Chapter Seven

Tim Harmon

Rocketdyne – Lunar Ascent Engine[1]

The ascent engine was the last one from the moon, and I want to focus on the idea of redundancy and teams in regard to the engine. By teams, I mean teamwork – not just within Rocketdyne. It was teamwork within Rocketdyne; it was teamwork within Grumman; it was teamwork within NASA. These were all important elements leading to the successful development of the lunar excursion module (LEM) engine. Communication, rapid response, and cooperation were all important. Another aspect that went into the development of the ascent engine was the integration of technology and of lessons learned. We pushed all the above, plus technology and lessons learned, into a program, and that led to a successful result. One of the things that I like to think about – again in retrospect – is how it is very "in" now to have integrated product and process teams. These are buzzwords for teamwork in all program phases. That's where you combine a lot of groups into a single organization to get a job done. The ascent engine program epitomized that kind of integration and focus, and because this was the mid- to late-1960s; this was new ground for Rocketdyne, Grumman, and NASA.

Redundancy was really a major hallmark of the Apollo Program. Everything was redundant. Once you got the rocket going, you could even lose one of the big F-1 engines, and it would still make it to orbit. And once the first stage separated from the rest of the vehicle, the second stage could do without an engine and still make a mission. This redundancy was demonstrated when an early Apollo launch shut down a J-2 second-stage engine. Actually, they shut down two J-2 engines on that flight. Even the third stage, with its single J-2 engine, was backed up because the first two stages could toss it into a recoverable orbit. If the third stage didn't work, you were circling the earth, and you had time to recover the command module and crew. Remember how on the Apollo 13 flight, there was sufficient system redundancy even when we lost the service module. That was a magnificent effort. TRW Inc. really ought to be proud of their engine for that. (See Slide 2, Appendix I)

We had planned for redundancy; we had landed on the moon. However, weight restrictions in the architecture said, "You can't have redundancy for ascent from the moon. You've got one engine. It's got to work. There is no second chance. If that ascent engine doesn't work, you're stuck there." It would not have looked good for NASA. It wouldn't have looked good for the country. There was a letter written that President Richard Nixon would read if the astronauts got stuck on the moon, expressing how sorry we were and so forth. It was a scary letter, really. The ascent engine was an engine that had to work. (See Slide 3, Appendix I)

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[1] Please see Section 4 for Mr. Harmon's biographical information.

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Reliability was the name of the game; keep it simple. That was the architecture and the plan.

The lunar excursion module vehicle was an ungainly, lightweight vehicle. The vehicle walls were really thin pieces of metal. The ascent engine was buried inside. All you could see was a little bit of the nozzle extending from the bottom of the vehicle (See Slide 3, Appendix I). The LEM vehicle ascent stage height was twelve feet, and the diameter was thirty-one feet. The LEM weighed about 11,000 pounds. Now, the ascent engine was fifty-one inches high; it wasn't a very big thing. It produced 3,500 pounds of force (lbf) thrust. It was a very "cozy" environment, this LEM vehicle. By cozy, I mean it had to be lightweight. By cozy, I mean they couldn't even install seats due to the weight penalty. The astronauts stood! They had parachute-like harnesses to provide stability. The astronauts stood and looked out "tilted" windows to see the landing area. The descent engine had a backup, the ascent engine, and the reaction control engines on the vehicle (there were four sets of four) were redundant. Again, the situation was: we did not have a backup for the ascent engine. When you don't have a backup, you make the thing simple. NASA was smart in this. They said, "All we want you to do is one on/off switch…. You don't have to throttle – constant thrust is okay. We are going to fix the mount and we are not going to gimbal this engine. We are going to have redundant valves and hypergolic ignition. Get the two propellants together, it lights." This is the plan for a simple, reliable engine. That was the approach, and I think it was a sensible idea. (See Slide 4, Appendix I)

The specifications for the engine were: pressure-fed, 3,500 pounds of force vacuum, a 310 specific impulse (Isp), and hypergolic propellants. One possible hypergolic fuel, hydrazine, freezes like water at two degrees Celsius. This was unacceptable, so unsymmetrical dimethylhydrazine – I don't know who comes up with these names – suppressed the freezing temperature. Reliability was the name of the game; keep it simple. That was the architecture and the plan. (See Slide 5, Appendix I)

It's important to remember Rocketdyne did not start out with this contract. This was the Bell Aerospace contract, which began in July 1963. Bell had challenges. Every development program does. Their biggest issues were thrust chamber erosion and combustion instability. These continued in the program all the way up to 1967. If you followed the descent engine program, you knew it was through qualification testing (also known as "qual") in 1967. In 1967, Bell hadn't even started qualification testing. So, suddenly NASA realized they could get to the moon, but they might not be able to get off the moon – not a good situation. NASA awarded a backup program to Rocketdyne in August 1967. We were successful with the main issues. By 1968, we had won the complete contract and were off and running. A calendar was established to set the major development schedule milestones (See Slide 7, Appendix I). The Bell program was given to NASA in July 1963. The Agena engine was Bell's basis for the ascent engine. It was a reasonable upper stage engine and had several successful satellite launches. I think it was a 16,000-pound thrust engine. In late 1964, I believe, NASA said, "We want to do stability testing. We want the engine duration to be longer." So, the specifications changed

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a little bit, and Bell began stability testing. The original injector was unbaffled. As soon as they bombed it to test stability, they had instability. They put a baffled injector in to improve stability, but were not successful in eliminating the instability problem. That created a situation in which Rocketdyne became a backup program. (See Slides 6, 7 and 8, Appendix I)

Because I did not work for Bell Aerospace, I can only provide my impressions of the ascent engine development problems based on NASA's historical documents. One of Bell's development issues was their program had limited test hardware early in the development cycle. When Bell had instabilities, there were manufacturing issues that could be blamed. You also get the impression there was some denial that there was a problem. When engine combustion went rough, they were never sure of its cause. "Was it manufacturing; did we do something wrong there? If we had an ablative wall thrust chamber, instead of steel battleship-type thrust chamber, maybe the ablative would change the acoustics, and it might absorb it." Instabilities tend to do a lot of hardware damage. I think their rough combustion cutoff was a little slower than Rocketdyne's, or what would be typically used, so they sustained a fair amount of hardware damage by the time they shut the engine down. It didn't quite tell them what the issues were. All those variables added up to mask the root cause of their problem.

