ORAL HISTORY TRANSCRIPT

THOMAS J. KELLY
INTERVIEWED BY KEVIN M. RUSNAK
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RUSNAK: Today is September 19, 2000. This interview with Tom Kelly is being conducted in his home in Cutchogue, New York, for the Johnson Space Center Oral History Project. The interview is Kevin Rusnak, assisted by Carol Butler.

I'd like to thank you for having us into your home today.

KELLY: You're quite welcome.

RUSNAK: If we could start off with you telling us something about your background, maybe some of the interests you had in either aviation or engineering, kind of growing up and getting into college.

KELLY: When I was a kid, I made airplane models and flew them. So I was kind of interested in planes. I won a Grumman [Aircraft Engineering Corp.] scholarship when I was a senior in high school, which paid my college tuition and it also included a summer job at Grumman every summer. So I started at Grumman in the summer when I was kid, seventeen years old, and worked in the shop for two or three summers and then got into engineering for one or two summers. So I was pretty well indoctrinated into aerospace by the time I graduated from Cornell [University, Ithaca, New York].

RUSNAK: From there, after you spend your student summers, as you said, working in the shop and that kind of thing, once you graduate, did you go to Grumman as a full-time employee?

KELLY: Yes. Yes, I started out working on their supersonic ramjet-powered missile program, called the Rigel. That was a Mach 2 missile, 'way ahead of its time. This is like 1950 or something. So that was kind of fun, and that program was canceled before it was really completely finished, although we did some test flights. Then I worked on some of the latest fighter airplanes. We had a supersonic fighter by then, too, the F-11F [Tiger].

I worked on the propulsion systems, the inlets and exits, supersonic propulsion. So that was fun. But then I had to go into the Air Force, because I had been in the Air Force ROTC [Reserve Office Training Corps] at Cornell. So after five years at Grumman, I went into the Air Force to the aircraft lab at Wright-Patterson Air Force Base [Dayton, Ohio]. I worked on quite a variety of projects. The Air Force had a lot of new airplanes under development at that time. It was the mid-fifties. So that was pretty neat. I got to visit all the companies in the industry, just about, and work on some of the latest programs. So that was a fun time.

While I was there, the Russians sent Sputnik up, so then I got interested in space. When I got out of the Air Force, instead of going back to Grumman, I went out to Lockheed [Aircraft Corp.] in California, Palo Alto, because they had a Space Division out there that I wanted to work with. So I had about a year out there, got kind of a basic grounding in space from people who were really working at it, but my Grumman pals kept after me to come back to Grumman, and they told me they were going to start a space operation, space group.

They finally talked me into coming back to Grumman, which I did, and I got in their newly formed space group. I worked on a couple of their proposals, one of which was successful. It got us the Orbiting Astronomical Observatory [OAO], which was really the forerunner of the Hubble Space Telescope. The same idea, just a somewhat smaller telescope. That was a very successful program. I didn't actually work on the program once we won it.

They asked me to investigate this program to land men on the Moon, that NASA was talking about. This was in 1960. So I went around and talked to a number of people including, George [M.] Low and Ed [Edgar M.] Cortright, who were kind of involved in the early studies and considerations of the Apollo Program.

I reported back to Grumman and said, "Hey, this thing is really moving along and it looks like it's going to be a big program. We'd better get with it if we want to compete on it." So we formed a small engineering group to study the lunar mission, and I headed that up. I guess we had about ten people at first, but it kept picking up and gaining momentum.

In May 1961, President [John F.] Kennedy officially announced we were going to go to the Moon. Then it became a very big deal for the industry. NASA had a pre-bidders' conference where they described the program and the bidding process they were going to go through. So we tried to get positioned to compete on that. By that time we probably had fifty people working on it.

When the RFP [Request for Proposal] came out from NASA for the Apollo spacecraft, at that point our company leadership got cold feet. It just looked like too big a job for Grumman. So they said we couldn't bid it as prime. We had to get on somebody's team and do a piece of it. So we got a berth on the General Electric team. We were responsible for most of the command module. It was a big competition. I guess that was 1961. But we lost. North American Aviation [Inc.] won. And there we were.

RUSNAK: How much direction from NASA did you have at that point in terms of the design for the command module, or was this left pretty much up to the contractors to figure out?

KELLY: They had pretty well specified the shape of the command module and the size. So the basic design they had established. What they hadn't done was figure out how they were actually going to perform the mission. They really hadn't worked that out at all. So after we lost the job, we began looking at the various ways to do the mission, and pretty quickly convinced ourselves that lunar orbit rendezvous [LOR] was the best approach.

We did some studies of that and showed them to NASA. NASA had been doing similar studies. In fact, we went down to Langley Field [Langley Research Center, Hampton, Virginia], I remember, on Pearl Harbor Day. It must have been 1961, that was right a month after the award to North American. We went down and met Dr. Bob [Robert R.] Gilruth and Max [Maxime A.] Faget and their group, Owen [E.] Maynard, Caldwell [C.] Johnson. All the guys that were working on Apollo were down there at that time. That was before there was a Houston. [Laughter]

We showed them what we'd been studying and why we thought lunar orbit rendezvous was the best approach, and they agreed with us. They had come to the same conclusion. So we had a very good session with them that day. They gave us a lot of encouragement to hang in there and maybe compete for the lunar module, which was going to be required if that's the way they went.

So we did. We helped them decide to go lunar orbit rendezvous and then we competed for the lunar module and won it as a result of maybe two years of solid work on it.

RUSNAK: What was it about lunar orbit rendezvous that really made you think that that's the way we were going to get to the Moon?

KELLY: It had two very appealing attributes. One is, it was the most efficient way to do it. You could do it with a single launch of the Saturn V, and the competing schemes like Earth orbit rendezvous or direct descent all required at least two launches. So it was the most efficient.

The other thing it did that was really good was that it divided the mission tasks between two specialized spacecraft that had very different requirements. The command module was totally dominated by the need to reenter the earth's atmosphere, so it had to be dense and aerodynamically streamlined and all that, whereas the lunar module didn't want any of that. It wanted to be able to land on the Moon and operate in an unrestricted environment in space and on the lunar surface.

It ultimately resulted in a spindly, gangly-looking, very lightweight vehicle that was just the opposite of all the attributes of the command module. If you tried to do that all in one vehicle, it would be a real problem. I don't know how you would have done it. But this way, with this mission approach, it was very neatly divided in two halves.

RUSNAK: When you won the proposal, what did your initial design for the LM [lunar module] look like?

KELLY: Well, that was an interesting thing. The NASA made it very clear in their bidders' conference and in the RFP that they weren't buying a design as a result of the competition at all.

They didn't think anybody knew how to design the LM at that point, and they intended to work with the contractor to develop the design jointly after the award.

Now, for the proposal, if you wanted to show them a design just to illustrate your points and your knowledge of the mission and all, that was okay, but they weren't buying that. We did, of course, show them a design, and it was similar in concept but different in just about every detail from what finally evolved. It was a two-stage vehicle with the two crew members in the upper stage (ascent stage) and a lot of propellant and equipment stowed in the descent stage, [and] landing gear in the descent stage. But all the details were different from what ultimately evolved.

RUSNAK: The way you describe working with NASA not buying a design but buying this team and this expertise, that's a little bit different than the way, say, Grumman might have worked with the military as a contractor designing a plane or something.

