Chapter One

Robert Biggs
Rocketdyne - F-1 Saturn V First Stage Engine

Robert "Bob" Biggs worked forty-seven years at Rocketdyne, and spent nine years as lead development engineer and development project engineer on the F-1 Engine Program. He spent several months on the canceled Navaho cruise missile project, three years as lead engineer in the Jupiter Program performance analysis group, and a year as manager of the Dynamic Analysis Laboratory. Biggs also worked thirty-four years on the space shuttle main engine, serving as development manager and chief project engineer.

Before I go into the history of F-1, I want to discuss the F-1 engine's role in putting man on the moon. The F-1 engine was used in a cluster of five on the first stage, and that was the only power during the first stage. It took the Apollo launch vehicle, which was 363 feet tall and weighed six million pounds, and threw it downrange fifty miles, threw it up to forty miles of altitude, at Mach 7. It took two and one-half minutes to do that and, in the process, burned four and one-half million pounds of propellant, a pretty sizable task. (See Slide 2, Appendix C)

My history goes back to the same year I started working at Rocketdyne. That's where the F-1 had its beginning, back early in 1957. In 1957, there was no space program. Rocketdyne was busy working overtime and extra days designing, developing, and producing rocket engines for weapons of mass destruction, not for scientific reasons. The Air Force contracted Rocketdyne to study how to make a rocket engine that had a million pounds of thrust. The highest thing going at the time had 150,000 pounds of thrust. Rocketdyne's thought was the new engine might be needed for a ballistic missile, not that it was going to go on a moon shot.

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In July 1958, we began the International Geophysical Year, wherein the scientists of the world were going to plan and execute experiments to learn more about the earth. It was an eighteen-month program. As part of that, the United States planned to launch an artificial satellite to circle the earth, and they were going to do it within the geophysical year. President Dwight Eisenhower intervened with one portion of that. He had a fear of what he called the "military industrial complex" becoming too powerful. He wanted the space program, the satellite program, to be done without benefit of any weapons system or, in fact, weapons system personnel; so, all of the people who knew best how to make rockets go up weren't allowed to work on the project. They had to get other people, "civilians" as they referred to them. That's what happened to bring the Vanguard Program into being outside of what we had; the Jupiter, the Thor, the Atlas, the Redstone, the Navaho, all of these were already flying and almost operational. This was happening at a time of decreasing national prestige due to a number of events.

The first one was in October 1957. The world and the United States were shocked by the Soviets announcing they had put up a satellite, Sputnik I. It was a satellite weighing approximately 183 pounds. It was shocking to us that they could do it before the United States did. Before we recovered from that shock – it was within a month – they launched Sputnik II; it had a dog as a passenger. Sputnik II also gave the United States information on how well the Soviets were doing. The third stage did not separate from the orbiting package, and the third stage alone weighed 16,000 pounds. The Soviets had managed to put 16,000 pounds into orbit! Our Vanguard satellite was going to be eighteen pounds, by the way. From what was put into orbit, the United States was able to calculate that the Soviet booster must be three times as powerful as the most powerful booster we had, which was the Atlas cluster of three engines. That gave emphasis for starting to look at a much higher thrust engine. During this time period, an organization called the Advanced Research Projects Agency was formed within the Department of Defense to manage the new technology for all of the services. The Air Force, Army, Marines, and Navy were all developing the same technology. The new agency was designed to prevent that; it was going to develop the new technology for space. (See Slide 3, Appendix C)

The first attempt at launching the Vanguard satellite was December 6, 1957. It went up four feet; it blew up four feet off the launch pad. By this time, Eisenhower had relented and allowed the Army Ballistic Missile Agency (ABMA) to step in and put up a satellite. They actually used a Redstone vehicle with a Redstone engine, and they called it a Jupiter-C. Dr. Wernher Von Braun, who headed up the ABMA, let it be known that he could put one up in two months, and they finally turned him loose.[1] Very shortly after that, Explorer I was in orbit. NASA

[1] For more details on this, see *Dr. Space,* a biography of Wernher von Braun.

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absorbed ABMA in March 1960 and took over all of the non-military space effort. In May 1960, the U-2 spy plane, which was supposed to be able to fly above Russia without harm coming to it, couldn't be reached. The Union of Soviet Socialist Republics had shot the plane down. The next shock came when Yuri Gagarin was put into space; a human was in space for the first time on April 12, 1961. That was followed five days later by the Bay of Pigs fiasco. John Kennedy had been president for just a few months and had allowed himself to agree to a CIA-coordinated invasion of Cuba under the assumption that all Cubans would rise up and fight against the dictatorship of Fidel Castro, and that didn't happen.

In May 1961, Alan Shepard completed a fifteen-minute suborbital flight test as the first American in space. Based on the results of that, John Kennedy made his famous speech about sending man to the moon and returning them safely. He waited until we had success in space before making the announcement. The success was this small fifteen-minute suborbital flight. On May 25, 1961, that speech was made, the same day the first test was performed on the F-1 engine. (See Slide 4, Appendix C)

The F-1 mission was to provide seven and one-half million pounds of thrust for the Saturn V first stage. It was based on, except for size, pretty much the same technology being used for the ballistic missiles. The difference was that it was a lot bigger, and the biggest challenge was just *that* – its bigness. It was ten times the thrust of the biggest current production engine, which was 150,000 lbf (pounds-force). This was going to a million and one-half. Upratings (upgrades in power, size etc.), traditionally, even in other things besides rocket engines, are reaching if they go 10 percent. We had several 10 percent upratings before, but nothing like this. The engine was eighteen feet tall, twelve feet wide. It had a thrust level that started out at 1.5 million pounds force, plus or minus 3 percent. They made a change to it and called it an uprating by going to 1,522,000, plus or minus 1.5 percent. If you do the math, all that did was move the million up to the middle or the high part of the tolerance. The engine essentially had to be designed for the same pressure anyway. The specific impulse (a measure of engine performance efficiency) was 265 seconds, which was good for those days. It looks not so good today. (See Slide 5, Appendix C)

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Combustion Chamber pressure was another challenge. This was designed at 1,100 pounds per square inch (psi). The highest chamber pressure of the day was 520 psi, so this was a doubling of the chamber pressure and significantly more thrust. The engine burned liquid oxygen and Rocket Propellant-1[2] (RP-1, a highly refined form of kerosene) at a mixture ratio[3] of 2.27, and

[2] Rocket Propellant-1 (RP-1), highly refined form of kerosene.
[3] Mixture Ratio - Ratio of mass flowrate of oxidizer (liquid oxygen) to mass flowrate of fuel (RP-1).

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it had a mission duration of 165 seconds. Well, it started out at 150 seconds, and the first two Mercury flights were 150 seconds, but they were unmanned. They had the whole stack, but they didn't have the astronauts. They made flight changes for the first manned one, and from that point on, the burn duration was 165. It was designed for a qualification life of twenty starts and 2,250 seconds with a weight of 18,000 pounds. We later ran this engine at 1.8 million pounds of thrust[4], which gave it a thrust-to-weight ratio of 100, but it was pretty close to 100 anyway, and if you stripped off the stuff that was not providing thrust, the remainder of the engine would have been a 100:1 thrust-to-weight ratio. The major features are that it had a single turbopump, and it had a shaft that was parallel to the axis of the thrust chamber. It had a liquid oxygen (LOX) pump on top of the shaft, then a fuel pump, then a turbine. It took the single turbine to run the two pumps. The nozzle had an area ratio of 16:1. It was tube-wall down to the 10:1 expansion, which is where the turbine exhaust was put into the nozzle through a skirt extension. The tubes went down to 10:1, and from then on, it was a double-wall, hot, gas-cooled nozzle extension. In the turbopumps, both the fuel pump and the liquid oxygen (LOX) pump had a double discharge, a discharge on each side of the pump. The reason for doing that was to prevent the entire head rise across the pump from becoming a delta pressure radially for a fixed load. It divided the total load by two, having two different directions.