Rocketdyne had heads-up information the ascent stage was in trouble. There's a story I can't deny or confirm: that Rocketdyne marketing people at NASA's Johnson Space Center in Texas had the ability to read documents upside down on a person's desk. Doing so, they realized there were problems with the Bell ascent engine. It did not take a rocket scientist to realize that problem, because in 1967, Bell hadn't started qualification testing. Rocketdyne thought, "There's something wrong here. Maybe this is an opportunity." It did prove to be an opportunity. NASA recognized the issue and said, "We need a backup ascent engine system, just in case." They put out a Request for Proposal in June 1967 for a backup injector system that would address the stability issue. Three companies were looked at and down-selected. TRW might have been one; but I'm not positive about that. The others were Aerojet and Rocketdyne. Rocketdyne's approach was to put everything we could think of into stability. We decided we had better design in baffles. We incorporated the best manufacturing technology that was available. We went with electron beam (EB) welding. We incorporated electron discharge machining (EDM) drilling, which is a real nice, advanced, repeatable system for drilling orifices. Then, we put in acoustic cavities.

Acoustic cavities were another stability aid. Rocketdyne had, in 1965 or 1966, an independent research and development program on a small rocket engine. It used a beryllium thrust chamber with a stainless steel injector. Beryllium is a brittle material. If the injector gets warm, it will expand, and the brittle beryllium material will break. To make up for that, engineers put a gap between the injector and the thrust chamber. We tested this in a pulse mode multiple times.

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This was a small engine, just a little pulse mode engine. It turned out this little beryllium engine with a stainless steel injector occasionally had low performance pulses; i.e., the pulses wouldn't go quite as high on the Datelink Independent Gateway Retrofit (DIGR). Mostly, pulses were to be a certain height. Occasionally, 3 percent of the time it turns out, pulses wouldn't go quite as high. We didn't understand that. We didn't know what was going on there. There was no high-frequency instrumentation. It was just that we noticed this data anomaly. The hardware didn't break, and there wasn't a problem with the hardware. We thought, "It is working and it isn't broke; let's let it go." But management said, "We have to understand the problem." During the analysis, we thought, "Well, maybe it's that gap between the injector and the beryllium chambers, and propellants are sneaking up there and detonating and causing some sort of instability." The question then became: "Make the gap smaller or make it larger?" We chose to make the gap larger, and cut the diameter of the injector down. The instability disappeared. They were all now the same height. Engineering said, "Aha! We've got the problem solved." Management said, "We don't think you do because you don't know what you did." We had to analyze it.

We then decided maybe it was a Helmholtz-type resonator disrupting the instability. Most of our engines in 1965 and 1966 were in production. We were not going to add acoustic cavities, which was a precursor of this type of stability aid. That idea went on the shelf. Then, along came this opportunity. We had come up with this injector and put a baffle in it. The president of the company, Sam Hoffman, said, "Let's put those acoustic cavities in there." I'm not sure we had all the analytic background, but that seemed to work on this little internal research and development (IR&D) engine. Hoffman said, "Put it in there." Of course, we already had our design, and we had to do some redesign to get the acoustics cavities in there, but it was a brilliant idea, and it helped sell the program to NASA as the backup program for the Bell problem.

People talk about the competition at that time. It's true we were in a space race, and we were doing pretty well maybe by 1966 or 1967. But NASA said, "Rocketdyne, you are still in competition with Bell." To set the stage, Bell was conducting their development program in parallel after we won the backup contract, which put us in competition. We had the competition of the space race and the competition with the schedule. Near the end of 1967, we hadn't even started qualification testing on the ascent stage. Rocketdyne had to respond to this competition. They recognized right off that this program had to be an integrated effort, and put together a team consisting of engineering, development engineering, design, and other personnel. It included inspection and quality teams. It included NASA and Grumman. It included a member of the test stand team. The test organization was represented there. They were all in one place, on one team.

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Every morning at eight o'clock, we had a standup meeting. It was truly a standup meeting. The offices in those days were fairly small. At eight o'clock, people piled in there. Every morning, it was like trying to see how many people you could stuff in a Volkswagen. For fifteen minutes, they discussed the results of yesterday, what we would do today, and marched on. It was a twenty-four/seven type of operation. Rocketdyne really went on this twenty-four/seven operation with a vengeance. Because of schedule constraints and schedule pressure, the team pushed down the point at which decisions were made. This was 1967; I had only been with the company four years, a fairly junior engineer. I was in charge of stability testing, which was run in two shifts. The first shift and second shift were stability testing. The third shift cleaned up the mess we made in the first and second shifts; then, it started all over the next day. I was the development engineer, and my job was to get stability tests done as rapidly as possible. They said to me, "If we can gain schedule, you can work the crew weekends – Saturday and Sunday." That part of my charter was a lot of responsibility for a guy of four years' experience because the test and operation staff was thirty people a shift. I was a junior engineer able to say, "We're going to spend some money this weekend to gain schedule." We were really pushing. We had the long pole in the tent for 1967. I don't mean that I was particularly special; that was the way it was for everybody on the team.

