NASA JOHNSON SPACE CENTER ORAL HISTORY PROJECT
ORAL HISTORY TRANSCRIPT

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INTERVIEWED BY JENNIFER ROSS-NAZZAL
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ROSS-NAZZAL: Today is April 14th, 2009. We are honored today to be with Dr. Christopher Kraft, former Flight Director and Center Director for the Johnson Space Center. He is speaking with members of the JSC History Office staff, Jennifer Ross-Nazzal and Rebecca Wright, on the topic of the Space Shuttle development, a tremendous technical challenge for engineers at NASA.

KRAFT: I would like to say that being the Director of the Johnson Space Center, which I was from 1972 to 1982, was an interesting dichotomy. Up until that time I probably had the best job in the world as an engineer and as a manager. I don't mean to say that I was home-free or anything; I had a lot of battles, but that was okay. Some parts of it I didn't like, but 95% of what I did every day I enjoyed thoroughly. But after I became the Deputy Director and then Director, that changed significantly from a personal satisfaction point of view. There are a lot of reasons for that: people, associations, responsibilities, etc. Now what do I mean by that? Not sure I can explain that very well, but I'm going to try.

From a technical engineering, engineering management, or contract management point of view, I loved every minute of it. For an aeronautical engineer, it was one of the greatest challenges you could have. Here we were going from the fastest speed that we could go (in an X-15, about Mach 6) to fly at Mach 25 both in and out of space. We were going to face some of the most formidable challenges that could ever face an aeronautical engineer.

When we began the Shuttle Program, I had responsibility for Skylab and the Apollo-Soyuz Test Project. At that time we had a tremendous relationship with North American Aviation, North American Rockwell, North American Space Division—those were all the names the company went through. Before I even got in the space program, as a young aeronautical engineer, I had a great respect and admiration for North American Aviation. One of the first airplanes I ran a test on was an XP-51. They built the XP-51 in about three months, from zero to first airplane. So a lot of those people that I became associated with had been responsible for doing that.

I was on the evaluation committee for choosing the contractor for the Shuttle. Had I been given the choice, I probably would have chosen Grumman [Aerospace Corporation] but for good reasons we chose North American. The relationship was outstanding between North American and the Johnson Space Center which had the responsibility for the overall program as well as the Orbiter. The relationship we had was probably the best relationship with a contractor that we had ever had. They had built the Apollo Command/Service Module [CSM]; we knew those people too. They had had a struggle with the CSM, did a lousy job at first, as stated by Mr. [Floyd L.] Thompson [Director of the Langley Research Center, Hampton, Virginia] in the review after the [Apollo 204] fire. So North American had come a long way with us.

The work on the Shuttle couldn’t have been done without that kind of relationship. I’m making the point that these were good things. These were interesting ways of doing business, a rewarding way of doing business. We never had any disenchantment with each other no matter what we did. We went through a lot of hell together in those ten years [of development] until we flew.

On the other side of the coin, though, was the management aspect of NASA. Now why was that so bad? Well, in the first place, everybody wanted a space program. Nobody wanted to do away with the space program but nobody was willing to pay for it, in any shape or form—the Congress or the White House or the OMB [Office of Management and Budget] that was a part of the White House.

Many of the aerospace industries were absolutely nonsupportive. I mean that literally. You had guys like the president and creator of Lockheed Martin, [Norman R.] Augustine. He came in twice, at the request of the government, and said we shouldn't build the Shuttle, and we ought to get rid of it. Why was he that way? I'm not quite sure I know, but I know he had a vehicle (Titan II) which the Shuttle was a competitor to and NASA's spacecraft kept it from being the vehicle he wanted it to be. He's classical of the people that were opposed to the Space Shuttle. They fought it at every turn: financially, technically. They didn't see it.

The White House in the form of Mr. [Richard M.] Nixon—he didn't care about the space program. He showed up on the carrier (USS *Hornet*) when Apollo 11 landed and made the most of it politically. From that point on, he helped us none. When we came to the Shuttle, he did not support the space program. He just didn't want to kill it, because he knew it was one of the most inspirational programs in the country, and he knew that stopping it would not go over very well. The same was true of the Congress.

This was in contrast to the way it was in Apollo. In Apollo, we had a commitment in this country, not just from the 400,000 people who were space cadets working on the Apollo Program—they were marvelous. I'm not talking about them. I'm talking about the fact that we had the commitment from the Congress, we had the commitment from the White House, we had the commitment from the OMB or whatever they were called at that point in time. They argued with us, fought with us on many occasions, but they were dedicated to getting Apollo done. They were committed, and they knew the country was committed. When it came to the Shuttle, they didn't give a damn. One of the biggest disappointments of anybody's life in the space program was that at the end of Apollo, people could care less about the space program.

That's the way we saw it. Now, I don't mean that we were angry. I don't mean that we didn't recognize that there were all kinds of reasons for that. There were. But the contrast in the support of the program in the '60s to what we saw in the '70s was black and white. Now that's what made it a dichotomy. That was very hard for us space cadets to live with.

So here I am, having the time of my life as an engineer but a terrible time as the guy now responsible for all, at least pretty much all of it from a NASA Center point of view. There were lots of people at [NASA] Headquarters [Washington, DC] above me that were responsible for the Shuttle Program and did a fantastic job, starting with George [M.] Low [Deputy Administrator of NASA, 1969-1976] and Jim [James C.] Fletcher [NASA Administrator, 1971-1977], and eventually Dale [D.] Myers [Associate Administrator for Manned Space Flight, 1970-1974] and John [F.] Yardley [Associate Administrator for Manned Space Flight, 1974-1976] and their organizations, and the NASA Headquarters organization, including [William E.] Lilly [NASA Comptroller]. My goodness, they all did a fantastic job of supporting the program but getting little support particularly from the White House and the OMB specifically. There were too many people in the Congress that didn't want the program either, starting with [US Senator William] Proxmire and [US Senator Walter F.] Mondale.

ROSS-NAZZAL: As you pointed out, the Shuttle Program seemed to be so unpopular with the Congress, OMB, the President. Was there any one person or one event that really helped to keep the Space Shuttle off of the chopping block? Because for so long it seemed like it might not make it. There were so many financial concerns.

KRAFT: Yes. I think if you read the book *History of the Space Shuttle* [T.A. Heppenheimer, Volume 2], [George P.] Shultz [Director of OMB, 1970-1972] and [Caspar W.] Weinberger [Director of OMB, 1972-1973] both were saviors of the program from a financial point of view. They saw the value of the Shuttle. They helped us a hell of a lot, but we needed more. It's just that they were in a position where they couldn't do much to help us. We never got the fulfillment of the agreements, the commitments that we had gotten from them initially. We never came close to getting what they said we were going to get. That really made it, in the latter phases of the program, very difficult to manage.

It was a challenge but I think we did a pretty good job. Bob [Robert F.] Thompson [Program Manager for the Space Shuttle Program, 1970-1981] and Aaron Cohen [Manager for the Orbiter Project Office, 1972-1982] at our level, and then John Yardley fought, fought, fought, oh, man, brilliantly. So did [Robert A.] Frosch [NASA Administrator, 1977-1981] and [Alan L.] Lovelace [Deputy Director of NASA, 1976-1981]. They were strong people. Fletcher was marvelous, and came back again, and died in office almost, contributing his life to the space program. There were a lot of really wonderful people that made the program, saved the program in the '70s.

We were very fortunate to have them. It's just that it was distasteful as hell to watch the other side of the picture. Again I use that word dichotomy, because I go back to that statement I made. Everybody wanted to keep the space program. Nobody wanted to pay for it. Lord knows we didn't ask for a lot, relatively speaking. We wanted to build a totally reusable machine.

Well, that isn't what we wanted to do at all. What we all wanted to do was what Mr. [Thomas O.] Paine [NASA Administrator, 1969-1970] and the Vice President's commission [decided.][1] Both of those groups came up with what we wanted to do.

Dr. Paine had said, "We're going to have 100 people walking on Mars by 1986," so I say the Shuttle was a fallback position, as far as we were concerned, from a glow in our eyes point of view. It was what we decided within NASA. If we were going to maintain the space program, and all we were going to get was a pittance relative to what we want to do, then the right thing to do is try to build a lower-cost totally reusable machine to go to and from orbit, because that's where the next steps were going to take place.

If you're going to build a Space Station, if you're going to go back to the Moon, if you're going to go to Mars, if you're going to do things that make space commonplace from an industrial point of view, then you have to have a viable workable space transportation system. That's where it starts. That's when we said, "Well, okay, that's what we'll do. We'll go with that." Then when we presented the bill for the totally reusable machine and it turned out to be about $14 billion, Nixon said, "No, you can't have it. You can have half of that," is about what he said.

So we went back to the drawing board and came up with what we did. It was a compromise all the way around. It doesn't look like it today, but it was. We didn't have enough resources to build our dream machine. We didn't have those kinds of resources.

Shuttle was unlike Mercury, Gemini, Apollo, where we would use about 10% of our resources in developing new technology from which the next programs could benefit. Not so much in Mercury, but very much so in Gemini and Apollo. I'm talking about fuel cells and

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[1] In 1969, the Space Task Group released a report called, "The Post-Apollo Space Program: Directions for the Future."

computers and automatic reference systems, and IMUs (inertial measurement units), advanced materials, a more resplendent communication system both from a spacecraft point of view and a data collection point of view, and so on. All of those things we developed as we were going along, with a certain amount of the resources to get those things that we would use for the next program.

