Welcome everybody. We are extremely fortunate and proud to have with us today Christopher Kraft. Actually, Christopher Kraft, Jr. He told us last night that his father, Christopher Kraft, was born within about a block of Columbus Circle and that is how he picked up the name Christopher Columbus Kraft, which was passed onto Chris Kraft, Jr. I don't really need to say very much by means of introduction because Chris Kraft is a name that has been associated with America's Space Program since the very beginning. And, actually, from the very beginning of his career, right after he graduated from a university in Virginia, he went to work for the old NACA, the National Advisory Commission for Aeronautics. 01:00 And eventually the director of the Johnson Space Center which is the home of Human Space Flight in this country. He had that position through 1982, which was the end of the original orbital flight test phase of the orbiter. So, he really was in charge of the Space Center when the Space Shuttle was being developed. And, of course, this course is of course in the systems engineering of the Space Shuttle. I just want, in public here, to acknowledge that there have been expenses involved in bringing all of the special lecturers that we have had who have participated in this course. And would not have been possible without the support of the Draper Laboratory. And we thank Dr. Eli Gai who has provided that support. We couldn't have done it without you, and we really appreciate it. That is enough for me. We all came here to hear Chris Kraft talk about the invention and development of Mission Control and the systems engineering and development of the Space Shuttle. I will tell you that Chris Kraft is somebody who is not afraid to express his opinions. And we are looking forward to hearing them. Chris. Good morning. It is not hard but sometimes difficult to return to MIT where I have a lot of friends who came this morning. They sort of overwhelmed me then, and I am sure they would overwhelm me now if we got into some deep technical subject about which I knew very little at the time. And I will say a little bit more about that. What I did want to say, though, is that the people that preceded me in lecturing to you, you've been very fortunate. Because they indeed are the stars of the Space Shuttle. They did a fantastic job. And I hope you got that sense from them as they spoke to you. They are the best. And if I were going to say two things about management that I have learned in my lifetime, the first would be you are absolutely no better than the people around you. Without a lot of great brains around you you're not very good, no matter if you're the best person in the world. And too many people have learned that the hard way and not recognized that fact. The second thing we talked about last night around dinner, and that was the second thing you learn as an engineering manager is that every day is a compromise. Everything you do you have this idealistic view of doing it the best way possible, doing it better every day, doing it without worrying too much about the cost, too much about the budget, too much about schedule. You go in with that idea. But those things you have to face every day, and so managers become great compromisers. If the systems that you end up with are not what you really wanted, but if you're smart they do the job. If I were going to add two things to your education at MIT, that is where I would come from. The third thing I would say is that, whether you like it or not, you people sitting here, no you old heads, but you people sitting here are the people that are going to do the next Space Program. You are the ones that are going to take us back to the Moon, if and when we get there. It is going to be up to you to do the job. In 1968, the average age of my organization, and I think I was 44, was 26. We had an awful lot of young people who did the job and did it extremely well. The guy sitting there on Apollo 11 screaming into his headset that it was still go I think was 25 years old at the time, and he was a veteran. And if he hadn't been a veteran, he sure in hell was a few minutes after he kept yelling into that microphone that it was go. And I hope you've seen that on television. If you haven't it's a really great moment in Apollo. Let me start from the beginning. In Project Mercury, we started with a space task group of 35 people, eight of which were secretaries. And those of us that came out of the NACA, the National Advisory Committee for Aeronautics, were smart guys. We were very capable people, but we didn't know a damn thing about how to fly in space, believe me. If you would have asked us at the time how do you get fluid out of a tank at zero G, I don't believe you would get the right answer from more than two guys. Maybe Max Faget would have said well, you've got to put a bladder in there and put pressure behind it and squeeze the stuff out because it is going to be floating. You don't know where it is in the tank. And, secondly, how much have you got left in a tank? Kind of an interesting project if you don't know what zero G is all about. When we started in Project Mercury we didn't know much about systems design for space. We certainly had high questions about man's capability to perform a task in space. And I would say 98% to 99% of the medical community in the United States thought that the astronaut, when he got there, would be a blithering idiot, that he would probably swallow his tongue, that he couldn't see because his eyeballs were bulging out or that because of the worry he was going through he would have a 24 hour ulcer sitting on the pad. And they would suddenly have to be at his side, the medical community thought. That is where we were coming from, so we decided we're going to put man in space. It was a daunting task but one which most of us realized from the get-go that we were in the middle of probably man's greatest adventure. Believe me. We did know that. I felt it and I think everybody felt it. It was sort of a euphoria. And we were in what you might call engineering euphoria like Ed White was on Gemini 4. When he was outside the spacecraft, I am absolutely certain he was euphoric. The press said he must have been euphoric. And I said oh, no, he was worried about doing the right things and doing all the right things at the right time. He was euphoric. And you don't recall but they said something finally at the end of that. They said well, what does the flight director have to say? And I said get him back in the spacecraft as loud as I could say it. I think that is only one of the few times I have ever spoken on the air to ground. We were faced with putting somebody into this new environment for the first time. And how do you do that? What are the problems you are faced with? When we began to think about how we did flight tests on airplanes, you would sit it on the ground and you would write a flight test requirement, a set of things you wanted them to do on a flight. You would sit on the ground, hold a microphone and talk to him. And he would say I just did so and so. And, if he was one of the best test pilots, he probably didn't tell you damn thing. They just kept quiet like Neil Armstrong did most of the time. He just kept quiet. And you kept having to prompt them to tell you what they were doing. That is where we were coming from. We had instrumentation. We had been developing telemetry from the bomb drop tests that we had made at Langley. So, we knew quite a bit about telemetry. We knew very little about air to ground. We knew that we would like to talk this guy about 15 minutes or so. That is what you did when you went across the country as an airplane pilot. If you're going around the world, we would like to talk to them about every 15 minutes. And so we got out the geography books and said well, we're going to fly around this thing and here is what this Chinese finger puzzle looks like as it goes around the Earth. And we are going to be over this part of the Earth and this is where insertion is going to take place and this is where we're going to do orbit determination and this is where we're going to do retrofire. And we are going to be up there going around this particular section of the Earth. And you looked at the geography and said well, we've got a tracking range in Cape Canaveral. We've got tracking range on the West Coast. We have a few radars in Australia. But, if we're going to speak to them every 15 minutes, this is where we would like to be. And so we end up saying well, there are the Canary Islands, there is Kano, there is Zanzibar, there is Muchea and Australia and so on. And immediately said well, if we're going to have to talk to them, we're going to have reception there so we're going to have to build a station at each one of those locations. And then we're going to have to tie them all together. And, Lord have mercy, here we are with a whole requirement to build a worldwide network and nobody to do it with, 35 people to do it with. And so we immediately got a group together. And we got Western Electric and Bell Labs and a bunch of people like that and started building the worldwide network. That was a heck of a project to do at that point in time. And just the diplomatic requirements in all the states that we had to deal with around the world was a project in itself. Having done that we just said how many times around the Earth do you think we would like to go or need to go on the first flight? And what do you think would determine that? Well, in 1959, if you put a spacecraft up from Cape Canaveral or from Vandenberg Air Force Base and you asked is it in orbit, of the then flight director, he would say I don't know. I will tell you when it comes up over Kodiak, Alaska 45 minutes from now. And I am saying to myself well, if this thing isn't in orbit and I want to bring it down in the water before it hits the coast of Africa, I have got to know when to turn that spacecraft around and fire the retrorockets. I have to know immediately, or at least within two or three minutes to turn the spacecraft around and fire the retrorockets, what the orbit is. Because, if I don't, I don't know where it is coming down and I don't know where to send the ships to pick that young astronaut up. Realize that in 1959 nobody knew what a short arc solution