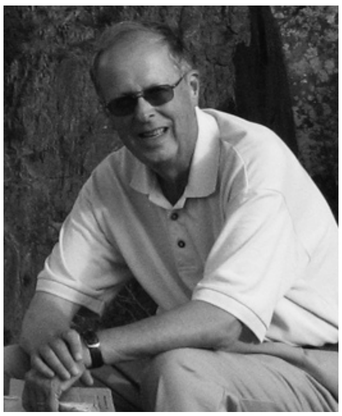
Chapter Four

Tim Harmon

Rocketdyne - SE-7 & SE-8 Engines



Tim Harmon has more than forty-one years of experience with The Boeing Company and its Rocketdyne Division. He retired as the chief systems engineer on the MB-XX Program, a cryogenic upper stage propulsion system. Harmon also was involved in ten Rocketdyne engine development campaigns, ranging from small attitude control engines to a large Aerospike engine. In the Apollo Program, he worked on development of the lunar module ascent and command module attitude control engines. Harmon earned a bachelor of science degree in aeronautical engineering from Purdue University, a master of science in mechanical engineering from the University of Southern California, and a master of business administration from Pepperdine University.

I hired in at The Boeing Company's Rocketdyne Division in 1963. There are two themes I would like to emphasize about my experience there: the environment at Rocketdyne, and using lessons learned.

It started out in 1957 with the first Sputnik launched into space and how much it weighed. The United States' response was a vehicle that went all of four feet off the ground before exploding. Then, in 1961, the Soviets put an astronaut in orbit. What was our response? We got Alan Shepard up in space for fifteen minutes. When I started work at Rocketdyne, there was a space race, and we were behind. We didn't look that good. That kind of environment was intense. Rocketdyne's response was to hire more staff. We had employee serial numbers in those days. I hired on in April, and my serial number was 318083. By the end of the summer, there were many new hires. The staff I talked to that hired in June, July, and August had serial numbers that were a thousand points higher than mine. It was a good environment from the standpoint that it was growing. When something is growing, there is opportunity, and it's a fun environment. On the other hand, in my first six months at Rocketdyne, I had three managers because they were getting promoted, moved, or changed. That was a little disconcerting. You have pluses and minuses with a growing environment.

Now, let's talk about off-the-shelf technology and lessons learned with the Apollo Program. There were a dozen SE-8 engines in the Apollo capsule; in the S-IV-B Stage, there were two SE-7 engines. These engines were similar in design and function. They were based on the Gemini Program vehicle attitude control engines. The Gemini Program used small engines that Rocketdyne built. These were buried engines. One of the technical issues with buried engines is keeping engine heat from soaking into the Gemini capsule. The solution was ablative-cooled engines that insulate the vehicle from engine-firing heat. The Gemini Program success was the basis that Rocketdyne used to win the contract to develop the engines for the Apollo Program's Saturn vehicle. (See Slide 2, Appendix F)

On the Gemini vehicle, we had orbital maneuvering engines (OMEs), and we had reaction control system (RCS) engines. The OMEs were 100-pounders (generating 100 pounds-force of thrust). The RCS engines were twenty-five-pound-force (lbf), buried systems, and depending on the angle, the nozzles were scarfed (truncated at an angle), so they wouldn't impinge on the vehicle. Rocketdyne said, "Well, let's go with an off-the-shelf design where we and you (NASA) can save money." It was a good idea, and I think it proved itself. (See Slide 3, Appendix F)

Gemini's 100-pound force Orbital Attitude Maneuvering System (OAMS) illustrates some of the problems we had. We had two propellant valves. We had an ablative thrust chamber with different wraps of ablative material. There were a silicon carbide liner and a silicon carbide throat. One of the problems with silicon carbide material, while very sturdy, was that it would crack due to thermal shock. The thermal shock issue was never a problem on the Gemini vehicles. The throats would crack and the sleeves would crack, but they would all stay in place. That was the design, and NASA went with it. It was man-rated (deemed safe to carry humans) and successfully flew. The Gemini thruster performance was adequate. As a pressure-fed system, it was fairly simple. The S-IV-B engine has the same look as the Gemini engine. They did de-rate the thrust level. NASA didn't feel they needed the thrust. It also was pressure fed (no propellant pumps). It had a 274-second specific impulse using nitrogen tetroxide and hydrazine propellants. The design year was 1965. This engine application, for the S-IV-B Stage, was to settle propellants into the bottom of the stage, so they could start and restart the J-2 engine. It was a continuous burn, with no engine pulsing. This fairly simple engine was a "lessons learned" direct application, and there were no development problems. (See Slides 4 and 5, Appendix F)

The 70-pound SE-7 engine is very similar with its two valves, ablative material, a silicon carbide liner, a silicon carbide throat, and overall configuration. There were different wraps. One had a ninety-degree ablative material orientation. That is important because it caused problems with the SE-8, but not for this application. It was not overly stressed. It was a validation of the off-the-shelf application approach. There were two SE-7 engines located on the stage near the bottom. They had their own propellant tanks. That was the application. All it did was give a little bit of gravity by firing to push the propellants to the bottom of the tanks for start or restart. It was not a particularly complicated setup. (See Slides 6 and 7, Appendix F)

Instead of a mere 17,000 miles per hour, it was going 24,000 miles per hour. That meant the heat load was four times as high on the Apollo vehicle as on the Gemini craft.