When we got to the Shuttle, we didn't have a damn dime for this purpose. As a matter of fact, I used to fight for $100,000 [at a time] and Yardley begrudgingly would give it to me. He wanted to get me more, but he didn't have it. That's so much of what it is today. I have talked to [Michael] Griffin [NASA Administrator, 2005-2009] about that. I said, "My biggest disappointment in the Constellation Program is you're not spending a dime on new technology." He said, "Yes, you're absolutely right. But I can't do it." He can't. That's what NASA is faced with today. They aren't spending any money on new technology. They are forced to use yesterday's technology, and they're forced to use the machines they've got: the engines, the APUs [Auxiliary Power Unit], etc. They are having to resurrect those things to make them as good as they can, but this is not what they ought to be doing.

We should be advancing the state-of-the-art. That's what we should have done for the Shuttle. I blame that on [Daniel S.] Goldin [NASA Administrator, 1992-2001], because he got something like $1 billion a year for quite a few years to renovate the Shuttle, modernize the Shuttle, and he spent it on the Space Station.

All of those things were difficult to deal with from a go-to-bed point of view. I don't know about you guys, but I go to bed and I wake up in the middle of the night thinking about those kinds of things. Kind of ridiculous, but I guess that's what I do. It's hard to know that you could have done better. It's hard to know that you can do better. It's hard to know that we aren't going to do better on the basis of what we can do.

Everybody talks about, "Well, if we could go to the Moon, we ought to be able to do *this*." Mr. [Barrack H.] Obama recently said, "We can go to the Moon, we ought to be able to solve the energy problem." [The President] hasn't got the slightest idea what he just said. It's a catch saying. He doesn't know the commitment and dedication that was required not just by the people that did it throughout the space and aerospace world, but throughout the government. Sure, we can do it. As a matter of fact, the biggest legacy of Apollo is that you can do anything you set your mind to, that is the biggest legacy. We forget it, but it is. We could solve the energy problem in a New York minute if we got the commitment to do it. He doesn't know what he said when he said, "If we can go to the Moon, we can do anything." He is right, but he doesn't know what he said.

This is a thought that I want to share when I stand up at the [Smithsonian National] Air and Space Museum [Washington, DC, on July 19, 2009] with the three astronauts who first went to the Moon during the [Annual John H.] Glenn Lecture. I've been asked to speak for 15 minutes. My chore is to set the stage but that's how I'm going to end. I'm going to say, "I want you to know we all say, 'Yes, if we can go to the Moon we can do anything,' and you're right, except you don't know what you're talking about. You don't know what it means."

ROSS-NAZZAL: That's a very good point. You started out the interview telling us about how technically complicated the Space Shuttle was, and how exciting it was from an engineering point of view. Would you talk about the complexity of the vehicle and the challenges that you faced during development?

KRAFT: Well, it was sort of like Gemini. With Gemini, we made a list of all the things we had to do for Apollo and did them: EVA, guided reentry, fuel cell power, docking to another vehicle, rendezvous and docking, fourteen-day flight. We set those as goals and did them, made a list, and built Gemini to do that.

If you made a list for the Shuttle, it would be the engine; it would be the automatic guidance and control system. All of these were technology challenges, which we did not have, such as a reusable thermal protection system that would stand temperatures up to 2,600 degrees Fahrenheit, structural development with extremely lightweight structures, and the use of graphite structures. First of all and last of all, the SSME [Space Shuttle Main Engine]. We were trying to build a hydrogen oxygen engine that was perfect from an energy recovery point of view. The highest Isp you could get from mixing hydrogen and oxygen is 458. We got 456 in the SSME; that much efficiency is unheard of. So that’s a list of the things we had to accomplish.

We were trying to build a machine which could do two major things besides being reusable of course. Number one was to be able to fly normal human beings to and from space without having to endure high G. Look at the Russian vehicle (Soyuz-TM); today it still comes in at nine G. The Space Shuttle comes in at one-half G because it’s a flying machine.

Second, we wanted to be able to take payloads into space, which had a relatively benign environment. When you put a payload on the end of an Atlas or a Titan (rocket) today, it shakes, rattles, and rolls. With all kinds of shaking and vibrations, you have to build the payloads to withstand the very very difficult rough environment. We set out in the Shuttle to fly normal human beings to and from space, and fly payloads that could transpose their structural requirements into paybackable measurements or whatever you wanted to take up there. You didn't have to design the spacecraft to be so structurally responsive to those heavy loads. We accomplished that. Now, that isn't what the Air Force wanted but that's what made the vehicle what it was.

The Air Force, why did we have the [Air Force]? We had to have the Air Force because if we hadn't had the Air Force, we would have never sold the Shuttle. It would have gone down the drain. The Air Force wanted to take a 65,000-pound payload and put that in orbit as a reconnaissance vehicle. They gave us the dimensions and that set the size of the payload bay. They wanted to be able to fly once around the Earth and land at the same spot and that set the second biggest requirement. Had to have a high L/D (lift to drag) relatively speaking, or in other words it had to have a cross-range of somewhere between 900 and 1,100 miles to do that.

Those two requirements, really, were the predominant requirements for the Air Force and therefore the Shuttle, and were not the requirements of NASA or the commercial industry. Now, I don't want to belittle the fact that once we had it, it's been a tremendous asset. Sixty-five thousand pounds into low Earth orbit is pretty darn good. Everybody complains about the cost. Well, it does cost a lot. Frankly, the next challenge ought to be being able to launch the Shuttle with two people in the Launch Control Center. Two.

ROSS-NAZZAL: This coming from the first Flight Director.

KRAFT: Two. Well, I didn't have anything to do with the launch activities. I didn't set the launch requirements, and I didn't design the Cape [Canaveral, Florida] facilities. I wish I had had that responsibility. Actually, I did have the opportunity, once in 1995, and told them how to get rid of two thirds of it.[2] They didn't listen. But I told them how to do it. That wasn't good enough.

We tried to build the Space Shuttle so it could be turned around in two weeks. The only way to do that was do away with Cape Canaveral, frankly. But to do that was to take the telemetry, look at the system performance, replace, and fix all those things that were wrong, and go again. You could do that today, if you wanted to, because it does have that capability. That was one of the other requirements of the Space Shuttle, which we tried and lost. I don't think enough attention has been paid to that.

ROSS-NAZZAL: Talk, if you would, about your relationship with the Air Force when you were Center Director and some of the challenges that you faced. You had worked in the 1960s as a very open agency, and now you were working with the Department of Defense.

KRAFT: I never had a problem with that. I said to my peers on many an occasion, "Look, we are here to serve the Air Force. We will do whatever is asked for us to do. You [Air Force] tell us what you want done, how you want it done, we will do it." I never had that as a problem. Most people begrudge the fact that we had to work with the Air Force. I did not. That's what we said we were going to do. We were committed to building a machine that would service the country. So I invited them into the tent; I trained 200 of their people continuously, because they had a group at JSC. We trained a group of flight directors, and we trained a group of flight controllers and sent them back to the Air Force.

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[2] That report was issued in February 1995, called the "Report of the Space Shuttle Management Independent Review Team," and is known more commonly as the Kraft Report.

We used them, too. They were a great asset to the program. We had a whole continuous contingency of the Air Force. We taught them the space operations as well as space engineering. We sprinkled them all over our whole Center, both in Engineering and Operations, and taught them everything they ever needed to know about spaceflight. So I don't cotton to the fact that a lot of people thought we did not get along with the Air Force. I don't think that was a problem whatsoever. Frankly, without the Air Force we would have never had the program.

ROSS-NAZZAL: Tell me about working with some of the other NASA Centers, in particular Marshall [Space Flight Center, Huntsville, Alabama] and Kennedy [Space Center, Florida].

KRAFT: Well, that's tough for me, but let me start my statement by saying, I thank God for Charlie [Charles J.] Donlan [Deputy Associate Administrator, Office of Manned Space Flight (Technical), 1968-1976]. Marshall wanted desperately to have its own space program from the get-go. At first, Marshall stayed out of NASA, hoping that they would get their own space program. Finally when they realized they couldn't get their own, they decided to join NASA. They wanted what we [JSC] had all the time. They wanted the astronaut corps. They wanted the Mission Control Center. They even built a Control Center without anybody knowing that it was there. Did you know that? They built a mission control center in Huntsville, Alabama, with the expectation of Skylab and they were going to run the program.

ROSS-NAZZAL: Didn't know that.

KRAFT: Absolutely. It was only because of this guy sitting right here that it didn't happen. They were always extremely competitive with us. When we got to the Shuttle, they wanted to run the program. They were unhappy when it was decided, and with the discussions that were being had [of] not being able to do everything. They wanted to do everything on their own as opposed to being under the auspices of what we now call Level II organization. They didn't like that. They didn't want it that way. They wanted their financing, their orders, their technical control to come from Headquarters, not from another source under Headquarters.

It was Charlie Donlan initially, and then under John Yardley, that it was recognized that that was foolishness. It was hard enough to build the Shuttle Program with one head, much less having two heads. So we always had a battle. Eventually after I was Center Director—it was '72 or thereafter, we had a meeting in my office. Marshall came in, and we were arguing back and forth about who was going to do what to who organizationally. Charlie Donlan met with us and said, "This is the way it's going to be." Thank God.

ROSS-NAZZAL: Can you tell us a little bit more about that conversation?

KRAFT: Well, it was very distasteful to Eberhard Rees, who was their Center Director at the time.[3] They were very upset about that, but they accepted it because they had to accept it. They eventually got their money from Headquarters. But we, Bob Thompson, who was really separated from me but under me, if that makes sense; he wore two—we all wore two or three hats—but he wore a hat that answered to me, but he also wore a hat that answered to Myers and eventually John Yardley. He was responsible for preparing the total budget from a Center point

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[3] He served as Director, Marshall Space Flight Center, from 1970-1973.

of view, and then the Manned Space Flight Organization Headquarters took that, put their own English on it and whatever else, and went forward with the total Manned Space Flight budget. Marshall would get their funds through that process. They got the money directly from Manned Space Flight. It's ludicrous, but that's the way it was. It was, "Well, okay, we'll do it that way if that'll make you feel better."