KELLY: Right. It's even different than the way NASA worked on many programs. Even the OAO they pretty much specified the basic design, anyway. But this was different.

RUSNAK: So what sort of challenges did that present for you guys in this proposal?

KELLY: It was a lot of fun, actually. Owen Maynard was the Chief Engineer for the NASA when we started. He had been one of the guys working with Faget and Gilruth up in Langley. He was a good guy to work with and he had a lot of knowledge himself and his people about the

LM and the mission. He worked very compatibly with us and contributed a lot, he and his people, to the evolution of the design.

In fact, I used to kid him. We said that he had in his desk drawer a drawing of what the LM ultimately should look like. Now, would you please show it to us so we can avoid a lot of the folderol we're going through? Now, he did have some designs, but he wouldn't show them to us because he didn't want to over-influence us. He wanted us to be free to develop our own ideas. So it was a cooperative effort for, I'd say, the first year until the full-scale mockups were finalized. We were evolving the basic design. I have some diagrams that can show you the before and the after, actually some pictures if you want to see them. Let me get them.

RUSNAK: Even coming up with something like this basic design for the proposal, even though you know you know it's probably not going to be the final version, doing this process is something that hasn't been done before. You're creating the first spacecraft. How do you go about thinking about how to do something like this versus creating an airplane or whatever else?

KELLY: Well, it was really a lot of fun. We just pretty much let our imaginations run wild and let the form follow the function. It just kind of evolved. You basically started out with the two astronauts, and you had to wrap everything around them or design everything so that they could get at it and use it. Then the ascent and descent stage split was something that we had to work out. It was very desirable to put as much stuff in the descent stage as you could because it saved weight. [Tape recorder turned off.]

Okay, where we were?

RUSNAK: You were talking about thinking about designing a spacecraft in form following function.

KELLY: Oh, yes. So it was just a lot of fun. We had sessions where we'd get up on the blackboard and sketch different ways of doing things. I remember one session that went on pretty much all day where we looked at different ways of positioning the attitude-control thrusters and finally worked out the arrangement that we used. One of the main things that made the design change from the proposal was the need to get reliability, and we did that by adding redundancy where we could, and where we couldn't, by making the system just as simple as we possibly could.

In the process of simplifying the systems, we realized that we had just fallen into accepting some basic things that weren't necessary, like symmetry. We found out that we originally had four-propellant tanks in the ascent stage because it gave us a symmetrical configuration. Then we said, "Gee, it doesn't have to be symmetrical." We could get down to a single tank each for fuel and oxidizer, but then you had to offset them by different amounts, so the LM ended up looking like it had the mumps on one side.

So we did things like that, that gradually changed the design. When we got to the full-scale mockup, we were able to work with the astronauts on both the crew station and the means of getting to and from the lunar surface. On the crew station, the big innovation was, originally, in our original design, we had a lot of glass in the cockpit and the crew was seated. I didn't like glass because it was heavy and not too reliable as a structural material, so I was after my people to try to get rid of the glass, and in the process they came up with the process of getting rid of the seats. That put the pilot's eye, when he was standing up, very close to the window, so he could have a very small window and still have a wide field of view.

Our people worked with the NASA people on that. Our guys were John Rigsby and Gene Harms and Howard Sherman. They worked with George [C.] Franklin and some others, NASA people in Houston, and they really jointly developed this LM crew station that was a standup flight station. So they were standing up right in front of the instrument panels, holding onto hand controllers. They had some foot restraints they could put their feet into, and they were held down by a restraint harness that kept them from floating up in the air. That worked out very well. It was very compact and gave us a small window area, which was something we were looking for.

So the astronauts were able to evaluate that in the full-scale mockup, which was about a year after we started the program.

RUSNAK: Do you remember what their reactions were to this?

KELLY: They liked it. We had been working with a couple of them all along, and they liked it on paper. When they got to try it out, they liked it, too.

The other thing we worked with them on was how you get to and from the lunar surface. There we had a variety of schemes. We had a block-and-tackle scheme and some kind of hokey stuff, but we ended up with a very simple arrangement with a platform on top of the landing gear and then the ladder going down.

We worked particularly with astronauts Pete [Charles C.] Conrad [Jr.] and Ed [Edward H.] White [II] in developing this lunar surface egress arrangement. We had a rig we called a

Peter Pan rig. It was hooked up to the big traveling overhead crane in the final assembly area, and we could lift five-sixths of the weight off the astronaut. So it was an attempt to simulate the one-sixth G lunar surface conditions. They had some fun getting that to work, but it was helpful after a while and helped us develop a lunar surface arrangement.

In the process, we had to enlarge the front hatch and make it rectangular instead of circular, the way we had it originally, because they had to come out with their backpacks on, which gave them a very rectangular cross-section as they were going through the hatch.

RUSNAK: The front hatch was also originally used as a docking port?

KELLY: Yes. In our proposal, we had proposed that you could get redundancy in the docking by making both hatches docking hatches, but that didn't go very far because North American had already started working on a probe and drogue docking arrangement. The astronauts liked it because it was similar to the Air Force probe and drogue refueling arrangement with which many of them were familiar in flight.

The other argument was that if you couldn't dock, you could still transfer EVA [extravehicular activity] from the LM to the command module. So it evolved that we really didn't need the front hatch to be capable of docking. And it was a good thing, because we had to make it bigger and rectangular in order to do the lunar egress part of the mission properly. We did add an overhead docking window so that you could use the overhead hatch conveniently in docking.

RUSNAK: One of the other things I was wondering about is the technology that goes into the landing gear since the LM is going to be going down on a surface that, at the beginning, you don't really know what the surface is going to be like. Is it going to be big pools of dust or hard and rocky? So how do you go about designing gear for a surface you don't really know what it's going to be?

KELLY: Well, we had a very wide range of assumptions about the lunar surface, anything from deep dust to hard ice and everything in between, slopes and all that, curbs. So we designed for a combination of these things. We did establish what the maximum touchdown velocities would be. That was ten feet per second vertical and four feet per second horizontal. So with those as the maximum velocities, we also assumed a specific maximum slope of the surface. I think it was six degrees.

With those assumptions, then you layered on the different assumptions about what the surface itself was like. We went through hundreds and hundreds of computer simulations of different combinations of the touchdown conditions and the lunar surface assumptions, and ultimately picked the tread width and landing-gear height that we ended up the final design. I think we assumed two-foot-deep potholes and two-foot-high boulders could be in the area too. So we had all those assumptions. We did a load of computer runs on that, and finally knitted it together into the design that resulted in the final version.

I didn't want to have fluid in the landing gear, because I was afraid of developing a leak if you had either liquid or gas fluid in the compression strut. So even in the proposal I said, "No fluid. We're going to have a solid energy absorber." The absorber that we came up with was basically aluminum honeycomb. It was just a [deep] cylindrical slug… of aluminum honeycomb material, which you could crush and it would absorb a lot of energy, but it had no fluid in it at all. That worked very well in all the testing we did of it. In the actual missions, the astronauts set the LM down so gently every time, that we hardly ever compressed that strut at all, just a couple of inches, usually, whereas it had, I think, about eighteen inches of stroke that it could have absorbed. So, yes, the landing gear was a very interesting design.

When we adapted the cruciform descent-stage arrangement, it worked out nicely because the landing gear support points were also the support points for the LM inside the spacecraft LM adapter [SLA, pronounced “slah”].