What had we learned? This was a proven engine in a space environment. There weren't any development issues. Off-the-shelf seemed to work. There were no operational issues, which made the SE-7 very cost-effective. Besides NASA, the customer for this application was the Douglas Aircraft Company. Douglas decided the off-the-shelf idea was cost-effective. With the Gemini Program, the company was McDonnell Aircraft Corporation, which was part of the reason the off-the-shelf idea was applied to the Apollo. (See Slide 8, Appendix F)

However, here are some differences between Apollo and Gemini vehicles. For one thing, the Apollo vehicle was really moving at high speed when it re-entered the atmosphere. Instead of a mere 17,000 miles per hour, it was going 24,000 miles per hour. That meant the heat load was four times as high on the Apollo vehicle as on the Gemini craft. Things were vibrating a little more. We had two redundant systems. Apollo was redundant where it could be as much as possible. That was really a keystone or maybe an anchor point for Apollo. We decided to pursue the off-the-shelf approach. However, the prime contractor was a different entity – the North American Space Division. They thought they ought to tune up this off-the-shelf setup. It was a similar off-the-shelf application, but at a higher speed. They wanted to improve it. What they wanted to improve was the material performance of silicon carbide. They were uncomfortable with the cracks they were seeing. They were uncomfortable with the cracks in the throat, and feeling that the environment was a little tougher, that maybe it was going to rattle, perhaps something would fall out, and they would have a problem. They wanted to eliminate the ceramic liner, and they wanted a different throat material. (See Slides 9 and 10, Appendix F)

The Rocketdyne solutions were to replace silicon carbide material with a more forgiving ceramic material. Also, due to the multiple locations within the vehicle, the shape of the nozzles varied. Some nozzles were long, and some nozzles were short. We came up with a single engine design with variable nozzle extensions and configurations to fit particular vehicle locations. (See Slides 10 and 11, Appendix F)

The engines cost about $35,000 in 1963, which was how much you paid for a Rolls-Royce automobile. So, there were twelve Rolls-Royces on every Apollo vehicle. That's important because it meant we really had a fair amount of investment by the time we got to the end product, and we didn't want some problem to show up that would cause us to discard the engine.

We came up with a single engine design with variable nozzle extensions and configurations to fit particular vehicle locations.

Another kind of issue was the work environment. There was a lot of competition at Rocketdyne for test site slots. We had a lot of simultaneous programs in the works of large engines and small engines. Test slots were an issue or a competition between various groups. There was another competition going on as well. It was organizational, between the quality and manufacturing departments. The environment was such that quality wanted to catch engineering oversights; or manufacturing wanted to catch engineering oversights screwing up. It was friendly, because we were all trying to win the race to the moon, but it was still a different environment.

I was the test engineer during engine development testing, and had to cope with the space race and its schedule pressure. I was assigned to assemble an SE-8 engine with a nozzle to get it ready to test. We accidentally installed an O-ring made of the wrong material. I tested the engine, and the seal leaked post-test. My name was Mudd. My boss, Cliff Hauenstein, who was the materials engineer, had to explain this to the vice president at Rocketdyne. This Rocketdyne vice president was a tough, old-school manager. He looked like Yul Brynner[1], and his management style was like Attila the Hun. It was not going to be a comfortable meeting. The vice president had jelly beans on his desk. He always ate jelly beans. He was a nervous guy. We walked into the office, and a jelly bean caught in his throat. He ran out, turning purple before the meeting started. Finally, he came back in, having coughed and dumped the jelly bean. But, we felt he must have seen God because he was extremely mellow. Everything was fine. "Don't let it happen again," he said. After that, my manager always had jelly beans in his office. It's a true story, but the lesson learned was, "You know, these things are expensive. You ought to have a little better control and awareness, so you don't make a mistake like that."

We also had an uneven throat erosion issue caused by uneven injector performance. When we went away from the silicon carbide throat material, the substitute material we chose was not as sturdy. The SE-8 program was still schedule driven. We could identify injectors that caused high erosion problems by hot-fire testing each injector in a specially built thrust chamber that used steel throat inserts. A poorly performing injector would erode the steel throats quickly. The plan was to devise some sort of tool for inspecting throat erosion post-test to identify samples with good erosion characteristics and samples with bad erosion characteristics.

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[1] Accomplished actor from who played several roles requiring a serious demeanor.

By this time, we probably had a database of fifty or so injector tests on steel throats of various discolorations or erosion patterns. I made up a board that basically consisted of samples that were good and samples that were bad. We put them on a metal strip. To do that, and do it in a hurry because we were in production, I went into the shop, found a welder, and said, "This is a 'G job.'" In those days, a G job was special. It took no paperwork, and you could get anything done you wanted. So, we would weld a throat on a strip of metal. Now, it was hot. You had to wait for the first weld to cool down before you could weld the next one. Again, we had injectors at the Rocketdyne test site we were trying to inspect and show were acceptable. This tool was needed in a hurry. We would weld one on, then wait for the thing to cool. It was time-consuming, and I needed to solve the problem. There was a men's bathroom right next to welding station. The welder would weld one strip, and I would run and flush it in the urinal and cool the metal weld immediately. We would then complete the next weld, flush it in the urinal, cool it right down, and repeat the process. (See Slides 12 and 13, Appendix F)

I had this nice board, all these welded pieces, delivered to the test site. I brought the tool out to inspection, and they were really happy with it. We fired the next injector. An inspector looked at it and said, "It feels all right to me. It looks just like this one on the inspection board." However, the quality inspectors were unaware that the samples had been in the bathroom being flushed. I thought that was kind of payback for all the grief I got from the inspectors.