It was a twenty-four/seven type of operation.

This was one of the most fun and fulfilling programs I ever worked on; it was a very intense program, but let me describe what Rocketdyne was able to accomplish. The contract proposal was submitted in June 1967. It was awarded as a backup in July 1967. We got a go-ahead in August. However, once we submitted the proposal in July, we recognized the need for speed. We started assuming we would win the contract, and we started building hardware. It's a phenomenal thought, but we were able to design and get ready to go in two months.

We conducted our first altitude test, then our first full duration test two months later. We completed our preliminary design review in November. We completed our critical design review in December, the first engine system full duration altitude test in January. The term "design feasibility tests" meant we knew enough of what we were doing regarding stability, to finish proving that in March. Our development program milestones give some sense of what we were able to accomplish, and we were not hardware poor (See Slide 8, Appendix I). We were able to get a lot done in a very short period of time. (See Slide 9, Appendix I)

For the design feasibility program, we had twelve injectors. We accomplished 872 tests, including 302 combustion stability tests. The combustion stability test used a little bomb. It was more like a blasting cap or a firecracker, but it was a little bomb. We built a battleship, just a plain steel thrust chamber. We could run this chamber about ten seconds before it got too hot. I could get five bomb tests off during a ten-second run. With every hot-fire, we could get

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five stability tests accomplished. NASA and Grumman were coming in to review the program one Monday. We were going to work through the weekend to get as many bomb tests off as we could. We wanted to have 100 bomb tests completed. We got ninety-nine tests done, and then, it went unstable. I couldn't believe it. I was crushed. It turned out the instability was caused by the bomb shrapnel damaging the injector. In post-test, we disassembled the injector and recognized we had damaged the injector with shrapnel from the multiple bomb detonations. The wiring to the blasting cap was going backwards, hitting the injector face, changing the injector orifices' shapes, and denting the injector. After that, we would take the injector apart after each test, and if we saw any damage to any orifice we would hand drill it back out. That eliminated the instability problem. But, it made for a very interesting NASA meeting that Monday because the injector went unstable Saturday night about eight o'clock, and we only had Sunday to figure out what caused this instability and whether we understood it. (See Slides 10 and 11, Appendix I)

To give an idea of the twenty-four/seven intensity of the schedule, Rocketdyne decided to appoint only one development engineer for stability, and it was me. I don't know why. But, to accomplish testing like that, I was to be available whenever the engine ran. In those days, I wore contact lenses and really couldn't wear contact lenses much more than ten hours. I just couldn't see beyond that. I had to do something to be able to see twenty-four hours with contact lenses. So, I would wear one contact lens at a time. I would look this way, or I would look that way. By three or four o'clock in the morning I knew it was time to change because my eyes were really getting tired. I was so tired, I managed to stick both contact lenses in one eye. It took a while to straighten myself out, but I did get the contacts sorted out and completed the test program. That shows you some of the dedication of the team. We really worked at it.

Another program issue was chamber erosion. There were a couple of others as well. One was baffle weld cracks. Last, we had to make the engine lighter. Within nine months of becoming a parallel effort with Bell, Rocketdyne had gotten to the point of showing NASA that we knew what we were doing, and we became the single contractor for the ascent engine. Within nine months, we had caught up with Bell, who was probably four years of testing ahead of us, and we became the prime contractor for the ascent engine. That was quite an accomplishment.

Finally, with combustion instability, we did one test where we verified that the acoustic cavities were doing their job. On one test, we blocked the acoustic cavities, and sure enough, on the first bomb the injector went unstable. The acoustic cavities were validated with that test.

The chamber erosion issue was very difficult to solve due to the need of getting uniform flow from the injector. One way to protect ablative material is to put film cooling material down the walls of the thrust chamber. But the engine loses performance when you do that. There

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is always a trade off. We wanted to protect the thrust chamber, but we couldn't do too much because the specific impulse performance goes down. After we had several tests that showed erosion, we discovered it was always occurring in the same general area. With the conventional wisdom of putting film cooling all around, we would end up with unacceptable performance. My manager, Mike Yost, said, "Well, you know, we don't need to put film cooling all the way around, we just need to put it where it is eroding." That really sounds like an easy solution now, but it wasn't conventional at the time. In those days, you put film cooling in a nice symmetrical pattern. But Yost said, "Let's just do it where we need it." That eliminated most of the film cooling performance loss. This was a good example of thinking out of the box.

Another milestone or key part of the effort was communication. It was rapid. It was effective.

I mentioned that we had hard starts. That happens when the fuel gets to the combustion chamber before the oxidizer. When the oxidizer hits, it goes "bang," which is not a good situation. Our solution was to make the fuel pipe large and add an extra little volume at the end of the fuel pipe, so that the fuel had to prime a large duct. When we did that, the oxidizer reached the combustion chamber first, before the fuel. The design looks pretty unconventional and is not real elegant. (See Slide 12, Appendix I)

Testing was key to demonstrating high engine reliability. We had test facilities everywhere. There were two test sites at Santa Susana in California. We used White Sands, New Mexico; Reno, Nevada; and even Bell Aircraft test facilities. We had to take our engine to Bell and run it there. Bell was, of course, extremely interested in our design. We were still in a competitive situation. After they installed it, they thought it would be a good idea to X-ray the engine. We said, "No way." They did focus on our unconventional inlet duct, thinking it was a stability aid. It was only a priming aid to keep the hard starts from occurring. If they thought it was the solution to stability, it wasn't – perhaps it led them down an incorrect thinking path. It was an accidental thing, not done on purpose on our part. But it did cause Bell a lot of consternation. We ran successfully in their facility, partly to verify that our performance was equal to theirs. It was.