RUSNAK: What about in terms of stowing the legs to fit in the SLA on the Saturn V?

KELLY: Well, all I needed was a one-shot extension and then lock in place, which was pretty easy. It was a spring-loaded arrangement. So we had them fold in like that, here they are folded, and they just swung out and snapped in place for the mission.

RUSNAK: One of the other areas I wanted to talk about was the thermal protection system.

KELLY: Yes. The LM had to have a very lightweight thermal protection system. In fact, the LM had to be very lightweight in general, because for every pound that we took down to the surface and brought back to orbit, we had to add over three pounds of propellant. So it was like a four-to-one growth factor for weight. So that’s what was driving the LM to be so lightweight.

Well, we had to thermally isolate it from the space environment, because in space it’s basically 250 degrees in the sun and minus 250 in the shade. We couldn’t stand that, so we basically wrapped the LM in a very thin aluminized Mylar cover that in a vacuum operated like a vacuum jacket. So the whole LM was wrapped up in that multi-layered aluminized Mylar cover. We combined that with the micrometeoroid protection by putting a thin aluminum shield on the outside…of it.

So we had a combination of meteoroid protection and thermal shielding which was very lightweight. It was something you had to be careful with on the ground, because it was very delicate. But that's basically what it was, filled in with the multi-layer insulation blankets.

RUSNAK: How well did this design work structurally when you were first trying to make this function?

KELLY: It worked very well. We didn't really have any problems with it. It was strong enough that it didn't tear itself apart in the G loads, mainly because it was so light, but it was also very effective as a thermal insulator.

We tested a full-size LM. It was called LTA-8, LM Test Article No. 8. That was tested in that big thermal vacuum chamber in Houston, full size, and with the astronauts inside for part of the mission. We put it through the complete thermal paces. It had heaters on it, heater strips, and the chamber had cold walls, so we could simulate any combination of thermal conditions that we were going to get on the mission. It performed very well in those tests. We were quite confident when we went into the mission that we wouldn't have any thermal problems, and we didn't.

RUSNAK: Speaking of part of the test regimen, one of the things I was wondering about was, what was the testing program developed for the LM to get it qualified for flight?

KELLY: Well, every component, major component in every system had to be qualified against its spec, and then the LMs themselves were tested extensively before they were ever used. In fact, we practically wore them out. We tested them for two years for a three-day mission. [Laughter] So they got an awful lot of testing. We basically ran them through all the mission paces and through a lot of failure modes as well, over and over again. We did it at Bethpage [New York]. We did it again down in Cape Kennedy [Florida] before they were put into the launch stack. So they were very extensively tested.

The flight crews participated in the testing, because many of the tests required a pilot in the cockpit to manipulate the controls and take action of various sorts. So there was a load of testing. That's what they were doing most of the time in Bethpage. It didn't take long to assemble the vehicle, but it took a long time to test it.

RUSNAK: Who's dictating the testing that goes on? Is it Grumman, NASA, or a combination of both?

KELLY: I guess it was a combination, but basically we just tested everything you could think of to test, everything that you knew you had to do, and then as many of the failure modes as you could reasonably simulate, we tested. It was a buildup program. We gradually built it up to more and more complex tests until finally we were going through the whole mission.

Now, it took about 40,000 engineering drawings to design both the LM and all the ground support equipment that went with it, so there was a lot of engineering effort at the peak. We had over 3,000 engineers at Grumman working on the LM and its support equipment. There were a couple hundred items of ground support equipment that we also designed and built specially for the LM. So it was a lot of work. We had to have a big push to get our drawing releases up, and at the peak we were pushing out over 500 drawings a week, engineering drawings. So you don't think of it as a big design job, but it really was, because every detail had to be worked out.

Now, we also had a big problem with the weight of the LM. The weight grew rapidly from the initial proposal and then for the first couple of years of the program, primarily as a result of adding the reliability provisions, the extra redundancy and that sort of thing, and also from gaining a better understanding of the mission requirements.

Anyway, the result was that by after about two and a half years into the program, we were busting through the weight ceiling, and things were pretty tense because the Saturn just couldn't take any more. It couldn't grow any more. So we had to basically go back and reexamine the whole design and redo whatever we could to reduce the weight.

So we had a program, we called it the Super Weight Improvement Program. I was personally in charge of that as the Chief Engineer because I went over all the designs and reviewed ways that we could change and simplify them. It was a very intensive effort for about six months, but it was successful. We stopped the growth and eventually we got the weight down…

That was a big effort, and it did result in a number of changes, some of which got us into trouble later on. One of the changes was, we went to the lightest wire we could get for signal wiring that didn't carry any current, 26-gauge wiring. And that damned wire was so fragile that our technicians just had to handle it with kid gloves. It was breaking all the time whenever you mated or de-mated a connector or what have you, so it was a big nuisance in the manufacturing process. The wires didn't break as a result of mission vibrations or forces, but they sure broke easily in the handling. That was a pain in the neck. We finally got a higher-strength copper alloy for the 26-gauge wire that was less prone to break. We were able to phase that in, I think after LM-5 or LM-6. Made our life easier.

Another thing that we did for weight reduction was we went very extensively to chemical milling, where you chemically milled out the aluminum or metal surfaces, both sheet metal and machine parts. We did a lot of that, because we would chem mill right down to the bare minimum thickness that you needed in each particular area. That got us into trouble later on, because the chem milling left the surface exposed or open and more vulnerable to stress corrosion. We started to get stress corrosion cracking problems, and we had to have a fairly concerted program to inspect for stress corrosion cracks and also to replace some of the items or parts that were most likely to crack. So that was another unforeseen fallout of our weight-reduction efforts.

RUSNAK: Since you had mentioned the wiring and how with your very thin-gauge wiring it was very easy to break in handling as the technicians are working on it, in terms of where wiring got the command module into trouble on the Apollo 1 fire, I was wondering what impact that event had on the lunar module program.

KELLY: Well, the command module problem, a good bit of it was the way they had done the wiring. They had a lot of rat's nests. It was just a mishmash of wiring. We didn't do that. I mean, we were smart enough from day one to know you should neatly comb out your wires and make it so you could tell whether you had a good secure wiring arrangement or not. We had to go over our wiring, and if we had any rat's nests or areas where there were a lot of wires jammed together, why, we did have to change that. But we didn't have too much of that.

However, there were a lot of materials changes that affected us in the crew compartment. We had to get rid of all nylon and we had to do things like adding fire-retardant covers, booties, we called them, over the backside of the switches on the panels, because the backside of the switches were plastic switch material that was quite flammable. We had to add these booties and then put a potting compound on top of that, which was fire retardant. So there [were] a lot of things like that that we had to do which weren't too big a change in themselves, but again they did tend to slow down the production and testing process, and they made it very difficult to change anything. Once it was all potted in, it was a big deal to pull it all out and change something.

So we got hit somewhat from the fire, but not too badly. They made some strict rules about having a support tie every four inches on each wire bundle, and we hadn't done that before. We had them at random distances. So we had to go back and change that, that sort of thing.

RUSNAK: This graph of the LM weight shows a fairly steady increase until the beginning of 1967 and then it starts to jump up and kind of goes up from there before it flattens out again. I'm assuming that was as a result of some of these materials changes and that sort of thing.

KELLY: Do you mean this over here?

