NASA JOHNSON SPACE CENTER ORAL HISTORY PROJECT
ORAL HISTORY TRANSCRIPT

MARK K. CRAIG
INTERVIEWED BY SANDRA JOHNSON
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The questions in this transcript were asked during an oral history session with Mark K. Craig. Mr. Craig has made minor modifications to several answers for clarification purposes and has provided additional information to enhance the interview. As a result, this transcript does not exactly match the audio recording.

JOHNSON: Today is March 24th, 2006. This oral history with Mark Craig is being conducted for the Johnson Space Center Oral History Project in Houston, Texas. The interviewer is Sandra Johnson, assisted by Rebecca Wright.

I want to thank you again for joining us today.

CRAIG: My pleasure. The NASA Oral History Project is so important because it captures the experience of one generation so that future generations may learn from both our successes and failures, and they may see us as individual people—understand our motivation and our dreams. Looking back, I'm truly astounded by, and very thankful for, the range of amazing experiences that NASA afforded me:

- Like learning human spaceflight directly from the people who invented it in America—Max [Maxime A.] Faget, Deke [Donald K.] Slayton, Chris [Christopher C.] Kraft, Bob [Robert F.] Thompson, and so many others;
- Like being detained at the Apollo 11 launch pad for hours the afternoon before lift-off, and then seeing it launch the next day for the first human landing on the Moon;

- Like being on the start-up teams for the Space Shuttle, Space Station, and Lunar-Mars Exploration programs in, respectively, 1969 as a co-op student, 1983 as a lead engineer, and 1989 as the program manager;
- Like inspecting the fueled Space Shuttle on the launch pad several hours before lift-off, and sitting in Columbia's cockpit several hours after it returned from space on STS-2;
- Like seeing the Space Shuttle booster staging system work flawlessly on STS-1 after leading its design, development, test and evaluation;
- Like presenting Lunar-Mars exploration plans to the Vice President at the White House;
- Like seeing NASA reorganize around the customer-focused Strategic Enterprise concept that I had invented, especially an Enterprise for the Human Exploration and Development of Space;
- Like being a member of the Shuttle Mission Management Team on console in the Launch Control Firing Room, and seeing over 20 Shuttle launches;
- Like negotiating partnership agreements for Space Station and Mars exploration with Europe, Japan, Canada and Russia;
- Like experiencing weightlessness in a test series on the KC-135 "zero-g" aircraft.
- Like delivering a keynote address at the 3rd United Nations Conference on the Exploration and Peaceful Uses of Outer Space in Vienna [Austria].

From these experiences, if I were to leave just one "message in a bottle" to those that follow, it would be this: For NASA human spaceflight to have a robust and sustainable future, it must intentionally, and by design, deliver value to the Nation.

Value as the Nation's citizens actually experience it, not-not-not as NASA merely claims it. And value they see as worth the investment. Value within our mission and policy guidance of course, but in addition, value that we have done research to define and then have actually shaped our programs to deliver—shaped mission architecture, operations concept, landing site, crew selection, experiment and sensor suite, bandwidth, mission coverage, etc. Value managed and resourced, not done on the margins or as an after-thought, and not-not-not dependent on serendipity.

But what types of value? Well, first, value that will actually motivate political support today. For example, NASA human spaceflight could deliver:

- Value as a foreign policy tool to express leadership or engage foreign technical capability. This was human space flight's founding value in Apollo but it barely sustained Space Station. By itself it is no longer adequate to sustain NASA human spaceflight.
- Value as a source of scientific, medical and engineering knowledge. We learned on Space Station that knowledge by itself is not adequate to sustain human spaceflight. Scientific knowledge sustains robotic exploration, but robotic exploration exists in an accepted "market" of the National Academy of Sciences that levies requirements and assesses performance. Human exploration has no such accepted "market" for its value. And robotic exploration requires an order of magnitude less funding than human exploration. Too often we confuse this with inward-focused knowledge—"we send humans into space, to gain the knowledge necessary, to send humans into space." It isn't.
- Value as a source of emotions and experiences, like hope, wonder, inspiration, thrills, vicarious involvement, etc. The commercial world has learned the power of building emotions and experiences as discriminators into everything from restaurants to cars to malls. Arguably this is our greatest source of sustainability, but it is largely untapped.

- Value as a resource to help the Nation meet its goals in education. This overlaps with emotions and experiences value but includes other dimensions like education material content support. Too often we confuse this with inward-focused value to educate people about NASA. It isn't.
- Value as a source of technology. We understand this value but too often deal with it on the margins or depend entirely on serendipity. Like most value, we deliver this value as one enterprise in a "chain" of enterprises, each doing its part. To deliver value to the Nation we must understand our place in the chain.
- Value as a provider of products or services to others, like access to space, space platforms, or propulsion testing.
- Value as an enabler, or at least not a dis-enabler, of space commerce. This could be an engine of sustainability. NASA explores the frontier and enables space commerce, which motivates space commerce to demand more exploration.
- Value as a source of high paying jobs. Yuk, so pedestrian and base. Pure pork politics. Jobs contribute to sustainability far more than they might otherwise because we have not paid enough attention to the other components of value.

Notice that I didn't mention any value associated with the destiny of the human species or finding a new home for humanity. Wonderful concepts. And perhaps ultimately true. But they won't motivate meaningful political support today. We must only focus on value that does.

When it comes to managing value effectively, hopefully the NASA team will not be surprised to learn that state-of-the-art tools will be required, as well as profound innovation. For example, in defining value, using "deliberative polling" to tease out informed opinions from a large, diverse population. Or in creating emotions and experiences, "open sourcing" system requirements, operation concepts, etc. to both capture the expertise of non-space "communities of passion" and to generate much, much broader program ownership and excitement. The components of value must be managed as a portfolio. When one is more valued, others will be less. It will change with time and audience.

A closing thought. Even as NASA struggles to deliver value, and makes missteps, just the fact that it understands its value based on research and is demonstrably deliberate about delivering it in more than speeches will advance sustainability.

Well, that's my "message in a bottle." Hope somebody reads it.

Working at NASA from 1967 to 2005 was a high honor and a great privilege. Thank you for taking the time to interview me.

JOHNSON: I'd like to begin today by asking you to briefly share some information with us about your background and how you first became interested in the space program.

CRAIG: Okay. We moved a lot when I was young. I was born in St. Louis, Missouri. My dad worked for Shell Oil [Company]. We lived in Paducah, Kentucky, we lived near New York City [New York], and we lived in New Orleans [Louisiana]. We ended up living in Midland, Texas, which is where I consider myself to be from—junior high and high school. That was during the days of Gemini [Program].

My dad, who just loved space, would wake my brother and I up at oh-dark-thirty to watch the launches. I had always thought of being an archaeologist and actually had done some things as a student intern in the summers in high school in that vein, but finally as Apollo was ramping up, the excitement of that really grabbed me. I knew I wanted to go in the space program.

Therefore, engineering seemed to be the path to do that. How did I know that? I don't know, but it worked out okay. In looking at universities, looked at several but went to Purdue [University, West Lafayette, Indiana], which ended up to be just the right university to get into the space program. I don't think I particularly knew it in explicit detail, but Purdue has had a number of people—starting with Neil [A.] Armstrong and Gene [Eugene A.] Cernan—who have been involved in the space program, and still does. Besides that, just a great university. So I went there, launched myself down a path that I was clueless about, basically, but where I wanted to go, and got there and found that Purdue had a co-op [co-operative education] program, which I had never heard of. One of the places that Purdue placed co-ops was the Manned Spacecraft Center [MSC; now Johnson Space Center, JSC, Houston, Texas].

Well, being from Texas, and my high school sweetheart going to the University of Texas [Austin, Texas], I thought, "Gee, this could really work." Come down here every other semester, work during the week on the Apollo Program, and then drive to Austin Friday night and have a social life, come back Sunday night and work on the Apollo Program. I started after my freshman year, came down here in June of 1967, and just loved it. It was right after the Apollo fire [Apollo 1/AS-204], so it was a very—although I didn't appreciate it so much at the time—it was a very stressful, energetic period in the history of the Center.

There was a lot of activity going on. The group that I was in was working on training devices for the astronauts, and I was assigned to design a ladder for one of the neutral buoyancy tanks—an extra-wide ladder for divers to rescue astronauts testing the redesign of the Apollo Command Module hatch after the fire. I did that my first semester here, the summer of '67. I wanted to get a little bit closer to the spacecraft than training aids, so I talked to the co-op coordinator about getting into the Engineering Directorate, and did, and ended up getting into a group in the Engineering Directorate that was doing system studies, trajectories, mission kinds of things.

The first thing I did in that group was, I thought, fascinating. The Soviets had just landed a Venera spacecraft on Venus and sent it into the atmosphere, so it was the first real data on the atmosphere of Venus. I was—as is NASA's way "Here, kid, do it"—given the job of assessing and looking at how one would do entry trajectories for the planet Venus with the new atmosphere data that the Soviets had just gotten. I worked on that my second semester here. I was given a job and the tools and access to whomever I needed to do it and just started doing it.

In that same division, I also was given—and this was all in 1968—there was a lot of work going on about how to be more mobile on the Moon. One of the engineers in our division had done a lot of the mathematical analysis on a lunar flyer. Rather than just a rover, the idea was that the astronauts would actually have a flyer that they could use to have mobility on the Moon. I was assigned to work with this engineer, which I did—very mathematical and way above my head—but I learned a lot. The Venus entry trajectories and a lunar flyer for a sophomore in college was pretty cool, and then having a great time on the weekends in Austin. Life doesn't get much better than that. That was the year 1968.