was from a C-ban radar in 30 seconds of data. Furthermore, they didn't have a computer to do it with. We were slide rule people, Marchant computers, crank computers. And you were suddenly faced with the fact that you've got to build a computer system to take radar data from Cape Canaveral and Bermuda, massage that data and within 30 seconds of the short arc solution tell the people that have got to turn that spacecraft around and fire the retrorockets in two minutes. Today that sounds unbelievable. When you talk about air to ground communications or ground to ground communications, in Africa the best you had was 20 words of teletype per minute. Now, you've got to know what is going on in the spacecraft or what the astronaut said as he flew over Kano, Nigeria. You were going to get it back in 20 words of teletype. How do you make real-time decisions under those circumstances? What is a real-time decision? Where are you going to make a decision? Do you need some central facility which invented Mission Control? And suddenly then, if we're going to do this job and we're going to have people looking at this data, we have got to train a group of people to go to all these locations around the world. And if you're going to make decisions in a central location then you've got to have some means of getting that data back to them, of massaging that data, letting people know outside the limits of that control facility what is going on so they can interrelate with each other. Nobody had ever done that before. And the first time we cranked ourselves up in a bunch of small cubby holes in an old wind tunnel building in Langley Field, Virginia and started doing what we would call the initial simulations, we found that we didn't even know how to talk with each other. And everybody was talking at once. And so we had to invent a whole new language and had to have negative reporting and things like that which people had never heard of before. And rapidly then we began to realize that we had a big task in front of us. If you're going to recover this gentleman at the end of the flight, that is not too hard. We can send a few ships out there. And we probably ought to have a helicopter there to pick them up. And maybe we could have one of these light carriers. But if the doctors are right, we might have to come down anywhere in the 360 degrees on those three revolutions. Now, who are we talking to? We're talking about talking to the search and rescue people. We're talking to destroyer captains. We're talking to people that have got to fish this thing out of the sea. And how do they do that and how do they not get burned with the fuel that might be running out of the spacecraft. And suddenly we have to train probably 10,000 people on how to recover this machine. If the spacecraft is sitting in the water, we've got to train several hundred frogmen how to jump out of an airplane with tools to get to the astronaut. It was a tremendous task for a group of people who had never done much but do wind tunnel tests or flight tests out of Langley Field, Virginia. The early days we had to come up with orbit determination. How to look at the astronaut's health. How do we get something down that we can look at? Can we get an EKG down? Can we get his breath rate down to each one of these stations so we know what the man's health is? An interesting story. We did eventually build a simulator to train the astronauts, and we had no way of getting data to each one of these sites around the world that would allow us to run a full-fledged worldwide simulation in real-time. We would put it on tape. Cut it up in sections. Send out a script of what the astronaut was going to say and do. And play this six or eight minutes of a tape as that's what they would see as the spacecraft appeared over their station. And when we said we've got to train a bunch of doctors, an interesting story was we went down to the Veteran's Administration in Houston and said we'd like to put some instruments that we were developing on people that are sick here. And so, as they come in, various types of diseases. And, fortunately, one day we had a guy instrumented and he had a heart attack. We were able to record all of these things that were going on in this gentleman, his temperature, his EKG, his breath rate, what his blood pressure was and so on, and put all that on the tape. And we sent that out to the remote sites. And then at each of the sites, as this occurred, had the doctors diagnose what was wrong with the astronaut. I don't believe in any one of the 17 stations we had anybody diagnosed it as a heart attack. They all said he had an appendicitis or he was having some kind of shock take place to him because he was frightened to death. Anything but a heart attack. So, that was sort of classical of the things we did and improvised in order to get ourselves capable of running a worldwide operation which allowed us to make decisions in real-time. Now, the other thing that we invented at that time, I say invented, it just came about by evolution, was a book called Mission Rules. And that was probably the smartest thing we ever did. As we began to look at the spacecraft systems, we started asking questions. If this system is failing, what are the measurements that we're going to have there? And, if it is failing and it isn't operating at the right temperature or the right pressure and it is off nominal, what will the system do? And how do we measure that on the ground? How do we detect it? Where is the instrument located on the system because it might be effected by the position it is located in the spacecraft. It might be hot. It might be cold. It might be suffering different kinds of pressures than it was measured on the ground. And, as we began to ask those questions of the system engineer, the "system" engineer. Not "systems" engineers because I don't think we had any at the time. And they would say why the hell do you want to know that? The system is either working or it ain't working. And we said yes, that's a good answer except that now we've got this system in space. And if we want to continue this flight and not have a contingency operation, we would like to know how long the system is going to last if it isn't operating under normal conditions. That prompted us then to start thinking about how the system failed and what we were going to do about it. If the thermal system that kept the astronaut from getting hot or getting too cold wasn't functioning properly, what could we do about it? How long could he stand being at a temperature of 85 degrees inside his space suit? And then that said well, if it stays there and we can only go X number of minutes, what are we going to do about it? What is the rule of the game that says we should re-enter or not re-enter or go to the next primary recovery area, et cetera? And it allowed us then to write down, for every system, and the man what we would do under certain circumstances. Called those a set of mission rules. And that prompted us to develop a bunch of malfunction criteria. What malfunction procedures are you going to go through? And then that prompted us to ask the contractor and the manufacturer of the systems. And that developed a whole new set of schematics that they hadn't been used to. It cost us a lot of money to do that, and they didn't want to do it. They didn't know why we wanted to do it. But as they began to see the mission rules -- We got those out in front of them and said we're going to do this with your spacecraft and your system. Then they began to realize they better start thinking about those things. And that is what brought, in my mind, a group of people together in "systems" engineering because you began to find out how the systems reacted with each other. And that was a question that most engineers didn't think about. If the thermal control system is not functioning properly, what does it do to the reaction control system? Or, as we had on one of our first orbital flights, the seats on the small thrusters they were using for attitude control were not seating properly. And the experts said it is freezing. It is getting slush in the system and is causing the valves to stay open and they're not getting the proper fluid to it. So we put a thermostat on the next spacecraft and it wasn't freezing, it was getting hot because the feedback from the thruster was getting on the lines and causing the seats to warp. And it was sitting there dribbling out and causing the attitude to be sloppy and jump around. And, as a matter of fact, on one flight we had to reenter early with the first chimpanzee flight because the machine was running out of propellant. It began to have everybody start thinking about how does my system fit with everybody else's system? How does that fit with the game plan that we're trying to come up with? And, at the same time, the organization then was able to look at all of these things that we said we were going to do and became a heck of a management tool. I remember James Webb used to come down, the Administrator of NASA at the time, and I would show him, in the Control Center, how we ran an operation and how we made decisions. And he was absolutely livid about that because he said that's what I want in Washington. I want to be able to have those kinds of things put in front of me so I've got all these things so I can make a decision. I need you in Washington. I want you to come up here and tell me how to build a system like that to do management. I must say that I have never been able to do that, but he was very emphatic about wanting to do that. Jump to the conclusion of Mercury. I think we learned an awful lot form that program. We learned that man could do a job. He could do it just as well at zero gravity. Particularly, in Mercury where he couldn't move around and he didn't get sick, fortunately, as he did eventually in some of our spacecraft. But certainly man could do the job in space as well up there as he could in a fighter airplane on the Earth. But it was child's play. Mercury was child's play. We put it up there, we fired the retrorockets and it landed, and then we picked them up. A hell of a job at that time, but it was child's play. And so Mr. Kennedy, in his great wisdom, in April of 1961, when he saw the reaction of it, we were all down in Sheppard's first flight, asked