How was the RP-1 fuel used for purposes other than just burning? These were unique things at the time. For instance, we used the fuel for lubricating turbopump bearing. Prior engines and, in fact, the original F-1 design had a separate lubrication pumping system to lubricate bearings. It also was used as hydraulic power instead of using hydraulic fluid. It was used to power the engine valves and the thrust vector control actuators, and in addition, it did not require any auxiliary starting power. (See Slides 6 and 7, Appendix C)

The F-1 turned out to be a very simple engine, but it started out with its initial design as a very complex engine. The first design, which went through a design review and was approved, had three turbopumps on it. It had a hydrazine pump, which required a hydrazine gas generator to run the turbine on the hydrazine pump. The hydrazine gas generator would run the LOX pump and turbine and the fuel pump and turbine. It had a separate pump for the LOX pump, and a separate one for the fuel, and a separate one for hydrazine. There were three pumps, each with a shaft and each with a turbine, and that was replaced during development. Actually, it never made it to the first engine test. It was replaced with a single turbopump. It also had the lubrication oil system for the bearing that was eliminated.

[4] F-1A was rated at 1.8 million pounds force of thrust.

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There was one design that was really troublesome, and we did not get rid of it before the first test. We had to live with it for some period of time, and it was called a triple manifold thrust chamber. Picture three doughnuts stacked on top of each other; those were fuel manifolds at the top end of the thrust chamber. The fuel for the thrust chamber went into the middle manifold, then went down the tubes to cool the tubes. It went down half the tubes, then back through the other half of the tubes to another manifold. There were four trombone tubes that ran from the bottom manifold to the top manifold in order to get the fuel from that end of the injector. They had tangential inlets and outlets. It set up a racetrack in both the bottom manifold and the top manifold, and the pressure loss was horrendous, but we managed to struggle by for a while until we could get a better design. (See Slide 8, Appendix C)

On the F-1 engine schematic, the turbopump was in the upper left, with green for oxidizer and red for fuel. Since the turbopumps had two discharges, they required two fuel lines and two LOX lines going to a valve. There were two LOX valves, one on each side of the engine, and two fuel valves, one on each side of the engine as well. The hypergol cartridge in the middle of the control system held a fluid that would automatically ignite as it got into the chamber. It didn't need a pyrotechnic device to ignite it. (See Slide 9, Appendix C)

Many people have wondered how the start sequence looked. It took about five seconds for the engine to start under what is known as a tank head start[5]. It had no help from outside. It started by opening the engine control valve, which was a four-way hydraulic valve that ported hydraulic fluid to open the main LOX valve. The hydraulic system on this engine was quite robust. All of the valve actuators were way overpowered. There was no concern of hydraulic contamination with the engine. By opening the LOX valves first, the LOX started flowing through the pump in such a way that it treated the LOX impeller as a turbine, and it started to turn the pump. It would turn the pump up to 700 to 1,000 revolutions per minute, which got rid of the breakaway torque concerns and started the engine going up in power. Right after that, the gas generator valves opened. The gas generator had mechanically-linked valves, one for the fuel and one for the LOX, so they both opened at the same time. The gas generator would ignite at a very low pressure and then start building up. It would take two or three seconds for the pressure to get up to the point where the igniter fuel valve would open, allowing the fuel to go into the chamber and start the thrust chamber ignition. As soon as the thrust chamber ignition was sensed by another valve, by just measuring the fluid pressure, the main fuel valves opened, and the thrust was allowed to come on up. At about 80 percent, the thrust laid over for a little while and then went on up at a different ramp (i.e. rate of increase). The reason was

[5] Tank head refers to the pressure at the pump inlet due to the weight of propellant in the tanks located above the engine.

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that the thrust chamber was primed with ethylene glycol, so the initial fuel burning during this engine start transient period was an ethylene glycol and water mixture. It didn't provide as high a chamber pressure as the full RP-1 fuel so, when that ran out, the chamber pressure kept going on up and reached the 100 percent value. (See Slide 10, Appendix C)
There was a qualification test requirement to take two engines off the flight line. Supposedly, the concept was to grab two engines at random and put them through a qualification test series. One of those series was life demonstration, which demonstrated the twenty tests and the 2,250 seconds. The other one did that and also demonstrated a lot of simulated engine malfunctions and different environmental tests. These two series were quite successful and completed the contractual requirements for qualifications testing, but they were not the end of running a lot of seconds on engines. This was a supposedly expendable throwaway engine with a mission duration of 165 seconds, but we actually tested six engines to an excess of 5,000 seconds. The only reason this was a non-reusable engine was it was non-recoverable. If we could have recovered it after a flight, it would have reusable. (See Slide 11, Appendix C)

We adopted the idea of acceptance testing, using the concept of an "all up" test at every opportunity – test the whole thing. The concept was to do that with the full stage, so, when we had a series of production engines, they first would have to be acceptance tested on the engine test stand. That required two tests of duration – a forty-second calibration test and a 165-second mission duration test on every engine. After that, the engines were grouped in clusters of five and put into an S-IC stage, the actual flight stage. They then were tested for 125 seconds, which was the maximum duration they could get without having some acceleration. The first three stages were tested at NASA's Marshall Space Flight Center in Huntsville, Alabama. The rest of them were tested at NASA's John C. Stennis Space Center near Bay St. Louis, Mississippi, on the B-2 Test Stand. The total time required for the acceptance test was 495 seconds – for a mission duration of 165 seconds. All of that added up, but the highest time any engine achieved was 800 seconds. (See Slide 12, Appendix C)

There were a couple of development problems with the F-1. The first one was the most famous one. I think many of people who know nothing much about the F-1 know that it had a combustion instability problem. It was thought before the first engine test – a couple of years before – that just by making it this much bigger, it would not be stable. It would have to be unstable. We ran some tests on a device called "King Kong," which was a solid-wall, steel chamber, and the tests were run for a very short duration. The test stand could only go through a start, then maybe half a second of main stage firing and then a shutdown before it ran out of propellant. Of course, this was all pressure-fed, a pretty difficult thing to arrange. The first few tests had some instability, which never was understood properly, because with the demonstration tests, everything was stable. That allowed us to make the conclusion that it probably was stable, and to go on with the plan. (See Slide 13, Appendix C)

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In the first year of testing – because of other problems – we were unable to operate at rated thrust (the performance level an engine is designed to achieve). That's not unusual. In fact, it's more usual than not that the first engine in a new design is unable to achieve rated thrust for some reason. The maximum thrust the F-1 could hit for the first engine was 1 million pounds; so, for the first year, testing was limited to 1 million pounds. During that year, we got some spontaneous combustion instability strikes, but only seven times. That's a rate of about 10 percent. The tests we ran[6] would not have been able to predict whether it would have a random instability with some probability; it would only detect if it was always unstable. Well, this was a low probability, but not nearly low enough to be used. During the year, we would have instability detected by accelerometers on the thrust chamber; then, the engine would be shut down by a thing they called the rough combustion cutoff device. It was a nuisance simply because we were losing tests. It wasn't doing much damage. I guess it wasn't doing any damage because we were able to go test again.

in order to prove the injector was a stable design, we had to put a bomb in it, detonate the bomb, and, then, damp it out within forty-five milliseconds.

Then, in the second year, we were able to run rated thrust for the first time. The thrust level went up to 1.5 million, and the testing continued. Then, we got a spontaneous instability that was so severe, it destroyed the engine. The initial shock was bad enough to cause both of the dual fuel lines to rip off the engine, so the engine was running with LOX and no fuel. It was burned up. It was a total loss. We had eleven such episodes in that time period. All of them did some damage. Only three of them blew the ducts off and totally destroyed the engine, but the rest of them did a considerable amount of damage. As soon as that first one hit that destroyed the engine, the problem of instability got more attention than it had previously. "Project Go" was formed, headed up by Jerry Thompson at Marshall Space Flight Center and Paul Castenholz at Rocketdyne with Bob Levine, Dan Klute, and Bob Fontaine. They made some changes to the injector. The injector had baffles sticking down, dividing it into thirteen compartments. We had fifteen different arrangements of baffles that were tested. There were also fourteen different injector configurations behind that. All of those were tested, and, eventually, the instability went away. We never again had a spontaneous instability. After a while, in the third year, we were not getting any spontaneous instabilities. However, we were getting forced instabilities because, in order to prove the injector was a stable design, we had to put a bomb[7] in it, detonate the bomb, and, then, damp it out within forty-five milliseconds. Even though the injector was not spontaneously going unstable, it was still a good requirement to make sure that if you ever did that, it would damp out immediately. In that third year, we got nine cases where we were bombing it to prove that it was stable, and it went unstable. However, a lot of the other tests were successful, and at the end of the testing, the configuration was smooth running. It then

[6] Tests with King Kong.
[7] A small charge to provide a pressure impulse in the combustion chamber to test for combustion stability.