It's always been that way. … On and on. I'm just very prejudiced, though, so you have to take whatever I say with a grain of salt.

ROSS-NAZZAL: Everyone's got their own perspective on things, yes.

KRAFT: I realize that. I got along very well with Eberhard Rees. He and I were pretty close friends. [William R.] Lucas [Marshall Center Director, 1974-1986] was [not supportive]. I'd call him from my office when we would want to do things from the Center point of view, and I would ask him to support my ideas, and tell him specifically what my ideas were. He would agree to all that and then go to Washington and fight me tooth and nail, every time. The people that worked for Lucas, I'll tell you, I really feel for those people. A couple people in recent years have gone over there and worked in the environment in Marshall and stayed there six months and quit—very bad environment over there. That originated from the German military type of management style. Nobody says anything without the boss saying you can say it. That's the way it is. Still is. It's still that way today, this very day, at Marshall.

ROSS-NAZZAL: JSC was the lead center for the Space Shuttle Program.

KRAFT: Yes.

ROSS-NAZZAL: Can you talk about that and what impact that had on the program as a whole and perhaps the development, how that proceeded?

KRAFT: Well, in any project if you start having multiple heads, you're going to get in trouble. When I make my speech to the co-ops (students at Johnson Space Center), I always start off with, "I don't like to criticize other people's work." Because if and when you do that, you have to know what the constraints are, and then you have to know what the compromises are. Unless you know both of those things, you have no business criticizing other people's work.

When you start with a major objective, somebody has to decide what the constraints are, and then somebody has to make the compromise decisions that have to be made every day. It's impossible to get everybody to agree that that's the way to do it. But that's management. That's what program management is. When you don't have somebody in charge, you lose that management or leadership tool. That's the way I see it anyway. Therefore you have to have somebody in charge.

We had somebody in charge in Headquarters, and then from a really technical management point of view you needed somebody below that level. Bob Thompson used to say, correctly so, "we'll let them make 2 or 3% of the decisions, and we'll make the other 97." You can't make those decisions at a very high level. You have to make those decisions at a consensus level. If you don't, they aren't very good decisions either. You have to battle out the real tough decisions; you have to know all the ifs, ands, and buts. If you don't, then it isn't the best decision, but it is a decision.

ROSS-NAZZAL: Can you give us an example of some of those decisions that were made?

KRAFT: Sure. We made them every day. How much are you going to test this? Are you going to test it? Are you going to build a test configuration? Are you going to do this, which costs money, costs resources? Somebody has to decide whether that's a requirement or not, every day. You can say, "Well, if I wait another few days or another few weeks or another few months, I can make a better decision." Of course you can, but you might spend a hell of a lot of millions before you get there, and you'll never get there if you make that kind of decision.

That's the reason scheduling is so important. You have to make a schedule which is realistic but forces the system. That's what financial technical management is in the engineering world. You have to be willing to make the compromises. I think I said this to you before, relative to the software on Apollo—we couldn't get it out of MIT [Massachusetts Institute of Technology, Cambridge, Massachusetts]. Everybody needed it. The analysts needed it for structures, the trainers needed it for training astronauts, people needed it for making flight plans, on and on and on. We had to know what the software was going to do, how it was designed, what its tradeoffs were. We couldn't get it out of MIT.

George Low asked me to go up there. I wasn't there ten minutes, not ten minutes was I there that I didn't see what the problem was. They were all just continuously making it better and doing whatever anybody wanted done in the software. I just said, "Well, I'll give you 30 days. In 30 days from now we're going to freeze the software. No change will be made from that point on without my signature." My God, the software came out of there like spitting out seeds. Literally.

That's all that had to be done. I didn't do anything. I didn't know a thing about software, but I knew a little bit about management, and I knew that that's what their problem was. Well, that's what most engineering problems are, is that you just got to suck it up. You make some wrong ones (decisions). You just have to go correct them when you find out they are wrong. We had to correct quite a few in the Shuttle.

I don't know if Bob Thompson talked about this or not (in his oral history). He should have, because he had to carry it out. But when we started the detailed design and structural building, the actual building of the Shuttle, we decided, "look, we've got a lot of experience now in systems. We know environmental systems, we know hydraulic systems, we know flight control systems, etc., structures, on and on." In the past when we have developed these things we always had a development set of hardware. A development environmental control system, a development of control systems, a development of the electronic systems all set up and operating. That's what this total automatic control system was. We had those things which were actually hardware which was never meant to fly, or systems that were never meant to fly, or software that was never meant to fly that we would do first, learn all those things from that, and then build the actual flight or hardware or software.

We said in the Shuttle, "We're pretty smart now. We have all this experience. So we know what we think we can do without those development programs, because it will save a hell of a lot of money. Let's just go build the hardware. Let's go build the environmental control system without going through the step of a development system." Did that on fuel cells, we did that on the hydraulic systems, etc., etc. We failed in some cases. We had to redesign the whole hydraulic system. Cost us a lot of money. We had hydraulics research built the first set, and it was terrible. We had to go to Moog [Inc., New York] and start all over again with a whole new company and a whole new system. But most of the ones we decided to do paid off.

ROSS-NAZZAL: There were some complications with a few of the systems, like the tiles for instance.

KRAFT: All of them.

ROSS-NAZZAL: Can you talk about the challenge of coming up with that system, then attaching them to the Orbiter, and the problems that you encountered as Center Director?

KRAFT: With the tiles? Well, that's quite a story. Yes, I can do that. I lived it. I spent many a day at Lockheed, Palo Alto [California], watching it being done, management meeting after management meeting. I'm not talking about all the technical stuff that was going on but what happened there in retrospect was a very, almost comical situation. We had General Electric [Company] and another company inventing reusable insulation. They were both using different approaches to develop the same material.

Max [Maxime A.] Faget [Director of JSC Engineering and Development, 1961-81], and his people in thermal analysis had come up with this material. Any good insulation is air. Insulation is air, so what we tried to do was build a foam type insulation which could withstand high temperatures. We selected one of those approaches. Turns out it's mostly glass. Take sand and make glass out of it, or insulation, that's what we use.

We knew what the concoction was. We didn't know how to manufacture it very well, that is—build the foam and then figure out how to mix it and make the process a repeatable process, determine what size we could build it in, and how to machine it. We had some ideas. We had contracted through Rockwell with Lockheed to build a factory and produce the tiles, because they had a lot of experience with that kind of material. At that point, we didn't know how we were going to put them on [the Orbiter] either. We had some ideas, but we didn't know how we were going to put them on.

Well, we produced a couple hundred tiles and measured the physical properties of the tiles. They were about what we wanted. One of the things we measured was the tensile strength of the tiles. We found that to be somewhere between 12 and 14 psi [pounds per square inch]. Okay, so that's what we decided to use in the design of the Orbiter structurally. We've got a material here that will withstand 12 or 14 psi. The loads are aerodynamic loads, thermal loads, and internal stresses.

We decided that we could build the structure out of titanium. However, there were three things wrong with it: very expensive, relatively heavy, and we don't know a thing about the physical properties of titanium —I don't mean that literally. But we didn't have the engineering know-how and experience that we do with aluminum. We had been building airplanes with aluminum for 50, 60, 70 years. We know all the different classes of aluminum, different alloys of aluminum, 24ST, 22ST, 28ST, on and on and on. Some were built for various purposes and heavy stresses, heavy shear loads, temperature, constant temperature. We knew all the physical properties that you could possibly think of and had experienced them with aluminum. All the airplanes were that way; all that manufacturing, even welding with aluminum, which is very difficult. So we wanted to use aluminum. That said, we wanted the bond line temperature of where we put on this insulation to be no greater than 270 degrees Fahrenheit, because that's where aluminum starts losing its strength. Actually it's about 300, and 270 keeps you 30 degrees away from that.

Okay, I've got this tile, and I am going to use this material. I've got 12-14 psi, and I know all the properties. I'm beginning to understand how I'm going to machine it. I know that I got these stresses and therefore I can't build just any size pieces—I'd like to build big pieces, but if I do that and stick it on there, it's going to break because of the structural loads which the aluminum is going to see. Any airplane wing goes up and down and moves. The wing on a [Boeing] 747, when you lift off, moves up six feet, from what it is on the ground. It deflects six feet, so the wing is doing this. [Demonstrates] It doesn't look like that, but that's what any wing on an airplane is, doing this. It flops, just like a bird. Now if you try to stick on too big a piece of tile, it's going to crack, because it doesn't have that kind of strength. We had to build small pieces and allow for the tile to move. That's the reason there are gaps between the tiles, to allow the tiles to move up and down.

At the time, I didn't have the money to build a factory. It wasn't a high enough priority yet, and I didn't need the tiles until down the road. So I can't build a factory, and when I do, it's going to cost me 200 million bucks. It's going to cost me almost that much to buy the machines because you have to have a five-axis machine. At that point there were 32,000 tiles on the machine. Every one of them has six different faces, all different. This way, bottom and top, and the sides. [Demonstrates] Six different surfaces that have to be done by drawings.

We have to make the drawing for 32,000 tiles because all of them vary in thickness. Why? To keep the aluminum at 270-degree temperature maximum. Then, say I want the variation in temperature from here to here to be no greater than ten degrees. Why? It produces another stress. If this over here is 160 degrees, this over here is 180 degrees or 200 degrees, it moves. That puts another stress on the tiles. So I got to keep the surface temperature relatively constant all over the whole machine. The thickness varies. The thickness on those tiles on the machine varies somewhere between a half and four inches thick. Half to four inches thick. That's a pretty big requirement for 32,000 tiles.