In 1969—came back in the summer of '69 —it was just before we landed on the Moon the first time. Dr. Faget was putting together a group to design the Space Shuttle. Myself and one other co-op were selected to be in that group, which was located in Building 36. We were sequestered away as the Shuttle Skunk Works, engineers from across the organization, to design the Shuttle. I was given the responsibility for helping senior engineers do vehicle sizing, where you marry trajectories with the design of the vehicle. You fly a trajectory mathematically. That tells you how much propellant you need. Then you design the tanks and the structure around the propellant that you determine from the trajectory, and that's iterative.

Well, we got tired of iterating it manually, so we decided to write a computer program that lumped it all together, both flying a trajectory and sizing the Shuttle, which became very useful to Dr. Faget and others. We got a lot of attention. As others were landing on the Moon, we were doing the Shuttle design. In fact, the picture up there, [indicating drawing hanging on office wall] that's Max Faget's original drawing of what he conceived the Shuttle to be. At that point it was a two-stage reusable Shuttle, and it was roughly the size of commercial airliners, each stage—a [Boeing] 747 for the first stage, and a [McDonnell Douglas] DC-9 for the second stage.

It was classified "Secret" as you can see, I later learned, because Dr. Faget didn't want the Air Force to find out about it. He told me many years later when I asked him "Exactly why was this secret?" It was a very intense team of people. It was engineers, many different disciplines, designing the Shuttle. We were developing material that would go up to [NASA] Headquarters and get into the system up there. They were working the politics and the top-level engineering of the Shuttle. It was an environment where we had Dr. Faget and his senior leadership team leveling requirements on us and asking questions, and then questions coming down from Headquarters. So we were in a quick response mode.

I left and went back to school at the end of that summer of 1969—decided to get married to my high school sweetheart in January 1970 and skip my last co-op semester to finish school. Then came back full-time in January of [19]'71 after I graduated and stepped right back in the middle of the Shuttle sizing. By that point, the Shuttle was further down the road technically. It was starting to converge on what it might be, or the main options. There were at that point three or four options. Contractors were being brought onboard. The basic structure of how the Shuttle would be set up was being put in place.

I came back in the same group in the Engineering Directorate that was performing these sizing studies. Also we were trying to expand and perfect the computer programs we used to size the Shuttle—this iteration between trajectories and all the equations that define how big the tank is, how big the wings are, how big the wheels are, and how much does it weigh. When I got back down here I went back into where I had been, but the program was further down the road, and that was a very exciting time because so much was happening.

JOHNSON: You mentioned when you first went to Purdue you heard about the co-op program, which you'd never heard of before. As far as the application and the screening process to actually get into the co-op program, do you have any memories of that process or how you were chosen to come to NASA?

CRAIG: There was a formal application process. There was a gentleman there named Professor Cargnino, Larry Cargnino, who was just excellent. One of the courses one took at Purdue in your freshman year was called Freshman Engineering, and it was, well, you're here, it's a university, you said you're interested in engineering, what is engineering? It was really a good idea. It was "Okay, you're in some school, you think you're going into some branch of engineering, what is it really?" The whole idea was to help young people figure out, or as best you can as a freshman, what is engineering and what do you want to do?

And a part of that—I'd gone into the aero-astro school because space was where I wanted to be—Professor Cargnino ran this Engineering 100 course for young engineers, and brought up the co-op program. He had a very good relationship with a woman named Bobbie Lerden, nee Barbara Ebner, who was the co-op coordinator at MSC. After he told me what it was and I expressed an interest in it—again, for two good reasons to get back to Texas—he said, "Well, sure, let's talk."

So he talked to her. MSC sounded very interested, and so I put in my application and was accepted primarily based, I think, on a very good recommendation from Professor Cargnino. I think he saw my passion and my desire to do something. I hope that's what he saw. It worked.

JOHNSON: During 1969 when you were working on those first Shuttle designs, the Moon landing occurred. What are your memories of Apollo 11 and were you at NASA at the time?

CRAIG: I was. My best memory of Apollo 11 involves going to the launch. A friend from high school and I decided to go to Florida for the launch. As was the case at MSC at that time, I assumed that with my NASA badge I could get us both on site. Turns out that didn't work at KSC [Kennedy Space Center, Florida]. So my friend got out of the car at the gate and I proceeded on site, sure that I would meet some security barrier and be back to pick him up in 10 minutes. I could see the Apollo 11 launch vehicle in the distance so I just kept driving toward it. Very much to my surprise, with my NASA badge I was able to drive right up to the perimeter fence at the base of the launch pad. Busses were whizzing by with launch guests leaning out the windows taking pictures. I got my camera out and was clicking away when a guard came over and asked who the heck I was, and what I was doing. Turns out NASA employees weren't supposed to have cameras at the pad without permission. He took me into the guard shack literally at the base of the launch pad and told me not to move until he could reach his supervisor.

He never could, so he finally sent me on my way after trying for three hours, while I stared at the Saturn V launch vehicle the whole time. His final stern admonition to me was "and don't ever come back." We saw the Apollo 11 launch the next day, but I didn't return to Pad A until I led the Shuttle launch vehicle inspection Red Team in 1981.

I was here when it landed on the Moon, working on the Shuttle, curiously. Or not "curiously," but I mean how nice, and of course, it was such an exciting time. It was just electric and although I wasn't involved directly in Apollo at the time, just being on the campus, one knew something's about to happen.

Another Apollo 11 memory is that I had guessed in 1968 that Neil Armstrong would be named the mission commander. Of course, we all knew who the astronauts were. There weren't that many at that point. I knew that Neil Armstrong had gone to Purdue, and Professor Cargnino said, "Well, just go by and say hello."

So I sucked it up and went to Building 4 and went to the top floor and just walked in. Neil Armstrong was at his desk and I introduced myself. He was very gracious, "Welcome to NASA and tell me about what you're doing." This was in 1968 sometime—it was just a very pleasant conversation.

While I was in there, Gene Cernan came into his office and said, "Congratulations, Neil, that's wonderful."

I hadn't thought anything about what that meant. I only remembered it at a later time. It turns out that was the day I think that Armstrong was selected to command Apollo 11. Before that, I had thought he might be selected for two reasons. One, he was a civilian, which I thought would be important for the first person on the Moon. And, two, he'd had a horrible accident out at Ellington [Air Force Base, Houston, Texas] in a free-flyer and punched out at the last minute.

Plus, he had some on-orbit anomaly experiences with Gemini. So in my mind, all that fit. The guy's a civilian, he has really proven experience in very trying circumstances, so I'll bet he's picked to command the first landing flight.

But then to have had that conversation with him and have Gene, another Purdue grad, come in and congratulate him. How neat.

JOHNSON: That is amazing.

CRAIG: I'm just a kid who's an engineer out here, and to have that opportunity.

JOHNSON: And you were very young. You were nineteen, right after your freshman year when you first came out.

CRAIG: Yeah, nineteen.

JOHNSON: Were the other co-ops that young, or was that common for them to come after their freshman year?

CRAIG: Yes, yes. There were a lot of co-ops. I would bet there were three hundred probably at that point, at least, and we were everywhere. We didn't go anywhere and work on something without rubbing elbows with other co-ops. It was a very active program, and there were a lot of social activities. The co-op office, rightly, did a lot of work to pair people up to be roommates, so it was a pretty tight-knit community.

JOHNSON: Where did you live when you came?

CRAIG: I lived—the first summer I was here in ’67—in Nassau Bay. It was called the San Sebastian. It’s still there. It’s called something different now. And then every semester after that I ended up living near Hobby Airport in the Villa Monterrey apartments. I don’t remember how—there was an Air Force lieutenant here named Kerry Sandstrom—somehow I was tagged up with him and so we lived together for the semesters I was here. He was here full-time, of course, with the Air Force, but the next three or four semesters I lived with him up near Hobby Airport and drove down here.

JOHNSON: You also mentioned, and I’ve read this in other interviews, that NASA routinely threw people in over their heads.

CRAIG: Absolutely.

JOHNSON: And expected results and then gave help as needed. Was that something that you had to adapt to, or how did you feel about that when you first came?

CRAIG: I don’t think I ever knew it was happening. I was that clueless. I was just a wide-eyed kid. Sure, do it. I was given something to do, so my assumption was, “Well, they assume I can do it, so I will.” And of course, sometimes I couldn’t, so I would—but it was a very tight-knit group of people and I always knew that people were there to help and they were always, “How you doing?" It was just a wonderful environment. And I can articulate it today in hindsight that that's what happened, but I wouldn't have said it necessarily at the time. It was "isn't that how work is?" I knew nothing else.

JOHNSON: And what an opportunity for you to learn.

CRAIG: Absolutely. I learned so much. Not just technical things, but about people and how things work. How people work.

JOHNSON: To be twenty or twenty-one and working with Max Faget.

CRAIG: Yes, yes. A lot of this I have to pinch myself even to remember was real. It's just incredible, because, as any young person, you launch yourself down a path and who knows what's going to happen. But to have had all this happen, that's just amazing. My whole career is that, I have to pinch myself to think of all the things I've done and how thankful I am for it and the people that made that happen.

JOHNSON: You were beginning to talk about when you first came on full-time in 1971 and how you continued working on what you'd worked on earlier. In 1971, that was a time period, '71, at the end of Apollo, '72, when not as many people were being hired. In fact, they were scaling down because of budget.

What was that experience like, for one, being hired during that time period, and why do you think you were retained during that time period?

CRAIG: Well, that's another interesting story. I was, I think, the last person hired by NASA at the tail end of the Apollo Program, and I was then RIFed [Reduction in Force] in '72. Of course, the system is "last in, first out." I actually still have my RIF letter. I was RIFed in May, sometime, spring, late spring, early summer of '72.