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went through a complete qualification test[8] and a lot of bomb tests, and never again was there any instability. That problem was solved considerably before the first flight.

We also had another problem that was kind of interesting because it had a catastrophic effect. The LOX pump had six vanes in it. The vanes were weak. I don't want to say under-designed, but it was weak for that environment. I think the basic problem was they were scaled up from the smaller ones, and you never really had to worry much about the forces across the vane as much as this size did. It made it worse. We had failures of that vane four different times. These were four engines that were destroyed by vane failure in the LOX pump. It occurred at 110 seconds, 110.5 seconds, 107.7 seconds and, then, at 109 seconds. Statistically, this looked extremely significant. There was something going on that was a function of time, and at 110 seconds we had a problem. We did an exhaustive investigation twice and could not find any justification for that and concluded it was just a freak coincidence. We made some changes to eliminate fretting (wear and corrosion damage). What we really did was to set a limit at 3,500 seconds for the impeller for ground testing. All the flight engines never got up above 800 seconds. The last engine that went up in 1965 had 5,000 seconds on the impeller. From that, we concluded you could set the limit at 3,500 seconds and be okay. One thing about this was that on every flight, the people who were familiar with the F-1 program would notice when 110 seconds went by and, then, breathe again. (See Slide 14, Appendix C)

One significant milestone in the F-1 program was moving from the first test to the first rated duration and thrust test. It took one year to run a test that was rated thrust and full duration, and I think that's better than a lot of programs were, including some recent ones. The first flight was November 1967. I was in Firing Room 2 at the window for that flight. I considered that the highpoint of my career. I've never had such a feeling of pride, just watching the thing go up and imagining that the earth was trembling. The glass window in front of me was moving inches. It was quite an experience. (See Slide 15, Appendix C)

We got over 280,000 seconds of total burn time throughout the entire program. There were twelve Apollo flights that used the F-1 engines, then the Skylab used the last one that flew. That added up to thirteen flights or sixty-five total engines in flight. For those flights, those sixty-five engines were 100 percent reliable. In addition to that, we had a formal reliability demonstration program where we pre-declared the firing of the ground test engine would be one that counts and, then, went 336 total equivalent tests without a failure, all pre-declared. The engine was quite successful in that regard. (See Slide 16, Appendix C)

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[8] Qualification testing for rocket engines.

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At times, I've been asked, "What was it like to work on such a program?" Well, it was great. It was the most important thing going on in the country, and we were in the middle of it. A lot can be said about it.

I want to share one other aspect of it. At the time we were doing ballistic missile development in 1956, the total employment at Rocketdyne was 5,000. At the peak of production of these missiles, the employment was 14,000. When Kennedy's "Man on the Moon" speech was made, there were 11,000 employees. That got a fast buildup to 20,000 in 1965. At the time of the first unmanned Saturn V flight, early in the program, employment was down to 14,500. When the first moon landing took place, we were down to 9,000, and when the last moon landing took place, we were down 2,500; 17,500 people were laid off in a few years.

The total work force on Apollo peaked at about 400,000, and I imagine the whole program went down about the same amount. (See Slide 17, Appendix C)

It was the most important thing going on in the country, and we were in the middle of it.

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

STEVE FISHER[9]: Just one comment I wanted to make while Mr. Biggs was talking about work force population and stability in the F-1 Program. Several years ago, I had the opportunity or the task to create a briefing on F-1 stability. While I was doing that, somebody lent me an old Rocketdyne phone book. Within the Combustion Devices Group - there were several different groups: main injector, gas generator, gas generator injector, main chamber, etc. - there was a group called Main Injector Stability. All they did was stability, nothing about performance, fabrication, whatever. Under Main Injector Stability, there were *thirty-five* names in the phone book that year.

QUESTION: Back in 1961 to 1965 when you were working with RP fuels, what was the state of the liquid hydrogen technology?

BIGGS: The J-2 (engine project) was developing hydrogen technology.

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[9] Steve Fisher served as facilitator during the *On the Shoulders of Giants* seminar series.

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QUESTION: In 1963, the plan was changed to do "all-up" engine testing or "all-up" stage testing. Did that have any effects on the F-1 Program? Are you aware of any changes to the qualifications/certification program?

BIGGS: Well, I can say the "all-up" testing requirement probably saved us from a flight disaster because of a stage test that found a problem. The acceptance test of S-IC 11 had a large fuel leak caused by an incorrect installation. The hydraulic fluid was being supplied from an engine to the hydraulic actuators through a line that was installed on the engine by Boeing at the stage level. It went through Rocketdyne with a test plate, a good test plate cover. At that time, the line was installed for the stage test, and that would be the same as it would be for a flight, supposedly. Well, the mechanic installed a line over a cover that was left on the port. It caused a fuel leak during the test, which caught on fire. It led to other things on that test, which resulted in scrapping two engines. It would have been bad in flight. I can't say how bad because there were other things wrong on the test, but certainly, that was a condition only an "all-up" test would have found.

QUESTION: I'm Pete Rodriguez from Marshall Space Flight Center, and we're doing an assessment of what kind of testing stands and capabilities we need to have available. What kind of damage happened to the actual test stands during the instability failures, and how long did it take to fix and to get back up and running?

BIGGS: Engine test stands, in general, are quite robust because if they fail and come apart, that energy is lost in destroying the engine. The test stand can be damaged by fire, but I think most of the damage cases were wiring and similar items. In some cases, a lot of damage can be done. But in the instability of the F-1, the worst it did was to blow off the propellant supply lines. That was pretty bad, but it kept the additional damage local to the engine.

FISHER: I think typically, there is a lot less damage in an engine stand than in a high-pressure stand, as you can imagine. Obviously a lot of repairs would need to be done, but most infrastructure remains.

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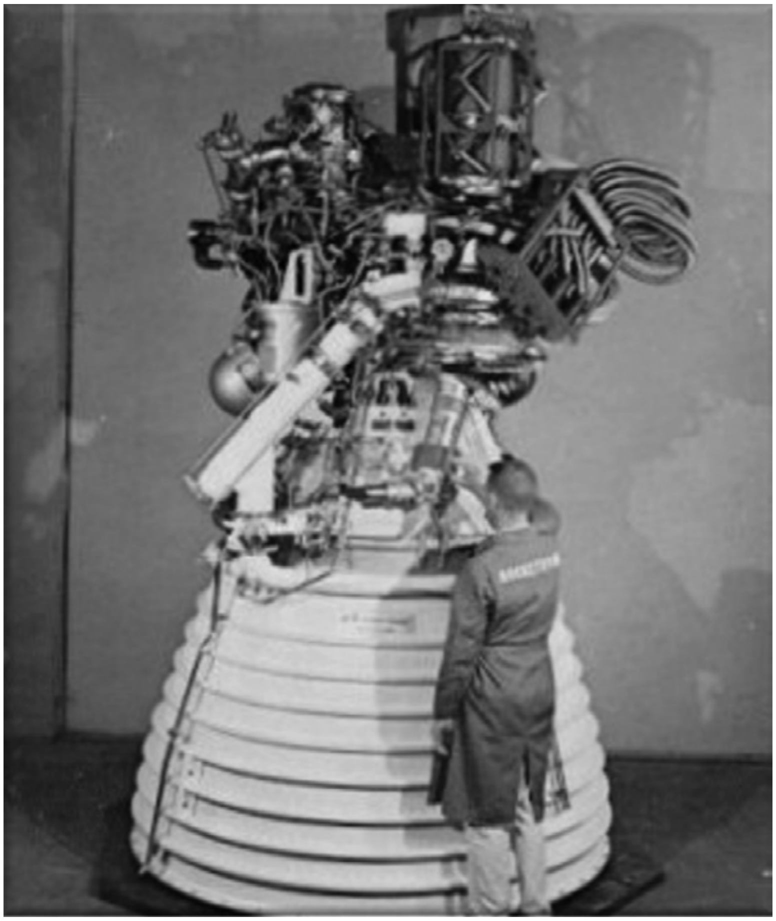