So, I don't have the money to build a factory. I don't have the money to buy the machines yet, and I'll have to buy those from Japan. They're the only ones that make five-axis machines at that point in time, and each one of them cost something like $250,000 apiece. I don't know how many we needed—somewhere between three and six. I know we ended up buying more than we thought we needed.

We didn't know how to make these ingots, out of this material, and have them all have the same properties all the time. We didn't know at what temperatures to bake them to get this thing into the condition that I wanted the foam to be in. All these things I didn't know how to do.

I'll tell you a side story there. We were having trouble trying to figure out how we would prove statistically what the strength and properties were. So we called in the Franklin Institute [Philadelphia, PA], and they made all these studies for us. They came in and made this presentation to us. I'm sitting in the audience. They say, "You got to make all these tests to prove what the repeatability is and therefore what the statistics is of this material." I asked them, "Well, how many do we have to do?" The guy says, "About 10,000." I said, "We aren't even going to build 10,000." That's what he said. You have to test 10,000 before you can believe the statistics. I think he's right, probably true.

Because NASA didn't have the money to build the factory, we said, "We don't need them until T minus 18 months. We'll have the factory ready at that point in time. So we can delay that money until two years before we need them." We finally got the money and got the factory built. We started producing the materials, and we had a lot of trouble with that, processes, control. What we ended up doing was buying a bread factory.

ROSS-NAZZAL: Did you really?

KRAFT: Literally bought a bread factory. You know those big paddles that you mix the dough with? We had two of those machines, and that's where we put the glop. Put glop on this, add all these chemicals in there, and silicone. Do all this, bring them out. We had to figure out how to cast them, what size we pour in.

Bread goes down a long belt controlled machine with electrical heaters in it, that's the oven. The bread goes through there and that's how you bake the bread. We bought a couple of those machines and baked the ingots. Ended up with these ingots about like this. [Demonstrates] Then figured out how to cut the ingot with a special saw and figured out how many we needed. Thirty-two thousand of them—had the drawings for all of these.

We determined how to do the tests. We cut the tiles with a laser. We measured the density of the material, which we had to control very carefully, because if you don't, you don't get the consistency of the material and therefore they don't get the thermal protection out of it. We had to determine how to measure when we got through, how to measure each tile, what the tolerances are in N dimensions, etc. We got all that figured out. Started producing tiles, started cutting them, started getting them on machines.

We came up with this idea of not gluing the tiles directly to the aluminum, but gluing the tile to a strain isolation pad, SIP, very fancy name for a piece of nylon felt. But we did that because that allowed the tiles to move. The skin would move. Instead of the tile giving, the SIP gives. We had a lot of people, a lot of very very famous people that told us that it wouldn't work. But, that's another story.

We decided to use a specific kind of glue. We had to use it under a vacuum, because this glue has to be very carefully controlled in its temperature and its atmosphere, because if not, it changes the characteristics of the glue. So here's the way the tiles are put on. You build these big squares full of tiles that are on the SIP. Then you put a big vacuum jacket around that one section, slap them up there, and glue the SIP to the aluminum. That sounds fine.

Well, now we got this material, but what are the physical properties? Okay, we're going to go measure it. You know what the tensile strength we got out of that was? Seven psi. Half of what we wanted. Half of what we wanted. Boy, you don't think that crap didn't hit the fan that day.

Now how are you going to solve that? Pretty simple really. It is now. It is pretty simple. You just go where you're going to glue the bottom surface of the tile to the SIP, go make it denser, because it turns out that only about half the fibers of the tile and the SIP are in contact. That's the reason the strength is what it was. If you go densify the tiles, then you get the strength back. You can get it back to about ten, eleven psi. That's what we did. That's the tile story.

ROSS-NAZZAL: That's a great story.

KRAFT: It is quite a story.

ROSS-NAZZAL: It is.

KRAFT: It's a hell of a story. Our guys, they did a great job figuring all that out. Now during this time we're having quite a time getting the tiles on the machine. We would put them out there and then run a test on a big section of them. The things would fail until we figured out the process of how to do all that. Yardley is up there [at Headquarters] driving us crazy. We were taking tiles off, putting them back on continuously on the first machine. We'd get about 1500 or 2,000 on, and then the analyst would come up with another story, and we'd have to rip them all off and put them back again. He got so mad about that he cursed me out one day. He literally cursed me out. He made this decree, "From now on you can't take a single damn tile off that machine unless I approve it." We absolutely ignored that [decision]. If we had done that we'd have still been out in California putting tiles on the machine. Those kinds of things were funny.

ROSS-NAZZAL: Are there any other stories or examples of other systems on the Orbiter that you can recall, like the APU or other systems?

KRAFT: Oh yes. The APU drove us crazy. That thing turns up at 72,000 rpm [revolutions per minute]. You know what an APU does? It's got a wheel with all these fins, with all these blades on it like the internal guts of a jet engine—well, that's what this is, only one blade. But you put steam in there and drip it onto a catalyst bed. That produces steam at about 2,000 degrees Fahrenheit, and that's what goes through the APU and turns it up at 72,000 rpm, drives a pump, which drives the hydraulic system. This thing is a bang bang system. You just put the amount of whatever that chemical is on the bed, depending on how much power you want to produce—and that varies with time or with use and depending on maintaining the hydraulic pressure at 3,000 psi. Very high pressure by the way.

We wanted strength versus weight. We used a poppet valve, and it sits there as you drip this stuff out, and it induces very high loads into the valve, which has a seat. The valve is going like that [demonstrates up and down], and the seat—we couldn't get the material in that seat to withstand the loads, both the thermal and impact loads. We tried material after material, and we'd come up with the answer, then go build it and work it, run tests on it, it didn't work. That was a big struggle. We probably used six different very complex alloys to make that seat. They're still changing the seat alloys. A couple flights ago they had to change the alloy again.

Also, we were afraid the thing was going to explode on us because as these blades turn up to 72,000 rpm literally, the grain structure in the blades grows. Starts out [demonstrates], then it ends up being another quarter of an inch bigger in diameter because the centrifugal force makes the blades grow. You can't have too much bypass at the cover where it is contained. The blade is going around and it's got a cover, and so you don't want it to bypass too much around the edge of the blade, but you don't want it to run into the cover when it expands, because it'll explode. It'll get so hot in there the thing will blow up. We had several of them blow up. Plus, it's sitting in the back end of the Orbiter. You don't want one of those machines blowing up, blowing the side out of the Orbiter. That was a big problem. So it took us a long time to get a satisfactory APU.

Structures—when we built the main fuselage, Convair had some very special machines that they had developed down in San Diego [California]. They'd been building rods—when you build a rod, you put an aluminum fixture on the end of it, and you either glue it or weld it to the end of the rod. It has a little shaft and a rod-end bearing inside that hole. You had to have that on both ends of this strut.

They came up with this process of rolling graphite with fibers. You can build these metallic fibers to embed in the graphite and roll it and then put it in a very high-temperature and high pressure. They developed that process. That's what we used to get a lot of weight out of the struts that we built the fuselage out of. That took a lot of doing, a lot of testing, a lot of process work, a lot of work on the machines that did that.

We had to build a very strong lightweight thermal environment set of structures to take the loads of the engines in the back end of the Orbiter. The B-1 [Lancer Bomber] had been building its attach structure for the wing to the fuselage out of this process. They took pieces of titanium—we wanted to use titanium because it was lightweight and very high-strength and would withstand pretty high temperatures. They'd come up with this pressurized process on the device where you could get the pressure and the right temperature simultaneously. What you do is you lay up strips of titanium on the order of three quarters to one inch thick, and you just stack them up. The reason for doing that is that the strength of a bar is higher in the middle than it is on the sides, because the grain structure is different and you get better strength in the middle. But you can't make the bar any more than about three quarters of an inch thick, because now it gets too weak.

What they came up with was laying up little bars, and then with just the temperature and the pressure forcing that into one big piece of structure, which now is a big thing like this. [Demonstrates] It took us a while to figure out how to do that with such a large piece, and then how to machine it so the whole mass will be in the shape you wanted when you got it out of this device. This fusion bending process took us a long time, a lot of hard work, very expensive.

Let’s talk about the lines that go from the tank into the three SSMEs, the hydrogen and oxygen lines. You’re delivering something like 4,000 pounds per second of oxygen and about half that in hydrogen through the pumps, pumping that from the tank. So we had to have jacketed lines, one of them was 17 inches in diameter, and the other one was eight inches in diameter. Those lines had to come all the way in from the interface with the tank all the way down into the three engines. They curled around inside the back end. They had these compound curvatures, and then were vacuum jacketed to insulate the liquid propellants to reduce the thermal loss.

We had a hell of a time down at a place called Arrowhead in southern Los Angeles [California]. We had people living down there for about three months to figure out how to weld those pieces together and then maintain the validity of the vacuum, and run all the tests necessary to prove that it’s structurally sound as well as would do the job thermally. This place had an ex-Marine general running the company who didn’t know much about what we were doing. So we had to send a whole group of people from North American and JSC down there to live with them for something like three or four months until we got that stuff figured out, how to get it out of that factory. We were stuck with them. We had given them the contract. We had about 75 major subcontractors.