When I was in college, I thought, "This space thing, it's got to be bigger at some point than the U.S." So I'd taken Russian in college. And not to say I was in any way very good at Russian, but I had taken it, was aware of it, could get around in it. The human resource folks here—I think that I had done enough work that the people wanted to try to keep me, and NASA was very good at finding ways to keep people. Well, one of the great HR [Human Resources] people was, I think, given "Find a way to keep this young man, or if not, find him a job."

So NASA had already found me a job with TRW, or helped me. They hadn't obviously found it, but they helped put me together with some people at TRW. I had already been talking to them. And when the woman in HR saw my Russian coursework and knew that Apollo-Soyuz [Test Project] was coming up, I was yanked from the RIF. A month or two later, got a letter back saying, "Cancelled." I learned later why, but went to the brink and was pulled back, and was then immediately assigned to a group working on Apollo-Soyuz.

I was taken out of my Shuttle work and began working in a group—because my expertise, technically, one of them, was dynamics. I was put in a group doing docking dynamics with the new, at that time new, docking mechanism with the Russians. I was put on Working Group 3 to both do engineering work and translation. NASA, to the great disdain of the professional translators, said, "Well, here's this young engineer that knows Russian," and, of course, they were much better at Russian than I was." But I was there and did work in that.

Then there was a year maybe, I don't remember the exact amount of time—but then once Apollo-Soyuz started to fly I was put back in the group I'd come from and started working on the Shuttle again. I enjoyed working with the Russians and made some friends that I still have to this day and still see around in the Russian, or Soviet at that time, space community. I enjoyed that. Again, it was a different experience and I appreciated the opportunity and it saved my job. Then I went back into Shuttle.

JOHNSON: So did you ever work with Skylab or anything on the Skylab Program at all?

CRAIG: No, I did not work on Skylab.

JOHNSON: Why don't you share with us when you went back into Shuttle and what you were working on and those experiences.

CRAIG: Okay. Shuttle, of course, had continued to mature. There were contractors onboard. The design, certainly, matured. I went back in working the sizing things, marrying trajectories with sizing things. But obviously at some point that ends, that's very front-end work on a program. I was assigned to work in an area on the staging dynamics, SRB [solid rocket booster] separation.

At that point, the decision had been made to have solid rocket boosters, the basic configuration we have today. And the group I was in, we were an integration group, we worked across discipline lines. When you do trajectories, you often have to do that. It marries all kinds of different things, like the sizing stuff. Structures people don't do that; they participate in it. So it's an integration job, and that's been a theme of, I think, many things that I've done.

It was clear that here was a very different—this wasn't just a cylinder as a launch vehicle, it's a very different shape. And here are these boosters on the side, and they've got to go away in about two minutes at burnout. Well, how do you get them off? A woman named Ivy [H.] Fossler [Hooks] was leading that effort, along with the separation of the external tank. There were two separations on the Shuttle. I was asked to go to work for her on the booster separation, which I did, and really enjoyed it, it was very different.

At booster separation, there's still enough atmospheric drag, and you're at about Mach 4.5, so it's supersonic aerodynamics. It's a very strange configuration. I went to work for Ivy working on how do you separate the boosters, which meant physically how do you do it? Well, how are they attached? You can bust the attachment to get them off physically—which are big bolts, pyro-bolts. How do you motivate them away? You have to decide on propulsive devices, motors, solid rocket motors to get them off. How do you size the motors, given the fact that you still have a fair amount of aerodynamic pressure? So it's not just you fly away from it. What's the sequence of things that has to happen and when?

We recognized early on with the tiles, with the external thermal protection tiles on the Orbiter, firing large rocket motors near them, and at them, is probably not a very good thing to do. One has to be careful because the tiles are fragile. We looked at all kinds of concepts. Using pistons to push the boosters away, anything we could do to get away from having solid rocket motors propel them away, the spent boosters away. We finally concluded that the risk in the other approaches was just too high, so we'd have to find a way to have separation motors that would not harm the thermal protection tiles, and that was a huge challenge.

In 1977 the decision was made to create a Subsystem Manager for Booster Separation and one for External Tank Separation. I was made the Subsystem Manager for Booster Separation.

JOHNSON: I have that as being around 1977?

CRAIG: Yes, somewhere in that time. I'd been working on it for Ivy. Ivy then went up, got a broader job, and I was made SRB Separation Manager, and Barney [B.] Roberts was made External Tank Separation Manager. I'd been in Shuttle since the very beginning, to now being a Subsystem Manager on a fairly complex subsystem, and not a standard one. This wasn't power or propulsion or software. It was all those things, and trajectories, which is the kind of thing I like where it integrates lots of different aspects in ways nobody's ever done it before.

So I ended up as Subsystem Manager, and then they called it Integration Manager in 1978. I was responsible for the software, was responsible for the sequencing, was responsible for all the requirements on the bolts, the motors, did all the trajectory work, how they fly away, led all the wind tunnel tests. Those were very complicated tests we did at the Arnold [Engineering Development Center [(AEDC), Arnold Air Force Base] in Tennessee, the Air Force tunnels up there. The separation motors—they look small when you look at a Shuttle—but they are twenty thousand pound thrust motors, and there are four of them at the front end and four of them at the back end of each SRB.

The way we got away from the problem with the thermal protection tiles was several-fold. One, we pointed the separation motors almost forward, with a little component of thrust out to get the booster away. Two, we made them only burn for 0.75 seconds so that they didn't come back and streak the side of the Orbiter with their erosive exhaust plume. And three, we had developed a new propellant that had very little aluminum in it, because aluminum is what creates kind of a grit, it's like sandpaper, which is what causes the damage.

We spent a lot of time on the motors and their sizing and duration of burn and propellant type to eliminate the damage on the tiles. We then had to do tile tests where we actually fired motors and then put tiles in the plumes where we thought they would be in flight, to prove to ourselves that the tiles would be okay. That was a huge effort in the separation system design, the whole tile/SRB separation motor plume interaction.

The other huge problem, though, was when you fire motors like that in an aerodynamic flow, the plumes from these separation motors are like another solid body. They disrupt the airflow coming in over the Shuttle, which means when you do wind tunnel tests, you have to simulate these separation motor plumes because it changes all the aerodynamics. That made the tests very complicated. It wasn't just a body in a wind tunnel flow. It was a body that was actually emitting plumes. Figuring out how to scale those plumes so you had the right forces on the vehicle was key.

JOHNSON: How did you simulate those?

CRAIG: Well, we ended up doing some very—I thought it was very innovative work, thinking about how do you come up with a scaling parameter? There are typical aerodynamic scaling parameters like Mach number and Reynolds number. We did a lot of work with some technology tests trying to figure out how you scale a plume, so that it gets the right effect and then use that to size these—we had actually little tiny jets on the model. These were 1 percent models and had little jets on them.

But the other thing that made it complicated was the boosters move while they're firing. It's not just that you have a plume, or a shape—it's moving. And the aerodynamics is changing as they move. So we actually built models where the boosters moved, and that was very difficult. Those tests were extremely complicated tests, a real challenge for the Air Force guys in the tunnels and our model builders.

But a bigger challenge from my standpoint was, because it was new, it gives you so many degrees of freedom. You not only have the Mach number of the air, standard scaling parameter, but you have then the angle of attack (alpha), and angle of sideslip (beta) of the Orbiter/Tank stack. Now you have three variables. Then you have the positions of the boosters: up, down, left, right, and their relative-to-the-stack alphas and betas. If you populated the database with all those grids, you'd have trillions of data points, and the cost would have been excessive, because you end up with eight degrees of freedom, eight independent variables. I really struggled with that for a long time, because we, obviously, just couldn't afford to do that.

I finally came up with a way that I called Hypercubes, where you would find paths through the eight-dimensional data space that were realistic paths for the boosters, and you would only take data along those paths. That meant then I had to come up with a mathematical construct to get the aerodynamic coefficients out of those paths to apply in our trajectory program. I ended up having to conceptualize the math to do this and then write the Fortran code, which was daunting. Called it Hypercubes because the construct was basically a set of "concentric" five dimensional "cubes" expanding along the SRB path relative to the Orbiter/Tank stack. That was one of the bigger technical challenges of this thing. The aerodynamics were very complicated, hard to get in wind tunnels, and then harder to get efficiently and put in a trajectory program. It was just a wonderful—the whole separation system was a wonderful challenge.

JOHNSON: Did you do that mostly out in Tennessee, or did you ever go to [NASA] Ames [Research Center, Moffett Field, California] for any of that?

CRAIG: No, it was all done at the Air Force Arnold Engineering and Development Center. There was a lot of testing done at Ames. The group I was in did all the aerodynamic testing, as well as the trajectories because they were so intimately wed. I was aware of all the testing at other places—[NASA] Langley [Research Center, Hampton, Virginia], Ames. But this particular set of tests, because of the Mach, about Mach 4.5, and because of these very complicated models and plumes—AEDC was the only place to do it. I spent a lot of time at AEDC.

JOHNSON: About how much time did you spend there?

CRAIG: I used to kid one of the Rockwell [International Corporation] techs [technicians]; I thought he and I were probably common-law married in Tennessee. [laughs] We ran six or eight test series there. They were run at night because they are big tunnels and take a lot of power, and that's why they are in Tennessee. You have TVA [Tennessee Valley Authority] feeding all the energy into these. You'd sleep during the day and go in at night. I did not spend all of my time there for all those tests because of the Rockwell technicians that were on the ground doing everything. But they were so complicated that I was very concerned that we were getting the data we needed in a way that we needed it, so I ended up spending, I don't know, half time, third time there probably, on the tests.