J-2 Engine

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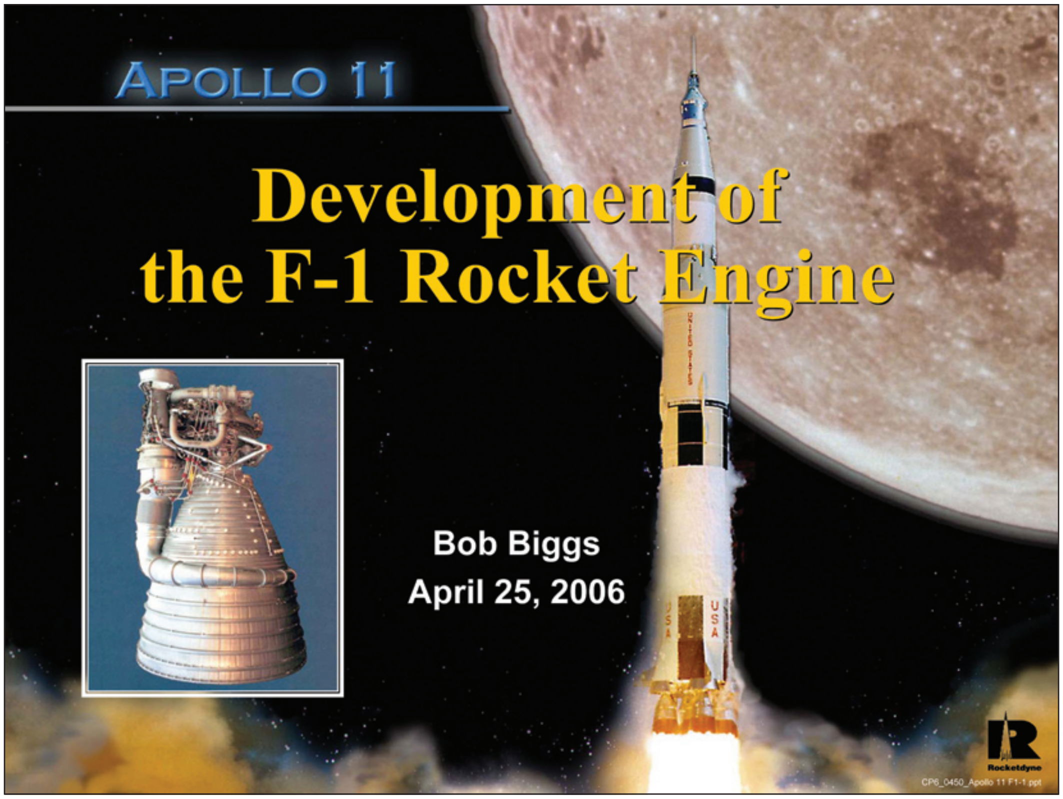
Appendix C

Robert Biggs' Presentation Viewgraphs



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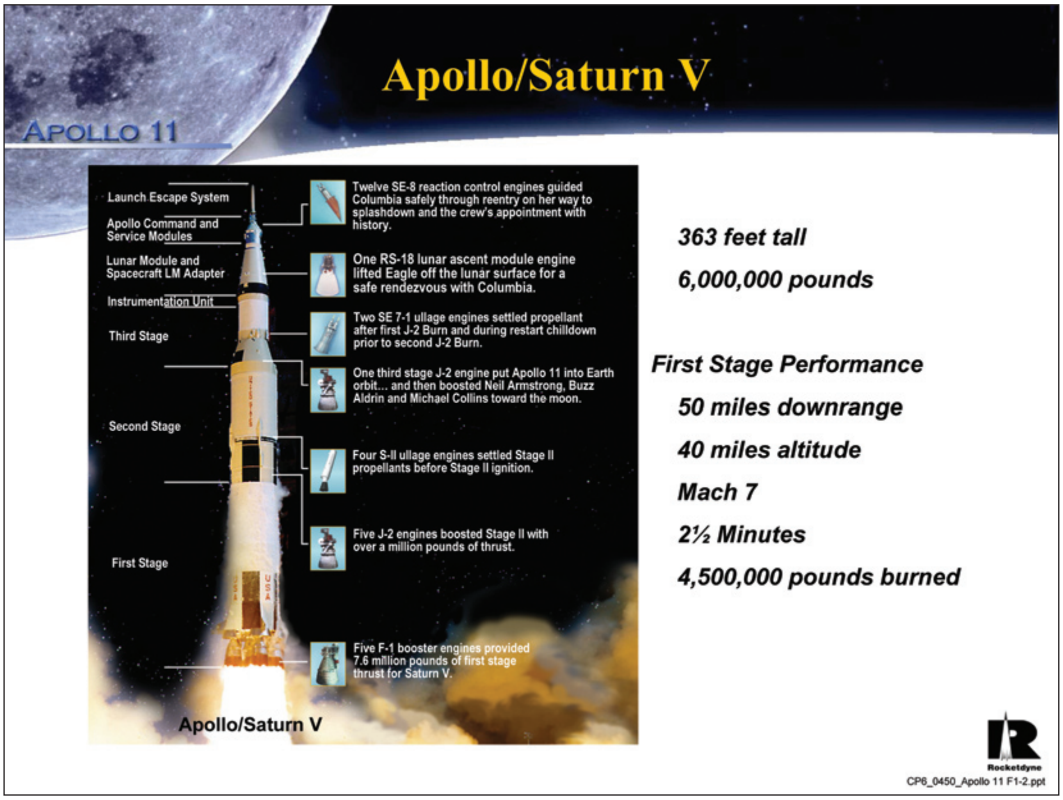