I visited every one of the contractors at least three times along with Cohen and the Rockwell management. Some of them 20 times depending on what kind of problems we had. George [W.] Jeffs [North American Aviation/Rockwell], Ed Smith [North American Aviation/Rockwell] and their contracts guy, and Aaron Cohen and myself and whoever was the appropriate engineer from JSC, we got in a Sabreliner about once every—depending on what the problems were—about once every two, three months. We’d meet in Los Angeles, get on a

Sabreliner, or they'd pick us up here, and we would visit about six to eight prime subcontractors in about two and a half days. We went everywhere.

We went to Corning, New York, where they built the glass for the windshield. You ought to see that process, that was really something, I tell you. The way you make glass is you melt sand, and when you melt sand you make what they call boules. You grow it. You start with a little piece of melted sand, and you just build it up and build it up and build it up. That's the only way you can get glass that would withstand 1,700 degrees Fahrenheit and still have structural integrity. So we built these big glass boules that were maybe about like that in three dimensions, [demonstrates] and then you cut the heart out of it. That's the piece of glass you'd use. It'd have to be as close to optically perfect as you could make it and still withstand 1,700 degrees Fahrenheit and not be shattered by meteorite impact. That's a piece of glass.

ROSS-NAZZAL: That is, that is.

KRAFT: We had maybe about ten or 12 pieces of glass in the cockpit. I went up there to look at those factories several times. We went in, and they'd show me the sand and show me the glass being done and the boules being made. It was very important for somebody like me to go there, not because I knew a thing about glass. But it was good for me to let them know that what they were doing was important to the program.

ROSS-NAZZAL: How was that similar to what you did during the Apollo Program? Was Shuttle development and Apollo development similar? Or were they very different?

KRAFT: No, I don't think so. I think North American did most of it themselves, from a management point of view, not from an engineering point of view. All of our engineers were all over the place like ants. But I guess it was me. I don't know.

That's what I wanted to do. They wanted me to do it. I'm Chris Kraft now. That doesn't mean much in most places, but it does mean something in the space business. It was good that Aaron [Cohen] and I would show up—here's the program manager from NASA, here's the director of NASA, here's the president of Rockwell Aerospace, here's the program manager, here's the chief engineer, and the engineer that's got the responsibility within North American for the APU. We were in Sundstrand [Iowa] one morning when it was minus 40 degrees.

ROSS-NAZZAL: Wow, that's cold.

KRAFT: Went there a lot. Sundstrand is in the middle of the Corn Belt. We'd get off the airplane, one of these small airports, and drive down through the cornfields, these big cornfields. We landed in Binghamton, New York, in an ice storm. All kinds of experiences.

ROSS-NAZZAL: The Shuttle was so complicated. You were going to launch in what—'78 originally? Then it kept getting pushed back. Was there ever a sense from your perspective that gosh, we're never going to get off the ground?

KRAFT: Well, it's one of the stories I came here to tell you about budget, about management. I don't remember the exact dates. In about '76 we had a big, big meeting at Goddard [Space Flight Center, Greenbelt, Maryland] with all the top management throughout the whole program.

Initially it was just NASA, and then with the major contractors, where we discussed the budget problems. They were horrendous. We had been pushing about a 10% bow wave in dollars every year after about '75. We had been promised a fixed amount of money. We accepted a fixed price contract. We had accepted a certain amount of money to be doled out in certain fiscal years with inflation, with contingencies. We never got any of that.

They wouldn't even admit that there was inflation in the OMB. They still don't today. Whenever they do the budget they don't mess with [inflation]; so when NASA gets its budget if inflation rate in 1975 was 3%, you got the dollars the same but the 3% less buying power. They were supposed to give us that in addition to the money. We were supposed to give us a certain amount of money every year. Never got a damn dime of it. Always got less, on the order of 5-10% less. Or you got a continuing resolution because Congress couldn't come to an agreement, like they still do today. So we were fighting a big bow wave of money. In '75, '76 we needed probably—I'll guess, it was about $400 million short.

ROSS-NAZZAL: That's a lot of money.

KRAFT: We couldn't do these things that we should be doing. And we couldn't lay the people off either because we'd never get them back again. We had them trained. We were in a real dilemma. We had these big things about here's the total budget, the schedule, how we can play with the schedule. It took us two days to go through this with all the top management there. I remember talking in the back of the room—I'm a Center Director, but I'm in the back of the room—but I'm responsible for the budget for the Johnson Space Center, even though Thompson submits it. I'm still responsible for the $2 billion that JSC is spending.

So I spoke up and said, "When are we going to tell these people what our problem is? We keep delaying and delaying, first thing you know we're not going to be able to build this thing. We're not going to meet any kind of schedule. We're going to be behind the eight ball saying we could have done it, saying we could do it when we can't. We know damn well we can't do it." I made that speech. That went over like a lead balloon. Nevertheless I felt better about it, even though nobody else felt better about it.

But that kept going on and on. In 1978 we had a meeting in Room 45, ninth floor, big conference room. We had that place full of people. We had the top management of the agency there with all the program managers and the Center Directors—that's probably 25 people with the Administrator, the Deputy Administrator, Bill Lilly the Comptroller and his henchmen, and several guys from our budget world and all the other managers.

I laid it all on the table as to what our problems were. We didn't know exactly at that point how much money we really needed. But we knew in that fiscal year we needed at least another $400 million or the whole Shuttle Program was going to be in jeopardy. Totally incapable of meeting any kind of flight schedule. We could have postponed it for another five years maybe, but when you do that now you're really in a fix, because the nonproductive capability of your organization is too high. That's just too many people on the payroll so that they're just sucking up the money without producing anything, because you haven't pushed them to a schedule. I don't know whether that makes sense or not, but it's true.

So the discussion was maybe what we ought to do is declare this a research vehicle like the X-15, just build one of them instead of the five we have scheduled, and give up the fact that we're going to be a viable delivery system to Earth orbit with the Shuttle. Let's just take what we can get out of this machine and run tests on it, and just do it as a research vehicle. That was pretty much the consensus that came out of that meeting. Pretty much the consensus.

Frosch and Lovelace, Frosch being the Administrator, Lovelace the Deputy Administrator, Yardley, Lilly went back to Washington with that in their minds. Mr. Frosch goes to the White House. There's Mr. Jimmy [James E.] Carter who had just come back from the SALT [Strategic Arms Limitation] Talks. This is in here. [Points to book.] Not in the way I knew it, but the way it's out of the literature.

Jimmy Carter had made this big point at the SALT talks with the Russians that we were going to be able to fly the Shuttle over Moscow [USSR] continuously and do reconnaissance with this machine. He used that as a talking point to get them to do what he wanted them to do. He came back to Washington, and Frosch went to the White House when he got back about—I don't know how long Jimmy Carter had been back. But he heard this discussion from the staff that Jimmy Carter had been over there bragging about how great the Shuttle was going to be. Frosch is about to declare this thing a research vehicle. He said, "What am I going to do with this?"

He goes back to Headquarters and convenes his staff up there and they said, "Well, we're just going to have to level with him." Which they did. When they went and met with Mr. Carter and the people from the OMB, and I'm sure the science advisers, etc., Mr. Carter's answer to that was, "How much do you need?"

ROSS-NAZZAL: Finally.

KRAFT: Literally that's what he said. "How much do you need?" Now if you don't think that didn't create havoc at NASA. I won't go through the machinations we went through there relative to that statement, but he came back and that filtered down to all organizations that said, "Go out to all your major primes, figure out what you need this year, what you need in the program, and come back. We're going to build this budget, that's what we're going to take to the President, take to the OMB, and they'll give you the support."

They didn't say the Congress. Two weeks before that we'd been up there telling the Congress, "We don't need any more money," because that's what the OMB tells you to tell them. "This is what you're going to get, and you better not say that you need more because you ain't going to get it, in the first place. In the second place, that's what we don't want you to do. We're running this budget. We got an overall budget for the country. This is what you're going to get and that's it." "Yes, sir."

We'd been up there briefing the Congress for several months now telling them, "Everything's fine, we don't need any more money, we're doing okay." We weren't. Now they go back to the President—there are several stories here—go back to the President and tell the OMB, to the President, "We need an immediate $200 million supplement in this fiscal year, and we need $600 million in the next fiscal year, and we need this number of million dollars in the following"—two years I believe it was—"in order to meet a flight schedule of 1980." That's up from '78. But most people knew we weren't going to make '78 at that point.

The second story is when that goes to the Congress, they went bananas. They absolutely went bananas. They got their pint of blood and a pound of flesh out of all of us, but we got the money.

Now internal to that, I want to tell this story. I'm head of the award fee committee. I'm the guy that gives the contractor their award fee which is based on a lot of inputs. It was North American Aviation at that time and we said, "Okay. Now this is the problem (explaining what we had just learned from DC). This is what we want you to do. Tell us what you need." So within about two weeks, they gave us their needs. JSC was responsible for submitting that, I was. We submitted that, and that was part of this buildup of money.

After we had gotten that stuff all the way to the White House, Aaron Cohen got a call from Ed Smith [the Rockwell Chief Engineer and Program Manager] saying the initial estimate was incorrect. We need another X number of million dollars in this fiscal year, and we need this much more down the line. I was livid. I was absolutely livid. Here we asked them to tell us what they needed, and then what they had done was they had done it themselves without going out to their primes (contractors). After they gave us their estimate, they went to the primes, the primes gave them the amounts, and they put that all together and beat it to death and then said, "Well, my God, we need X number of million dollars."

So when they came to the award fee six months later, I gave them zero. First time in the history of any program. I gave them zero. A lot of heads fell as a result of that at North American. I was sorry to see that, including Ed Smith, who was the program manager at that point in time. They relieved him of his duties, but it made me so damn mad. They deserved zero fee as a result of that. He never forgave me for that, by the way. To this day, I don't think he ever forgave me for that.