NASA what can we do to ace the Russians? And NASA, in its great wisdom said well, probably in about ten years we can go around the Moon. George Low and others at Washington had been doing some work on a lunar spacecraft. And in the great wisdom of whoever made such a decision, the president asked why can't you land on the Moon? Now, I want you to know that that was 1961 and Chris Kraft did not know how to determine orbital mechanics from 30 seconds of radar at Cape Canaveral. And this man, in 1961, says we're going to the Moon in this decade. And I thought he was a little daft. I must say, I thought he was a little daft. The second day I thought a little bit better of it. And then about three months later, when he came to make that famous speech in Rice Stadium, I was called back from Cape Canaveral to tell him how we were going to go to the Moon. And, I am telling you, I did not know a damn thing about how to go to the Moon. If you had said free return trajectory to me, god, I'd a thought it was a pass to the Astro's baseball game. But here I was faced with the fact I've got to stand up in front of the President of the United States in a room, much like this one, only with about ten or 12 people in it and tell that gentleman how you're going to go to the Moon. And that was a quick learn, I'm telling, a really quick learn from people like these guys, John Mayer and Bill Tindall taught me in a few hours how to do the orbital mechanics to go to the Moon. Not how to do it but what took place. Here we were at the end of Mercury. And we are going to then have to go to the Moon. And how are we going to get there? And how are we going to train ourselves? What are the systems we need to do the job? What new control center do we need? What kind of operation do we need to think about? What kind of trajectory analysis do we need? And what kind of computers do we need? And what kind of communications do we need? Suddenly, we've got a whole new set of problems. If we're going to do rendezvous at the Moon, we've got to teach ourselves how to do rendezvous at the Earth. If we're going to send something around the Moon, we better have a heck of a system to determine whether we are truly aiming at the Moon or whether we're going to hit the Moon. And, in fact, on Apollo 8, I wasn't sure that George Miller, who was the head of Manned Space Flight, was sure we weren't going to hit the Moon when we told him that we wanted to do the trajectory as we were going to do it when we landed. Then it ended up being 60 miles above the lunar surface as you entered orbit around the Moon. And can you really tell me 270,000 miles away whether the spacecraft is going to hit the Moon when you are ten hours away or is it going to go around the Moon? So, we were faced with all those new problems. That is what got us to the Gemini program. We wanted to be able to build a spaceship that would allow us to do maneuvering in orbit. That would allow us to stay up there 14 days, which is how long the spacecraft flight to the Moon and back would be, that would allow us to do reentry guidance using the L/D of a blunt body, enough to skip it out as you came back to Earth and then go back up and then reenter at a much lower velocity so you wouldn't burn up the spacecraft. Those are the kind of things we were suddenly thinking about as we built the Gemini spacecraft. We needed an onboard computer. Unheard of in that time period. The Air Force had been putting some on airplanes but never had we had on onboard a spacecraft. So Gemini was designed to be a maneuvering capability in space to rendezvous and dock with a target, to determine the capability of man to survive for 14 days, to do a heat shield which was much more flexible and reusable. And to build a maneuvering system. And, finally, to do guidance and control for landing point and control and develop a footprint on the Earth for Gemini which is what we were going to have to do on Apollo. Gemini was a very successful program. Without it we could never have gone to the Moon. We learned how to operate in space, how to maneuver in space. We learned how to do EVA, which was a total disaster as we flew in Gemini. I don't think we even, by doing it five or six times on the final flight of Gemini 12, Buzz Aldrin was able to do a reasonable job in extra vehicular activity. We had to build a suit that was flexible to be able to walk on the Moon. We had to build a backpack which was, in truth, another spacecraft to do Apollo. We had to build a new control center because we had a computer which we actually doubled the storage capacity on Mercury and then gave it 64,000 words. Today, you have that in some kid's thing that he carries on his airplane and one touch of his stroke. But 64,000 words was all that we had then. When we flew Gemini, we had a million words. When we flew Apollo, we had 5.5 million words, so that computer complex was changing on us continuously. When we did Mercury, we used a grease pencil to write down the numbers as they came back from Kano, Nigeria and 20 words of teletype. We had to build a new display system, a digital display system with a computer. And the first digital display system was not graphics at all. What we did was build a slide that was the background for the display that you wanted. We had a set of 4.5 inch lantern slides, a bank of 100 for each station in the Control Center, and then the computer filled in the numbers. Now, that was in 1964, '65 and '66. It wasn't until we got to the latter stages of Apollo that we had computer graphics. I don't know whether you can realize that or not. Computer graphics today is, golly, you have football games on computer graphics. But then we didn't have it so we had to redesign a control center and continuously redesign a control center. We had to have a computer controlled communication system. All of those things were built. We had to utilize and build in NASA the first communication satellite from which came the revolution in the world, in my opinion. I want to go through Apollo and things like translunar trajectories and free return trajectories and what might happen if you were off by a few feet per second or a few tenths of a degree when you fired the orbital maneuvering system of Apollo on the backside of the Moon, which is where you had to do it for optimum performance characteristics. When the thing showed up as it came out on view on the front side of the Moon, and it was not in the right trajectory, what the hell are you going to do about it? Where is it going? Is it going around the sun? Is it coming back to Earth? Is it going to hit the Moon? And what am I going to do about it if it is on one of those paths and my maneuvering engine, which has 10,000 pounds of thrust, is not working or not working properly or it wasn't pointed in the right direction? You had to be prepared to think about those problems and make a real-time decision as to what to do. I hope I am impressing you with that because that is what you guys are faced with in going back to the Moon. It isn't just a simple problem of orbital mechanics. It is a problem of what are you going to do if it isn't correct, if it isn't on the right path? If the system isn't working properly can you land? Those things have to be thought out and thought out carefully before the fact, not in real-time. You can make all of the decisions in the compute which you would have made after you had thought about it in real-time, but think of the orbital mechanics problems associated with that in real-time and the background then of the math and the thought processes that have to go into making those decisions. You're descending to the Moon. And as one of these gentlemen sitting here, you start to do the descent to the Moon, and, low and behold, you bring up the system on the LEM and the abort light is on. What the hell does that mean? Well, it means if you start the engine right now it is going to start doing a rendezvous back with the command module. It is not going to land on the lunar surface. And I've got a computer program that is hardwired to do that job with. I don't have the capability of reprogramming it like you would have by just sending up a whole new set of software. How am I going to figure that damn thing out? I've got a thousand words of pad in this computer. Is it possible in real-time to obviate that abort signal and still land on the Moon? And this gentlemen sitting over here figured that out. He figured out how to tell the computer to ignore that signal by going into the certain places in that hardwired software and saying don't listen to the abort signal for a while. Don't listen to it, but if I need to listen to it on the way down then listen to it. You've got to do that with a thousand words. That is a pretty tough problem in real-time, one which nobody had thought about before until it happened. Or, as I said, this 25 year old young man on Apollo 11 and the vehicle is descending to the Moon and he is getting all these signals back that says the computer is overloaded and is doing so many tasks and stopping. Why is it doing that? We've done it on Apollo 10 when we started down to the Moon and it worked fine, and we did a rendezvous from it, but we had the radar on. And going down to the Moon, we didn't need the radar on it. That radar was going into the computer, it was flooding the computer with data, but these guys didn't know that. They had to figure out how to get around that signal. If I sound like that is a big problem, it is a big problem, and it is going to get bigger. With a spacecraft you're going to get more complex with each passing day and you're going to have to figure out how to do that stuff in real-time. And that is what you, the flight operations people and the designers of tomorrow are going to be, and that is what you're going to be faced with. I know you're working on the Space Shuttle trying to make it better. That is what your task is in this class. We should have had you around for the last 25 years because it needs to be made better. And it is a travesty, I will use that word again, that we haven't been making it better and making it less costly to fly. We should have been doing that. Let me start into the Space Shuttle a little. One of the questions that Jeff asked me that these people will be interested in hearing is how did