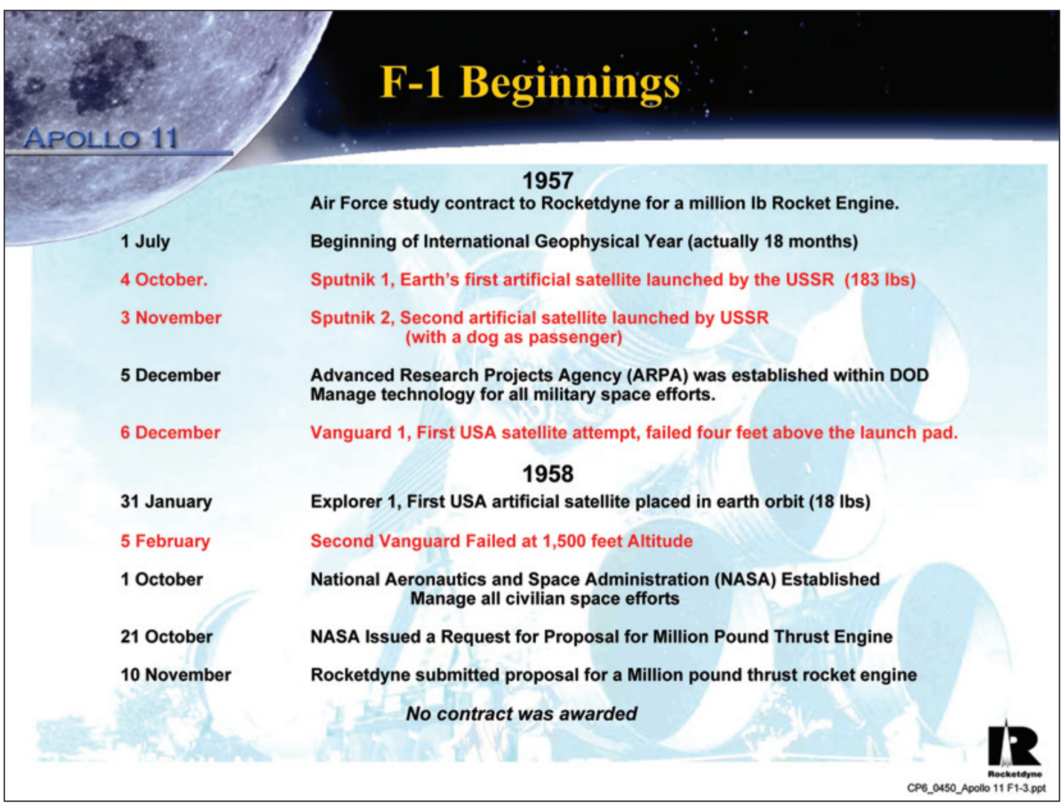

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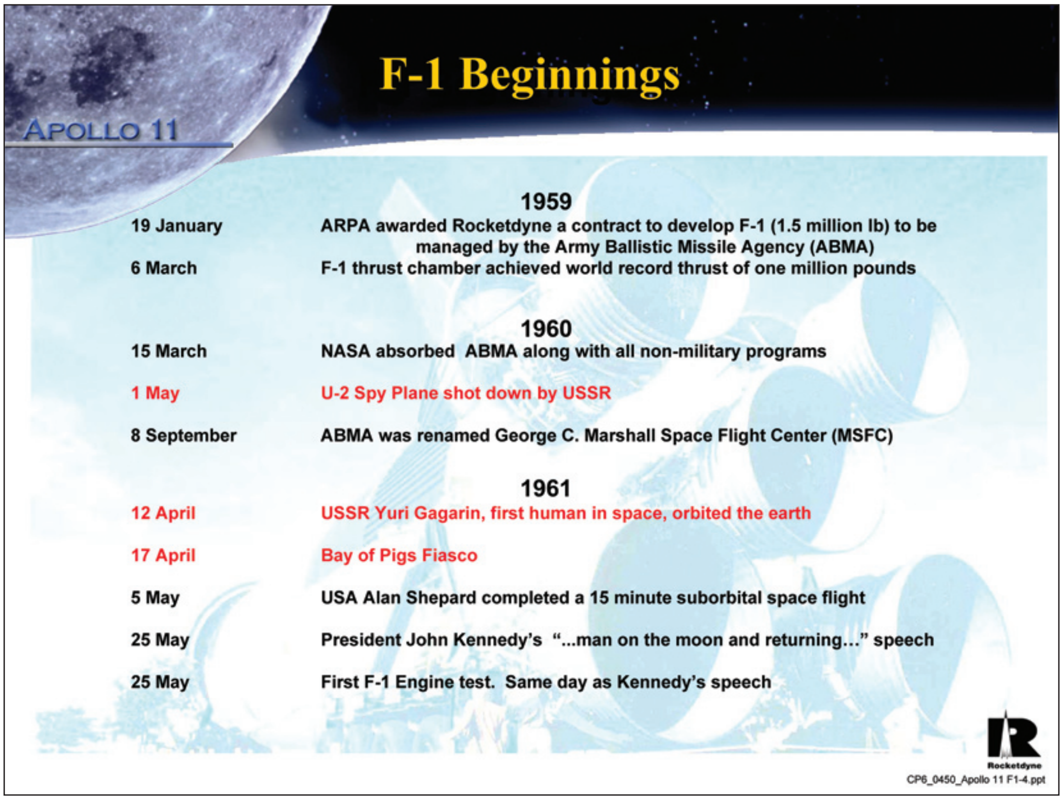

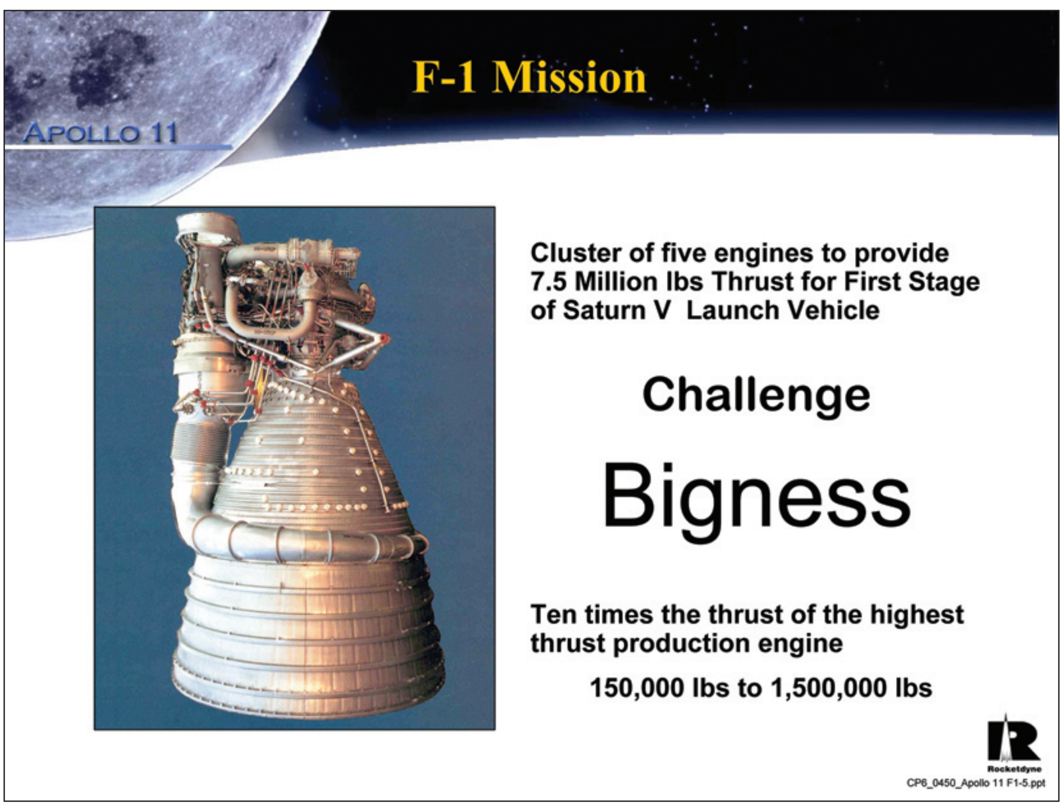

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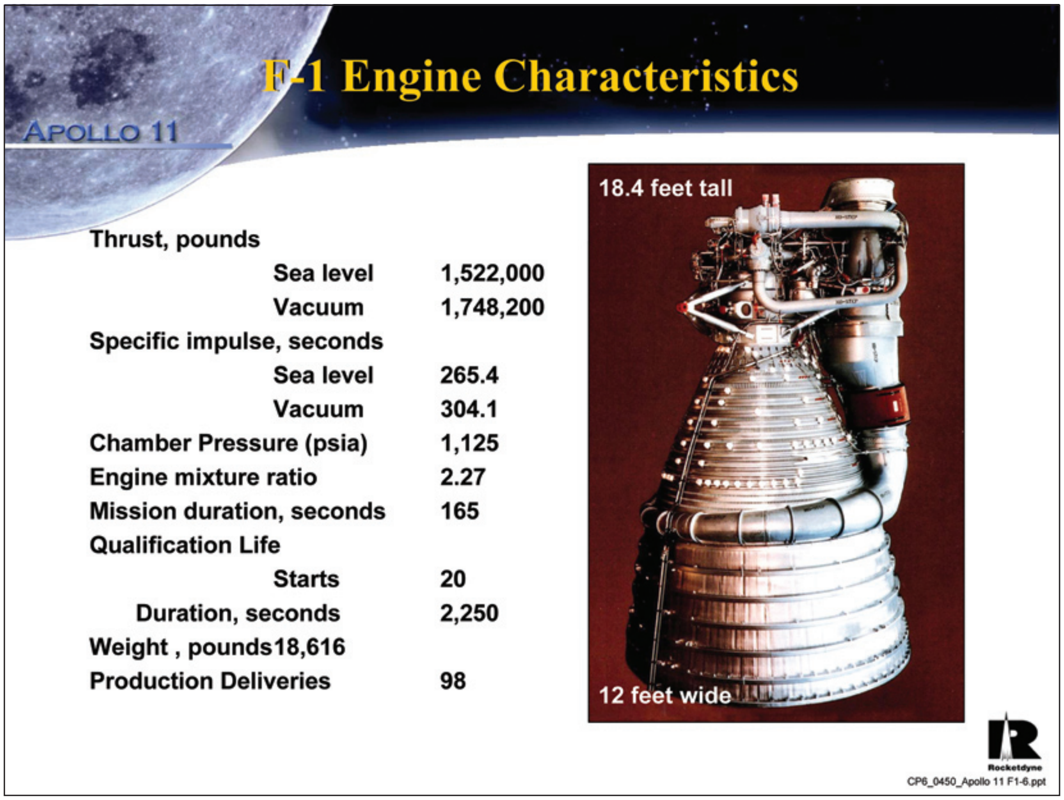