JOHNSON: What type of teams did you have working with you as far as when you were out there doing those tests and how many people did you have underneath you?

CRAIG: Well—and that was another thing I loved about that—nobody was underneath me, per se, but as Subsystem Manager hundreds of people were underneath me. I was the manager for the subsystem, which meant there were a lot of people here at JSC because it involved sequencing, it involved trajectories, it involved aerodynamics, it involved software to do the sequencing, etc. It involved training the flight crew, how do we design the crew interaction? It was all the JSC kinds of stuff in the subsystem.

But the thing that made it really challenging and I really enjoyed was that [NASA] Marshall [Space Flight Center, Huntsville, Alabama] was responsible for the boosters and the booster separation motors and the explosive bolts. It was a Level 2 [program-level] subsystem. It wasn't just the Orbiter. It was a subsystem, which was why it was later called an integration system, across elements, across the Orbiter and the Exterrnal Tank and the SRBs because it touched all of them. I had a very good relationship with the folks at Marshall, the solid rocket booster people, their Subsystem Manager for the separation motors, their Subsystem Manager for the explosive bolts, etc. Maintaining that relationship was challenging at times, but I enjoyed it because I really enjoyed the people at Marshall. I respected their capabilities and what they could do. We formed a wonderful team. The Marshall people were involved in these AEDC tests, too, they'd helped us do a lot of the scaling work—how do you scale separation motor plumes—because they have a lot of wind tunnels and a lot of expertise in aerodynamics. We formed a great team on that. Some of my best friends have come out of that experience, of people at Marshall.

JOHNSON: Are there any other experiences during that time that we haven't talked about that you'd like to mention?

CRAIG: The Shuttle itself, no. The biggest thrill, slash, heart stopper was that first flight, STS-1. Boy, when you're a young engineer, one has confidence in equations and tests, but the more experience one gets: okay, I've thought of everything I could think through. We've had these reviewed by the smartest engineers in the country, and I've done everything I can with each one of these pieces, and I've thought through how they all come together. And now you're actually going to launch it? Because then your image is the boosters come off, they come through the wings or something, or they don't come off. Because these are 200,000 lb boosters, so they're starting to fly around, and they're flying around the vehicle with the crew in it. The launch of STS-1 was an adventure.

JOHNSON: When you moved into the Integrated Entry Analysis Branch, that was before the launch?

CRAIG: Well, I think so. I don't know. I lose track of what the organizational—

JOHNSON: It was all the same thing, basically?

CRAIG: It was called, as I recall, the Engineering Analysis Division, which had aerodynamics, had trajectories, had the separation stuff, had the "dirty," not discipline-specific kind of stuff. But then that—the Shuttle, the separation system experience—laid the foundation for what was to come next at Shuttle. We get through STS-1, breathe a huge sigh of relief, and then, of course, start to get the data now of what did actually happen on the flight to look and see how it compared to what we predicted. It looked good and the SRB separation system has worked on every flight since. [knocks on table] Thank God.

JOHNSON: Where were you during the launch of STS-1?

CRAIG: I was in the MER, Mission Evaluation Room. We were just barely breathing, didn't need to be in Mission Control, because it either works or it doesn't, and there's no—you're monitoring this, you're monitoring—there's no monitoring anything. It either works or it doesn't, and it's got less than a second to do it. And you know if it did and you know if it didn't. There's good in that, I guess. But that was breathtaking.

But it then laid the foundation for at least one thing that happened next on Shuttle. When STS-1 came back, there was a huge gash in the tiles on the nose landing gear door, and that got a lot of attention as one can imagine. Because I'd been working with thermal protection tiles and rocket motors for a long time to get the SRB separation subsystem ready, I was asked to lead a team to look into it. Plus there was a lot of other damage on the tiles. That one big gash was a really spooky one, but there were a couple of others back on the body flap, and then there were hundreds of others, small, little, not very deep kinds of damage.

I was asked to lead a team to figure out what had happened with that. That was my next adventure in the Shuttle—debris assessment and mitigation—which has a curious connection with the present. Put together a team of a couple of folks from here at Johnson, couple of folks from Marshall, couple of folks from Rockwell and Kennedy [Space Center], and we very quickly decided as we looked at the damage and looked at what film we could find—there wasn't a lot, it was all pad kind of film—and determined several things. The cause of the damage on that first flight on the nose gear door was what was called a lightning band. The early External Tanks [ET], because they were on the pad so long, had a carbon phenolic band that went around about halfway up the nose of the tank. And it was hard like concrete. Well, that band had come off, and that's what caused the damage. We also found some sites that we felt were caused by something also hard, not ET insulation foam, and we concluded it was probably ice. There's a vent, the LOX [liquid oxygen] tank vent at the very tip—I mean at the very tip—of the External Tank.

We very quickly made recommendations back to the program. Get rid of the lightning band and do something about the ice. So a "beanie cap" was created as part of the launch pad support tower, which goes over the tank, and that came from that initial investigation. We also determined that it was a good idea for somebody, a Red Team, to go out and look at the vehicle right before it was launched, and decided that was probably us. So we created a Red Team, and that was one of my next great adventures—and talk about an experience. Going out with the flight crew, about that same time, and walking around the pad, walking around the vehicle. I'll talk more about that in a minute.

We also determined that there had been some damage on landing, so we expanded our assessment to look at the landing site, Edwards Air Force Base at that time. We went out and began to conduct landing investigations, too, and then we wanted to be the first people to see the vehicle once it got back so we had a fresh snapshot. That whole debris identification and mitigation activity was a very focused, very intense activity, which involved some fascinating things I'd never done. I've been around some hardware, but to actually be around a launch vehicle is incredible.

There was a lot of ET insulation foam coming off, which is what caused, we thought, the hundreds of small damage sites, and we began to identify places where it was coming off and put in place a program to mitigate that. We did that, for it still goes on today. That Red Team still goes out. Everything we set up is still in place. I left it when I went to work on Space Station in the early [19]'80s, but actually I did debris stuff while I was beginning to work on Space Station. I started on Space Station in '83 but was still doing debris stuff to hand it off to people until early '84. So I just set it up and then went off to my next assignment.

That was a very powerful experience, which I wish everyone had the chance to share. When you go out to the launch pad, and it's usually at night for many missions, and the vehicle's lit up with these white, I mean white beyond any white you ever seen, lights, and the whole area's cleared and you're driving out there. And you drive up to the launch pad, you're looking up at this vehicle, it's smoking, and puffing, and it is so white. And you go up an elevator and get out on the deck of the Mobile Launch Platform [MLP] and we took telescopes and cameras and did all kinds of stuff.

You're out there, and at that time the deck of the Mobile Launch Platform didn't have railings on it, they were removed before the launch. You're walking around on this deck that's already a hundred feet in the air. You just know you're going to be so enthralled with what you're looking at, you'll walk off the edge or walk off into the flame bucket, and then the launch has to be scrubbed to retrieve the body of the bozo engineer that was up there. That's always in the back of your mind, so your adrenaline is pumping like you can't imagine.

The vehicle is just amazing to describe. It's alive. It moans and creaks because of the cryogens. It's raining. There's so much moisture that's pulled out of the air as condensation, so it's wet. There's water running down everywhere. And all this is lit with this intense light. And this moaning sound, these moans in the background from the aluminum stretching and contracting, and the valves are firing off like shotguns, constantly, boom, boom, boom, boom, boom, boom. There was a giant hydrogen burn pond next to the pad where the excess hydrogen was dumped and some kind of chemical additive was put in there so you could see it because you can't see a hydrogen fire. It was green and orange. You had these giant green and orange flames coming up right next to the pad. I mean it is Wagnerian [relating to composer Wilhelm Richard Wagner]. It is just surreal.

And you know you're out there doing some very important things. All that is running together in your head. That was probably one of the most amazing emotional experiences I've ever had in NASA.

JOHNSON: What were the type of things you were looking for during those inspections?

CRAIG: Well, I'll tell you what we looked for, and then I'll tell you what we found.

JOHNSON: Okay.

CRAIG: We were looking for ice, if there were any kind of fissures in the foam insulation on the tank where ice could form. We were looking for failures of the "beanie cap" to engage, which we didn't expect because those are already covered by cameras pretty well, which you can view in the [Launch] Control Center. We looked for any kind of anomalies on the vehicle. But mainly it was ice on the foam, and that was a great challenge. It's hard to see ice often.

We've done a lot of technology work with other Centers, with the Army, looking for ways to scan the thing to look for ice, so that hopefully you didn't have to send people out there at some point. There was mainly ice. But anything else, debris, and we're looking for any kind of debris that could be a source of problems, and we found things. We found a cable that had been left on the deck of the MLP, just a giant power cable that the procedure hadn't picked up. We found a hat, somebody's ball cap that had fallen into the "water sausages," we called them, over the flame trenches to cut down the acoustics. And there was a hat in those. We would find things that in the crush to close out the vehicle had been missed. The hat wouldn't have been a problem, probably, but that cable could have been. That MLP deck, as the vehicle takes off, all those giant plumes spray the deck and shoot things back up.

I'm trying to remember how we first found it. One of the most dangerous things we found was that the SRB hold-down posts on the pad were coated with a cement-like material to protect the pad from the plumes of the solid rocket boosters, and pieces of that were coming off. We had seen some was missing, but then as soon after launch as we could get them, we were down at the Patrick Air Force Base [Florida] where the launch films were developed, we would look at the films, and we began seeing huge pieces of this stuff shooting past the vehicle.