Another issue we had was the appearance of the thrust chamber post-test. This ablative material looked like a piece of polished wood before hot-fire testing. After we hot-fired it, it had ablated, so it looked a little rough, with something like the appearance of burned wood or charcoal. After one hot-fire test, the Air Force inspector said, "Well, it doesn't look like this nice piece of wood, and we don't know whether to accept it or not because it looks worn." The solution to that was elegant, but silly. We changed the chamber inner diameter appearance to one that looked like it had been fired. We took this piece of the inner sleeve, and we charred it in an oven, so that it looked already used. Then, when it was hot-fired, it didn't change in appearance and the inspectors thought that was neat. Now, that kind of fix for an issue was a waste of money. Everybody was happy, but it was an added step. Eventually, we convinced them that it was a stupid idea, and this fix was eliminated. That was sort of humorous, but it also was a sign that people were not working together or were not understanding the processes. Who was at fault? Nearly everyone – engineering, inspection, NASA, and the customer.

Those were two big issues and their solutions.

Our test facility, Santa Susana (California), had an interesting history. A lot of B Western movies were made there before it became a test facility. If you see a 1920s or 1930s Western, there was a good chance it had been filmed at Santa Susana. Rocketdyne purchased the area for testing rocket engines and built many facilities. This was the facility that tested most small engines. It had four or five small engine test stands. It was a very active facility. Engineers were pushing for their test slots and trying to get things done. We had to test our engine at altitude conditions. We had a very limited capability in terms of altitude simulation testing. It could run approximately fifteen minutes before needing to be reloaded with propellants. To hot-fire calibrate an engine or run development tests, we conducted a test, analyzed our data, and determined our next test condition. If we wanted to change the mixture ratio and the various tank pressures to get another test, we tried to do that as fast as we could with our handy, dandy slide rule calculators. Times were different for testing in the 1960s than they are now. It was fairly frantic because we tried to get as many test conditions as possible in the shortest time span. What we did have were Datelink Independent Gateway Retrofit (DIGR) data recorders - we called them diggers - for instrumentation, which was interesting. The DIGR was a circular plot with an ink pen that showed the test data. A development engineer would run a test, go over and look at the DIGR, and it would tell the value of pressure or thrust or whatever. But, it wouldn't tell right away because there was a hysteresis (or lag time) in the pen. We would have to go over and tap the DIGR to get our values. As soon as we ran a test – we had probably ten DIGRs we had to pay attention to – we were going along tapping every DIGR to get our value. It looked like we were doing some sort of comedy because we would tap all the DIGR, use our slide rules, do all the calculations, and then yell new test values to the test conductor. We would yell, "Change the tank pressures to this." Then, we would do the next test, and start all over again. It was very frantic and very challenging. (See Slides 14 and 15, Appendix F)

Times were different for testing in the 1960s than they are now. It was fairly frantic because we tried to get as many test conditions as possible in the shortest time span.

When I was training to be a development engineer, I was mentored by a very seasoned engineer who had hired in six months earlier than I had been. We worked together for about two weeks, then I was on my own for running tests. The very first test we ran, the engine split in half. I could not believe it. I had a guilt trip that I had just ruined the space program. I got over it, but it was still traumatic. However, in those days, failures were somewhat acceptable because we were trying to develop engines, and it was exciting to be part of the space race.

Development programs generated a huge amount of data. We had a lot of people doing tests. If one person wrote the test report on an engine, that was fine. That was not a problem. However, when you had twenty engineers conducting tests and writing reports, there was no consistency.

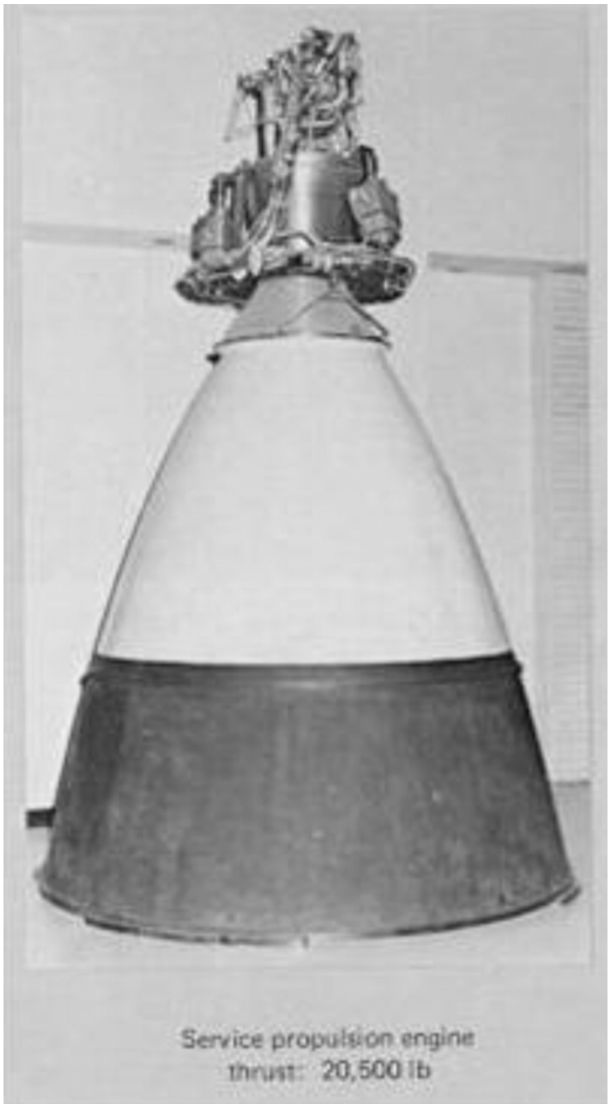
What one engineer thought of the engine, another engineer would have a different slant. That turned out to be a major issue. *The solution was to develop a simplified reporting process, a template system for reporting processes.* (See Slides 16, Appendix F)