RUSNAK: 1967, I guess. It's going down and then it starts to kind of go back up. The fire would have been right in about there.

KELLY: Yes, but the other thing that happened about that same time was they approved an extended-stay LM which was heavier, it was allowed to be heavier, 4,000 pounds heavier than the previous LM. It could stay three days on the Moon instead of one, and it could carry the Lunar Rover and more scientific equipment and lunar sample return payload. So those changes were in there, too.

RUSNAK: One of the pieces of hardware that we haven't talked about yet is the propulsion system, both on the ascent stage and on the descent stage. Both of them, I understand, had some issues in terms of their development and such, so if you could talk about that for a little bit.

KELLY: …The ascent propulsion system lifted the LM ascent stage off the lunar surface and brought it up into rendezvous in lunar orbit with the command module. This was obviously such a vital system that we sought to make it as reliable as possible by making it as simple as possible. It was a constant, fixed-thrust, pressure-fed engine. There were no pumps with hypergolic propellants, so there were no igniters. There was an ablative-cooled nozzle, plastic nozzle, so there were no intricate cooling passages. It was just as simple as we could make it, and yet it did have a serious problem of combustion instability.

There had been a big problem with combustion instability on the huge one-and-a-half-million-pound-thrust engine for the Saturn V, and that problem had caused several explosions during tests and it had taken over two years of intensive work at Marshall Space [Flight] Center [Huntsville, Alabama] and by Rocketdyne [Division of North American Aviation] before they finally got the combustion instability solved. So NASA and we were very aware of the hazards of combustion instability.

In the course of solving the Saturn problem, they developed what they called a bomb stability test, where they set off an explosive charge in the operating rocket engine to try to induce instability. Otherwise, you just had to wait for it to happen spontaneously, which was very unsatisfactory. So NASA decided, and we agreed, that our engines both ascent and descent stages, should go through these bomb stability tests. The descent engine never had any trouble with it, but the ascent engine did. The bomb stability test required that after you set off the explosive, the pressure spikes should damp out within, I think, four-tenths of a second.

In the case of the ascent engine, the pressure spikes didn't damp out at all; I mean, they just continued. They didn't get any worse, but they didn't damp out either. So it was kind of a strange thing. It didn't have the kind of instability that the Saturn engine had, [which] just got progressively bigger and worse until it exploded. But on the other hand, it couldn't pass the bomb stability test either because the spikes never went away once you started them.

So after some debate, we decided that…was not acceptable, that we had to get the ascent engine to pass the rigorous test criteria. There was…no formula for how you make a rocket engine stable. It's very complex. It involves the injector pattern and flow rate and propellant ratios and many other things that all interact together. So it's basically a cut-and-try process.

We did a lot of cutting and trying, but we weren't getting anywhere. It still had that same characteristic [and] couldn't get through the bomb stability test.

So NASA got impatient and directed us to get another contractor involved. Bell Aerospace had been our ascent engine contractor. We also brought Rocketdyne along, too. They both worked on versions of the ascent engine. Neither one of them was completely successful, but in the end, a combination of the Rocketdyne and Bell designs was put together by Rocketdyne and it was satisfactory. It was able to get through the bomb stability test, and everything else about it was okay, too. But that took quite a while, took a couple of years, and for a while the LM asset engine was on the infamous "showstoppers list," something that was potentially [able] to stop the whole Apollo Program if it didn't get fixed.

The descent engine didn't have stability problems, but it was more complicated because it was variable thrust. It had to be in order to effect a landing. The rocket engine could be throttled all the way down to 10 percent of full thrust, which was a first at the time, first time there had been such a high degree of throttle-ability in a rocket engine. They did it by having a movable pintle in the injector head, so we were actually changing the spray pattern and the flow rate of the injector. Considering all the innovations that…required…it went very well. Most of their problems were mechanical in nature, getting the movable pintle to work smoothly and go where it was commanded and that sort of thing. But it just…never had the stability problem, which was a really much more frustrating kind of problem. So although the ascent stage was simpler, the development of it was more difficult.

On the reaction control system, we were able to borrow heavily from the reaction control system that was used on the command and service modules. We basically used the same

100-pound thrusters that they used, and we followed a lot of the design techniques in the system design. That was kind of a [hand] off….

RUSNAK: With the ascent engine, one of the things it's doing is when it first lights off, it's using this fire-in-the-hole technique where it's sitting on top of the descent stage. What sort of issues did that bring up?

KELLY: Well, we wondered about that a lot, because nobody had really ever done that before, light up a rocket engine with a plate of sheet metal right in front of the exhaust [nozzle]. We just didn't know what was going to do, but we tried it in tests many times out at White Sands [Test Facility, Las Cruces, New Mexico]. We had a test facility that we operated for NASA out in White Sands, New Mexico, and we could fire our rocket engines out there. We had a rig where we could do fire-in-the-hole testing.

We didn't really notice much effect from having the plate there in the way as long as we moved the engine pretty quickly up out of there, so the test results were encouraging. Analytically we couldn't show a problem. And when it got to flight-testing, that was one of the things that we did on both the unmanned LM, LM-1, and Apollo 9, which was the first manned LM flight, and in neither case did we see any particular problem with this fire in the hole. So it was a cause for question and concern. We did devote a lot of time to looking at it and testing for it, but in the end, it turned out not to be really a problem.

RUSNAK: I'd also like to cover some of the internal subsystems of the LM, like the environmental control system and the guidance system particularly.

KELLY: Okay. The environmental control system was similar to, but different from the command and service module. It was designed by the same contractor, Hamilton Standard, but the components had to be different because it was supplying two men instead of three with a different geometric arrangement. We also had the requirement of emptying out the cabin every time we went out on the lunar surface. So we had to have quite a bit of gas aboard just to refill the cabin every time they came back in.

There were some weight problems with the environmental system, and we had a pretty complex packaging arrangement for the major components that were inside the cabin, and those things took some development time and effort. But in general, the environmental control system was pretty well behaved.

The guidance system was—well, we had the primary navigation guidance system, which was basically designed and supplied by MIT [Massachusetts Institute of Technology, Cambridge, Massachusetts]. They supplied it to both the command module and the LM with different software to go with it. The amount of computing power just seems ridiculously small by today's standards. I think it was like 36,000 bits per second, something like that, minuscule compared to what you've got on your laptops today. But that's what we had, so in order to conserve the bits, they programmed everything directly in machine language, so only experts could touch the programming of the guidance system.

So MIT supplied the primary system. We supplied what was called the abort guidance system. It was the backup to the primary system. It only had the capability to abort and get you back to the command module, in the event the primary system failed. We never had to use it for real, although we used it in tests a lot. In fact, it got us into trouble a couple of times when it was mistaken for the [primary] system. That was designed and built for us by Space Technology Laboratories, STL.

RUSNAK: Up to this point we've talked a lot about the hardware involved with the LM, so I want to ask you about some of the other people who were involved, particularly on the Grumman side. Who were the people that you felt were key in this and the people that were your managers and the other people that were overseeing the program, that kind of thing?