The aerodynamics was such that if things were loose, they didn't just go out the flame trench, like you'd expect, but there were flow conditions that would actually shoot things back up. Here's the Shuttle taking off, and we'd see this white thing go [demonstrates noise] and we determined they were these big pieces of this protective material from the pad—only blown back up. They were actually going faster than the Shuttle, and that stuff was like a rock. That was one of our early finds.

We had another breathtaking moment. We had the experience of seeing the vehicle right before its launch, which was amazing. Right after its launch, we'd go back out and look at the pad, look for debris, look for whatever we saw that we could fit into our puzzle. And we'd find all kinds of amazing things, ALL kinds of amazing things: animals in fences. The violence at launch is just hard to imagine. It's impossible to imagine the violence around the pad in one of these launches. It's like hell, a very fast-moving hell. High temperatures, tremendous pressures. But after STS-3 or 4—I had been up at the pad, and was walking down the pad apron, and found an Orbiter thermal protection tile. That about caused my heart to stop. Then we found some more tiles just down the ramp from the pad.

We, of course, immediately called the folks here, and that caused some—turns out they were tiles off the body flap, the upper part of the body flap, not the under part. There had been some kind of a spill of hydraulic fluid or something from the main engines so that it dissolved the bond with the body flap and so the tiles had come off. We then found it on film. That was a stop-your-heart minute, because the vehicle, by that point, had gotten in space, and we found whole tiles lying out there. Whenever you investigate something around an event as energetic and multidimensional as a Shuttle launch, you find all kinds of things you wouldn't necessarily—or I wouldn't have ever—expected, which is why you need to inspect it.

JOHNSON: Did your team have recommendations after each flight?

CRAIG: Oh, yes. I think we were the most eagerly anticipated team to come in. "What did the guys find this time?" In fact, I would call Bob [Robert F.] Thompson, the Program Manager, or Dick [Richard H.] Kohrs, the head of System Engineering, immediately after each phase of our assessment. "Here's what we found, here's what we think, here's what we don't know, everything looked good," because they, obviously, were very interested in what we were finding.

JOHNSON: Did things improve from one flight to the next?

CRAIG: They definitely did. And we kept detailed maps of where all the damage was on the tiles, and they improved by at least two or three—just the number of little dings on the tiles improved by two or three orders of magnitude in the four or five flights that I worked on. It wasn't because of me, it was because we really were paying attention to what was happening and trying to address things that cause a problem.

In hindsight, I'm not sure we were looking at the right things. But damage reduction was being made. None of the big stuff showed up again, big damage, within those first few flights. We thought we understood the phenomenon that was causing the smaller damage. We actually found on one flight, found some fairly significant damage on the OMS [Orbital Maneuvering System] pods in the back, and determined it was a urine icicle from the Orbiter itself. There's a vent where urine is taken overboard. There's a heater on that when it sprays out. And that heater had failed, we learned later, and a giant icicle had formed and the icicle came off on entry and hit the [OMS pod].

One of the things we had to combat was a natural human inclination if you see something, "Oh, I know what caused that, the tank." Well, maybe, but maybe not. We were always very careful to make sure we understood the data and looked at it very carefully, and then came up with some options but just not leap to what appeared to be the obvious. That's hard for people.

JOHNSON: Were you able to eliminate some of the things that people left behind, like the cables and the hats and that sort of thing?

CRAIG: Yes, very much so. Probably the second or third major action we recommended and the program accepted was doing a whole sweep of the pad, because anything in place around the vehicle is very process oriented as it ought to be. You had one process, you make sure it's right, and you make sure people follow it. There were very detailed processes about picking up stuff. But at the end of the day we found, in a rush to close out, not enough was being done. The program—they'd send another team out to do a sweep, and that's all they would do is walk the pad looking for stuff. It's a good thing to do.

JOHNSON: You published a paper in [19]'83, the *Shuttle Launch Debris Sources, Consequences, and Solutions,* and in that, I think this is a quote, "All known safety of flight debris sources have been eliminated," as far as you knew. And then you mentioned a few minutes ago that maybe you were looking at some of the wrong things.

CRAIG: I'm not sure we were looking at the wrong things.

JOHNSON: Well, you might have been looking for other things?

CRAIG: Every source we understood at the time, or could conceive of, we felt was not safety of flight based on the best knowledge we had. And that knowledge was based on what we had seen in terms of the foam on the tank, and the amount of foam that would come off the tank at that time. The foam that would come off was very small, it was popcorn-sized stuff. In fact, we called it "popcorning." That was the name of the phenomena.

And we did not have, early on anyway, the camera looking down at the tank that was in the Orbiter umbilical well, so in orbit you could look down. And that was one of our recommendations, that that be put in to do that. Based on everything we'd seen, both in terms of the damage we saw and knowledge of the material that was being dealt with, we thought we had eliminated safety of flight risk.

And I, frankly, don't know enough, given everything that's happened, to know whether that's true or not. I do know that the foam has changed over time, I mean chemically, and as a result its physical and mechanical properties. Its chemical composition has changed because it had to meet, like everything else we do, the EPA [United States Environmental Protection Agency] requirements that were changing with time.

One of the things that—I guess it began to set the seeds then, and I've had other experiences since, or just thinking about it has taught me—there are some materials that are just not good engineering materials, and foam is probably just not one of them. It's like making a cake. And there are other materials like this. Solid propellants are like that. It's like making a cake. There are things that can happen even with the best controls that you may not be aware of or able to deal with. I, as an engineer, much beyond this in maturity, hopefully, I've learned there are some materials you ought to avoid, period. They are just not good engineering materials. They're not predictable. They are very predictable within some band, but not a broad enough band in which to do work, especially space work. That's an intuition I have of something I now keep in consideration that I wouldn't have had then.

JOHNSON: Was it thought at that time, and like you said the foam has changed over time, but the popcorning, was your team looking at that as a significant danger, or was it just something that was an acceptable risk?

CRAIG: Based on all the experience we were seeing and the damage we had and its size, and it was pretty much distributed over the whole bottom, we thought it was acceptable. Small size, lots of them, but, just almost cosmetic. We were never concerned about the RCC [reinforced carbon-carbon] because of that small size, correctly as later testing would show. Now, had we'd actually done an analysis to figure out if a piece of popcorn hit the [Orbiter], no, we didn't do that? Probably should have.

JOHNSON: Well, as you said, hindsight is looking back.

CRAIG: Yes.

JOHNSON: You also went out and inspected the vehicles once they landed. Can you share some of those experiences with us?

CRAIG: The most amazing experience was climbing in the Orbiter cockpit and sitting in the commander's seat – climbing into a spaceship that had hours before been in orbit. As to debris assessment, the reason I had special access, it was always "Well, what did happen?" [laughs] We thought we'd done everything we could do. Are we going to see something different this time? And by and large, we didn't. It was within the family of what we were learning to expect, as we eliminated the big things right up front, like the lightning band, like ice, like the cement from the SRB hold-down post, and so those were obvious, and we got past that threshold of things.

And then the tank guys were working real hard to make sure their processes were controlled on the foam, and where the foam was applied, and where there was rework—always on the foam it seemed like. They would find a divot or a hole, so somebody would go in and rework it. They were really trying to minimize that, because you just open yourself up to another—you fix one thing, but what have you created? They were really working hard on that.

And then we began to see the number of damage sites drop. Even the little cosmetic things were going down. We thought we were on a good trend. We were still finding things. We found on the runway, which caused us concern, we found ammunition, we found nails, we found—so we started doing walk-downs of the runway and the lake and the lakebed runway at Edwards. The thing has been a bombing range forever and a machine gun range, so there's a lot of stuff in that lakebed. We sensitized ourselves and the system to don't assume it's just a nice lakebed.

Blow a tire, or a tire can run over something and throw it back up into the—the consequences of tile damage aren't much at that point, but again, just learning to think about debris as something you need to keep paying attention to. Because it's everywhere. The ubiquitous.

JOHNSON: Kind of hard to keep it all completely clean, especially on a runway of that sort.

CRAIG: Yes.

JOHNSON: Were you able to inspect the Orbiter after the landing in White Sands [New Mexico]?

CRAIG: Yes. That was one of ours, and that was a real adventure, being in White Sands. I'm from West Texas, from Midland, and it's close to where I grew up, so I liked that country. But that gypsum lakebed was a whole different—not particularly for our systems, but it caused other engineers a huge problem. It's a very fine dust. It's chemically reactive. That was, I know, for engineer colleagues, that was a huge problem and a huge concern, getting all that gypsum dust in a payload bay. Talk about debris, a different kind of debris.

So we covered that, did the same thing we did when it landed out in California, from our debris standpoint. Other than being a different place, without all the infrastructure there to support us, it was our same process.

JOHNSON: Before we leave this area, I was going to go back and ask you, I had read that you had some involvement with Payloads Purchase Plan Project along with some other AIAA [American

Institute of Aeronautics and Astronautics] members, as far as getting schools to purchase small payloads.

CRAIG: Yes, that's correct, as part of AIAA. I was on the student affairs committee both here and then nationally. John [F.] Yardley, who was the Associate Administrator for Space Flight at that point, who was a brilliant engineer, and I have other stories about John about that. One of his manifestations of brilliance was to realize we ought to try to get more people to use the Shuttle—like kids. So he created a thing called the Getaway Special, which was named after, as I recall, a TWA [Trans World Airlines], promotional tour thing at that time. They had a Getaway Special. You'd fly to the Bahamas or something like that. So John said, "We're going to have a Getaway Special on the Shuttle and have a standard payload container the size of a trashcan that's very inexpensive to integrate—all you do is put it in the payload bay. And whatever the kids want to do as long as it's safe, we're going to let them do it." Well, we latched onto that right away. That is a great idea.

