdale to Kennedy. We moved the Huntington Beach engineering support mostly to JSC but some to KSC. And, of course, we've got the International Space Station support going on. So there's some organizational elements that are unique to Columbia this time; but there are some Challenger organizational elements, too. You know, the JSC leadership was being shared by Jesse Moore at that time between JSC but he was also running the space flight program as an associate administrator. Also, we had an interim administrator at the time during Challenger. Are there any parallels that you're seeing between the organizational aspects between Columbia and Challenger?

**DR. VAUGHAN:** At the administrative level?

**GEN. BARRY:** Well, just organizational elements that we might be able to draw from.

**DR. VAUGHAN:** One, but it's cultural. It seems like there is a gap between perceptions of risk between working engineers and top administrators. So at the time of Challenger, engineers were very concerned with every launch, even though they had gone through all the rigors of the procedure; but at the same time, the people at the top thought it was an operational system. The parallel I see is, you know, working engineers really familiar with what's going on and having concerns, but decisions made that really do echo the period of Challenger where it's okay to take citizens along for a ride, which suggests that top-level administrators have rather lost touch with the fact that it is an experimental system, a message that they clearly understood post Challenger.

John mentioned symbolic meanings, and they can be really important. It's hard to judge exactly what the effect is of a top administrator believing that it's again safe enough to fly people who are not trained as astronauts. Subtle things like "faster, cheaper, better" can have an effect on a culture, even at the same time that you're doing everything possible to encourage safety.

Certain actions have symbolic meaning. The fact that you have a safety representative sitting in on a Mission Management Team or in a particular wherever they're assigned can have symbolic meaning. Signs posted that it's safety, safety, safety can convince that you have a safety culture; and yet when you look at the way the organization works, you may not have as strong a safety culture as you wished. The safety person who is assigned to Mission Management Team decisions, if that is the case, is in a position of not having hands-on information and reviewing their decision but not, in a sense, dependent upon them because they have the leadership responsibility. So what kind of weight, you would want to know, is that person really bringing to that situation? Do they have the influence that they are listened to? Do they have the data to really do anything more than oversight at that point? How do you really put them in a position where they can recognize a warning sign and talk with people who are higher ranked than they are, in a definitive way, that is convincing in a crisis situation?

**ADM. GEHMAN:** That leads to my question. That is, would you be content -- let me just outline this in rough form -- of a process to satisfy that issue. That is, that senior management, the management who's got the ultimate responsibility for these decisions, that they would kind of be forced to listen to these engineering doubts because of an organization in which you had checks and balances among essentially coequal branches of some kind. In other words, that the engineers were organizationally and culturally equal to the project managers and the safety and mission assurance people were not only -- I agree with you. I understand exactly what you're saying. It's not good enough to just sit at the table. You have to come to the table with some clout and usually that clout's in the form of analysis or data or research or else I won't sign your chit for your money or something like that. You've got to come with something. And my model suggests that if you did that, you would be creating some degree of managerial chaos but, on the other hand, you would be making sure that engineering reservations and engineering concerns were well researched and got surfaced independently at the right level. So you've kind of got this trade-off between a little bit of managerial chaos, you would have the danger of the organization not speaking with one voice and all those kinds of things but, on the other hand, you would satisfy the requirement that signals would get heard.

**DR. VAUGHAN:** Surfaced.

**ADM. GEHMAN:** Does that sound reasonable?

**DR. VAUGHAN:** It does sound reasonable. Someone said if every engineer aired every concern, you would never launch a mission; and that's probably true.

**ADM. GEHMAN:** Probably true.

**DR. VAUGHAN:** It seems in post-launch conditions where the clock is ticking, in line with Dr. Barry's suggestion about how could we restructure the post-launch decision process, that it would be especially important, then, to create that kind of an open process.

**ADM. GEHMAN:** Okay. Well, thank you very much, Dr. Vaughan. You've been very patient with us. We hope we haven't tried your patience too much as we try to understand the very sound principles that you have exposed us to, both in your book and in your briefing here today.

The board is sensitive about the law of unintended consequences, and we want to be very careful that we understand more about these managerial principles before we go writing something down on a piece of paper that we might regret. But your study has had an influence on this board and we're indebted to you for coming and helping us through it today.

**DR. VAUGHAN:** Thank you. Thanks for having me.

(Hearing concluded at 4:38 p.m.)

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