KELLY: Joe [Joseph G.] Gavin [Jr.] was the Vice President and Director of the whole LM program for Grumman. The Program Manager initially was Bob [Robert S.] Mullaney. He reported to Joe Gavin. Then the Engineering Manager was Bill [C. William] Rathke. He was the Lead Engineer, and I was the Project Engineer. I reported to Bill. That's the way it started out. After about two or two and a half years, Mullaney left the program and Rathkey became the Program Manager and I became the Engineering Manager. So that was the hierarchy. Now, I had three project engineers reporting to me, assistant project engineers. Bob [Robert W.] Carbee was in charge of the design subsystems, the design groups. Arnold [B.] Whitaker was in charge of the analytical subsystems. John Coursen was in charge of the ground support equipment, as we did all that design, too.

Another key player with me was Eric Stern, who headed the Systems Analysis and Integration Group, which in the beginning was very key in putting together the overall concepts for the LM. Beyond that, we had engineering section heads in each of the technical disciplines and they were all key players. There were about a dozen of them. Manny [Manning] Dandridge was the propulsion section head. That was a very key job. Ozzie Williams headed the reaction control system. Don McCloughan was the environmental system, and Ross Fleisig on the guidance navigation control and so forth. We had a list of key players there.

In addition, when a particular problem arose, we often appointed somebody to fix that problem. That sometimes took a lot of work and a large group of people to do it. One of the problems was leaks in the fluid systems, particularly the propulsion systems. Will Bischoff, who had been a Deputy Head of structural design…was tagged with trying to finally fix our leaks, which had been a problem for many years. Leaks were something you were never completely 100 percent free of, but we did make a lot of progress with Bischoff's efforts. So there were a number of things like that.

Our engineering activities at Kennedy Space Center were headed up by Herb Grossman. He was our launch systems engineer and Kennedy systems engineer…

Where were we?

RUSNAK: We were talking about some of the people at Grumman.

KELLY: Right. George [M.] Skurla was the leader of all the Grumman activities down at Kennedy Space Center. He interfaced directly with [NASA Kennedy Space Center Director] Rocco [A.] Petrone, so he had a tough job keeping Rocco happy and making sure that everything went well on the LM. We were the last contractor down there, so we got a lot of attention because all the other guys had been there and knew the ropes. But we did all right. We got onboard and up to speed pretty fast.

RUSNAK: Rocco Petrone was at NASA first and then obviously went down to the Cape. There were also a number of NASA people at your own plant, including the resident manager and such, so if you could comment on some of those and how the relationship worked there.

KELLY: The local NASA manager, let's see, the first one, I guess, was Small. Jack Small or John [W.] Small [Jr.]. They were more administrative in nature. They handled all the paperwork and led us through the major formal activities that we had to go through with NASA. Of course, we had a lot of NASA inspectors, quality-control inspectors that were out on the floor all the time participating in all the activities and witnessing and signing all the papers that certified we'd done things according to the book and what have you.

The engineering contact was more informal and it was directly with Houston. As I mentioned, Owen [E.] Maynard was initially the NASA leader, and then there were others, Bill [William F.] Rector and Bill [William A.] Lee. Bill Lee was assigned by NASA to be my counterpart during that Super Weight Improvement Program, so he spent a lot of time up in Bethpage looking at the weight reduction items and activities that we were involved in.

So we got to know a lot of the NASA people, engineering people. During the missions, we supported the mission out of the Spacecraft Analysis Room, which was right across the hall from the main Mission Control Room. Either I or Carbee or Whitaker were usually in that Spacecraft Analysis [SPAN] Room. That was the top-level room for the spacecraft contractors. We were only allowed to have two people in there at any one time. North American was in there also and MIT and some NASA people. But we had access to everything on the mission. We had control consoles and all the instrumentation readouts and the headphones that gave us all the nets. So we could be fully active in supporting the mission.

There was another building about three blocks away, Building 45, I think it was, where they had a much bigger room and we were allowed to have about a dozen engineers up there, so we had one for each specialty in that room. They also had all the similar access to the mission information. Then in Bethpage we had a Mission Support Room of our own, where we could bring in as many people as we liked and also bring in our subcontractor people and we could contact our subcontractors all over the country if need be.

So depending on how much time we had to work a mission problem, [if] we only had a couple of minutes, why, I would do it right from the SPAN Room, Spacecraft Analysis Room, we called it. If we had a little more time, we'd get the people in Building 45 [Mission Evaluation Room, MER] involved. If we had plenty of time, hours, we'd get Bethpage and our subcontractors across the country involved. We did that, for example, on Apollo 13, where at one point it became very critical to know exactly what the consumption rates of power and water were for each actual piece of equipment that was on that LM. We didn't want the general spec value; we wanted to know exactly what [it] was on that particular piece of equipment.

So we had to have our subcontractors and suppliers look it up wherever there'd been a test run. If there hadn't been a test run…they ran one. So that was a big supporting effort that went on for a day or so and was quite helpful. But there were a lot of things where we were able to get help and ideas and plug them into the mission with beneficial results.

RUSNAK: Let's talk about some of the flights that the lunar module was on. Let's start with the first unmanned test flight.

KELLY: The first unmanned test flight got off to kind of a rocky start, because the idea was to control the flight through the LM mission computer, and they had preloaded all the instructions into that. But there was a software error in the very first activity, which was a descent engine burn and it shut the descent engine off early. But the backup was to control it manually through the LM mission programmer. Gene [Eugene F.] Kranz writes about that in his book. They did that very well. They had practiced how they would use the LM mission programmer if they had to, and they did have to because of this software mistake, and they were able to pull off the entire mission. They got every mission objective, so it worked out to be a totally successful mission, even though there was this glitch right at almost the very beginning.

With LM-1 being successful, it did demonstrate fire in the hole. By the way, that was the first flight demonstration of fire in the hole. So it basically went through the abort stage sequence, jettisoning the descent stage and firing up the ascent engine simultaneously and then completing a rendezvous, and it went through all that in orbit unmanned. That was very successful.

As a result, we did not have to fly LM-2, which was the backup unmanned LM. I think LM-2 is the one that's in the Smithsonian Institute right now. It was refurbished to look like Apollo 11 when it landed on the Moon.

Then the first manned LM was an earth orbital flight, Apollo 9. That was Jim [James A.] McDivitt and Rusty [Russell L.] Schweickart. They basically did everything you could do in Earth orbit to simulate the lunar mission, including a rendezvous from starting about 115 miles away from the command module. It all went very well, except Schweickart got pretty sick for the first couple of days, but we didn't even know anything about that. They always kept anything about the astronauts' personal problems pretty secret and switched over to a guarded channel. So we didn't even know he was having a problem. We just wondered why they were cutting short some of the activities and EVAs and all that. But then after the mission we found out what the story was. Anyway, he recovered enough to basically perform all the most necessary parts of the mission, so it turned out to be highly successful.

Apollo 10 was a flight to the Moon, but not landing on it. There was some debate as to why they should do that, why not just land, but there was enough concern about the details of the gravitational differences of the Moon, the real Moon, versus the models that we'd been using. Also that LM was kind of overweight because we didn't think it was actually going to have to land on the moon, so we didn't put all the weight-reduction items into it. So, I guess, a combination of things. They flew the entire mission except for the landing, simulated the landing. It was very successful, and they had basically no problems that amounted to anything.

RUSNAK: Just a bit of a tense moment with the wrong guidance system selected, I think.

KELLY: Yes, there was a moment where the LM kind of went bananas. It was thrashing around wildly, and it turned out they had flipped the switch into the wrong position for guidance, and it was trying to do something it couldn't do at that point. So when they flipped the switch back, which they did just before we figured out that that was the problem, everything straightened out again.