Engine development issues were generally resolved through an extensive test program. That's a lesson learned. For the next Apollo-type program, I think you have to be able to anticipate issues. Every application is slightly different, and the customer is slightly different. The customer wants to improve the engine. Many of those improvements cost development activities that are not necessary. It's hard to say, but we certainly had an engine that was developed and worked. However, you have to anticipate there will be problems. I think that is the same situation you will find with the J-2X upper stage engine development program. That application is slightly different. Nothing goes quite off-the-shelf, but it's better than starting from scratch.

Engine development issues were generally resolved through an extensive test program. That's a lesson learned.

In summary, Apollo in the early days was certainly a challenge. The challenge was the fact that we were behind. As a country, we didn't look nearly as smart technically as the Soviets. That was a challenge, and that was a driver. Using the off-the-shelf approach saved time. It leveraged previous technology. However, we also needed to work together. The goal was the same for engineering, for quality, for inspection, for the customer, and for NASA – work together.

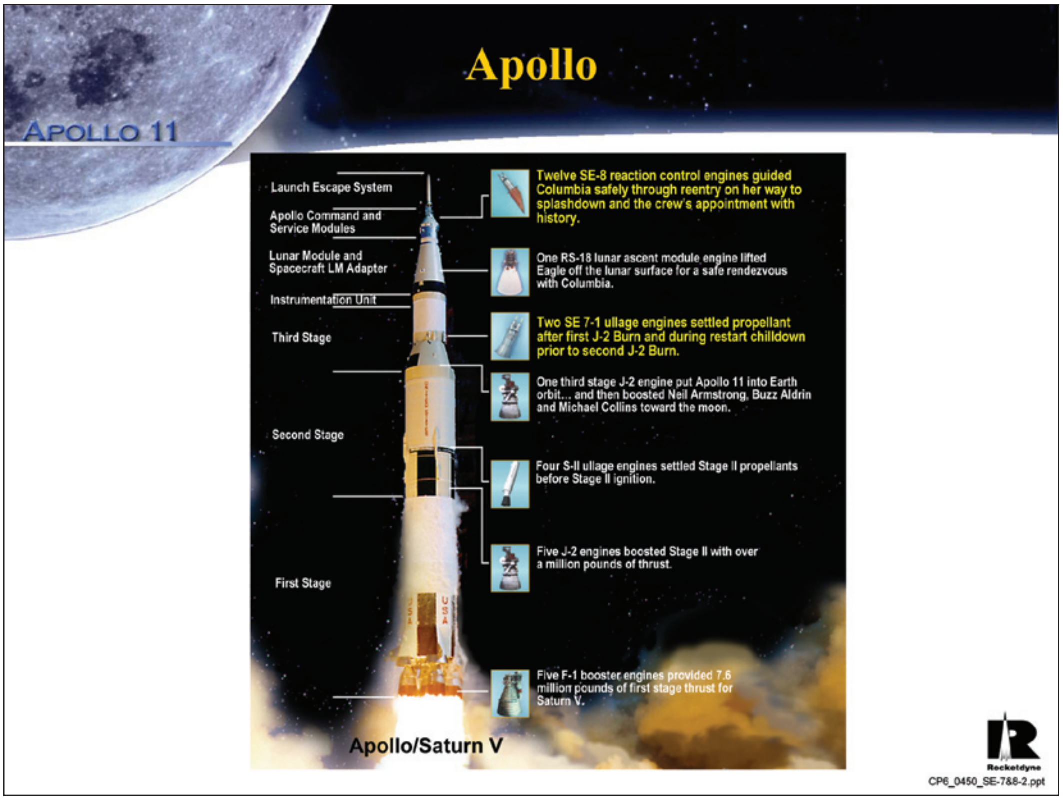
Editor's Note: *The question-and-answer session was held after Mr. Harmon's second presentation, the transcript of which appears in Section 7.*