The LEM engine was on the critical path. It really was a twenty-four/seven operation. We had this team that included everybody. It really was an integrated effort. Another milestone or key part of the effort was communication. It was rapid. It was effective. Decisions were made in timely order for anything. Decisions were down to the lowest person. It was interesting that we had this close working relationship with Grumman Aircraft, as they had chosen Bell, but they recognized the issue and so did Bell Aircraft. I should also say that Bell was very helpful in the program. We had the injector. We assembled the engine. But the valves and the thrust chamber were Bell Aircraft's. Everybody worked in concert, because the goal was to get to the moon and to get back. (See Slide 13, Appendix I)

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When trying to understand how fast we were able to respond, it's important to remember we were not hardware poor. We essentially got going within a month of the contract award. Our feasibility testing was completed. Then, the solution was demonstrated literally in eight months. This was a prototype integrated product and process development (IPPD) team. It was a totally committed, very goal-focused team, in which all the disciplines were involved. I think Rocketdyne really showed what they could do in a critical situation. I think we did put the lessons learned in this engine. We implemented them in an effective manner, and we integrated technologies within that environment. Once we got the engine working, NASA asked us to reduce its weight. This engine only weighed 171 pounds, but still, the weight had to be reduced. The reason was that NASA wanted to bring home more rocks from the moon. If the engine weighed less, they could do that. I was put in charge, and we took a 171-pound engine and reduced its weight by thirty pounds. That meant an additional thirty pounds of moon rocks could come back to Earth. That was a significant amount of improvement. That was a 15 percent weight reduction on a pretty well-developed engine. (See Slide 14, Appendix I)

Editor's Note: The following information reflects a question-and-answer session held after Harmon's presentation.

QUESTION: One of the things that we run into with the "can-do" attitude that you showed on your last slide is you don't want to sacrifice quality, and that's always the issue. How do you balance that? How did you balance that back then to make schedule and still maintain quality? What were you doing? What advice would you give?

HARMON: One way was that quality was part of the team. When you put manufacturing, quality, and engineering personnel together, quality can look at your design work and say, "Man, that is really hard to see whether that is going to be a good weld or not." They are right in tune. I was talking recently with some gentlemen who had testing personnel as part of their team. They were there every day. They were there in the standup meeting. When an engineer said, "I need 100 strain gages," the test guy said, "I got thirty. You are going to have to make do with thirty, or it is going to cost you 'X' bucks to go to sixty and it's going to take 'X' months to get it available for you." We had this immediate feedback of what we were asking for, whether it was doable, whether quality staffers could do it, and that was the virtue of that team. The quality check certainly was built into the design as best we could do.

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There was one instance where we found weld cracks on this system. There is an art to welding. This piece was machine-welded, but there's still an art to it in the setup. What was the problem? Well, it turned out, we were working two shifts, and the machinist on the night shift didn't quite make the setup right. It was a difficult weld. It was difficult enough that we would sometimes overstress that weld if the setup was not perfect. It was a weld penetration issue. We solved the weld problem by removing the second shift welder from the task.

I got to do the inspections on that weld, to see whether I felt the penetration was correct. We actually had one of our LEM engines in a "bird" (referring to an Apollo vehicle on a Kennedy Space Center launch pad) at Florida. Since it was not a big engine, it was hard to look from the outside and see how good the weld penetration was. It was supposed to be a one-day trip.

The welding, though, was interesting because of how we were able to solve that issue and figure it out quickly and verify the welds on the LEM were fine – the same way I verified the quality of that paper swimsuit.

Rocketdyne met the challenges. The Lunar Excursion Module Ascent Engine was a prototype IPPD program, but it was probably the best yet for integrating lessons learned and technology. It was one of the best programs I ever worked on. I think almost every team member who worked on the LEM looks back on it, and is very pleased with the results.