We tried to set up the infrastructure to support that, to help motivate kids to do it, to provide funding and other things, to provide mentoring and expertise through AIAA. It didn't go as far as I would have liked, but I thought it was a great idea and was a great start. That was all AIAA stuff.

JOHNSON: When did you first join AIAA?

CRAIG: I was a student member at Purdue, and I'm still a member so I've been a member a long time and then got active in the section here—was a counselor in the section here, and was then at the national level on education, because that was part of my passion then, and still is. And that was just the beginning of it, looking back. How do we use space to benefit all people, not just engineers and scientists? I think we do ourselves a huge disservice as we treat space like our private little club.

The people of this country pay for this, certainly what NASA does, and to better involve them in it—and I mean really involve them, not just on the margins, not just with whatever we have leftover—is a tremendous responsibility we have. And one we've not lived up to, in my opinion. I'll talk about it later, because inside NASA I have tried to do a lot about that, not very successfully

JOHNSON: Was there anything else during this time period that we haven't talked about before you left and went to Headquarters?

CRAIG: Well, there was one other thing I did. The SRB separation system we had under control and it was heading down the path. Before the debris thing showed up on STS-1, I was asked to help lead an effort for my colleague Barney Roberts, who was doing the External Tank separation. People began to think more about Shuttle abort scenarios—the nominal tank separation is fairly straightforward because you're in a vacuum, you're in orbit. You still have to blow bolts, still have to do things, still have to fly away from it, but it's fairly benign. But an abort call to return to launch site, RTLS, there is still a lot of propellant in the tank, potentially, or more than you have at a nominal end of mission, and there's aerodynamics.

You've flown out. You've tried to burn up as much propellant as you can. You're now headed back to the Cape [Canaveral, Florida], and you've got to get off the External Tank to land, obviously. The more folks thought about that, they were really concerned about if you have any significant propellant left in the tank, like 10 percent of the propellant, how will that propellant mass affect the separation dynamics, especially because of the aerodynamics and drag? It's a very good question.

As the program was approaching STS-1, it began to put resource as it was freed up with everything else being ready, on looking at some of the more exotic domains of activity, like the RTLS abort. This was one area where a number of people had concerns. And we had math modeled, or Barney had math modeled, and his team, the dynamics of getting the tank away from the Orbiter with aerodynamics in an RTLS. But the nagging question, as I say, was what if you had this big slug of propellant in the External Tank? It's not just this body the tank you're getting rid of, it's two bodies, or three. You have the tank, plus a ball of liquid oxygen propellant up there in front of the ET, and a ball of liquid hydrogen propellant in the back of the ET. The hydrogen is less of a concern because it's so much less dense, so weighs less. But this oxygen's what really concerned people because it's at the front of the tank. You can let go of the ET, but then you have this ball in there and maybe it hits the tank and knocks it back into the Orbiter. That was the concern.

I was asked to lead an effort to figure out how you model that phenomenon. There were so-called "slosh" models which are for waves set up on the surface of the propellant which generate force. Those are pretty well understood and modeled and have been for a long time, since launch failures where people hadn't figured that one out going back to the Germans. That one was pretty well understood.

This was a completely different kind of "slosh" because it wasn't about wave motion. The propellant is just a ball. It's in a weightless state or it's a slug, even if it's in a partially weighted state. The tank is experiencing aerodynamics, so it's slowing down. The ball, the slug, isn't. So how do you model what the propellant's doing and then how do you model its forces, the forces it will induce on the tank? That was basically the challenge.

We established a contract with Martin [Marietta Corporation] in Denver who had done a lot of thinking about this. And I'd started thinking about how to do it. I'd concluded you really couldn't do it with—at least didn't need to do it—with solving all the fluid dynamics equations, which would have been very complicated. I had actually concluded that you could do a so-called "mechanical analog." You come up with a math model to represent a mechanical situation that's analogous to what the effect of this propellant would be. I was headed down that path and doing the math on that. The Martin guys had come to the same conclusion and were doing some work on that.

When we got together and I was assigned to lead it, since we'd come to the same conclusion, it was just a matter of how do we mathematically model this analog. We came up with a way to do that. To give you an example. Let's say you had a bunch of balls tied together by springs. I could model that mathematically. Well, it's not unreasonable to think that's not a bad analogy for what this slug of propellant is. I can't really do the math to solve the fluid equations of what the slug of propellant's doing, but I can do the math to solve the equations to describe what these balls tied together by springs are doing. And when those balls tied together by springs hit the tank, they'll induce a force, and that will be my math model. We ended up with something a little more complicated than that, but that's the idea. If you can't use math to solve what's actually happening, pick an analog you can use the math on that you think is close enough. And then do tests to verify that it's close enough. That was our approach.

We did that, developed this mathematical model, and then decided, "Well, you know, this is an assumption. This is an analog." So we thought, "How can we test this?" This led to one of my other neat experiences, just out of the blue. We ended up putting together a test program in the Zero G [gravity] aircraft, and flew a number of campaigns in that. Actually, we'd found, somebody had already built a Plexiglas model of the LOX tank that was about six feet tall, and we did studies to figure out, like the aerodynamics, what's the scaling parameter, what kind of a fluid do you put in it that will scale and behave like liquid oxygen would and induce the same forces?

We figured out what the scaling parameters were, came up with a fluid, and it ended up we had to use Methocel, which is what McDonald's uses as a thickener in their shakes. We used water, put Methocel in it, and that gave us the right scaling parameters so the fluid both moved like and exerted the force like liquid oxygen would.

We then undertook a test series in the Zero G aircraft where we didn't fly zero G exactly, we'd fly to low G, so the fluid would move like we thought the LOX would in an RTLS abort. That ended up verifying the math model to our satisfaction, and to the program's satisfaction. That was a neat program.

We had one hiccup along the way. We used several fluids, one of which was benzene, and the tank over-pressured and cracked. The tank broke while we were in the test series in the [aircraft]. [Laughs] That was kind of exciting, got the attention of the safety people, and us. But that was fun, I mean flying in that aircraft.

JOHNSON: What was that experience like?

CRAIG: It was wonderful. You're as close as—unfortunately, I'll ever get to being in space. You go into the zero G maneuver at about two Gs, so you're pressed on the floor. And then you hit zero G or low Gs, very low Gs, and you're weightless, and then you just start to float. The thing I found most amazing, you can feel your organs moving around inside your body. Not drastically, but it's just very liberating. You can feel your heart beat. In a way you don't, at least I don't, in a weighted condition. It's very liberating.

And, of course, you can do all the somersaults. But I found just the floating was incredible. Then, of course, after thirty seconds, slam, you're into two Gs again, and you do that about sixty or seventy times. So it's slam, float, liberated, slam, float, liberated. It was a very different experience. All in all, I really enjoyed the weightless experience.

JOHNSON: You didn't have any problem with nausea?

CRAIG: No, although many people did. In fact, the crew on the airplane had a ritual. You're wearing a flight suit, of course, and they require, rightly, that everyone have a barf bag in their pocket. Then what they will do—one learns, after the fact—one of them will pretend to get sick into their [bag] and then reach in and pick out something. What they had in there was fruit cocktail. At that point, if you're anywhere near gonna, you do. [laughs] They'd be, "Oh, Bob, look what I had today." [laughter] Typical test jokers.

JOHNSON: Pilot humor.

CRAIG: Yes, pilot humor, which for those of us that didn't tend to get sick was, I guess, at least okay, but for those that were right on the edge and then lost it, it was, oh, no. Then you're a member of the club once you've done that, and they give you a certificate. One certificate if you didn't get sick, and one if you did. So it's fun, I guess.

JOHNSON: One of those experiences you really didn't expect to have when you first started.

CRAIG: That's exactly right. Yes. Who would have thought I would ever have a chance to go and walk around a launch vehicle or climb in the Orbiter cockpit as soon as it landed or fly weightless. I mean who would have thought?

JOHNSON: What was the relationship like, especially when you were on that debris assessment team with the crews themselves and the astronauts?

CRAIG: Really didn't have much of one. They were, of course, very interested in what we were finding. But we would often go out at about the same time the flight crew was going out and we would see each other out there, but we had certainly no real interaction on the pad because they were very focused and had their team getting them installed, and we were off in other parts of the pad doing other things. The main interaction was the regular programmatic interaction between a team doing something and the crew in the flight office wanting to know what we were finding and what the program's going to do about it. It was more that kind of an interaction.

JOHNSON: When you were inspecting the vehicle after landing, was that when the crew was still on before they came off or after they had already left?

CRAIG: No. They had been removed from the vehicle, and the vehicle had been declared safe, because there are all kinds of dangerous propellants and things that could leak out. So the first, literally the first, people that go out there are in SCAPE [Self Contained Atmospheric Protective Ensemble] suits and they're really protected. Once they've done all their sniffing and everything looks okay, then it was cleared for us to go out, because the last thing you want to do is have somebody maimed that's on the debris team. Again, like falling off the edge of the Mobile Launch Platform. Oops, there's one of our debris guys passed out under the fume of noxious odors out there.

JOHNSON: Not a good picture.

CRAIG: Not a good picture. And not something we wanted for ourselves, either.

JOHNSON: Any other memories during that time period you'd like to share?

CRAIG: No. That's probably a pretty good summary.

JOHNSON: Okay. Well, do you want to move on now to that first experience with Headquarters and how that came about?

CRAIG: That would be great. May I take one break?

JOHNSON: Sure. It's a good time.

[pause]

JOHNSON: When we stopped, we were getting ready to talk about your first experience with Headquarters, and if you want to go ahead and talk about that and how that came about.