AJ10 Service Propulsion Engine

Appendix F

Tim Harmon's SE-7 & SE-8 Presentation Viewgraphs


Apollo
APOLLO 11
Launch Escape System
Apollo Command and Service Modules
Lunar Module and Spacecraft LM Adapter
Instrumentation Unit
Third Stage
Second Stage
First Stage
Twelve SE-8 reaction control engines guided Columbia safely through reentry on her way to splashdown and the crew's appointment with history.
One RS-18 lunar ascent module engine lifted Eagle off the lunar surface for a safe rendezvous with Columbia.
Two SE 7-1 ullage engines settled propellant after first J-2 Burn and during restart chilldown prior to second J-2 Burn.
One third stage J-2 engine put Apollo 11 into Earth orbit... and then boosted Neil Armstrong, Buzz Aldrin and Michael Collins toward the moon.
Four S-II ullage engines settled Stage II propellants before Stage II ignition.
Five J-2 engines boosted Stage II with over a million pounds of thrust.
Five F-1 booster engines provided 7.6 million pounds of first stage thrust for Saturn V.
Apollo/Saturn V
Rocketdyne
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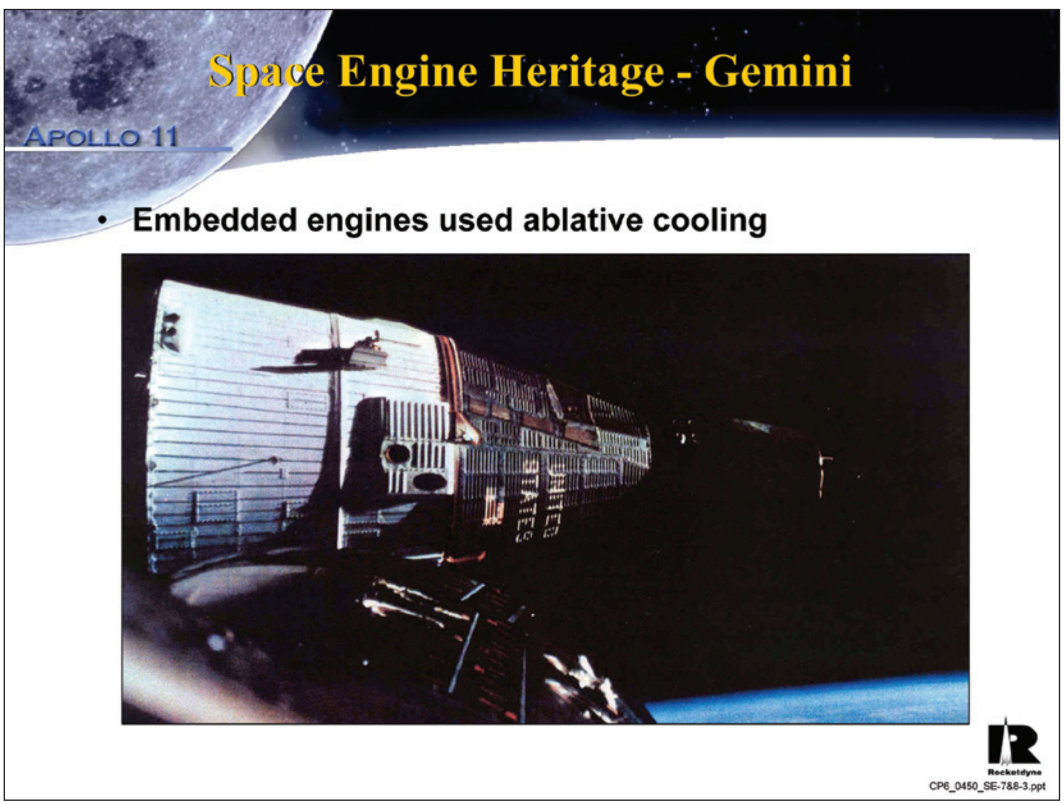
Space Engine Heritage - Gemini
APOLLO 11
• Embedded engines used ablative cooling
Rocketdyne
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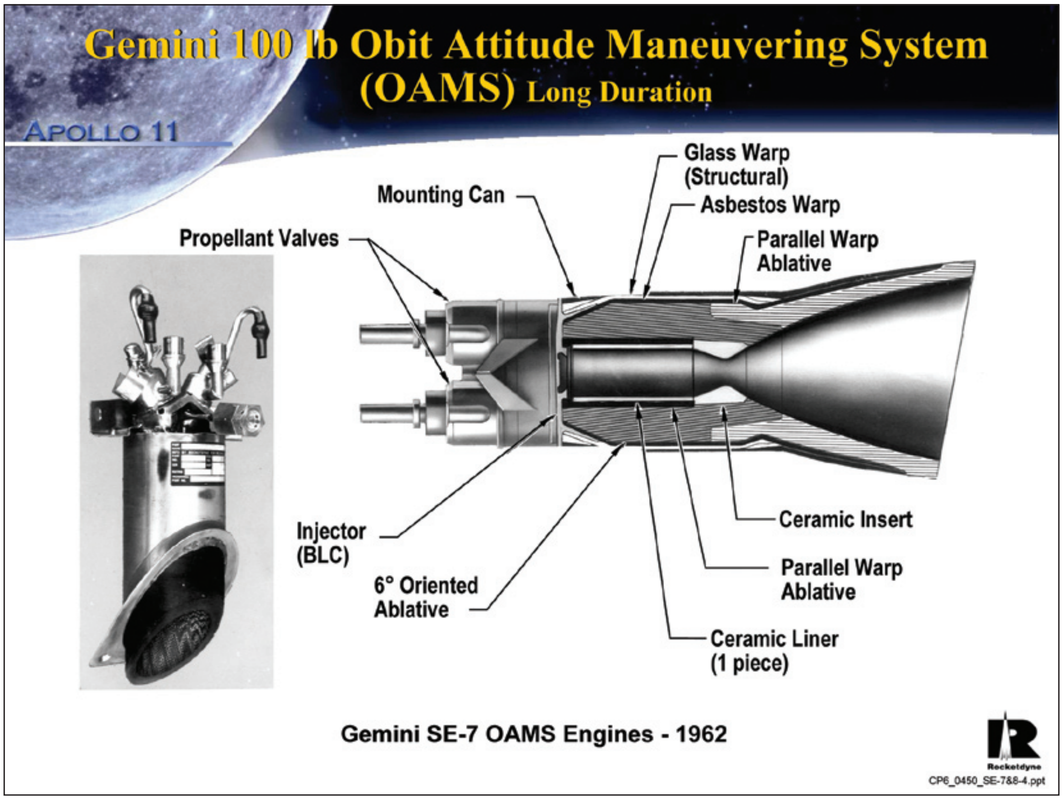
Gemini 100 lb Obit Attitude Maneuvering System
(OAMS) Long Duration
Apollo 11
Glass Warp
(Structural)
Mounting Can
Asbestos Warp
Propellant Valves
Parallel Warp
Ablative
Injector
(BLC)
6° Oriented
Ablative
Ceramic Insert
Parallel Warp
Ablative
Ceramic Liner
(1 piece)
Gemini SE-7 OAMS Engines - 1962
Rocketdyne
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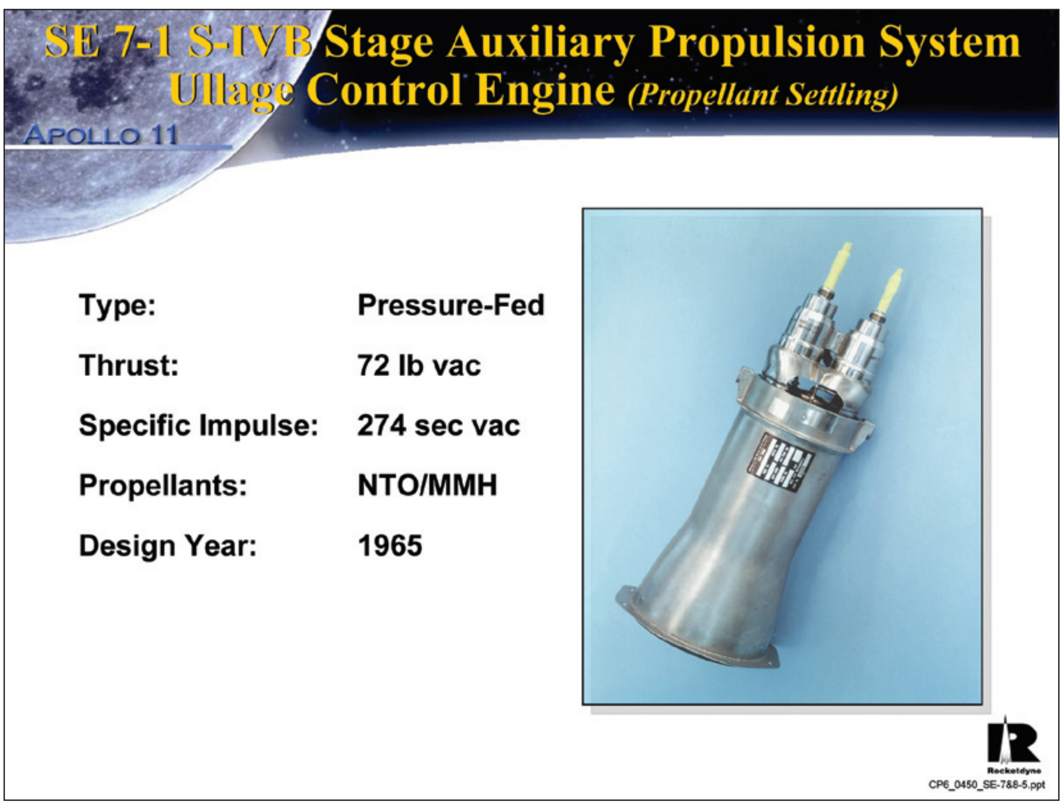