RUSNAK: The next flight, of course, was Apollo 11.

KELLY: Apollo 11 was the culmination, and it was pretty exciting. There were a couple of things happened during the descent that basically happened so fast that we didn't really get involved with them. They had to be dealt with instantaneously.

One of them was the program alarm that they got. Fortunately, a couple of the NASA controllers had studied the MIT program alarms that were built into the software and they had basically memorized every one of them. There was a long list of them. All it did was come up with program alarm and then a number, Program Alarm 28, and you had to know what that meant. Well, nobody knew what it meant except these two guys that had studied it, and they knew what it meant and they told Kranz, "No problem. Go ahead." So he did. They later found out why they got the program alarm, but it really was no problem.

The other problem was the computer was directing them to a field full of boulders, so [Neil A.] Armstrong had to take over and steer it around. By the time he did all that, he almost ran out of fuel. But they got down with thirty seconds to spare or something like that. They made a nice gentle landing and everything worked great.

Then we had a little panic right after the landing. About three or four minutes after landing, we noticed that the pressure in the fuel line leading to the descent engine was going up pretty rapidly, and this was a segment of line between the fuel to helium heat exchanger and the shutoff valve on the head of the engine. What had happened was the fuel had frozen due to a surge of cold helium after the engine shut down. The fuel had frozen in that heat exchanger so it made a solid block on that end of the line. The other end was blocked by the engine shutoff valve. As the heat soaked back from the shutdown engine, the pressure and temperature in the line was going up pretty fast.

We didn't like that, because if it got up about 400 degrees…the fuel could explode, go unstable. There wasn't much fuel in there, just vapor, but still, we just didn't like the idea and we were nervous about it. So we had some very hasty consultations with the NASA people and our own propulsion people, and we finally decided we were going to burp the engine. We were going to ask the astronaut to flick the engine on and then off right away, just to relieve the pressure in that line. We didn't think it would start up enough to [cause] any problem.

George [M.] Low had gotten with us in the SPAN room, and he had bought this scheme. The capcom, the capsule communicator, was just about to tell the astronauts about it when the problem solved itself. The ice plug in the heat exchanger melted by itself, and all of a sudden the pressure dropped down to zero, so no problem, it went away. But we sweated that out for about ten minutes right after the landing.

People ask me how did I feel after the landing, and I tell them, for the first ten minutes, I was too busy to know where we were, whether we were on the Moon or what. When we finally figured out that we were there, it really was a pretty intense moment. We were very curious as to what they would find, so it was very interesting when they got out on the surface and took pictures, showed us what they found.

That was the first landing where we saw how gently they set it down. It hardly even stroked the landing gear at all. They all did that, by the way. They're very good pilots. So from there on, it was just neat. We watched them take all the stuff out of the LM and set it up on the surface, experiment with how you could walk around on the Moon and all that. It was all brand-new and very exciting.

RUSNAK: At that point, you had only really fulfilled only half of Kennedy's goal. You still had to get the guys safely back.

KELLY: Right. Well, the ascent part of the LM mission was pretty tricky, because you had to simultaneously disconnect the descent and ascent stages, which meant firing about eight different explosive devices and fire up the ascent engine at the same time. So if you thought about it, there was a lot that could go wrong. But the saving grace was it all happened in an instant so you knew right away whether it worked or not. Fortunately, every time it worked, everything fired and off they went.

Once they were on the way up…it was very smooth. They didn't have a problem at all. When I talked to a couple of the crews after the missions, they told me the ascent was just like riding in an elevator in a building. You knew you were moving, but you didn't feel a whole heck of a lot of acceleration, which was kind of amazing because they were standing right in front of the rocket engine. But they didn't feel much vibration or anything.

RUSNAK: With each of the succeeding missions, they're getting a little bit more complex in terms of the activities that are going on, the longer stays, the precision landings, that kind of thing.

KELLY: Yes. I tell you, Apollo 12 was kind of an amazing mission. I mean, that thing got hit by lightning. It was kind of amazing they even fired it off under those conditions. But having done so, and having it get hit by lightning, I think we were very lucky that nothing really went wrong.

The LM wasn't so vulnerable at that point because it was still tucked away and inert inside the spacecraft LM adapter. But the command module and the service module were hanging right out there and they got the full dose. It did knock everything off the line at first, but they were able to get it back on pretty quickly.

They made the first precision landing of the program. After the first mission…NASA decided that they needed to be able to land more precisely, and they developed a technique for doing that. To prove it on Apollo 12, they wanted to land right near Surveyor, which was an unmanned spacecraft that had been sent up and landed there a couple years earlier. And they did it. They plunked it down within a couple hundred yards of the Surveyor, and it was very impressive. They walked over to Surveyor and took pieces off it and all that. That was the beginning of the ability to do precise lunar exploration.

Pete [Charles C.] Conrad [Jr.] was a fun guy to work with. He was one of the most expressive of the astronauts. He had worked with us on the lunar surface egress and the Peter Pan rig stuff, so we got to know him a bit when he was up there doing that. Then we got reacquainted with him when he was up testing his LM, and he greeted us like long-lost buddies. He was just a neat guy to work with, so I was very glad to see him recover from that mission the way he did. I thought he did a great job.

Then came Apollo 13. Of course, that's a story in itself. On Apollo 13 I had basically left the LM program at Grumman. They had decided that after seven years and the program having successfully landed on the Moon, that I could use a little R&R. So they sent me up to MIT, the Sloan Fellows Program for a year. So I was up at MIT when Apollo 13 was launched.

I got a call around midnight from a Grumman colleague of mine who was also up in Boston at Harvard, Howard Wright, and he told me to put on the radio and listen to what was going on with Apollo 13 and then to meet him down at Logan Airport, because Grumman was going to send a light plane up for us to get us down to the Mission Support Center in Bethpage.

So I did that and I arrived down in Bethpage about three in the morning and stayed there working nonstop for about the next three days, with a little nap once in a while… We helped NASA determine exactly what the consumable requirements would be. We also helped them evaluate different techniques for realigning the platform with a minimum amount of power and things like that.

There was quite a lot to do. One memory I have of that, when I arrived at 3:00 o'clock in the morning and I was approaching the front door of Grumman, there was a whole crowd of engineers coming in with me. It looked like it was 8:00 o'clock in the morning, the start of a normal shift. [They were] all just people who had heard what was going on and just decided to come in and see if they could help. That was pretty great. And it was good because we did need the help.

Of course it had a happy ending. Again, we didn't know how bad things were, because anything personal about the astronauts was not revealed to us or anybody else. So we didn't know that Fred [W.] Haise [Jr.] was as sick as he was. He was really in bad shape for a while. …We knew they were cold and uncomfortable, but there just wasn't anything we could do about it. We had to keep the power off because there wasn't going to be enough to get back. So they were pretty lucky on that one. They did make it, but just barely, especially with Fred being sick.

RUSNAK: Had you ever done any studies or made any preparations for this kind of use of the LM?

KELLY: Yes, we had. We had done a mission definition series of studies the first year or two into the program. We were trying to define—we actually headed up a group which NASA supported and which all the other Apollo contractors supported, to develop a basic design mission that could be used by all the system and subsystem people and spacecraft people as a source for their design requirements.