ROSS-NAZZAL: Tell us about finally getting to that point when you recognized that you were going to fly, and your memories of STS-1.

KRAFT: Well, from that point on it wasn't a question of whether. We got off this kick of making it a research vehicle and back to the point that it's going to be a viable delivery machine. From then on it was just a matter of solving the technical problems and getting them done on a schedule. The way you do schedules in any development program is you set optimistic schedules in order to drive the program. You have to be very careful how you do that, because you don't want people making outlandish decisions, but you try to fit the schedule into what you think will properly drive the tenure of the program.

So it was solving the tile problems, convincing other people and ourselves that we had the right software particularly, understood the reentry, understood the thermal values. As I said, we were putting the tiles on and taking them off just about as fast as we put them on, and you are doing analysis. Back in the '70s, although we had good computers, it still took us a long time to do a thermal structural analysis. The first time it took us a year, to give you an idea how long that took. Even at that point in time, it took us maybe three months to make a complete analysis.

We had to redesign the tank a couple of times, because the structures in the tank were not sufficient to carry the loads from the Orbiter, which were changing all the time. They were changing their capabilities, we were changing the loads where it is attached to the tank, had to redesign the hooks inside the tank. We were having trouble with the insulation on the tank, having trouble with the insulation on the Orbiter, and having thermal guys coming up and saying, "It isn't thick enough there." That sounds easy to fix. Well, that changes the whole contour of the vehicle. So there's several ways you can do it. Take the tiles off and build up the aluminum with an epoxy RTV, [real-time vulcanization] and then put the tiles back on, or redo the tiles, or do it thicker or thinner. All of that took a lot of effort because we were still doing analysis, and we had a lot of kibitzers [outside engineers brought in to serve as an oversight committee].

The kibitzers, as I said, we could not convince them that when we got through the reentry and this machine had seen those high 2,300-degree-Fahrenheit temperatures, that the tile was going to survive. We hadn't convinced them of that. We built about eight or ten different test articles. We couldn't test the whole machine. (That's another story. We did test the whole machine structurally.) But we took pieces maybe about this big [demonstrates] and took them up to Langley, and Ames [Research Center, Moffett Field, California] where they ran combined loads tests (aerodynamic-acoustic and thermal).

We ran all these tests. Tried to get the most combined loads we could—the vibration and thermal at the same time, or thermal and aero at the same time. Couldn't do them all at once, because you didn't have enough devices to make all that happen like it was going to see it in flight.

The problem we had there was most of the time you used worst case loads. In nature, worst on worst on worst doesn't happen. The thermal loads are highest here, the structural loads are highest here, the vibratory loads are highest here, and the aerodynamic loads are highest here. They don't all occur at one time. Both during ascent and descent. By the time we'd run all those tests, we all felt pretty confident that except for worst on worst case we probably were pretty conservative.

Same was true in the automatic controls for a reentry. We didn't really know what the aerodynamics were. There was no wind tunnel, no blowdown surface types of devices that would give the right environmental conditions for the Mach number being flown. We had pretty good measurements up to Mach 6 but from Mach 6 to Mach 15 it was just pure guess. Above 15, it didn't matter, because then you're out of the sensible atmosphere and could use pure physics.

We did it by analytical means. We used what is called Newtonian flow. That's pretty simple to do, easy to make your calculations, easy to analyze the loads and therefore the structural analysis. But again, from Mach 6 to 15 we were really guessing.

The Shuttle is both a spaceship and an airplane. Therefore, the forces required to stabilize and guide the vehicle require the guidance system to utilize the forces of the Orbiter control surfaces and the attitude control rockets (thrusters) depending on the flight regime. During launch, the Orbiter control surfaces can be used to trim the loads imposed by the aerodynamic forces. However, the capability to gimble the Shuttle Main Engines during launch provides the ability to control the direction of the vehicle during the entire launch phase.

During entry, the automatic control system must utilize both the thrusters and the aerodynamic surfaces of the Orbiter to provide guidance, control, and stabilization of the vehicle. The use of these forces is complicated by both the density of the atmosphere and the speed at which the Orbiter is flying. When the Orbiter is above the sensible atmosphere, all of the forces necessary to provide stabilization and guidance are provided by the thrusters. However, as the Orbiter descends into the atmosphere it is necessary to start utilizing the aerodynamic forces produced by the Orbiter control surfaces. Initially these forces are small because of the low air density and must be blended in with the force of the thrusters.

As the altitude decreases, the density of the air increases and the force produced by the control surfaces increases while the thrusters become less effective. Eventually the force of the thrusters becomes relatively small compared to the aerodynamic forces and is terminated. The other complexity that must be accounted for is the effect of Mach number (the ratio of vehicle speed to the speed of sound) on the aerodynamic parameters used to compute the aerodynamic forces. The Mach number effect is not well known at Mach numbers between about 2 and 8, which makes the forces produced somewhat indeterminate. As a result the gains in the autopilot are more complicated to formulate in order to provide a stable machine. (Gain is the amount of control deflection required to produce a given aerodynamic force.) The gains are varied during the entire entry and are a function of such factors as Mach number, air density, etc.

Because of the uncertainty of the situation described above, it became necessary to utilize a mathematical process called a Monte Carlo Process. This statistical technique allows a random selection of the value of the parameters involved (approximately 35 parameters are included in the analysis). Each test performs a thousand runs with a random selection of the parameters. Variations in parameters are used which take into account the range that might conceivably be expected. Then for each .1 Mach number a set of calculations is performed which predicts the ability of the automatic control system to stabilize and control the Orbiter. If the Orbiter is unstable or marginally stable, the gains are changed until the system can operate satisfactorily for all 1000 runs.

The use of this complex and lengthy analysis allowed the engineers to confidently conclude that the automatic control system would perform satisfactorily for the entire reentry of the Orbiter.

When you run the Monte Carlo analysis, if you have a single failure, you start over again and change the gains in the system. We did that. First time, probably took a couple of years, second time we got better. Then probably at the end we could run one in several weeks. The computers were improving too. We were at it for ten years, so the magnitude and capability of computers were going up too. We did that kind of thinking, that kind of analysis, that kind of judgment with the best brains that we had in the organization and outside the organization.

At T minus three days, we took something like 100 tiles off the nose and replaced them because we had an analysis by the thermal guys that said some of them were going to fail. We had to build scaffolding on the pad to take those tiles off and then put them back on under a vacuum at T minus three days. Again, that would be a worst case situation. But we did it.

Somebody asked me, "How did you know you were ready to fly?"

ROSS-NAZZAL: How did you?

KRAFT: I didn't know what else to do. We did not know what else to do.

ROSS-NAZZAL: You had done everything that you could.

KRAFT: We had done everything we could think of. We convinced ourselves that we had done the best we could, we didn't think it was going to fail. When you start out with just thrusters, these attitude thrusters are shooting and balancing the loads—the moments on the airplane, forces on the airplane. I said before the flight, "Well, we'll probably have to change those gains after we get through the first flight." After it landed I said, "We won't touch a thing, it worked. Don't touch it." I don't know whether they've touched them since or not. But it worked and we decided not to fool around with it anymore, the damn thing worked.

ROSS-NAZZAL: What did you think of that first flight being manned? Were you in favor of that, or were you in favor of unmanned?

KRAFT: Oh yes, oh, sure. The systems required the operation and the oversight of the pilots during reentry—not during launch, nothing they can do during launch. But during reentry if the Orbiter had gone unstable, they probably could have helped it; the systems on board had an awful lot of redundancy. So if you had a system fail, you could have them switch to another system. You had the crew's brains thinking as well as the people on the ground having the capability of oversight.

We went through a lot to prove that we should launch STS-1 manned instead of unmanned; it was the first time we ever tried to do anything like that. We convinced ourselves that the reliability was higher and the risk lower, even though we were risking the lives of two men. We convinced ourselves and the top NASA management that that was a better way to do it.

ROSS-NAZZAL: After STS-1 landed, you've been quoted as saying, "We grew infinitely smarter." Could you explain what you meant by that?

KRAFT: Yes. Mostly from the aerodynamics and the thermal point of view. Thermally, we were more knowledgeable than a lot of people thought we were. We were not too worried about the machine to be able to withstand the thermal, environment, at least for a single entry.

How good it would be for reuse—I don't think we had more than a 90% confidence. But after the first flight, we certainly had a 99% confidence, maybe even 99.9. Aerodynamically, though, today they still don't know what the aerodynamics is at Mach 10. You get maybe two or three or even four parameters that go together for the total effect, but you don't know what the individual parameters were to make up that force—this is what we found out the most from the first flight.

The rest of the machine, we were able to tell before the flight that the systems were going to perform adequately—the APUs, hydraulic system, thermal environment system for the crew, the computers, software, how we wanted to do the reentry from an operational control point of view (i.e., that to land at a given point you banked and reverse-banked and banked, to either add or kill off the lift). We knew very well how to do that. We'd done that in Apollo, although we didn't have the L/D capability in Apollo we had in the Orbiter.

We were very confident about the basic systems of the machine. We probably had some concerns about the opening and closing of the payload bay doors. We certainly had some concern about the antenna system for returning the data from the onboard systems and anything you were carrying in the payload bay back to Earth because that antenna system was pretty fragile. Communications we understood, once you got it through the antenna.

I don't think we were ever worried about the windows, because we had enough capability on the ground to run the tests on the windows. But the tiles and the reusability of the tiles, that was really a rewarding result.

The automatic control system—we had the most doubts about it. We didn't doubt that we would get through it, but we believed that there would be a lot of places where we would want to change it. It turns out we didn't have to.