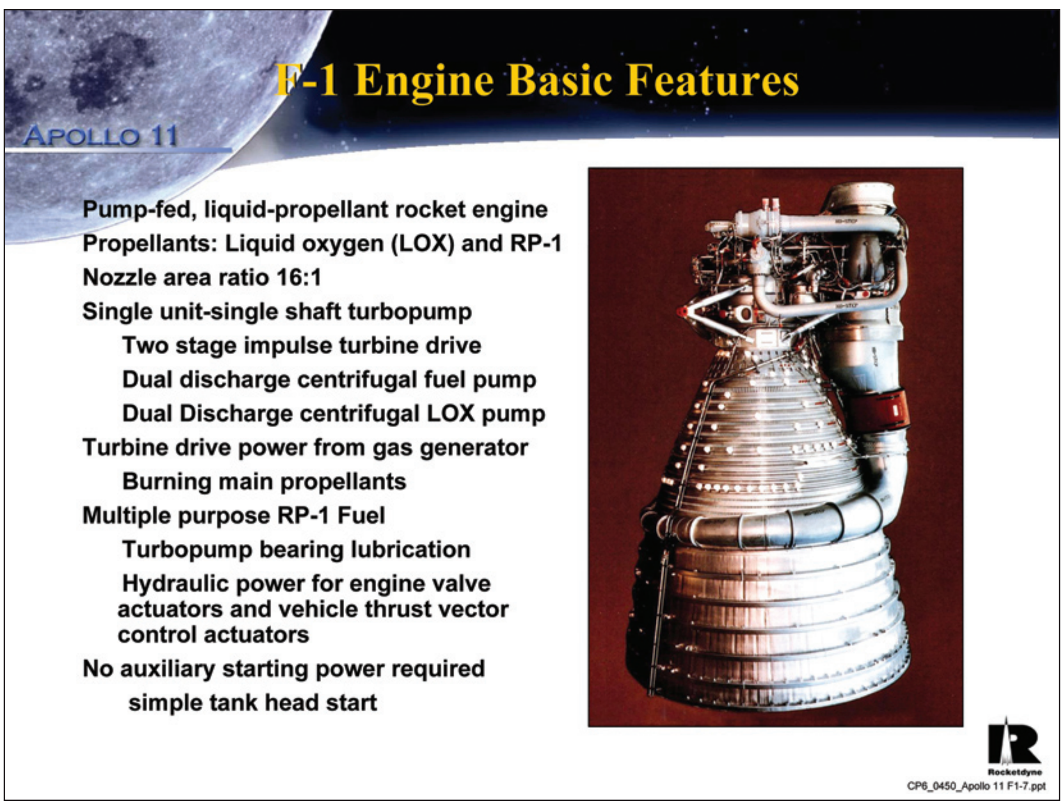

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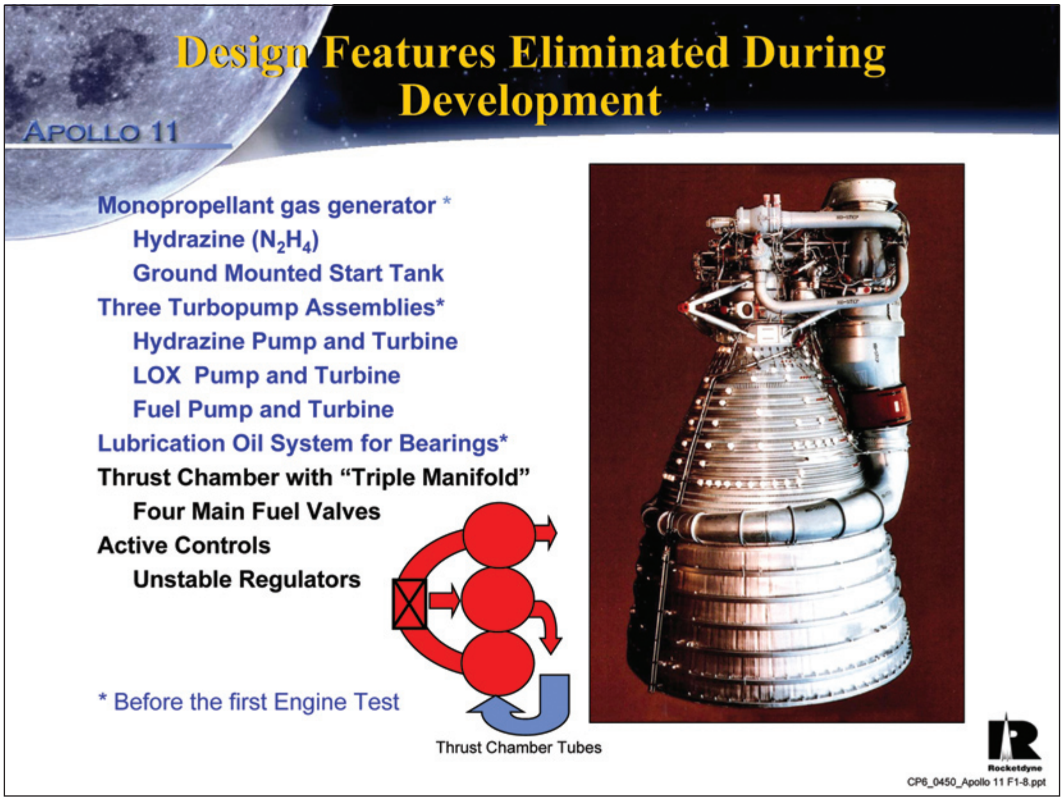