you decide to do it manned as opposed to unmanned on the first flight? Sort of out of necessity I guess you would say. The more we looked at the systems, the more we looked at the Space Shuttle the more we realized that the man could furnish us a certain amount of reliability in space operations and in space systems. And in choosing systems the more reliable the machine would become. But we had to convince ourselves that that was a rational thing to do. Now, let's go back and give you some thought process about the Space Shuttle design. As we did the initial design, we wanted an escape system. We wanted to build a pod into the cockpit to allow the astronauts to escape if we had problems. And building the Space Shuttle main engine was very difficult. Do these people know about sub-synchronous whirl? They heard about it from J.R. We couldn't find any bearings in the world that would withstand that load. They were failing. And you didn't know when they were going to fail, so we built an automatic shutdown system into the engine. And Aaron and I were talking about that this morning with Professor Cohen. That was well, we'll just figure out what all the parameters are that tell you when the engine is malfunctioning and shut it down because we don't want it to blow up. We are going to look at RPM of the pumps and we're going to look at temperature in the prompts and we're going to look at the pressure in the engine head and we're going to look at the fuel flow rates, et cetera. That sounds like we can do that, but how do you know it is right? How do you know you're not shutting down a good engine? And the point I am making there is that reliability of the instrument becomes more important than the engine. Think about that. You can say I will have an automatic shutdown. I will have the automatic abort and get the astronaut away, but somebody has got to make that decision. Nobody on the ground can do it fast enough if the engine is going to blow up. The astronaut cannot do it. His reaction time is about 1.5 seconds, no matter how much data you give them or how good the data is. So, it has got to be automatic. And that is a very difficult task for an engineer. He can make this system work but he cannot tell you very rapidly when it is going to fail. And rocket engines have a bad, nasty habit of going like that and it is gone. You've got to figure out when that is going to happen, so designing instrumentation to do that. We then started thinking about that in application to the Space Shuttle. And our experience with redundancy, reliability numbers thinking about that we said we want a system in the Shuttle that is going to be fail operational, fail safe. That is quad redundancy, so every critical system has quad redundancy in the Space Shuttle. It sounds like a good idea, doesn't it? We will come back to that in a minute. We said we would like to have an escape pod but the escape pod has got to have a stability and control system. It has got to have a control system because it is going to be a spacecraft. When is it going to use the pod? Is the pod going to be used at 100 feet off the pad, 100,000 feet off the pad, 500,000 feet off the pad? And if this thing is descending from any one of those altitudes, how are you going to control it? Very rapidly that is another spacecraft. It is probably a bigger job in building that spacecraft than building the Space Shuttle itself. So you can see why we didn't do it. It is too tough, too big a job. We said we would like to have a go around capability on this machine. It is going to have an L/D of about four to five at best and the descent angle that you come down to land is 23 degrees. Let me tell you something. I have flown in a Gulfstream II on a 23 degree descent trajectory and that is scary as hell. You're flying a brick. That machine is coming down like that and you're hanging on your straps. We would like to be able to have a go-around capability. OK, we'll put some jet engines on it. It has got to have fuel. It has got to have a tank. It has got to have lines on it. It has got to have a certain amount of redundancy with it and a certain amount of power. It has got to be absorbed into the thermal protection system and come out and extend. What I want to do is go around as I'm reentering from space so I can go once around the runway and land. It didn't take us long to figure out if we built that system we couldn't carry a damn pound into orbit. There went our payload. And we very rapidly started figuring out how to do dead-stick landings and how to preserve the energy and how to get this machine lined up on the runway at way high altitudes, et cetera. So we did away with the go-around capability. We've done away with the pod. We've done away with the go-around capability. Now we don't have an escape system. What is your escape system on the Shuttle? Well, on Mercury and Apollo the escape system is a solid rocket. Solid rockets have close to 100% reliability as you can get. Usually, if it lights it burns and it goes. God, we've got two solid rockets on the Shuttle. Why aren't they our escape system? Because, if we can get this thing to 200,000 feet, it will fly. We can return to the launch site and land from 200,000 feet because you aren't very far down range at 200,000 feet. That is a good idea, a great idea, but the rockets have to be 100% reliable. It wasn't 100% reliable in the Challenger accident. Unfortunately, I cannot account for the fallacies of man. And I will come back to that, if you want me to talk about the Challenger accident. But we built solid rockets to have 100% reliability, and they were our escape rocket. We've got quad redundancy, we've got engines that will perform to the best of our ability and shut down if they are going to explode, we've got solid rockets as an escape system, and we will teach the pilots, with the best control system we can come up with, to land this machine dead-stick. Now we've got to convince ourselves and the management that the best way to fly this thing is unmanned or manned on the first flight. And we looked at flying it unmanned. We could have done that. We could have put an automatic control system in to take the place of man. And these pilots that tell you they do manual control during reentry in the Shuttle, hogwash. Pure hogwash. The Shuttle will not fly without the automatic control system. The pilots are flying the outer loop. I could fly it. I have flown it in the simulator. You know how I do it? I don't touch the damn thing. You set the damn end of the runway into the computer, right down. And that's the way 95% of the airliners land today, on automatic control. And, frankly, that is how the astronauts ought to do it. They haven't done it yet. They keep telling me what are we going to do if the system fails? And I say to them you better wind your damn clock because if that system fails the thing is gone. It is an unstable machine.

From mach 25 to touchdown it is an unstable machine. If it diverges it is gone. If pilots tell you they are doing manual entry on the Space Shuttle, I repeat that statement, hogwash. It cannot be done. Now, I can teach them, however, by building a Gulfstream II into a space shuttle like vehicle. I can put the control system that they've got in there. I can repeat that. I can make it come down. I can put reverse thrust, if you believe, on both engines in a GII. And you're descending and you've got both those damn engines back there going like that as it does its reverse thrust to match the drag of the shuttle during entry. But I can teach them pretty well how to do dead-stick landings. And so, I put all that together. And Professor Cohen and myself and a few others go to Washington to convince the powers that be that we can fly this machine manned on the first flight because it is the most reliable way to fly the machine. And we convince them. It took a little doing, a lot of fancy talking, I guess, but that is what we decided to do. And I think it was a good decision. In retrospect, it was a lousy decision. Why? Because if we had had unmanned flying capability on the orbiter and we had the Challenger accident, we could have flown it again the next day with the unmanned control system and proved that it was OK. Well, we didn't have that capability. And, when you get into the politics of flying men in space in this country, rational thinking does not carry the day. Political thinking carries the day, even in NASA. You will find that out as young engineers also, that you not only have to be an engineer, you do have to be somewhat of a politician in order to sell your programs. We convinced ourselves that it was the best thing to do at that time to fly man on the first flight. Because it is in my head and it comes out, I want to say a little bit about the problems that they face today. Or the way in which they use the Space Shuttle today is frankly not how we intended the machine to fly. We have quad redundancy. And the way NASA uses it makes it less reliable than if we had just had a damn single string system. Why? Because they have to have all quad redundant systems working at liftoff. So all four systems have to be operating at liftoff. That is hard. It is hard enough to have one operating properly. Now you have to have all four in all the places where you have quad redundancy. That isn't how we intended it to work. What we intended it to do was, you would get to the pad and get ready to launch and one system fails, you would keep right on going. If you have two fail you keep right on going. That is the way we intended it to be because we wanted it to be a reusable system with quick turnaround. Two weeks we want to be able to turn that machine around. And you could do that today because they've flown in 100 and something times. They know that machine. They know it well. They know how the systems perform. You can look at the telemetry when it lands and say all three of the four were working and I've got a thing over here. I can fix that in ten minutes. I am ready to go. They put more time on the systems on the ground than they do in flight testing the machine. Is that expensive? My God, that's the reason it cost $4 billion a year to keep all those running standing Army at Cape Canaveral. If you're going to build redundancy in the future, you guys, if you're going to put redundancy