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Appendix I

Tim Harmon's Lunar Ascent Engine Presentation Viewgraphs

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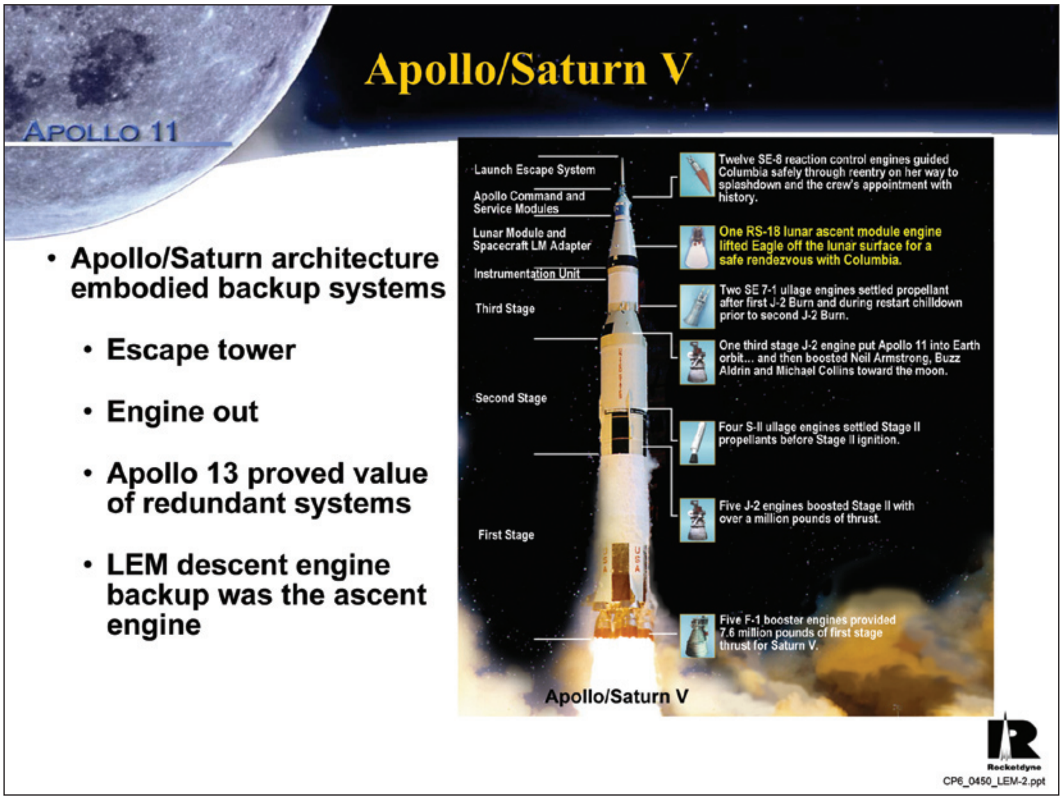

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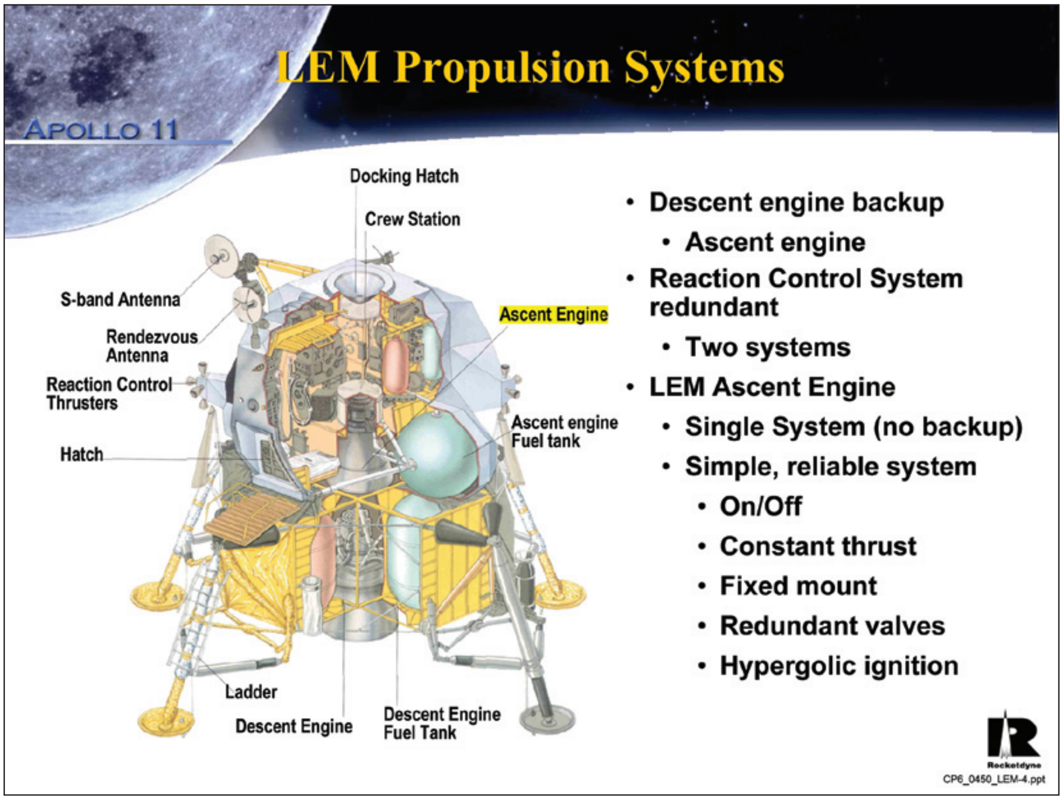