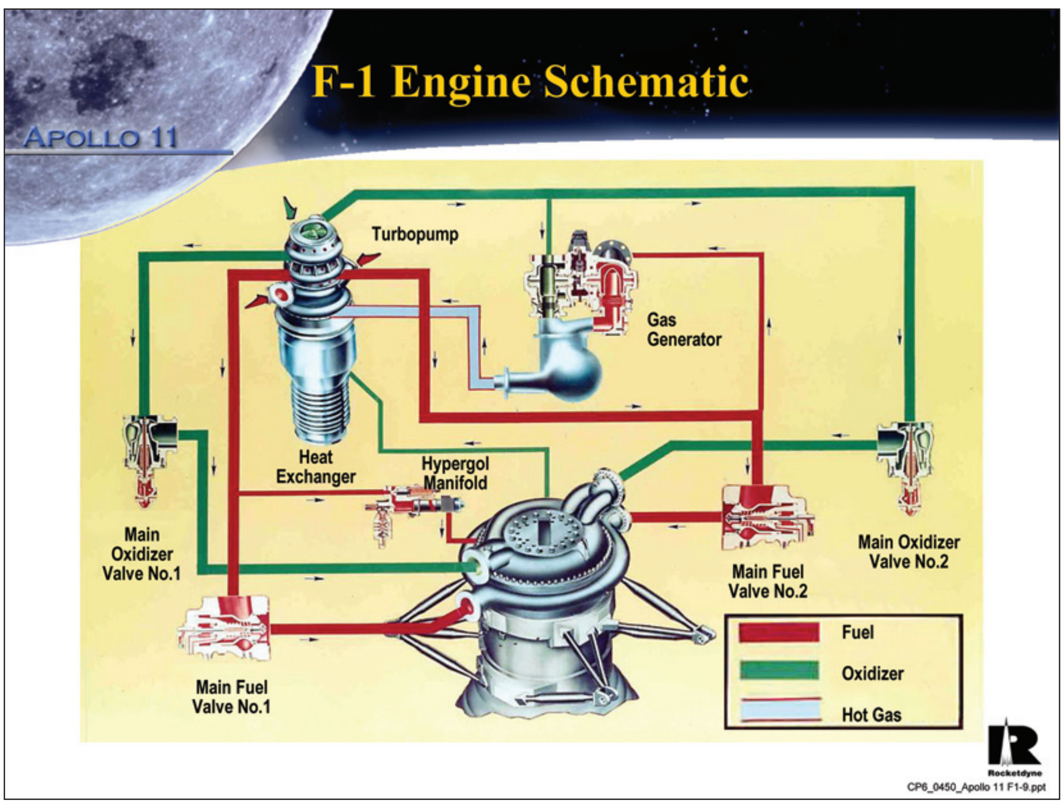

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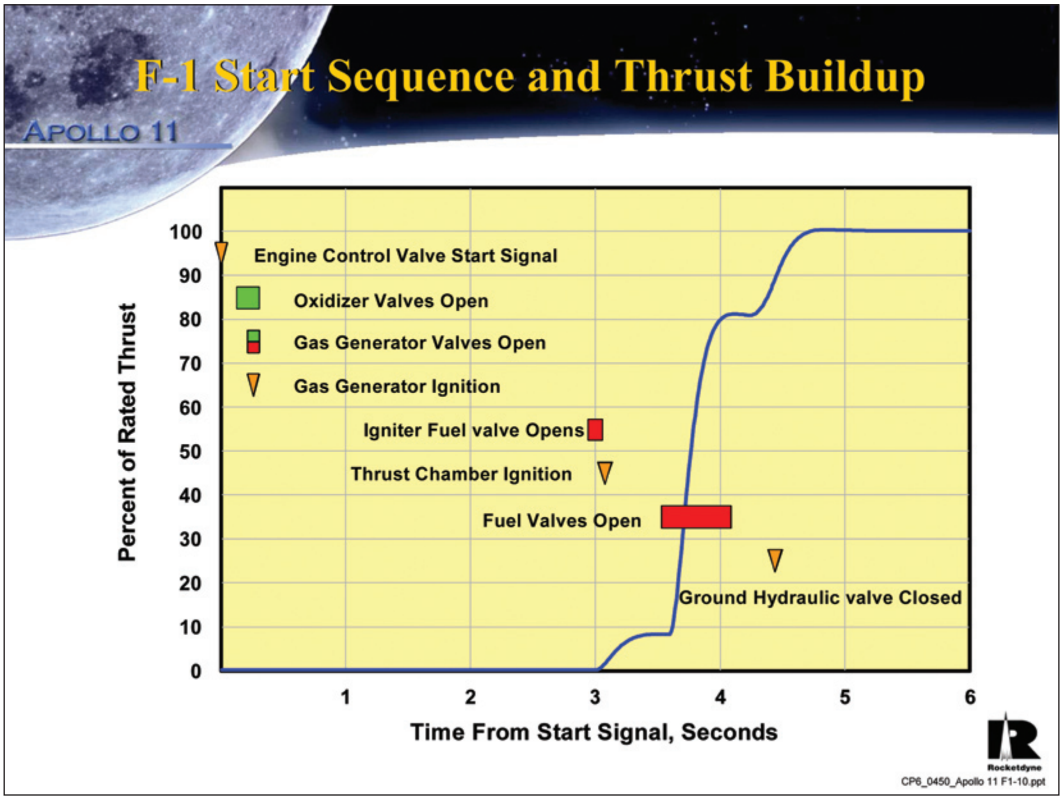

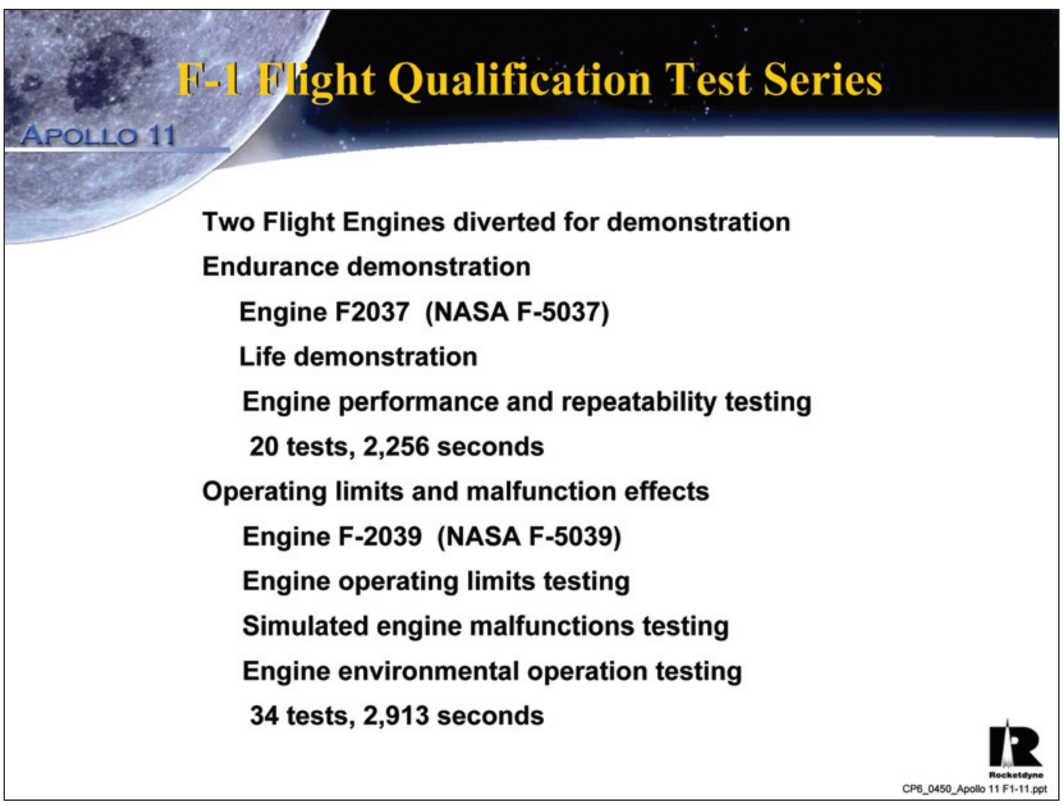

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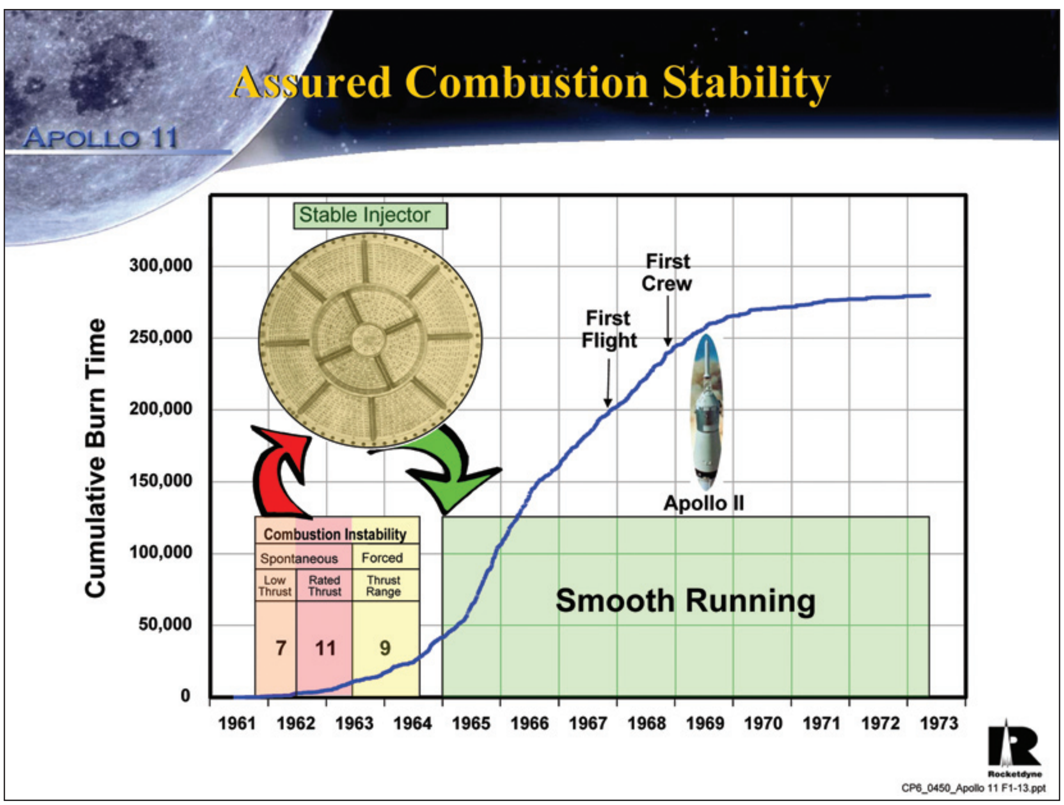