Having those questions answered and having done it, we were infinitely smarter than we were certainly ten years before that and certainly the day before that. We were hopeful from an overall STS, Space Transportation System point of view. We were all hopeful that we could reduce the cost a lot more than we did—that's probably the most unsatisfactory part of the Shuttle, the cost of operations.

In order to do something about that, you're going to have to change the culture of NASA. Change the culture of the management of NASA itself and the expectant management of NASA. This is a dangerous business with a certain amount of risks associated with it. It's run by people so the fallacies of the human being come to play. Therefore, going into an environment as harsh as space and the reentry into the Earth's atmosphere, you are subject to failure.

The people that sign the check and the people who manage you have to recognize that accidents are going to happen. We accept that in aviation. We accept that on the highway. We won't accept that in space. We are going to have to, because we can't make it perfect. It's harder in space because of the environment—you can't make a mistake. In an airplane, you can make a mistake sometimes and recover. In an automobile, you can do something wrong, you might destroy the machine, but not get killed. We accept 50,000 deaths a year in this country on the highways. We don't stop driving.

If you could change that thinking along with the culture of NASA itself (i.e., perfection), then you could get the cost down quite a bit. But it's still going to cost a lot, relatively speaking. No matter what you do, it's going to cost you more to fly in space.

Now as you gain experience, as you gain guts, as you gain better technology, then I think it will become commonplace. It is pretty close to commonplace now, but it will become like flying airplanes. Going into space will become like airplanes. The best comparison is the jet engine. In my time, my history of experience, gee whiz, when we went from internal combustion engines and propellers to the jet engine, you could only fly for 30 minutes until you ran out of fuel. The on-time capability of the [Boeing] 707 when it first went into service was atrocious. I remember flying to Baltimore [Maryland] in order to fly to Los Angeles and have to spend the night, because some black box in the 707 didn't work or wasn't working or had just come down and had failed and they didn't know what to do about it. That's changed immeasurably since then. Most of the accidents you have these days are not mechanical failures, they're mostly people failures.

The operating cost was a big disappointment. I thought we could fly it for a lot less money. It isn't that the machine isn't reusable because it is. I think even now the engines have become fairly routine to maintain. If you hold to the schedules for changing the pumps and changing the insulation on the engine bells and the various parts of it, you can fly each one of those SSMEs now maybe seven times, probably ten times if you stretched it. That's pretty good for a rocket engine, but we insist on testing it to death. We continue to insist that we have perfection.

The other part of it that has never been used is the redundancy. We didn't put the redundancy in there to make it more reliable from a *risk* point of view. We put it in there to make it more reliable from a *use* point of view. It's quad-redundant in all of the critical systems. This term FO/FO/FS: fail-operational/fail-operational/fail-safe. What we tried to build into the machine was quad redundancy. We never used it.

Today when you go to the pad, you have to have everything working. The philosophical design was not that way. We put the redundancy in there so when you went to the pad and something failed, you could still go. But they don't use it that way.

Now that makes it very difficult. Actually, what you do when you do that is make it less reliable, if that makes sense to you. The way to make it more reliable now is to take two of them off. It is, because now you only have two to make sure work instead of four. So they actually used FO/FO/FS in the opposite direction, which is stupid. They ought to be forced to do that, but they won't. You can't convince NASA of that. Probably can't convince the astronauts of that. Probably can't convince the Administrator of that. I'm not sure you could convince me of it, because I'm not there anymore. But that's the reason we did it. That drives the people.

The cost is in the people. Cost is not in the machine. Now, the tank does cost a lot of money. The tank probably costs I'd say maybe four times what it ought to cost. I think by working on the tank, you could get the cost of the tank cut by a factor of four. Maybe I'm being optimistic, but I think you could. One of those tanks I think today costs about $60 million. Our original estimates were $2 million. Literally. Go look at the literature. That's about what it was. The total cost of operation of flying the Shuttle was about—when we first started said to be about $20-25 million. I don't know what it is today, but it's at least $400 million, if not $600 million because of the small number of flights.

The standing army for the Shuttle is probably $3 billion a year, $3.5 billion a year. In today's dollars, maybe $4 billion a year. I think the total cost of flying the Shuttle is about $5 billion a year in the NASA budget. Now that's seven or eight flights.

ROSS-NAZZAL: Nowhere near your cost projections at the time.

KRAFT: Yes. So that's where you would have to attack the program.

ROSS-NAZZAL: In your book, [*Flight, My Life in Mission Control, 2001*] you talked about the Space Shuttle just for maybe a sentence or two. You say that it had some positive impacts, and it's had some major impacts on spaceflight. Can you talk about some of those positive impacts of the program?

KRAFT: I think the advancement in the state-of-the-art in almost every system is tenfold what it was in 1970. If you took today's technology in computers, in materials, in electrical power, you could replace all of the rotating machinery in the Orbiter. You would greatly improve the reusability and reliability and the cost. Take out all the hydraulics. You don't need all those hydraulics anymore. You can do it all with electrical power. Got better motors, better supplies, better fuel cells you could build.

There are a lot of ways that you could take the Shuttle and improve it and make it a more cost-productive and reliable piece of hardware. That's what ought to have been done. It should still be done today. It's just that they haven't done it, so trying to do it now is very costly.

But you can't go buy a 1980 computer that's on the Shuttle. You can't buy that machine. It's got to be specially built if you're going to use that machine, so you ought to replace it, and they have done that to some extent, but not anywhere near like they ought to do. Everything on it could be made better and therefore more reliable, therefore more productive, therefore more operational. You could have approached doing 40 flights a year with five orbiters.

ROSS-NAZZAL: Do you think that type of goal is still achievable?

KRAFT: Yes. I think a lot more achievable today than it was then, and I think it was achievable then. I don't think that it was as good as Mathematica as I read yesterday in here [*History of the Space Shuttle*]. I don't think it ever was as good as they produce, but they were playing the game. If they hadn't played that game, they wouldn't have got it. They had to beat the GAO [Government Accountability Office] down and prove them financially unsound in their projections and things. If they hadn't done that, they probably wouldn't have been able to get there.

So it was good to have the absurd opposing the absurd. You got someplace in the middle.

ROSS-NAZZAL: As you look back over the Space Shuttle Program itself, what do you think was the biggest challenge?

KRAFT: Still think it was the aerodynamics and the thermal protection. Certainly the engine, but the engine turned out to be I think better than we thought it might be. That's usually what happens, isn't it? The big thing that you think is going to be the biggest problem doesn't turn out to be the biggest problem because you spent the biggest effort on it.

Subsynchronous whirl, you know what that is? Well, the SSME has two big pumps—a hydrogen pump, an oxygen pump. They turn up at 35,000-37,000 rpm. They have staged wheels with the fins on, with the airfoils on them. It's on a big shaft and they're about twenty-four inches apart.

When we first started the development of those pumps, we would wear the bearings out that support that shaft. I don't know whether we had three or four shafts, but at any rate, that length of a shaft has an inherit problem that turbine designers call subsynchronous whirl. What happens is it gets in a resonance. At that high an rpm, the shaft is literally going up and down like this [demonstrates], vibrating at a given frequency called resonance. That going up and down wears the bearings out.

That was a problem at those RPMs of delivery rates under those kinds of temperatures. See, the temperature of the stuff going in is very cold and then gets very hot. The variation of those temperatures across the face of the delivery—one end to the other, delivering the propellant from one end of the pump to the other, pump in, fluid in, fluid out, gas out—is a hell of an environment.

That's the program we started first and we tried to get a long lead time on building the engines. It took a lot of effort and it cost a lot of money to develop that engine. But the results are fantastic. However, it's still a big problem and not an easy problem, and still has to be very carefully monitored. You have to check it after every flight, and then you have to tear it down after so many flights, like you do a jet engine. After so many hours in a jet engine, you have to tear it all the way down to the bare shaft, start over, build everything back up again. Now you could do that in this rocket engine after about seven uses. Frankly, I don't know what that number is anymore. The last time I had a look at it was 1995 when I did a review and tried to get the cost down, wrote a report on all that—me and George Jeffs and Frank Borman, several others. You can say that was a hell of an accomplishment.

The tiles, gee whiz. If you did that today, the material is there, the knowledge is there. You can do it. You can make a lot better tiles today than we did initially and they would be more resilient to damage. You could probably make them withstand a little higher temperature, just be overall better, and stronger, not quite so fragile. A lot of people wanted to build metal tiles using Rene and all that kind of stuff. But Bob [Robert R.] Gilruth said, "You got to build a special factory to produce this metal. By the time you get through doing that you'd do a lot better with the tiles we got." That's what we did. Ames wanted us to use a special nickel titanium metal. Metal tiles would certainly be a lot stronger and a lot less penetrable by debris, but I'm not sure we'd ever built the material. It was a whole new world.

It took a whole new factory and a whole new development of material to develop the consistency of physical properties. I don't think you'd still do it that way today. We know how to build better tiles already today, and there's no reason why you couldn't use it.

Now, about 25% of the orbiter surface no longer requires tiles. They use blankets, nylon type batts, and glue that to the surface to replace the tiles. The top part of the wing and parts of the tail and fuselage all have replaced the tiles with those blankets, FRSI [Felt Reusable Surface Insulation] they call it.

ROSS-NAZZAL: What do you think is the significance of the Shuttle Program?

KRAFT: Well, we proved that we could build a reusable rocket. Not as reusable as we wanted to, but it's still pretty good. It was an extremely successful idea that we brought to fruition.

We also made spaceflight one heck of a lot more routine. You certainly can carry ten or twelve people into space regularly. You have a highly maneuverable machine where you can go to a lot of different orbits and to a lot of different places in orbit.