in this machine, don't tell them about it. Now, that may sound funny. But that is how your computer is designed. You don't have BITE in your computer anymore, built-in test equipment. Do you know why? Because damn engineers kept using it. Now the computer builders build in the test equipment but they don't tell you it is there. The redundancy works automatically. Probably got three or four in there just like we do in the Shuttle, but your computer keeps working. It might be a little slower, sometimes it can get you as mad as hell, but they don't tell you about it. My advice is don't tell the people about it the next time. Don't tell the people at the Cape this thing has quad redundancy. Now, that is probably somewhat foolishness but I guaranty that if I had anything to do about it the next time, I might very well do it that way because it is not the right way to think about this machine. The machine is a beautiful, wonderful piece of hardware. The orbiter system, the most complex system ever built by man to fly, I was talking to some coops a few days ago, I've said that word 14 times, it has never had a failure. The orbiter has never had a failure that would have prevented that machine from landing safely. NASA is now going to use, however, all of the components that have failed. They are going to use the solid rocket. They are going to put a command-like service module on top of it with an escape rocket and fly it. That system has failed. They are going to use the tank. Engineers, this day and time, cannot figure out how to put insulation on the tank. Ridiculous. Not only ridiculous. Ludicrous. You mean to tell me there is not a design engineer sitting in this room that cannot tell you how to keep the foam insulation on that tank? Hell, my son could do it. In fact, my grandson could probably do it. The Space Shuttle main engines, now that is a damn tough piece of hardware. That is what we're going to use. That is what we're going to put in orbit and use as a propulsion system to send you to the Moon. Now they say we're going to make some changes to it and make it better. I will probably be dead and gone, but I would like to see it. That thing is designed right up to the teeth. The maximum power you can get out of hydrogen and oxygen has an ISP of about 460, and the engine on the Shuttle is 458. I don't know how you could get much more efficient than that, but that really is a tough engine. You're continuously changing components on it. But those are the three components. NASA says I am going to use those to go to the Moon, but I will throw the orbiter away. Never had a failure on the orbiter. We talked a little bit about RTLS, return to launch site. That sounds like something easy to do, but think about the software involved in that little dude in figuring out how to do it, how to take that machine back to land at Cape Canaveral if you do have an abort. Think about the software involved in that. Think about the possibilities. Think about the cutoff conditions. Think about the mach number range you're going to have to fly. Return to launch site was part of our philosophy of not having an escape system per se on the Shuttle. I know we have some navigation and guidance people in this audience. How then did we decide? Jeff asked me to fly the first time. That was tough, very difficult. We had some of the best experts in the world come review what we were doing and look at all the systems. The one thing, two things, really, that they had the most trouble with in making sure we knew what we were doing. First was the thermal protection system. And we never really convinced the experts that we did have a thermal protection system that would work. As a matter of fact, the man who invented lunar orbit rendezvous, he didn't invent it but he sold the day in using lunar orbit rendezvous. And the chief structures engineer in the United States, that is probably a stretch but one of them at Stanford wrote me a cosigned letter on T minus one month after we had reviewed this system, we had done everything they asked us to do. We ran combined loads test, we ran worst loads test, we ran combined worst loads test to prove to ourselves that the thermal protection system wouldn't fail.

I got this letter at T minus one month. It is now in my effects at Virginia Tech. As a matter of fact, Virginia Tech said are you sure you want this letter in your files? I said oh, yes, I want that letter in my files. It is probably the most important letter you will ever have in my files. But these two gentlemen said we implore you not to fly the orbiter because the tiles are going to come off. It may not come off while you're at the max heating pulse, but by the time you get ready to land NASA is going to be totally embarrassed because all the tiles are going to fall off. And we would ask you to put a steel net around this vehicle so that they won't fall off. I am still aghast at that letter because I don't know what else we could have done to satisfy them that we had done everything they asked us. They were concerned that the strain isolation pad, which is what the tile sits on, and you've had that explanation, they were concerned that the combined vibrations and aerodynamic loads would cause a failure in the SIP or at least at the glue joint. And that, indeed, all the major tiles that had gone through the large heat pulse would fall off. Professor Cohen and I met them on the Queen Mary at an AIEE meeting after the first flight had taken space. It was satisfactory. It flew well. It flew beautifully. Those two gentlemen came running out and asked Aaron if we could come and sit down and have a drink with them. And we said hell, no, and walked away from them. That is what I thought of that letter. Say that again. We didn't get the last part. Now, the other thing I want to talk about is the control system of the Shuttle. We had several gentlemen [NOISE OBSCURES] and said we are infinitely smarter today. Yes, I did. The public affairs officer said we need a comment from you, after the machine had landed, on what you think of this flight. I said we have just become infinitely smarter. Not so much about the tile were we infinitely smarter but the story I'm about to tell. The automatic control system, in terms of the aerodynamic parameters that it has to deal with, there are roughly 35 variables in the aerodynamics of the machine all the way from products of inertia to cnBeta. Does everybody know cnBeta? CnBeta is the capability of the rudder to stabilize the machine, the yawing moment due to side slip. And I still do remember a little bit of my aerodynamics. Anyway, there are no facilities in the world to measure those 35 parameters, very accurately anyway, that would tell you what to design the automatic control system to. It is not so difficult at high mach numbers above, say, ten. You can use, what do you call it, Newtonian flow? And, as you well know, you use the aerodynamic controls when you can. You use the thrusters when you can, and you combine the two as you transfer from one to the other in the range of flight regimes. But, actually, it is a guess. We looked at all of the possibilities that had been done on the X-15, had been done on the Dyna-Soar program, had been done in wind tunnel tests of almost every configuration for hypersonic flow. And you just couldn't nail down what those 35 parameters were. What we did was said here is what we think it is, here is a variation on top of that, and here is a deviation on top of that and here are those 35 parameters throughout the total mach range. And we are going to do a Monte Carlo analysis at every tenth of a mach number from 25 to touchdown and have no failures. And, if we have a failure, we have to change the gains and go back and run it again. I don't know about you. That sure convinced me that that machine would fly. But I still said we just became infinitely smarter. I said, before we flew, we certainly have to change the gains because there will be regions where the machine is oscillatory coming down and might frighten somebody, even if it were going to damp. That was post-flight. I said I don't ever want to change the gains. The damn thing worked. So, those two problems were the fundamentally hardest problems to be able to test and assure yourself that you were ready to fly. But, in the end, how did we decide to fly? Frankly, I didn't know what else to do. In my mind, Professor Cohen's mind, John Yardley's mind who was head of Manned Space Flight, these gentlemen sitting in front of me that worked on the automatic control system, we didn't know what else to do. We had done everything we could think of. We suspected that there were some unknown unknowns. A good old NASA term, "unknown unknowns". But we didn't know what they were. We didn't know how to test it so we've got to go light the torch and do it. I don't think it took a lot of guts or nerve. 