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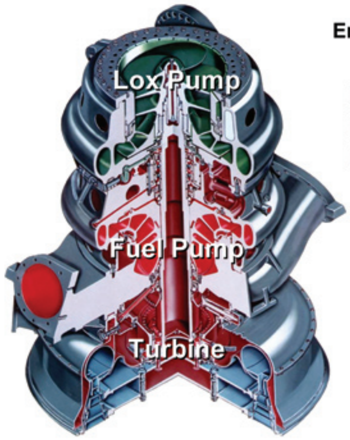
F-1 LOX Pump 110 Second Mystery

APOLLO 11

Mark 10 Turbopump



Lox Pump Impeller Vane failures

Engine	Test	Date	Run time
F010-2	423058A	11/18/1963	110.2
F014	424015	2/28/1964	110.5
F019	423027	4/21/1964	107.7
F029	421118	12/14/1965	109.0

Exhaustive Investigation concluded that the failure times were a freak coincidence.

Design Changes were incorporated to eliminate fretting and strengthen the impeller vanes.

Life Limit Set at 3500 Seconds. All flight engines below 800 Seconds.

Mark 10 Turbopump Rotor

Rocketdyne

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F-1 Milestones

APOLLO 11

First Engine Test	25 May 1961
First Rated Thrust Test	14 December 1961
Full Duration at Rated thrust	26 May 1962
First S-1C Stage 5 Engine Cluster Test	16 April 1965
Full Duration S-1C Cluster Test	5 August 1965
Flight Certification Tests Completed	9 May 1967
First Flight – Apollo 4	9 November 1967
First Flight with Crew – Apollo 8	12 December 1968
Last Engine Test	1 April 1973
Last Flight – Skylab	14 May 1973

Accumulated 280,527 Seconds in 3,248 Tests

Rocketdyne

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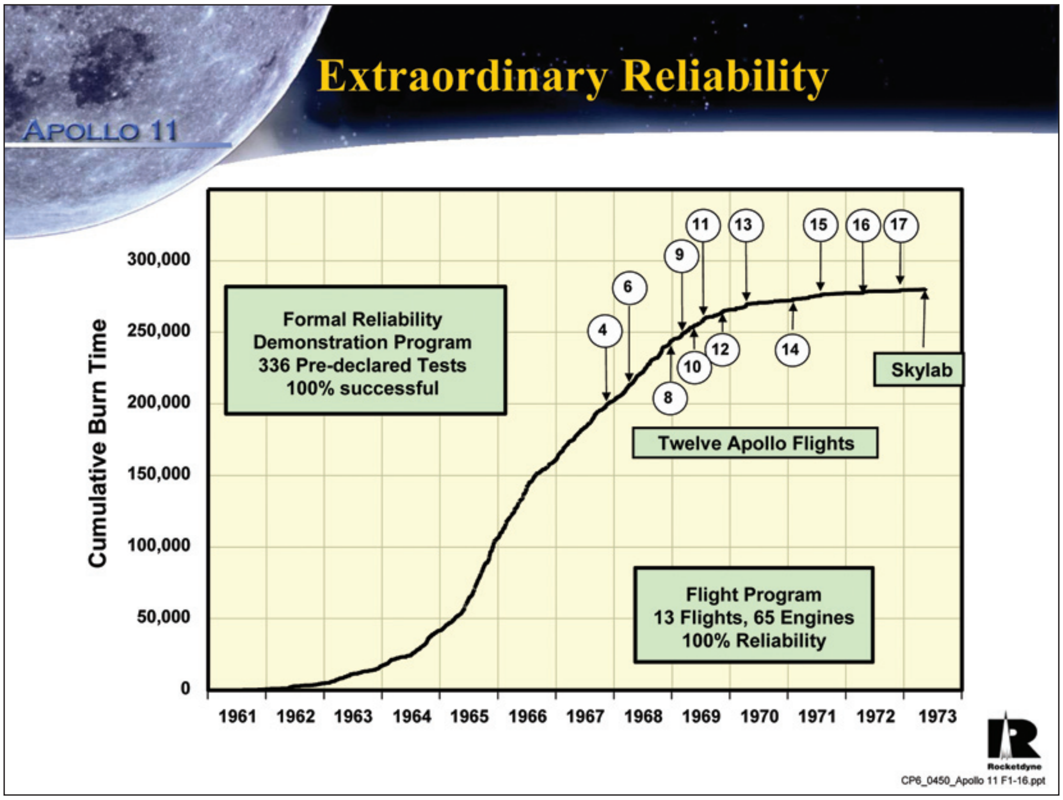

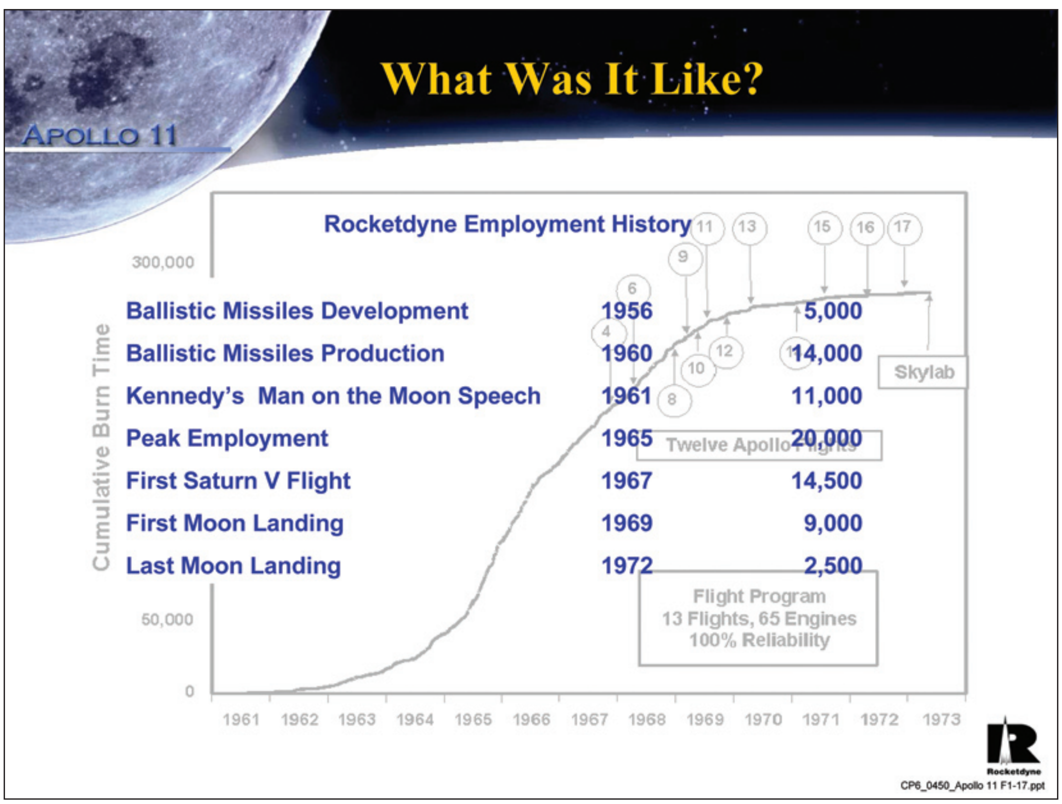

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