CRAIG: Okay. About two years after we had flown STS-1, the SRB separation system, of which I was manager, was being transitioned to the contractor at that time. The idea was that the Shuttle was either operational or near being operational, so the development team, of which I was a member, was transitioning to the operators. And at that time the idea was that we would transition basically our experience and everything else to Rockwell, which I had done.

The debris stuff had a process in place. It was running. The team was good. So I didn't feel like I was particularly adding anything to that. The propellant dynamics work I'd done on the External Tank was done. So I began wondering, "Well, what do I do next?" I'd heard that NASA was considering developing a Space Station, so I went to Clarke Covington, who was the JSC Space Station Manager, and said, "Clarke," who I had known for a long time, "I would really like to be considered, to do something on Space Station. Do you have any ideas? You know, as things come up, please keep me in mind."

He shut the door and said, "Well, funny you mentioned that. How would you like to go to Washington?" This was in '83, early '83, and NASA was developing what they called a

Space Station Task Force in Washington, and it was people from all the different Centers assembled to understand how we would do a Space Station. Not only technically, but programmatically and politically and everything else.

I said, "Gee, that sounds interesting." From that he asked me to go to Washington and work on what was called the Concept Development Group [CDG], which was the technical arm of the Task Force. It was led by a man named Luther [E.] Powell, from Marshall, who I did not know. I ended up in mid-1983, like June, July, went up to Washington with the expectation I'd be there for six months to a year, whatever the process was. As I mentioned, I continued to still do some things with the debris assessment to further transition it. I supported the next couple of Shuttle launches, but I really was living in Washington. I got an apartment in Arlington, Virginia.

The Concept Development Group had an office in what was called the GSA [General Services Administration] Building near the NASA Headquarters building. It turns out it had been a building built in the 1940s to store tanks, I mean like tanks with guns and treads, tanks, we were told. It was not a very up-to-date building. In fact, occasionally we would have raw sewage that would run out of the ceiling because the cafeteria was above. It was kind of a different environment compared to what I'd experienced at JSC.

It had a group of people from all over the Agency. It was a great group of people, assigned basically to figure out what the Space Station configuration was, what technology would we use, what would it do, and what would it look like as a result of what it would do, etc. There were other people on this Task Force from JSC and the other Centers, looking at the program, how do you set up the program, how do you set up the work between the Centers, etc.

I got there and was basically the senior JSC technical person on the CDG and was given—it ended up, that there were about eighteen different studies or tasks being done by the CDG, and I was given ultimately, I think, about twelve of those to lead with teams of folks from all the different Centers. Also the contractors were involved in this to the extent that they knew the studies we were doing. Each contractor was putting together their proposals, and they're making sure we had input of their ideas and where they were, etc. It was a very dynamic environment, very energetic environment, very interesting environment.

Working on the Space Station was something I had never done. Very different than a launch vehicle or an entry vehicle, so there was a chance to learn new technical things, which I enjoyed. How do you fly a Space Station? It really was the first exposure I had to, what I would like to call, the business end of a spacecraft. Why do you actually build a spacecraft? The Shuttle, I know, had gone through that with the Air Force and other entities in coming up with its configuration, the size of the payload bay, and everything. Why you do something, ultimately, to better shape how you do it. Not that we've done that at all, all the time, but we ought to. And with Space Station, that was very much the case. I really enjoyed that, really enjoyed interfacing with the scientists and other people, trying to understand their requirements so we could figure out what the Space Station ought to be.

The most interesting of the studies that I led, and probably the most important, was on the configuration itself. What is the configuration of the Space Station? That was the place I learned the most about how Space Stations fly, and that's where all the "why you do it" had better come together with "how you do it." I really enjoyed that, and I really enjoyed working with the folks in all the different Centers and the contractors.

As a result of my leading the configuration studies, I ended up occasionally—the management of the Task Force would do tours around the Centers and other places, and I would be taken along as the technical person to talk about the configuration and other things. Luther Powell, as the head of all of the technical things would be taken along, so it was a good chance to meet the people in other places. I enjoyed it.

We ended up writing a number of reports on all these different studies, and that was our last act, was to put those reports together and get them published, which they were. From that I ended up coming back to Houston in March of ’84. The Task Force had done its job of figuring out how to set up the program and decisions had been made about where the program would be resident and how work would be distributed between Centers. Johnson was designated the Level 2, the program management Center. I don’t know exactly when, but around early ’84, and that’s when things began to close up on the Task Force so I came back here to JSC.

Then there was a Skunk Works here, which Neil [B.] Hutchinson headed. He was going to be the Program Manager, and a lot of these same people from all the different Centers came here, and we were resident over in the Vanguard Building or Nova Building, one of the off-site buildings, thinking about how do we actually do this, taking this Task Force thing to the next level, which we did. It was a pre-Phase B, in a programmatic sense, which we did.

Then at some point, Phase B began, I guess in 1985. So we spent 1984 doing that, getting the Task Force group to the next level of maturity, then Phase B began in 1985. I was asked to be in the Systems Engineering and Integration Office as its Assistant Manager for Engineering. Al Louviere was the Manager of the Systems Engineering and Integration Office, again, for the Level 2 Program Office of the Space Station Program. Because of all the work I’d done on the configuration, I continued leading that work in Systems Engineering and Integration.

Ultimately, in late 1986, Al Louviere left, as did Neil Hutchinson, actually, the Program Manager, and I was made Manager of Systems Engineering and Integration, and John [W.] Aaron was made Manager of the Program. That is an era that I'm not sure how to talk about constructively. It was so different than my experience on the Shuttle, which was very focused, and had certainly involved other Centers and all kinds of teams, as we talked about earlier. This was not as focused. It was much more contentious. The so-called Space Station "Work Packages" had been created for the Centers, and there were four Work Packages. Let's see if I can remember what they were. There was one here at JSC. There was one at Marshall. There was one at Goddard. And there was one at [NASA] Glenn [Research Center at Lewis Field, Cleveland, Ohio], for the power system.

Our job in the Program Office at Level 2, classic system engineering, is to, if that's how the program is broken into pieces, is to assign the content of each of these pieces, and what is its interface with the other pieces, and assign requirements based on those that when they're built and the thing comes back together, you have a Space Station. That's basically what the Level 2 job is from an engineering standpoint. It also was doing the science, what science do we do? How do you do operations of the Space Station? It also had technology development, which was in my system engineering work.

We also at that time, and one of the things I enjoyed the most, were doing all the negotiations with the potential international partners to bring them into the Space Station. I was the engineering person on all those negotiations, which I really enjoyed. I really enjoyed getting to know and working with the Europeans and the Canadians and the Japanese, and again, to this day, have friends that I made in those negotiations.

The environment was very contentious in NASA. The Work Packages at the Centers, including Johnson, and I would probably overstate this because I was in Level 2 and living with the results of what these people did. They, in some ways, saw their principal job as getting as much work as possible for their Work Package. Our job, as I said earlier, in Level 2 is to assign the content of each work package and then the interfaces with the others. That's always a dynamic, iterative process, hopefully, against criteria about how you optimize the ultimate system. Each of those Work Packages, some more than others, but each of them saw their job as getting as much work as they could, period. And they saw Level 2 as the enemy of that, so it was a very contentious environment.

It was clear to me that actually producing a Space Station was somewhere down the list of the objectives of most people. Getting the most work possible was the objective. The worst contention was right here at JSC, because we had a Level 2 office and a Level 3 office, a project office. So as Level 2 was not giving work to the Level 3 office here, the Level 3 office saw us as the enemy, too. But we were at the same Center, and we had all grown up together. So it was not only contentious as it was with the other Centers, but it became visceral here, and relationships ended that had been formed for years. It was just appalling.

That was kind of the down-and-in dimension of that experience, which was very disconcerting to me, from Level 2 down to Level 3, the projects. There was an upward dimension, which was at the time even more disconcerting. The job of Level 1 is to create a basic statement of what something is, and then it's Level 2 that figures out how do you bust it up into pieces, how do you assign requirements to the pieces, how do you put the pieces back together to make that thing.

The Level 1 function was—and I understand the reasons for it, but the results were disastrous. The Level 1 function was both trying to figure out what this thing was, the Space Station, and sell it politically, and the contradiction between those two things was the source of a tremendous problem. I had grown up as a system engineer understanding that my job at Level 2 is to implement what you at Level 1 tell me this is to be, and then I bust it up and do all this stuff and put it back together and make sure it matches what you said it was. We were asked to begin that process in Level 2 without any definition of what it was at Level 1, which is impossible and just heightened and exacerbated the contention down below.

The reason the Level 1 folks couldn't write down what it was—their political support was tenuous enough in their view, and it may well have been. They felt to write down anything about what it was would also say what it wasn't, and if you say what it isn't, you lose support. They viewed their primary constituency, at least as viewed by the larger world, as being scientists. So there were large groups of people talking to Earth scientists, space scientists, all kind of space scientists: astrophysicists, cosmologists, astronomers, Martian scientists, lunar scientists, biologists. The Headquarters folks were trying to put together a coalition of scientists that would say this was necessary.

To that end, again, they didn't want to say it couldn't do any one thing, because as soon as they did, some group of scientist would figure out it wasn't going to work for them. At the end of the day, their basic approach was to assure everyone it would do whatever they wanted. Because of that, they couldn't write down what it was on a piece of paper to give to us at Level 2 to make happen. That's a huge problem. It's a huge problem because you then waste resource at Level 2 and Level 3; it's wasted. It's a huge problem because that just then furthers this contentiousness that was occurring with the Level 3s because there wasn't an ultimate set of requirements to hold the thing to. So it just fed the feeding frenzy of Level 3.