71:00 And the responsibility of the program because it may very well be something that just causes the Space Program to collapse in the United States. And that is a tough task. You don't learn that overnight. You just sort of have to learn to live with it. And, frankly, you have to like it. You have to like being in that position. I had one of my flight directors who became very much affected by it mentally. So affected that he quit and went and became a psychiatrist. Did not ever perform as a psychiatrist but got his degree in psychiatry. Phil Shaffer, if you know him, one of my very closest friends. He is now making me kind of rich because we own a lot of oil wells in Oklahoma together. It is a tough job but it is a marvelous job. There is nothing I can think of, including pitching in the World Series or winning the US Open that comes close to being in this business. Every day is a challenge, every day is hell and everyday is the best feeling you've ever had in your life. That is how you feel every day. You go through those transients almost every day. I highly recommend it to you. I don't think you can get rich until you retire and become a board member like some of us have, but before that you're not going to get rich but you're going to be happy every day. And you are going to feel like you contributed every day. And I don't know, at least in our business, anything better than that. And these gentlemen all sitting here in front of me will attest to that. It is a great life. With that I will stop and take your questions. [APPLAUSE] Chris, well, I'll start off. Aaron, can you stand up? Yes. What would be the systems that you would think could use most improvement on the Shuttle today? With today's technology and then as you see things, what would be the systems that you think could use the most improvement in terms of performance margin? Well, again my first answer would be political. I would approve the thermal protection system. I don't think it has to be improved very much, but it would sure get a lot of people off our backs if we improved the thermal protection system. And there are ways of doing that today. There are some advancements in the state-of-the-art of the materials probably in the way you attach to the plow to the machine, probably the way you proof test it. All of those things, I think, would be where I would go first. I would put an electric system in secondly. What about hydraulics? And get rid of the hydraulics because I think that is a maintenance problem. And I think that the APUs are always going to be a problem because that is something that is turning up at 400,000 RPM, a rotor that is about that big turning up 400,000 RPM. And, because at 400,000 RPM, actually, instead of being this diameter is now an eight to a quarter of an inch bigger because the metal is stretching under those conditions. The valves we've had trouble with, as you well know. The material where this thing is pulsing. And these are nothing new. There are designs, there are electric motors, there are power systems that would do it much better than a hydraulic system. Those two systems, I think, are primary. Now, the other thing is you have to keep up with the state-of-the-art. And one of the biggest problems you have with the Shuttle today is nobody builds the parts anymore. You go to the manufacturers and they say oh, we stopped building that system ten years ago. All the circuit boards and everything is passÃ©. And that sounds like, well, we'll just change the circuit boards. Well, that is a tough problem because the process specs have got to be looked at. The sneak circuitry, the sneak paths have got to be looked at because that was the thing that always got to us in space flight, everything works fine and then some day somebody turned something off and the thing glitches and it fired the retrorocket or something like that. And so you have to be sure that when you do redesign the circuitry into the modern world that it is properly done. A lot of things you don't need on Space Shuttle probably, you don't need the backup flight control system which costs a lot of money. And then I think the biggest thing I would do is force the system to use automated checkout. That is where all the money is, I think. And maintaining the machine, nobody is willing to use automatic checkout. It is there and you can do it very easily but the people at Cape Canaveral, they need to be flight controllers. What I mean by that is the people at Cape Canaveral who prepare and maintain the machine have a totally different approach to the space machine than the flight controllers do. The people at the Cape want it to be perfect when it is launched. And so, when they do the checkout and it doesn't work right, they go plug a new board in or they go put a new system in or change out the fuel cell. A flight controller does not have that prerogative. He has got to figure out how do I live with what I've got and make the best of it? I think that is the best attitude. And they need more of that in the maintenance side. I think that is where the biggest savings and the biggest improvement could be made in the Space Shuttle. The other thing I think about is the engine, SSME. I think if you derated the SSME that the turnaround time on the engine and the reliability of the engine would go up significantly. If you derated the engine, i.e., instead of asking it to put out 108% every time you go to the Space Station because you're going up to the higher inclinations. You just put a bigger head in it or whatever it takes to derate the engine. Make it run at 95% power. Gee whiz, the thing would last forever if you did that. Chris, you mentioned in your talk about going back to the Moon. And I was going to ask you a couple of parts of the question. One is what for? Two is it to go to the Moon or is it set in stone to do something else? And then perhaps you could comment on what your prediction is for the Space Program for the US in the future. You're going to get graded on it. Why go back to the Moon? Well, I think that there are enough resources on the Moon to make it economically viable, number one. Number two, I think you could develop enough electrical power on the Moon to provide enough power for the people that were going to live there and be stationed there permanently. And you would do it on the backside, by the way, not on the front side. That is where you would want your permanent base on the Moon to be on the backside because it would be shielded from all the electronic signals from the Earth. It is the best place in the world to look at the rest of the universe. I would build my space base on the backside of the Moon. And then I believe there are possibilities, although it is not technically sound yet. But I believe there are possibilities of providing enough electrical power to the Earth from the Moon that you could shutdown every power plant on the Earth. You get that much electrical energy from the Moon. And that would certainly offload the power requirements on the Earth which are almost logarithmic, aren't they? China is going to end up using more electrical power than we do shortly, so we need electrical power. And I think you could get that from the Moon. Plus, I think that the geophysicists and the geologists, astrophysicists all can give you a thousand reasons why you should go back to the Moon because of what Professor Yuri said. It is the Rosetta Stone of the universe. There is more to be known from the Moon about the Earth than you can ever get out of the Earth. It is still very useful to go back there from a scientific point of view. Plus, the engineering and economics of it. I didn't say it because I wasn't sure you wanted to have such a discussion. But I will. I think it is a travesty that we aren't doing it with the Space Shuttle and the Space Station to go back to the Moon or to go to Mars. Why do I think that? Because, in either case, I don't understand why you would want to build an Earth entering vehicle to go to the Moon. What you want is an interplanetary spacecraft. Why does it have to have a heat shield? Why does it have to have parachutes or some kind of landing capability? Why not just go to and from Earth orbit? And the Space Shuttle is the greatest machine for carrying things too and from orbit that has ever been thought of. And the one they are going to build, even if it's an unmanned vehicle, is still going to have an awful lot of complexity to it. And I think that if you've made the Space Shuttle economically viable, which nobody thinks you can. And maybe Chris Kraft is the only one that thinks you can. If that is true then that is true. I don't think that way. I think the Space Shuttle is an economically viable machine, and so it is a travesty to me to throw it away. And the Space Station could be used as the place where you assemble all this stuff. And everybody says well, it's at the wrong inclination. Yes, it is at the wrong inclination. You were foolish to put it there in the first place, but that is where it is. Every time I had a little bit of fuel left over, I'd inch it down a little bit, and the first thing you know we'd be down to 28.5 degrees [NOISE OBSCURES]. Today it costs you 15,000 pounds of payload to go to the Space Station, and that is a travesty, too. You wouldn't want to do that continuously. I would use the Space Station as my assembly point and I would use the Space Shuttle as the machine to go there. And then I would build myself a bunch of interplanetary spacecraft to go to and from the Moon and Mars. And when I did that I would be smart enough to build all these newfangled structures, inflatable structures, et cetera, which you could use not only as the interplanetary spacecraft. You would use that where you would live on the Moon. I think it has a better approach from an engineering point of view. Whether that is the political way to sell the program, Mr. Griffin has got to do that. I mean that is what his job is. Fortunately, it is not mine. I was asked to be the Deputy Administrator and the Administrator of NASA several times. And you can hear the way I talk here that I would have lasted about six days to six months. What do I think about the possibilities of today's plans? I hate to say this but I think it is going to fail. I don't think it will work. I don't think that the program as stipulated today is the way to do it. And I don't think that political climate is such that the budgetary support will be provided. And I hope I am wrong. I don't think I am. Do you think the Chinese will be there? Beg your pardon. Does that mean the Chinese will be there? No. Hell, the