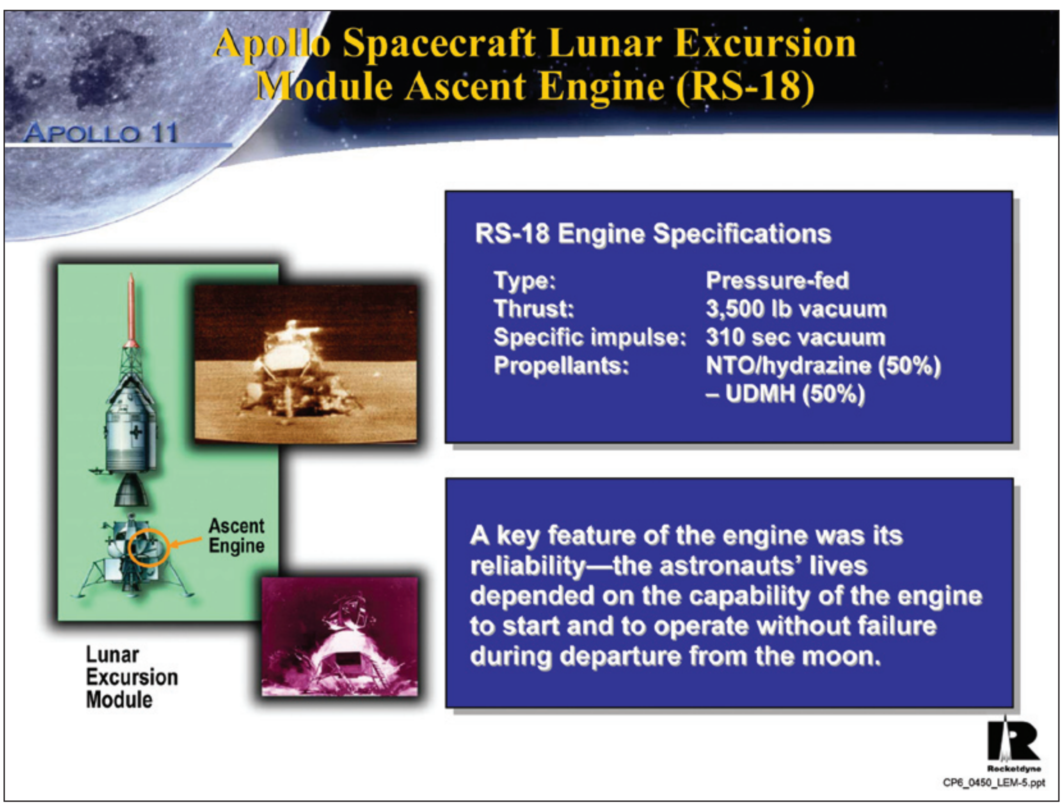

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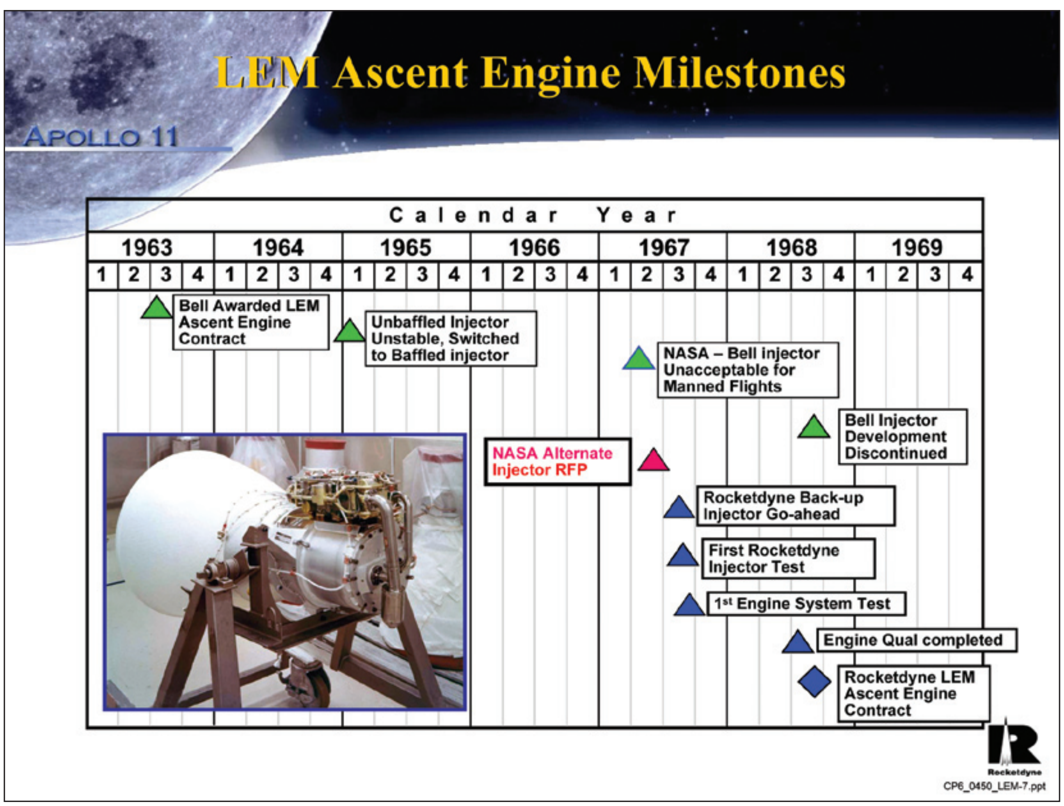

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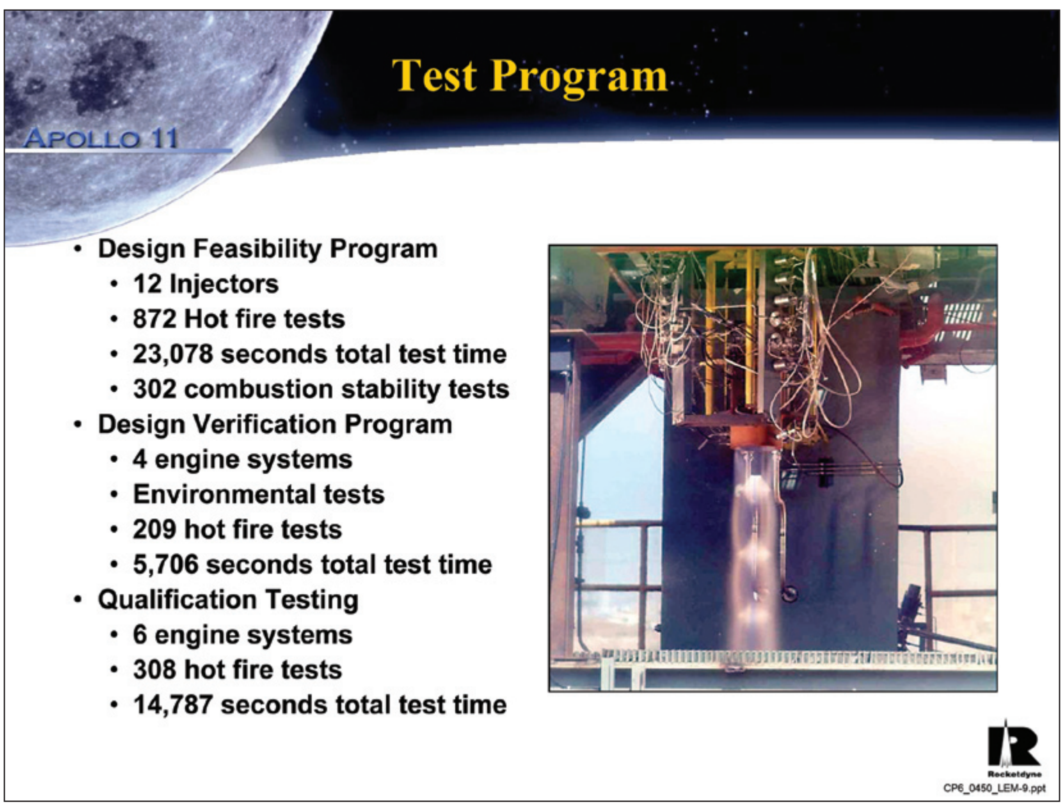