SE 7-1 S-IVB Stage Auxiliary Propulsion System
Ullage Control Engine (Propellant Settling)
Apollo 11
Type: Pressure-Fed
Thrust: 72 lb vac
Specific Impulse: 274 sec vac
Propellants: NTO/MMH
Design Year: 1965
Rocketdyne
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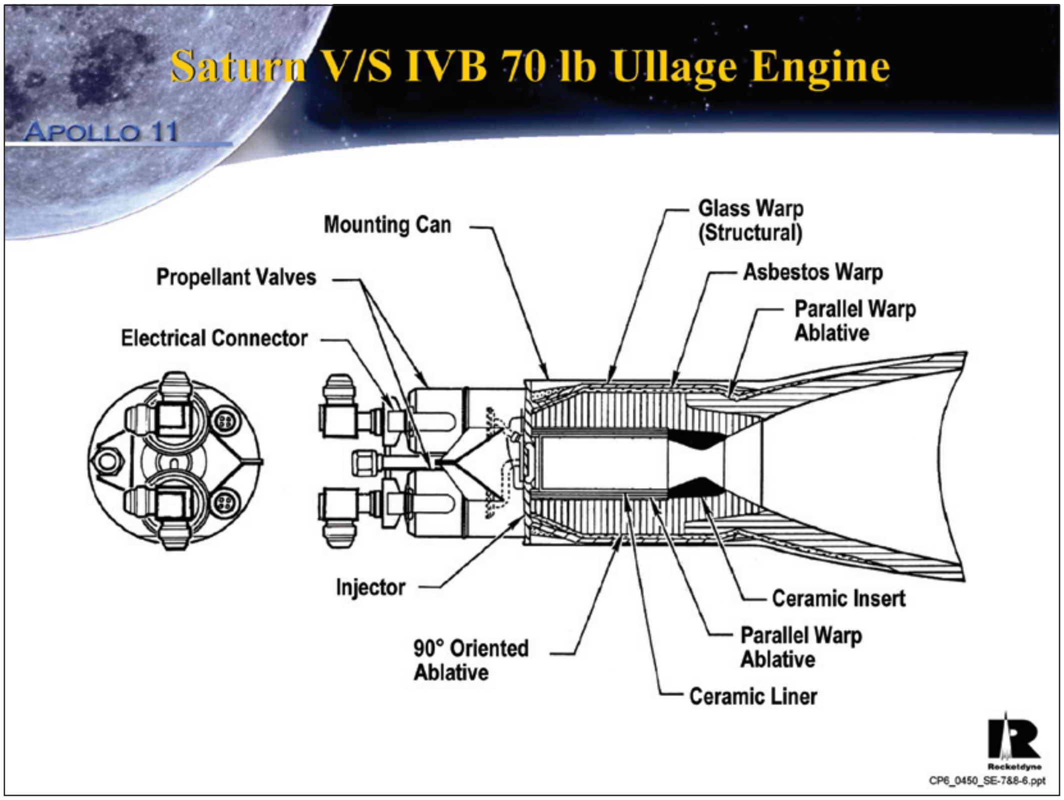
Saturn V/S IVB 70 lb Ullage Engine
Apollo 11
Mounting Can
Glass Warp
(Structural)
Asbestos Warp
Propellant Valves
Parallel Warp
Ablative
Electrical Connector
Injector
Ceramic Insert
90° Oriented
Ablative
Parallel Warp
Ablative
Ceramic Liner
Rocketdyne
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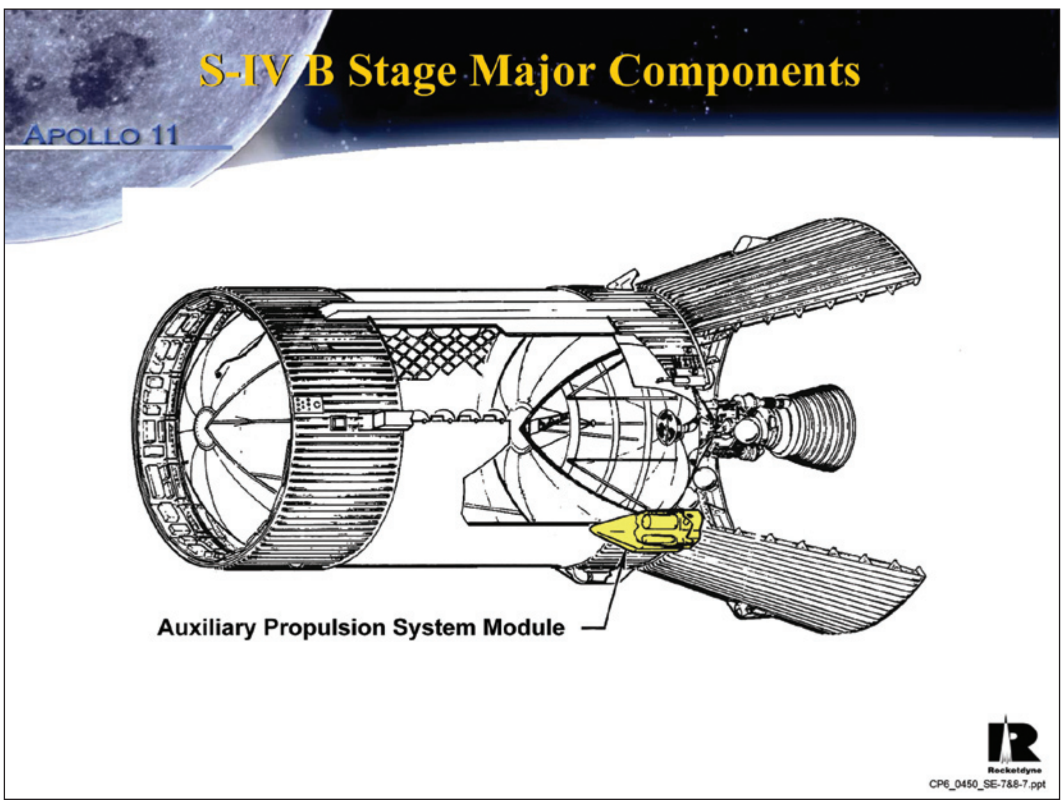
S-IV B Stage Major Components
Apollo 11
Auxiliary Propulsion System Module
Rocketdyne
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APOLLO 11