So in the course of doing that study, we looked at various failures that could occur, too, and what you could do about them, and we realized there was a whole category of failures on the outbound leg where you could use the LM as a lifeboat and get into the LM and live off the LM's consumables if something had gone wrong with the command and service module that denied you the use of their consumables. So it was written up, but it was never developed in any detail. It was there as a possibility, but they never worked out detailed flight procedures for how you would do it step by step, and it wasn't practiced with the crews. The crews didn't train for it or anything. So although it wasn't an unheard of idea, neither was it something that was just ready to go at the spur of the moment. It had to be worked out in detail as it went along.

RUSNAK: After the Apollo 13 flight, did you then return to MIT?

KELLY: Yes, I went back to MIT and I was back in Bethpage by June of that year. I did support the Apollo 14 mission, which was Al [Alan B.] Shepard [Jr.]. I went back to Houston for that, because after Apollo 13, I decided I'd better not get too far away from things.

That was a great mission. That was another precision landing, and that was the first mission where the astronauts really concentrated on lunar exploration once they got there. They had done quite a bit of field rehearsal with Lee [Leon T.] Silver, a geologist. He had showed them how to observe from the point of view of a geologist and taught them all the proper terms to use so they could converse with the geologists and scientists very knowledgeably about what they were seeing and observing on the Moon. That was very good. That plus the ability to do a pinpoint landing made it possible for them to lay out their whole route on the Moon well in advance and discuss with the scientists what they were going to be looking for and why, etc. Then when they got there, they did it and they were able to show the scientists what was going on.

Now, it got even better on the subsequent missions when they got the lunar roving vehicle, because that had a camera right on it and it also had a precision navigation system right on it. On Apollo 14, they got a little bit lost. It was very hard to find your way around on the Moon. It was kind of an undulating surface but no landmarks, nothing you could judge distance or height or anything by. It was very confusing. You were never really exactly sure where you were.

Even on Apollo 12 they encountered that a little bit, but it was even worse with Apollo 14, and there was a particular crater they were looking for. They got to within about sixty feet of it but never really saw it, never really knew they were there. So that was kind of frustrating. On the subsequent missions they didn’t have that problem, because the lunar roving vehicle carried with it a very precise navigation system that they could load in coordinates of the route they had agreed to take, and they didn’t have the problem of getting lost.

Also with the lunar rover they had the camera right there, so when they found a rock that looked interesting, they’d hold it up and discuss it with the scientists down on the ground. So that made for a very productive exploration. [Tape recorder turned off.]

RUSNAK: You spoke to this a little bit before, but these later missions used a modified LM for the longer stays. What were some of the changes that were made to accommodate this?

KELLY: Well, we were able to load more propellant in the tanks. I don't think we had to make the tanks any bigger. I think we already had enough capacity in the tanks. We added batteries, made that bigger, and took more consumables with us. We also modified the stowage bays in the descent stage. We had to outfit one specifically for the lunar roving vehicle, which folded up into the stowage compartment, and make some of the others bigger so they could take more scientific equipment. So they weren't major changes, but it was all aimed at increasing the stay time and the return carry capacity.

RUSNAK: With these last few missions, was your concentration then on Apollo, or were you looking to some other things then at that point?

KELLY: Well, I personally was off the program by then. I was involved with our Space Shuttle activities. We were getting ready to propose on the Space Shuttle and did propose on the Space Shuttle. But I kept in touch with the mission up at the Bethpage Mission Control Center. We used to work on the anomalies, they called them, that occurred in flight, anything that was outside the ordinary. We were getting fewer and fewer anomalies as the missions went on, but we tried to explain every one of them when corrections were required.

RUSNAK: Did you also have anything to do with the studies or thoughts about using the LM for some other purposes, either through modifying it for different types of missions on the surface or, say, using the LM for the Skylab as part of the Apollo Telescope Mount, any of those kinds of activities?

KELLY: We had a small group that was looking at that kind of thing, but it wasn't part of the basic LM program.

RUSNAK: Since, as you said, you'd moved to the Space Shuttle Program by this point, I'd like to talk a little bit about the Shuttle and some of Grumman's early work in studies for the Space Shuttle.

KELLY: Okay. We got involved with the Shuttle through Gilruth and Faget. The initial concept of the Shuttle was that it would be fully reusable with a two-stage vehicle, and each stage would be returned, directly returned. This got to be pretty elaborate. They were big vehicles, they had wings, they had turbo-jet engines and rocket engines, and it was a pretty complex system.

NASA went ahead and funded two studies that North American and McDonnell Douglas were given to develop that concept. But meanwhile, Faget and Gilruth got kind of disenchanted with that approach. They decided it was too complicated, and they wondered if there was some easier way to do it, so they got us involved. They asked us to do alternative systems studies. So we looked at a number of alternatives, most of which involved taking propellant out of the orbiter stage and putting it in the descent stage, the lower stage, and doing other manipulations of the payload and the propellant loading.

We…worked…cooperatively with Faget and went through a series of iterations, but eventually ended up with something that looked pretty much like the present-day Shuttle. Instead of a recoverable lower stage, it had an external tank that was non-recoverable, and it had solid rockets where you could recover the case by floating them.

So this was very promising in the studies, so promising that NASA decided finally that that's what they were going to do. They cut off the work on the fully reusable system, which was pretty amazing, because they'd done a lot of work on that, and announced that they were going to have a competition for this new version of the Space Shuttle.

So we were very happy with that. We thought we were in fat city because we had worked this whole scheme up, and our competitors were going to have to learn it and compete with us on it. So there was a hammer-and-tongs competition, but we lost. Exactly why, I was never sure. Our design was certainly what they wanted, but there may have been other aspects of our program that they didn't like as much.

So it ended up that we went to North American to see what we could get after they won, and we got the wing. We were able to get the design and development of the Shuttle wing. So that's what Grumman ended up with on the Shuttle Program.

RUSNAK: Then was overseeing the Orbiter's wings part of your job?

KELLY: It was, yes. By that time I was head of engineering for the whole company, so I was in charge of the engineering work on all our projects and that was one of them.

I felt bad about the Shuttle, because I thought we had done an outstanding job on the LM and we hadn't gotten into any big problems like North American had, and yet here they were walking off with the big prize. I never really was satisfied with that.

RUSNAK: I guess North American's, to some degree their experience there, just like with the Apollo, having gotten that after getting the X-15, I'm sure played a role in NASA's selection there.

KELLY: Right. And NASA had gotten very closely involved with North American after the fire, because they had to go in there in force to Downey [California] and help them work their way out of the problem, and in the process, the NASA people sort of became subsumed into North American people, or at least that's the way it seemed to me. So for whatever reason, we didn't get the really big prize, but we did get a piece of it.

RUSNAK: After that point, did you continue to have some involvement with the space program?

KELLY: Yes, as part of the engineering activities, but Grumman was getting less and less work in space and more and more in the advanced airplanes, so I got more involved with the aircraft activity. But we still had space work going. We had some work for the Air Force, study work. We participated to some extent in the Sky Lab Program. We proposed on a lot of stuff in space, but we weren't outstandingly successful. We didn't get too much of that.

RUSNAK: As you take a look back on your involvement with NASA, what do you think the biggest challenge you faced was?

KELLY: The biggest challenge for LM and the whole program, I think, was making sure the whole damn thing was going to work. I guess it was Al Shepard said, “Here I am sitting on top of this thing that was designed by the lowest bidder." You had to keep the cost down as low as you could, but also you wanted to be damned sure it was going to work.