That was the worst mistake I've ever made in my career, is not just saying, "Stop." I think our leadership here and at Headquarters, they knew there were these problems. They knew they didn't have the structure right. They knew there was contention, but at the end of the day, I believe, they continued to let this go on because they felt better at night. "Well, you know, we got our best people working on it, and they're working on it real hard."

Well, that's a good thing to have, and it's a good thing to depend on, but as a manager at the end of the day without those Level 1 requirements, I should have said "I'm not doing this anymore. You can find somebody else to do it, but I don't want you to kid yourself thinking this is going to work out because I'm working on it, and working hard, because it's not going to. It's flawed." I should have stopped my whole team and stopped myself. My hope, of course, naïve probably, management then would have asked harder questions about what is happening here. Even if Craig goes, you find somebody else, they're still going to have the same.

That was the absolute worst mistake I've ever made in my career, was not saying "Stop." At some point as a manager, as an employee, I think one has that responsibility. If you really, truly believe that something is flawed, which we found in a number of accidents and other things that have safety implications, I think the same is true in programmatic implications. I don't think we say that to ourselves enough. That's not to be used lightly. "No, I don't agree with it, so I'm going to stop," that is not what I'm saying. But if one comes to the conclusion that something is fundamentally flawed, it needs to be very drastically revectored, it's an important thing to say, "Stop."

We didn't. Just to give you two of the many examples of how strange things got. Let me talk first from Level 1 down to Level 2. Part of the process of selling this thing, as is always the case, is what is it and how much does it cost, which is always an iterative thing, because you've got to make the two at the end of the day coincide. But they don't at first and you iterate around the amount and what. We were early-on told and handed a requirement that this would cost eight billion dollars. Now, that eight billion dollars came from an assessment of what the market would bear. Well, that's fine, that's a place to start. We were handed that requirement.

We were also handed a requirement that there would be four NASA Center Work Packages, and those are basically the only requirements we had from Level 1. As we were laying out the engineering structure and the programmatic structure of the program, we began to do cost assessments on all this. And based on the way Work Packages were set up and the way the conflict was developing around those Work Packages, as we began to look at what it was going to cost to integrate this thing, it was going to cost more than eight billion dollars just to integrate it even if it had no hardware. It was almost we had a curve of, okay, we got to get to eight billion, so here's eight billion here. Here's content down here. We're going to start taking out content till we get down to eight billion. This is not quite true, but it's almost true. The intersection with no content was near eight billion, because of the way it was set up. And we kept trying to take that uphill, and we kept hearing "Well, you don't understand." And "Well, we'll get to it." Well, well, again, that's a big invitation to say, "Stop." So that's from a Level 1 standpoint.

From a Level 3 standpoint, I would chair the Systems Engineering Integration Board, where all the decisions were made about the boundaries between Work Packages. It got to the point where a decision was brought to that board about the springs in the keyboards in the computers, you know, under the letter "A" there's a little spring. Is that spring part of the data management system, which was at one Center, or is that spring part of the mechanical subsystem, which was at another Center? Now that is an indication of a problem, but that's the level at which it was going. That's the level at which the Work Packages were thinking about making statements. And those were the kind of decisions that were just grinding the Level 2 boards and processes and everything else to a halt.

The whole experience in Level 2 in Space Station was a real eye-opener for a lot of reasons, lot of reasons, and gives one an indication of why it took twenty-something years to even build the Space Station, because it went through several more of those cycles after this one. I'm not sure I could say anything more about that period of time.

JOHNSON: Well, during that time period, the [Space Shuttle] *Challenger* [STS 51-L] accident happened.

CRAIG: Yes, it did.

JOHNSON: And how did that affect the Station?

CRAIG: Drastically. And that's what caused the end of that period of time, certainly from my involvement. The Agency at that time decided, "Well, you know, we need to undertake an assessment of all management."

So General Sam [Samuel C.] Phillips was brought in to look at the Agency management structure. He had been the head of Apollo in Washington. And he came in and with other people looked at the structure and said, "This is a problem, and of course it doesn't work because it's not like we did it in Apollo." He then made a set of recommendations, which were accepted—most of which were accepted—and part of that was to "You don't want the Program Office here at the Center, that just feeds the turf. You need that in Washington."

So from his recommendations, Reston [Virginia] was created, and the idea was to take the Level 2 Program Office, which we had been running here, and move it to Reston. Two things about that—well, one could talk about a hundred things about that—but two things are very interesting. One is that when one really talks to people in the Apollo Program about how it was managed, that is not how it was managed. General Phillips believed he was running all of it from Washington, and he had a contractor there called BellCom [Incorporated], which was doing things, and he felt like that's the same model that should be used for Space Station. When one talked to both people at Marshall and here at JSC about how Apollo was really run, all BellCom did was funnel the data produced here and at Marshall up to Phillips. So that's not how it was run. That was his perception of how it was run. That's not how it was run. An important lesson. When you are asking a person how something was managed, make sure that you take into account that their view will be colored by where they were in the management chain. Collect the views from different points in the chain and integrate them.

The second thing is it just didn't, to us at the time, and of course in hindsight it doesn't—setting up a Reston, which was basically set up in a shopping center, independent of any Center infrastructure, no libraries, no HR [Human Resources] office, no pool of engineers and technical people to grow, to grow and have career paths, no any of that—it just didn't make any sense. It made no sense then to me, it made no sense to many other people, and it still doesn't. It was just a disaster waiting to happen, which, of course, it turned into.

So we were, in the Level 2 office here, we were—continuing the contention theme—we were persona non grata at Reston. "Well, you people were the people that got us into this mess. We don't like any of you anyway, so the last thing we want is to have you come up here." That was their initial take. Toward the end, they began calling some of us, "Would you come up?" We were all like, "No." I personally wouldn't have gone up under any circumstances. It was a disaster waiting to happen. I had an organization of a hundred and some people and I think three of them ended up going to Reston, and that was just in SE&I [Systems Engineering and Integration]. I think that was pretty true across the program office. That was literally denuding the program structure and starting it fresh with people that may or may not have had any experience. It was just creating yet another disaster, and, in fact, it did, in my view.

John Aaron, who was at that time the Program Manager, and I was the head of SE&I, were tasked with transitioning everything we did to Reston. We did the best we could in doing that. We documented everything. We'd say, "Here's where we are. Here's our take of where things need to go." Reston was so thin, we had trouble even engaging the transfer. Many of the people who we tried to transfer things to had no clue about what we were talking about. Many of them wouldn't show up at meetings. We tried to have telecons [telephone conferences] with them, they wouldn't show up. It was a sad deal. It was obvious something bad was about to happen, and something bad had been happening. Now it was going to change to a different kind of bad. Reston was a very bad management decision.

I was told much later by a senior official who was key in putting Reston together, that it was an experiment. Sadly, I'm sure that may well be true. Take your major flagship program for Agency Human Space Flight, and make it an experiment, it's a management experiment. What were people thinking?

That whole period is just a—I learned a lot, but it caused me really to have serious reservations about the management of this Agency.

JOHNSON: You moved into a different position as Special Assistant to the Director of the Engineering Directorate about that time?

CRAIG: I did. Well, JSC was, "Now what do we do with all these guys running our Space Station program here?"

The Center did a great job of really looking after the people that had been in the Program Office and really working hard to find places to put us. Unfortunately, for some folks, the well had been poisoned because we were the Level 2 "bad guys." We were the people that weren't putting everything at JSC, which was our job, right? So in some areas of JSC, especially the Space Station Office, my team was just persona non grata, which was a very sad, personally to me, situation.

I was put in the Engineering Directorate, which was okay. It was a holding position. With *Challenger* having just happened, they needed help with senior management, so I ended up being the Engineering Directorate representative to both the Shuttle and Space Station boards, which was very interesting. The Shuttle, especially, a lot was going on. My experience could add certain things, which were helpful, I thought and hoped, especially as the Program was wrestling with how to deal with some of these bigger issues. I welcomed the chance to participate in that and add to it as I could. Didn't last very long.

One of the things in that time that I did was for Administrator [James C.] Fletcher. Fletcher II, his second stint as Administrator, after Challenger gave an action to the Shuttle

Program to put together a history of crew escape and why we did not have a crew escape system. For one reason or another, I ended up getting that action for the Program. I put together a presentation, some of which I'd actually lived through in the early days of Shuttle, about things we'd looked at for crew escape and decisions that had been made over time to do things or not do things, and presented it to him.

It was interesting to have the history, because one of the things I built into it was who was the Administrator and who was the AA [Associate Administrator] when all these decisions were made. It turns out the key decision that caused us not to have a crew escape system Fletcher made as the Administrator the first time he was there. He did not necessarily like hearing that.

I think it was a good decision. I wasn't in any way trying to—in fact, I was literally not trying to second guess. It really frustrates me when people try to second guess, because the assumption is, "Well, if you made it based on what you know today." What kind of a criteria is that to use? That's just flawed. It is instructive to look at history if we can learn from it and do things differently in the future. That is instructive. I enjoyed doing that, both to rebuild some history, some of which I'd been involved in, much I wished I hadn't, but to put that out. I thought it was very interesting. Then to present it to Dr. Fletcher in his second stint as Administrator was an interesting opportunity.

JOHNSON: Well, it's almost noon. The next portion we probably would go to was your position as Manager of the Lunar and Mars Exploration Office.

CRAIG: Yes, that's a whole another chapter.

JOHNSON: So if you want to stop.

CRAIG: The clouds part.

JOHNSON: Right. [laughs]

CRAIG: The positive experiences begin to happen.

JOHNSON: Right. So we can go ahead and stop for today if that's okay?

CRAIG: Yeah.

[End of interview]