Chinese are 50 years from going to the Moon. They cannot buy it from Russia. That is what they're doing today. They're buying all their technology to put man in space from Russia. You know, that makes me think the Russians are still using the same spacecraft, with slight variation, that they put Gagarin up in 1961. Literally, it's pretty close to it. I've sat in it. Have you sat in it, Fred? You sit in it like this. But they used it over and over and over and over again. The B-52 has been used over and over again. It has a new wing. It has new electronics. It had new bombs. It has new everything on it. The only thing that is the same is the configuration. It had new engines probably five times in its lifetime. That is what we ought to be doing with the Shuttle, isn't it? We seem to have this great propensity in this country for building something wonderful and great and high performance and then throwing it away. We put up the SkyLab. Wonderful. Throw it away and don't build anymore. Build the Saturn 5. Gee whiz, it will put 200,000 pounds to the Moon. It is rotting away at Johnson Space Center. The Trekkies in the country got so mad at the Johnson Space Center that they made them build a hanger to put it in so it wouldn't rot anymore. We built a Space Station and we're throwing it away. We built a Space Shuttle and we're throwing it away. Golly, my mother would have gone bananas. We had leftovers almost every other meal. I know that's trite, but don't you think that is foolishness to do things that way? I think it is. We did learn from space flight that everybody seemed to learn from everybody else's experiences. That was an amazing factor to me, in the early days particularly. The astronauts, each one that flew was so much better than the one before. And knew how to do the job better than the one before. All of those things, you could see yourself advancing, and they just built on this experience of each man. And I don't know how they transmitted that to each other. They didn't, obviously, because they didn't have a brain connection. But that is the way we ought to be doing it here. We've got all these things that we build and then throw away and don't take advantage of. That doesn't make a lot of sense to me. Now, I know there are politics involved. And that is a reason I said you had to take into account the politics. When can you get the money? How do you convince people that you need to do things? What does it do to the job situation? How does it affect each senator's and each congressman's state in terms of the money that you bring into that area, et cetera. When we built the Space Shuttle we had a contract in every state in the union except Alaska. And we did that on purpose. Aaron and I flew to every one of those 75 major subcontractors in the Shuttle. They were all over the country, and we would go visit them at least three or four times n a period of a couple of years. The politics has to be there. We were lucky in Apollo. I call it the conjunction of the stars and the conjunction of the politics. That is a story I meant to tell. By 1978, '77 maybe, we were really behind a power curve on the budget for the Shuttle. We had been pushing a wave of about 10% less funds than we needed each year. At about that time period we needed, if we were going to have any semblance of making a 1980 or '81 first flight, we needed a $600 million supplement and about that much per year more than we were getting. And NASA had this big meeting down at the Johnson Space Center. And we all talked about what the problems were and how we were going to meet that. And everybody, absolutely all the politics said you cannot go ask for a supplement, you cannot go ask the Congress for any more, you cannot go to the White House and say we need more money. So we may just have to turn this thing into an X-15 project, a research project. The first Shuttle flight will be whenever we can build it and it will just be a test vehicle. We were all very downhearted about that. Dr. Frost, who was then the administrator, went up to the White House about three days later. And Carter, who was the President, called him in and said I want to tell you how wonderful that Space Shuttle is. And Frost said he could feel himself tighten up. And he said, you know, I just had this meeting with the Russians at the Salt Talks, whatever SALT meant. And I was pointing out to them that we were building this marvelous new space machine and we were going to be able to do all kinds of things with it. We were going to be able to fly over Russia and look at the world. And he said it carried the day. And Frost said, oh, my God, what is NASA going to do about that? He came back, thought about it for a few days and went back to see the President. He said, Mr. President, I have to tell you, this Shuttle is in trouble. We don't have the money. We're not going to make the launch dates. It is questionable whether we can even build the machine at this point in time because we haven't built the thermal protection system. We didn't even have the factory built yet to build the tiles in. Mr. Carter said how much do you need? And he said, well, I think we need about $600 million this year and I think we will need about $400 million a year. That was a WAG on Dr. Frost's part. And the President said you will get it. That was how close we were to the Shuttle failing from a political point of view. I don't know what the politics of tomorrow is that might change our mind. It would be wonderful if the Chinese would land on the Moon tomorrow because that might get the Congress back in action. But can you see the Congress, in the face of what has happened with Katrina and Rita and a few other things that happened in the United States, and the Iraqi War and the budgetary problems they face -- I cannot see them giving NASA the money they would need to do the program. And NASA says they can go back to the Moon between now and 2018 for $106 billion. Mr. Webb doubled the price. All us great cost estimators, we estimated the cost of the Shuttle, and Jim Webb got it and multiplied it by two. Today I would say you would have to multiply that by ten if you think you're going back to the Moon. I cannot imagine. Aaron and I worked on a program in 1998. When did we do the Mars study? In '89. We estimated the cost in 1989 dollars to go to Mars at $400 billion, and I think we were low. I keep have to catch myself. I know it's the politics that you have to be concerned about. If you told them that it was going to cost $400 billion dollars then for sure it would be cancelled, right? You've got to tell them something that is rational, but I don't think they will get supported even with the amount of money they say it is going to cost. I hope I am a pessimist. Yes, sir. I have two separate questions. One is the improvements you said that were made in computing capability from Mercury through the Shuttle, I was wondering if there was any thought into making the computer systems on the Shuttle more upgradable? And, if there was, would there have been any value in using modern systems? And then the second question is related to the comment you made about if the Shuttle was designed to fly automatically after the Challenger accident they could have just flown again the next day. I wasn't really sure what you meant by that so if you could elaborate on it a bit. Let me go to your first question. It isn't the hardware. It is the software. And it is the software checkout and it is the software validation that you have to worry about on the orbiter. When you have four systems that are operating on a 40 millisecond time cycle and checking with each other at the end of that cycle that they are all in lock-step -- John is looking at me saying my God, how did we ever do that? And I don't know how we ever did it, but we did it. It is the software and not the hardware. When you have an updatable computer, which you should have and will have, it is the software that is the problem, not the hardware. That has always been the case. Trying to make the software fit into the new computer, the way the hooks are in system is just totally different. And, therefore, the guaranty that the system doesn't have a bunch of glitches in it that are going to get to you, you know, when we flew to the moon on Apollo 11, we had a book about that thick with computer anomalies in it. We understood them all, but that is how many software fixes we needed to make. We just didn't make them because we didn't want to nor had the time to do them. What I meant by flying an unmanned shuttle was that you couldn't convince the politicians or the powers that be, whoever they are, that you could fly the shuttle the next day manned. But, if you didn't have a man in it, who would have cared? And so you could have flown it the next day and it would have worked perfectly because it was warmer at the Cape. Do you know what the condition on the pad was the morning they launched Challenger? There were icicles hanging off the gantry that long and that big around at Cape Canaveral. Let me tell you something. You know why they got there? They did what we did in 1920. They turned the water on and let it run all night because they were afraid that the fire suppression system on the pad was going to freeze and not be able to be turned on when they launched so they let it drip all night. And I am sitting there saying that solid rocket has not been qualified for temperatures below 47 degrees Fahrenheit. And they're convincing themselves that the core temperature of the solids is much higher than that because it has been sitting in the sun for the last two months and the temperature is so and so, but they didn't think about the seals. If you remember that professor sticking the seal in the ice. Well, that's what I meant. The next day the temperature would have been warmer, put new rockets on it. Max Faget said the next day, why don't you just put a heater around the joint and put a belly band over the top of it and fly? Damn good idea. Yes, sir. You mentioned that one of the reasons the Shuttle is so expensive is because you have so many redundant systems onboard. Now, what would be your solution? Not to have them onboard or just not to have them all upgrading at launch? No, you got the wrong implication there. It is expensive because they insist on having them operating at the time of launch. It is not the redundancy that makes it more expensive. It is the checkout and the testing and proof that it's there and the replacement of the systems and the use of the systems that makes it more expensive. But what makes the Shuttle so expensive are the numbers of people involved in preparing it. There are roughly 10,000 people involved in that operation who make X number of dollars per hour or day. And it costs, in today's money, about $5 billion a year to fly the Shuttle seven times. It probably cost $5 billion a year to fly it 30 times. Not much difference. Maybe $5.5 billion. So, it is the people. You've got to get rid of the people. And people have been trying to do that ever since Mercury, get rid of the amount of people. And they try and they put in the automaticity and the automatic checkout and then don't use it. Check it out. And, as I said, they put more hours on it in the hanger than they do in space. It wears out the system checking it. And it takes people to do that, so it's people. So what's your solution to that? I think you have to have some hardnosed SOB that says I'm going to get