The way we assured that was to analyze and test just everything we could think of. Whenever a test failed…we were on that like hound dogs to find out what the cause was, what was the problem, and fix it up. We just wouldn’t let anything go unexplained.

In fact, Joe Gavin told me he had some figures on this, that there were over 14,000 failures, test failures, in some part of the LM program. That would include our components and our subsystems. And at the end of the program we only had twenty-two of those that were still unexplained failures. So we really did work the problem very hard of testing as much as we could and then following up on the results of the test to eliminate any problems that they showed up. I think that’s the reason it all worked as well as it did because they also did that across the program pretty much.

RUSNAK: At this point, I want to give Carol a chance to ask some questions that she may have come up with.

BUTLER: I have a few. Mentioning these 14,000 failures throughout the program, was there any point where you wondered whether you were going to be able to get it all pulled together and to make that deadline that Kennedy had set back in '61?

KELLY: Well, I never wondered if we would be able to do it or get it all pulled together. I did wonder whether we were going to make the deadline, because the schedule was really very tight. We were following these procedures of testing and analyzing everything and correcting the failures. With that basic approach and using the program management techniques, particularly the PERT [Program Evaluation and Review Technique] diagrams of all of the events and activities, we were able to lay out in great detail what we had to do and then just follow up and do it.

BUTLER: When Kennedy had made the challenge back in 1961, what did you think of it at the time and of the possibilities of making that, even though you hadn't been quite involved in the program yet at that point?

KELLY: I just accepted the whole thing. I mean, I don't remember questioning any of it. It never entered my mind that we wouldn't get there if we decided to go to the Moon. That was never a concern for me. Indeed, the technology was ready. We never had any problem that looked like it was going to kill things. Even ascent engine instability, we were sure we were going to get a solution, but it was a cut-and-try thing that just took a long time. But there was nothing that looked like it was impossible to do. In fact, it all looked pretty doable, but you had to be attentive to detail and follow up on everything to make sure you didn't miss anything.

BUTLER: Being attentive to detail, in some of our research for preparing to come talk to you, we were looking at the book *Chariots for Apollo* by [Charles R.] Pellegrino and [Joshua] Stoff, who mentioned how everything that was taken into the lunar module was almost marked off and everything was checked off that could back out. Is that how intense things were in watching those details?

KELLY: Yes. I'm sure that was one example. We were embarrassed on Apollo 9 because some washers and nuts floated around in the cabin, and Jim McDivitt pointed them out on TV to the world. We had already done everything we could think of to find stuff and keep it from getting into the cabin and staying in the cabin, but we just worked even harder on it after that.

BUTLER: Luckily it was just a few washers and things and nothing.

KELLY: Well, yes, but, you know, it could be more of a problem than that.

We did have one problem that was a real quality problem that was on Shepard's flight, where we had what looked like a loose solder ball inside the abort stage switch. That was a bear, because we had to find a way to neutralize that or we were going to have to abort the mission. Fortunately, MIT came up with a set of simple instructions that told the computer to ignore what this abort stage switch was telling it, and the astronauts were able to plug that into the computer, and we just went ahead with the mission. But that was a quality-control problem that we should have caught. It was a not uncommon problem, because the instruments were all hermetically sealed and they were evacuated before they sealed them. They sealed them with solder, and sometimes a little bit of the extra solder would get sucked in and you'd have a solder ball floating around inside. They could usually detect that in the factory by shaking it and listening and looking, but this one got through the whole thing without ever being detected. So that was kind of scary.

BUTLER: You mentioned on Apollo 11 the frozen plug in the fuel line. What did you do for later missions, or did you change anything to try and prevent that from happening again?

KELLY: Yes, we changed the procedures. It was a very simple procedural change where we didn't vent the propellant tank right away. It was because we had vented the propellant tank right after landing that allowed flow through that heat exchanger that caused the freeze-up. So just by not doing that right away, we were able to avoid that whole problem from then on. So it was a very detailed procedural change.

BUTLER: Sounds like it was a successful one.

KELLY: Yes.

BUTLER: That's all the questions that I have. Thank you.

RUSNAK: I actually had just a couple follow-ups of my own, some stuff I wanted to go back on.

Last week we were talking with Andy [Andrew] Hobokan about some of his work there. He mentioned a couple of things that I wanted to ask you about.

KELLY: How's Andy doing these days?

RUSNAK: He seems to be doing pretty well. He had a good time coming in and talking with us.

KELLY: Good.

RUSNAK: One of the first things, I guess, was just kind of a funny story he told about a squirrel getting into the white room where the LMs were being prepared at one time. I wanted to see what you remember of that.

KELLY: I don't know about that one.

RUSNAK: According to him, anyway, a squirrel had gotten into the white room and was shot by a security guard.

KELLY: Really? I never heard about that. But I don't doubt it. It certainly could happen.

RUSNAK: One of the other things he talked about was a problem with the glass for the windows. I guess there were some issues with some of them cracking. I wanted to see what you recall of that.

KELLY: We had a failure during a pressure test of the cabin. I think it might have been LM-5, where the glass actually broke, and that scared the hell out of us. So we did some redesign on the mounting to be more sure that we weren't applying any stress to the glass when we locked it into position. We also worked with Corning to develop a stronger, more crack-resistance glass, and we did substitute that improved glass. So, yes, we were worried about glass. I never liked glass as a structural material. You couldn't analyze it. It's an amorphous kind of thing.

RUSNAK: You certainly got rid of as much as you could there.

KELLY: Yes. It's a good thing we did, because even with just that simple flat panel, we still had cause for concern. If we ever had a big curved dome or something, we would have gone nuts.

RUSNAK: Just one last thing, I guess, to provide clarification. You had said that you were the Chief Engineer for the LM. What was your job description and the area of responsibilities that were uniquely yours?

KELLY: Well, I don't think anything was uniquely mine, because I was responsible for all the engineering activity, but engineering was involved in just about anything that went on in the program. So program management was also always involved in things, too. But basically I was responsible for the engineering and technical activities of the program. We had a total of over 7,000 people at the maximum of the LM program, of which about 3,000 were engineers.

Now, I did change jobs at one point. In 1967, I was taken out of engineering and put in charge of building the LMs and the manufacturing, assembly and test activity. So that was kind of just punishment. I had to build what I designed, and that's where I found out what a bad idea some of those weight-reduction items were, because it was my technicians then that were trying to avoid breaking those wires and things like that. Then after that, I went into program management on the LM for the later part of the program and for supporting the missions.

RUSNAK: That's all the questions I had, so I just want to give you an opportunity to make any concluding remarks that you wanted to, anything to sum up.

KELLY: I think we've pretty well covered the waterfront. It was a great program. It got the NASA firmly headed down the path of space exploration. Those last three missions were really very intensive lunar exploration missions, and NASA never deviated from that path. All their subsequent manned and unmanned missions were directed towards exploring and understanding the world of space. So I think Apollo made a very significant contribution in that regard.

It was very valuable in its own right, and it showed us what people could do in space under some very demanding conditions. And we learned an awful lot about the Moon, very interesting place, and gave us an idea about what it would be like to possibly explore other planets in the future as well. So it was a very successful program. I was delighted to work on it and really very happy that it went as well as it did.

RUSNAK: I'd like to thank you for taking the time out to meet with us today.

KELLY: Okay. Very good.

[End of interview]