SE 7-1 Lessons Learned

- Engine proven in Space Environment
- No development issues
- No operational issues
- Cost effective application

Off the shelf applications work

Rocketdyne

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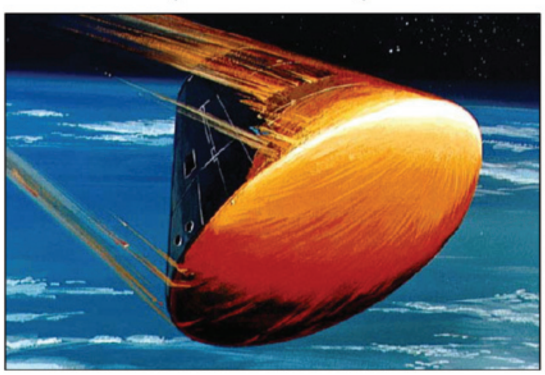
APOLLO 11

SE 8 – Command Module Re-entry Control Engine

- Maintain heat shield orientation
  - 4 times the heat load over Gemini
- "Steer" the module for re-entry into atmosphere
  - Gemini re-entry speed 17,000 mph
  - Apollo re-entry speed 24,000 mph
- Two redundant systems of 6 engine each



Rocketdyne

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SE-8 Command Module Reaction Control System

APOLLO 11

- Similar off-the-shelf approach
- Apollo Command Module reentry speed faster, heat shield thicker
- Engine "Improved"
  - ZrC throat insert
  - Pre-charred sleeve to eliminate ceramic liner
  - Single 93 lb thrust engine design, variable length nozzle extensions

Rocketdyne

CP6_0450_SE-7&8-10.ppt

SE-8 Apollo Command Module Reaction Control

APOLLO 11

Type:	Pressure-Fed
Thrust:	93 lb vac
Specific Impulse:	274 sec vac
Propellants:	NTO/MMH
Design Year:	1964

Rocketdyne

CP6_0450_SE-7&8-11.ppt

SE 8 Engine Post Mission Duty Cycle Testing

APOLLO 11

Rocketdyne

CP6_0450_SE-7&8-12.ppt

Each Injector Hot Fire Certified

APOLLO 11

- **Issue – Some engines experienced uneven material ablation & throat insert erosion**
- **12 Engines per vehicle…12 injector hot fire calibration cycles**
- **Subjective (visual) appearance required for approval**
- **Devised a tactile aid for inspectors to approve/disapprove throat wear**

Rocketdyne

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Component Test Lab IV, Santa Su

APOLLO 11

- Santa Su site of early B-movie westerns
- Two shift test operations
- Intense test slot competition
- Major data reduction effort

Rocketdyne
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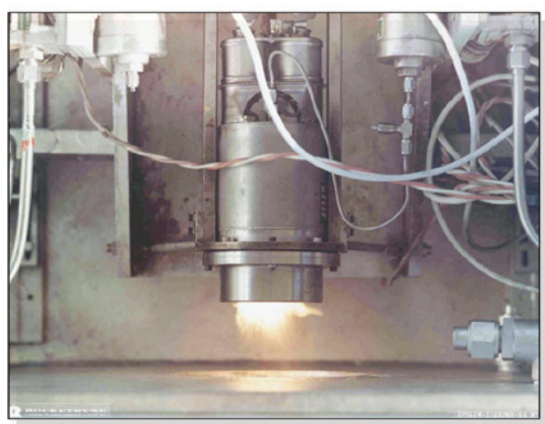
SE 8 Engine Test

APOLLO 11

- Test constraints
  - 15 minute altitude capability
  - Multiple data points desired
  - DIGR's (direct inking graphic recorder) instrumentation
  - Slide rule "calculators"



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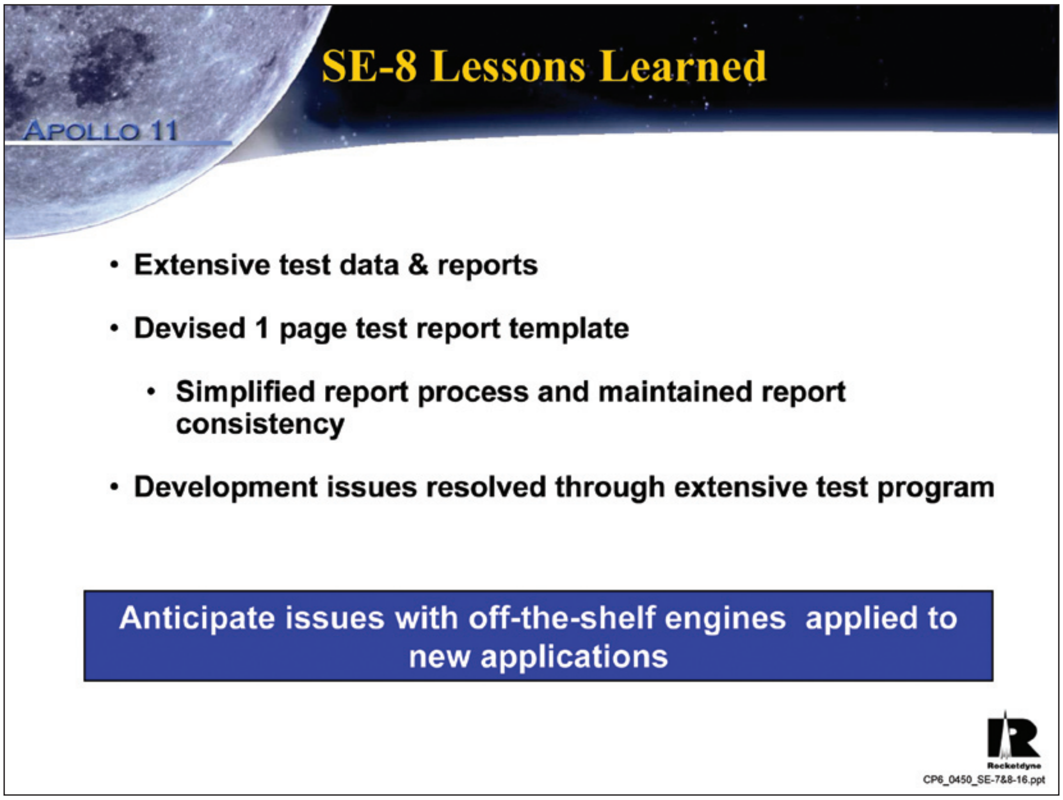
SE-8 Lessons Learned
APOLLO 11
• Extensive test data & reports
• Devised 1 page test report template
• Simplified report process and maintained report consistency
• Development issues resolved through extensive test program
Anticipate issues with off-the-shelf engines applied to new applications
Rocketdyne
CP6_0450_SE-7&8-16.ppt