rid of the people, and you do it with automaticity, automatic checkout, automatic everything. In today's world, why would you do it any other way? I will give you another example. When we built the caution and warning system on the Space Shuttle, the safety and reliability people said it has to be hardwired. Can you imagine that? Why wouldn't you use bits instead of hardwire? Oh, but it's a lot safer and a lot more reliable. I will use my same word, hogwash. It is a lot safer and more reliable with bits. But that's the system. You've got to change it. And two of us have tried. You can see us flying down in flames almost everywhere. Yes, sir. For the young engineer, a lot of us hear about the Apollo Mission and talk about the good old days where we wish we were in the days of engineering by the seat of your pants. Is that type of job and that type of excitement of engineering possible in NASA's environment today or should we look elsewhere like towards private enterprises? Could we find the type of job we hear about in NASA these days? I have to be careful how I answer that. I want you in NASA. It is important that you guys be in NASA. Or at least in the Space Program working in the industry. Because you are tomorrow's opportunity. Just because you hear Chris Kraft say things that doesn't mean a damn thing tomorrow. You have to do it yourself. And you have to want to do it yourself. And you have to bring the ideas to the program. And you have to be willing to do that. And this willingness to take on the things that must be taken on in order to get the job done. Your question about seat of the pants, et cetera, sure, we did a lot of things when we first started by seat of the pants because we didn't know any other way to do it. We did it by feel. We did it by past experience. A lot of us had been in an airplane flight test world. So, we did it by having seen the past doing things the right way. That was our seat of the pants. Our seat of the pants wasn't just a scarf around our neck, so to speak. It was an educated seat of the pants. And that is what you have to provide. In the end it will take a lot of the seat of the pants. I think the way I know Aaron and I have done it was to believe in the people you had. You have to learn how to find out who the guys are that know what they're talking about and trust them. You have to put them in the job, give them the responsibility and authority to do it and then trust them. And you have to build them. The biggest problem that you have today, that NASA has today and the aerospace industry has today, the biggest problem, I cannot say that too strongly, is that they have not built anything in 25 years. And so they've forgotten what it takes to do it. You don't know how to do it. But if I put you on the job and gave you the authority to do it, you could do it in three or four years. You need my help and guys like me to tell you where the bumps in the road are. But you're going to do it a hell of a lot better than I did given the opportunity to do it. Did that answer your question? [AUDIENCE QUESTION] I think it is. You might have to help it. You have to vote. In the `60s, I was hoping that all these space cadets, all these Trekkies, all those guys would now be in the Congress and that they would vote for the Space Program. Boy was I ever dead wrong. There aren't enough Grateful Dead fans around. Yes, sir. Do you think the success of the Apollo Project was in some way linked to the ferment that was taking place in the `60s? Oh, absolutely. I think that we had an enthusiasm at the time that is probably unparalleled in engineering circles. Now, we had the Manhattan Project to build a nuclear bomb. Draper had the project to build a Polaris submarine, but it was clustered. What is that word? And it wasn't seen as we brought it to the fore. It wasn't a national program. It wasn't a national priority. It wasn't national pride. Nobody knew about it. Everybody knew about Apollo. I was damn proud to walk into any room where I ever went to say I worked on Apollo. That reminds me of a horrible cartoon, to make my point. I was in Austin, Texas following the Challenger accident. And here I am one of the proudest people to ever be in NASA. The cartoon in the paper when I got up that morning was the following. It showed these kids playing with a Frisbee. The first one throws it over here to this guy. The second one throws it back. The third one the damn thing explodes in his face. The fourth was says his father works for NASA. Boy, that brings it home to you pretty damn fast, doesn't it? Nobody in 1967, '68, '69 would have dared put that cartoon in the paper. By having new people in a space program there is always this lack of experience which you have to train just to have. How do you transmit that experience to the new people? You intermingle the young with the old. You bring the elderly engineers into the system and make you responsible for designing the system but have me in your hip pocket. After six months, two years, you won't need me in your hip pocket anymore because you would have learned all those things And learned them better and done them better. You have to mix them. The ingredients for the pie and the cake have to be there. And that is part of the ingredient. And why hasn't that taken place? Because of two reasons. NASA hasn't done anything in terms of building new hardware, other than the Space Station which really wasn't testing the state-of-the-art. It was a great program but didn't test the state-of-the-art. The industry has been doing the same thing. The industry has been building airplanes, but they haven't been building any spaceships so they've lost that capability also. That's the travesty, too. You've got to rebuild them both at the same time. But it only happens by experience. I cannot take what Professor Cohen knows and what I know and put it in your head. You have to fail a few times. It is only by the failures that you're going to learn. I once heard a sermon that said when you're a young Christian or Hebrew walking down the aisle all your doors are open. I am walking down the aisle and I'm pretty close to the end and all the ones behind me are shut. You're willing to go in all those doors. I am frightened to death to go in those damn doors. We need you and you need me, but you don't need me very long until you get up to speed. Don't be frightened of it. Go do it. And don't be afraid to fail. You learn much more from our failures than you ever learn from our successes. Back there. Given all these problems with NASA that we've seen just growing over the years, what do you think about the commercial efforts to access space? Not necessarily what is going on now but also in the future? If we had that ability to sort of bypass NASA's framework with all the [UNINTELLIGIBLE] bureaucracy issues, is that a possibly way for us to continue? Well, I think it is very possible but the problem is investment. The investment specialists say if you cannot give me a return on investment in three years, maximum five years, I won't invest in it. And the aerospace industry is worse than that. They don't have any money. They aren't willing to make an investment in the future. The investors who have the money want a return. The guys that have the capability to do it don't have the money to invest. Until it gets to the point where it is a little more realistic from the return on investment, it is not going to get to the point where commercial ventures are willing to do it. Because it is just too expensive. And probably if failure is so high in our business that investors shy away from it. I think it will come to that, but I don't think it is going to come very rapidly as it did, for instance, in the airplane business. I mean even today we wouldn't be flying the transports we have or the supersonic airplanes that we have without government having made that investment at the time. The 707, the first big really good jet transport, was totally dependent upon the B-47 airplane, which is built by the same people, right? And so it was a government investment. I said, well, we did it in an airplane business, to a certain extent, but nowhere near as much as people think. All of the technology was done by the government investment in the airplane. And the next step, the supersonic transport, which we ought to have. That is another travesty, that we don't have a supersonic transport. That hasn't been done by Boeing or Lockheed because they won't invest that kind of money on their own. They take the investment of the government in supersonic aerodynamics and engines and structure and use it in a supersonic airplane. I think it is a ways off. A lot of people have tried it, the most notable being Kistler recently, and have failed. I think it can be done and done better. You can do it better outside of the government because you don't have all those regulations to contend with and all the GAOs on top of you. It is just going to take a while. I hesitate to say this but I will. Programs like SpaceShipOne, that is trickery, that is child's play what he is doing. Wait until he tries to go to orbit. That is his next step. Tell me when that is going to happen. He is kidding the world at the moment. Chris Kraft says that. I want you to remember that because I could be dead wrong, but that is my opinion. Just child's play. We did the X1 in 1946. And we didn't have any buckling in the structure either, which he had. Where do you think that buckling came from? What do you think happened there? Where did it come from? But if his plane renews interest in space, I mean if it inspires a ten year old to end up working for NASA 15 years from now, isn't that a good thing? That is great. Absolutely. But don't kid yourself that the next step is flying a machine to orbit. I am at fault for being so negative about it because, you're right, I think it does inspire the young to do it. As much as I hate to cut us off, it is 11:00. Class is over. Students again remember to pick up your papers. Chris, that has been just an extraordinary opportunity and an experience for all of us. And, once more, we are very appreciative. We know you don't give very many public lectures these days, and that you chose to come here and talk to everybody at MIT, we truly appreciate it and we would like to thank you again. [APPLAUSE]