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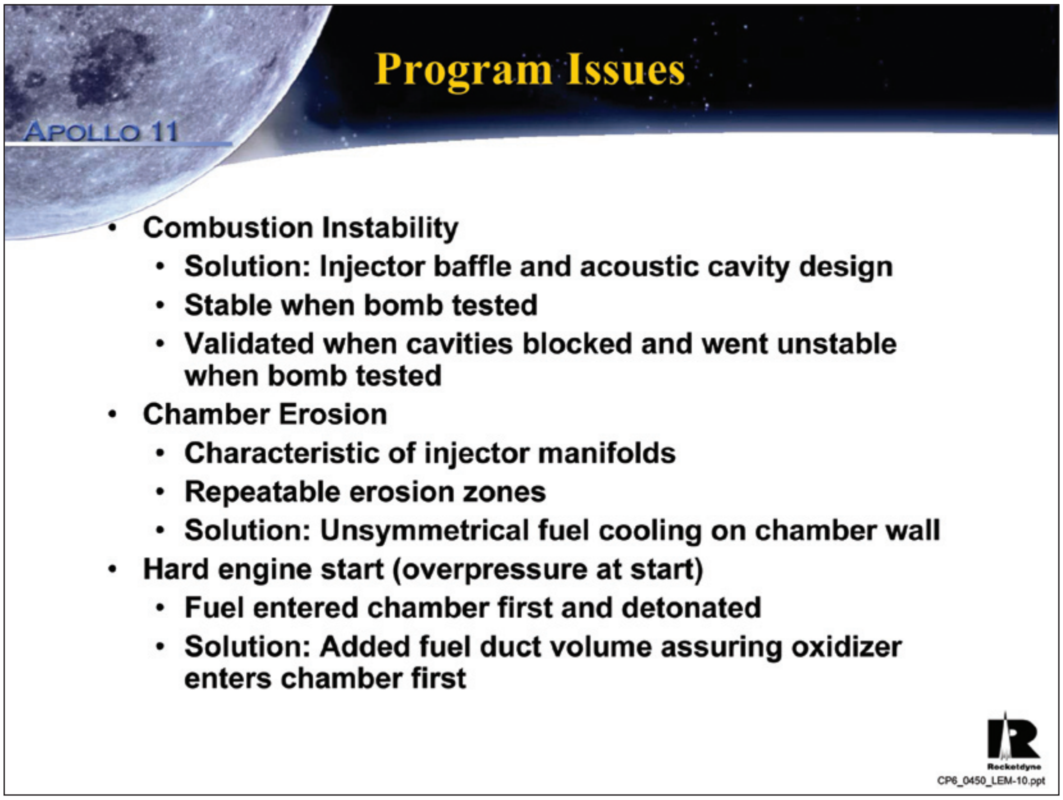