It has promoted the idea of maintenance and repair in space. We don't do it very often, but the Hubble Space Telescope is certainly a classic example of being able to take a costly machine and gain experience with it, and then come up with better ideas and still use it by changing the hardware on orbit. That's very significant. You can put machines up there and bring them back to Earth and fix them and put them back up there. That's something you couldn't do without the Shuttle. So a lot has happened to have caused advancement in operational thinking about what you can do in space. It [all] just hasn't been used, but it will be someday.

Also from the space program, we didn't invent simulators, but we improved the hell out of them, and made them extremely beneficial. Our capability to train people, to train systems, to make systems more reliable through simulation now is fantastic. That of course required the tremendous advancement in the state-of-the-art of computers and computer software and you can't separate [the two]—can't do the computer without talking about the software. The software is just as important today, if not more important, than the computer itself.

Of course that's what the space program from the 1960s did in communications. We didn't do that with the Shuttle. We just made the delivery of the communication satellite more reasonable and less costly and more rational.

I don't think the impact of the Shuttle has been what the 1960s technology did, primarily because we didn't make any effort to do that. We should have and could have, but we didn't. We only worked on the technology required to get the job done. We could have worked on the technology to get the job done ten times better.

ROSS-NAZZAL: Is that because of budget restraints?

KRAFT: Yes, yes, just simply because we didn't have the resources to do it. That's the biggest unknown to the general public about what the space program does or can do. The return on investment from the space program is probably 100 times better than the return on investment on anything that's ever been done. If you're on the board of directors of a company, you worry about the return on investment. Nobody appreciates that factor, that aspect of spending money on the space program. It's the ROI [Return on Investment]. There are a lot of reasons for that, including lack of communication to what happened, or lack of willingness to make long term investments.

You can't go to Wall Street and get the money for the space program, because the ROI is too long. George [E.] Mueller couldn't get the money for his rocket [Rocketplane Kistler] because the return on investment was too long. So we probably have helped that. Not enough. That's what [NASA Administrator Mike] Griffin was trying to do with getting the use of commercial rocketry, was to try to promote that idea. Maybe that's going to pay off. Who knows? Maybe.

ROSS-NAZZAL: I just thought of one other quick question. It's more of a story that you might be able to tell. There's a famous photo of you with Ronald Reagan in the MOCR [Mission Operations Control Room], I think, for STS-2. Can you tell us about your visit with him, and perhaps how he envisioned what the Space Shuttle Program could be?

KRAFT: That was kind of funny, because Reagan was a very simple human being. He's dumb like a fox, but still not very knowledgeable in the technical world. Matter of fact, probably one of the lowest presidents in technology we've ever had, but that wasn't important in his job, it didn't mean anything.

Trying to explain to him what we were doing in any form wasn't easy. What he said to me was, "You know, Dr. Kraft, I can't understand most of the stuff you're telling me, and I don't understand most of what's going on here, because I was only in the cavalry."

When you see that picture of him and me, that's exactly what he said to me, "I was only in the cavalry."

ROSS-NAZZAL: That's interesting.

KRAFT: But he certainly appreciated what we were doing and what we did. We seem to have seen both ends of that spectrum from Reagan to Griffin. Griffin is too smart. You can't be that smart and be a manager or be a NASA Administrator.

Now [Griffin] was very important to NASA, he did a fantastic job, and he is what they needed at the time. But he also is not what is needed today. He made NASA a leaderless organization, because he was too smart.

ROSS-NAZZAL: Who do you think should be the next Administrator?

KRAFT: Charlie [Charles F.] Bolden would be a great one I think. That's only a guess. Because Charlie is smart but he's not too smart. You don't want managers to be too smart. You want them to build people, build leaders, build responsibility. If you take it on all yourself, which is what Joe [Joseph F.] Shea [Manager of the Apollo Spacecraft Program Office, 1963-1967] did, then you end up with a pretty tough situation, because nobody is that smart.

ROSS-NAZZAL: Yes. We all need people.

KRAFT: Yes. If you're too smart, you think you know everything. You don't know everything. You're a damn sight far away from knowing everything in any complex situation. You're better off being a little dumb than you are being too smart because that makes the situation what it ought to be—you build more people, better people, and people that take and are willing to accept responsibility for getting the job done. They will do it a lot better when you teach them or allow them to be taught or allow them to gain the experience to do it. That's a simple criterion that ought to be followed. Now if you could come up with both, that would be the ideal, but also idealistic.

ROSS-NAZZAL: Was that your style when you were Center Director?

KRAFT: Yes. It was always my style, primarily because I'm not smart. Now maybe that sounds funny, but I don't consider myself to be a smart guy. I'm not a physicist. I'm a fair aerodynamicist. A fair automatic controls guy. I understand all that stuff, but I couldn't do it. I had to be surrounded by all the best people, by all the experts, by people that were willing to accept being the experts and making the decisions. That's the reason I was good at being what I was. I made it that way. I made Flight Operations and Flight Control that way, because that was my style. I thought it was great. Others may think it was dumb.

I know an interesting thing. Max [Faget] and I were always at each other. Friendly so, but we were always at each other. He didn't see the need for all those operational things. Later, I went to work for him. Not literally, but I mean he asked me to do some things for him, but then he asked me to be on his board [of directors]. So I served on his board for quite some time. Anyway, one day Max said, "I didn't realize what a good job you used to do, but I do now."

That’s a pretty good statement by him. He had learned himself from being president of that company what he had to do to run that company. So it takes both kinds. I depended on Max. I literally depended on him to be the top engineer, to come up with the ideas, to be the guy that ran the brains of the organization. He did a great job of it. But he wouldn’t have been a good Center Director.

ROSS-NAZZAL: Too technical, again?

KRAFT: Yes. He would have been like Griffin is, too technical.

ROSS-NAZZAL: When he [Faget] came at you with this idea of building a Space Shuttle, what did you think initially? We’ve all heard the story of him throwing that balsa wood plane and people being surprised.

KRAFT: I was an aeronautical engineer. If I was anything, I was an aeronautical engineer. That’s what I was trained to do as a college student, and that’s what I was trained to do for the first 15 years of my life. Sort of a specialized aerodynamicist, because I was in flight test. So gee whiz, the Shuttle, for Gilruth and me it was the epitome. What he [Gilruth] said was, “The Shuttle was dignified.” That’s a good statement. “The Shuttle is dignified.” It lands on a runway. Doesn’t dump the God blessed thing in the water and hope like hell it doesn’t sink or that the parachutes work. So the Shuttle is a lot more dignified than landing a [capsule].

When we go and build Constellation, we’re going back to the future. Kind of ridiculous, isn’t it? You’re going to have to get the Navy trained again. In Mercury we had 10,000 sailors deployed. We had 50 ships, hundreds of airplanes, literally, when we flew the Mercury spacecraft. Why would you ever want to do that again?

Now you don't have to do quite that much probably. I'll bet you do for the first flight. If you don't, you're foolish, and you better. It is better to be prepared for it to come down in any one of 360 degrees on the Earth. That's where we were on Mercury.

Why do that again? If you're going to spend money that's a good way to spend money, isn't it? A bad way, whichever one you want to call it. But it's done, so we have to go build it. NASA will build it, and they'll do a good job of it. It just isn't the way to do it. I don't go around saying that, by the way. I don't criticize them. That's what he could get, that's what Griffin could get, so that's what he got. That isn't the way he would have done it given his druthers. But you're stuck with it now.

ROSS-NAZZAL: Rebecca, do you have any questions for Dr. Kraft?

WRIGHT: I just have one. When you first started working on the development of the Shuttle, did you have a vision of what you wanted it to be and have you seen the Shuttle reach that expectation that you wanted for it?

KRAFT: Well, in terms of its capability yes. It more than met my expectations. As I said previously, think about putting 65,000 pounds into and out of orbit. To have said you were going to do that in 1960 was impossible, literally impossible in 1960. We did it in 1980. So yes, it more than met my expectations, even for 1972.

As I started out by saying, it's too bad we don't have the commitment from the country to test ourselves, to give us an impossible task to accomplish in space. That's what we need. We don't need one, we need a number of challenges. That's the way we ought to solve the energy problem. It's just the politics of the world, not just the United States, but the politics of the world make it difficult to do.

We can't get enough people committed to it. They will, because you're going to run out of fossil fuels. It's improving. It's certainly improving. I saw the other day where about 25% of the energy we're using these days is solar. That's pretty good. It really is pretty good.

We can solve the energy problem from space. We can do it from space, but it would be too expensive. That's not something we should tackle in my opinion. We should do the testing of those kinds of systems from space, i.e., put some solar panels first on the Space Station, which we already have, and transmit that to the ground and see how that works, and what the distribution problems are, etc. Then we should do it on the Moon.

We could do the experiments for a piddly amount of money. Not solve the world's energy problem doing it that way, because I think it then would be too expensive. But it's by doing those kinds of things that give the idea about how to do it better on Earth. Every time we did an experiment in Gemini and Apollo and lately, what we found is yes, we can do it better in space, but it gave us a lot better idea about how to do it on the Earth. That was the big payoff.

We did this thing called electrophoresis. Do you remember that term? By using the zero gravity and the magnetic attraction of electricity, you could separate things of different density and therefore manufacture medicine or whatever 1,000 times more pure doing it by electrophoresis. Well, the moment we started building all those machines, we found out we could do it on Earth. So you didn't have to go to space to do it, and that brought the cost down even more. Those are the kinds of things we've learned. That's okay. That's a good use of the money, to do that kind of experimentation.

ROSS-NAZZAL: Well, we thank you for coming by today and sharing your recollections of Space Shuttle.

KRAFT: Thank you.

[End of interview]