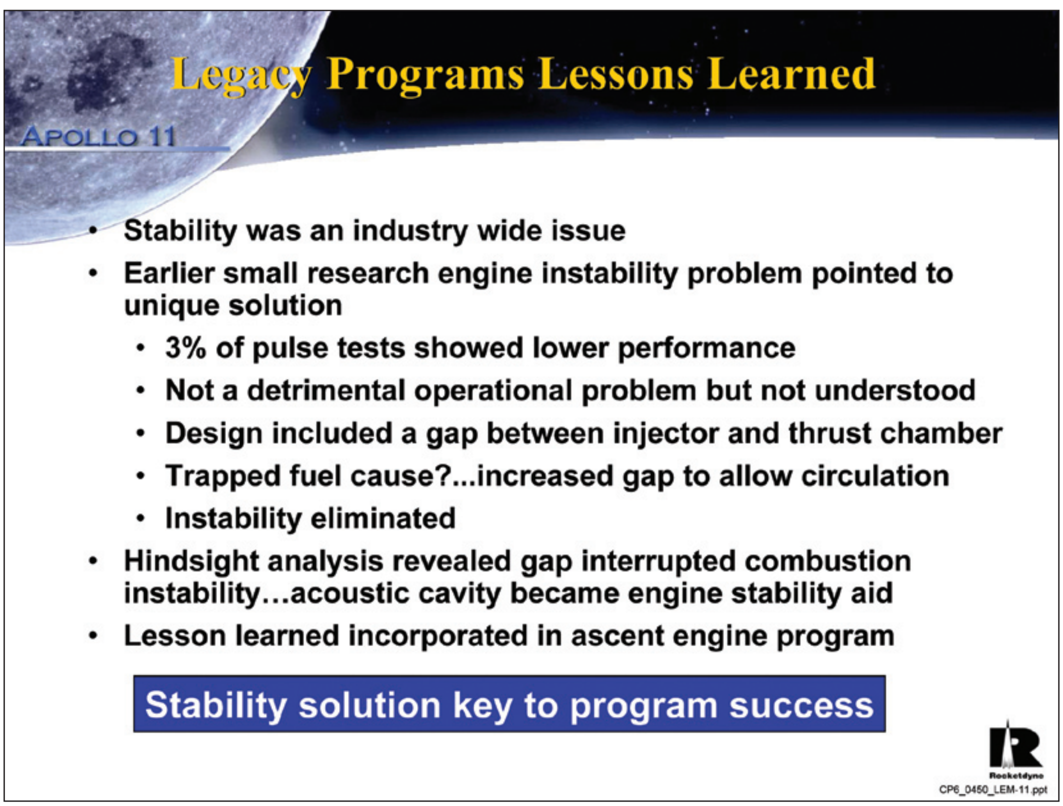

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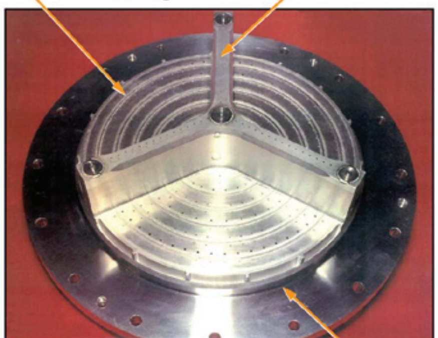
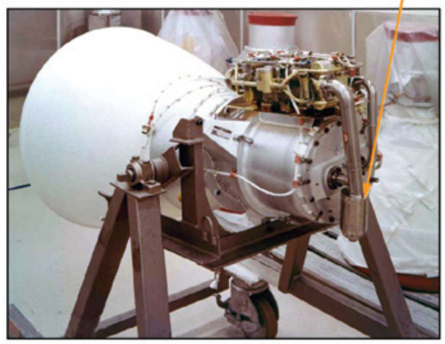
Ascent Engine Design Resolved Issues

APOLLO 11





Rocketdyne

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Development Program Success

APOLLO 11

- Engine was on critical path
  - Schedule was king!
  - 24/7 test operation, 2 shift manufacturing operation
- Development team included design, development, manufacturing, quality and test staff
- Program communication rapid and effective
- Decision/responsibility flowed down lowest staff level
- Close working relationship with NASA and the vehicle contractor Grumman Aircraft Corp

Rocketdyne

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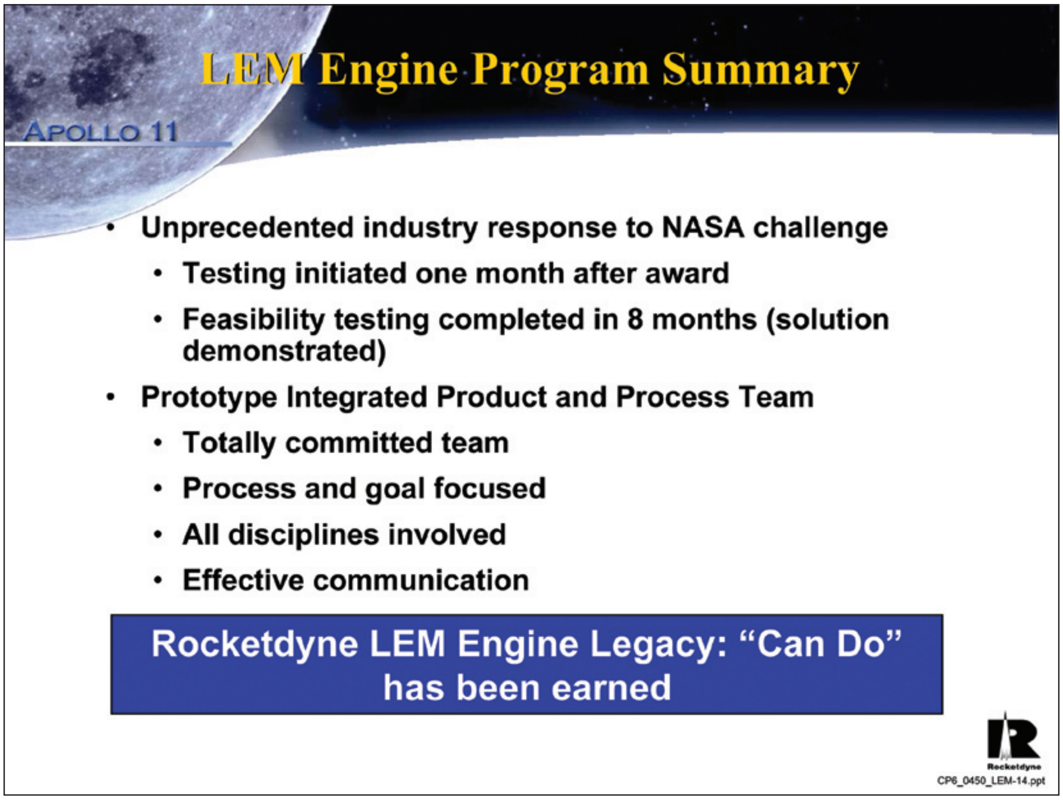

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