Chapter Three

Gerald R. Pfeifer

Aerojet - Attitude Control Engines

G. R. "Jerry" Pfeifer joined the Marquardt Company[1] in 1961, performing early work to develop the parametric rules used for Marquardt rocket design and teaming with a small group to build the company's first hypergolic rocket test facilities and rockets. When the Apollo reaction control system project came to Marquardt, Pfeifer helped shepherd it through its qualification phase. The work led to involvement with many other successful space propulsion programs, including work for NASA's space shuttle. Pfeifer eventually went to work at Rocketdyne to help develop its Terminal High Altitude Area Defense (THAAD) attitude control engines. (Altitude is the orientation of a spacecraft relative to its direction of motion.) He now is working on the Airborne Laser Program at The Boeing Company.

In late 1960, I went to work for Marquardt, which was an interesting company. *It was a big, little, big, little, big, little, gone company*[2]. When I went to work there in 1959, they had 5,000 people. I went to work on a program called Bomark, which was an interceptor missile. That program was downsized, and we had a chief engineer named Warren Boardman, who had this great idea after Sputnik that there had to be a future in space somewhere, and since we were a propulsion company, we would probably be good at something like that. We went off to figure out what it might be. He convinced the company to give us some internal research and development, and they turned five of us loose to figure out what propellants were and to try and figure out what the parameters were that could be used to make one of these silly things. (See Slide 2, Appendix E)

[1] Marquardt Company of Van Nuys, Calif., is no longer in existence. Carl Stechman is also mentioned in this article as a collaborator of the speaker at Marquardt.
[2] Italicized text represents certain "lessons learned" emphasized by the conference presenters.

Boardman had a really novel idea that instead of what the industry was headed for at the time – many different sizes of engines where you would run long durations to control attitude in space – if you pulse-modulated the things, you could do a whole job with thrust levels from five to about 100 pounds. We developed enough credibility in that early time that we managed to win a little program called SINCOM. In that program, we had two thrusters, with a single unlike doublet injector bolted assembly on both of them. Both the twenty-five-pound and five-pound single unlike impinging injectors[3] were what we had been working with in the backyard. The backyard was really what it was. This little group that we put together built our own test facility, and we made one mistake. Basically, the facility consisted of a six-foot high concrete wall with propellant tanks on one side, and two guys on the other side looking through the window to see what happened. The mistake was we didn't remember that the wind blew from the west, and we were on the east side of the test stand. The engines weren't very efficient, so, frequently when we evacuated, we went through this red cloud.

However, that program gave us enough credibility that we were able to convince North American Aviation Inc. and NASA to give us the contract to build what they called a common engine. It had three attitude control applications: the Apollo service module, lunar module, and the Apollo command module, which was to be a varied engine. We got about a year into the program, almost a year, before everyone came to the conclusion that this little company, which had gone from 5,000 to 500 employees really couldn't handle a large program of that magnitude; so, the command module part of that went to the Rocketdyne Company. (See Slide 3, Appendix E)

My colleague Carl Stechan started at Rocketdyne and came to Marquardt. I started at Marquardt and ended up at Rocketdyne. We did all of our development work with single doublets,[4] and one of us was convinced that a 100-pound single doublet could work at the 100-pound level very satisfactorily. It really wasn't too bad an idea, except the chief engineer said we had to have a specific impulse of 300; 270 didn't cut the mustard. The thing evolved then into what it is now and started out from the original configuration, the R-4A. The R-4A was an eight-doublet with eight film cooling holes and two valves. The fuel valve canted off to the side to a circumferential manifold, and the oxidizer valve fed right through the center of the injector to eight outward pointed doublets. It featured a molybdenum nozzle, coated with molybdenum disilicide or Durac-B. (See Slide 4, Appendix E)

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[3] Injector with a single element (i.e. unit) consisting of one fuel orifice and one oxidizer orifice that impinge the resulting fuel and oxidizer streams together just downstream of the injector face.
[4] A type of injector where two fluid jets impinge to create a spray.

Basically, we had three groups working. We had a guy doing the injector and combustor design. Carl Stechman was doing heat transfer work. We had another group doing materials studies. In actuality, the molybdenum system they came up with wasn't too bad except for two features. One feature was the material, which, if not coated, vaporized when it got hot. It was very, very sensitive to chipping. The way we tested the nozzles to find out if they were okay was to put them in the oven at 2,500 degrees; if they smoked, they were gone because you could see them while they smoked. They were also very brittle. It's a very brittle material. The ductile brittle temperature was about 60 degrees Fahrenheit, so once they got cold, they were like just tapping a piece of glass and, with our shocks, that was not a good thing. In order to keep an engine in one piece – because the nozzles kept splitting – we got the R-4B configuration in which we put on a ribbed L-605 nozzle attached to the molybdenum combustion chamber. That continued to grow, and they all looked the same. From the outside, they were all pretty much the same. (See Slide 5, Appendix E)

. . . a magic thing called the pre-igniter. It was both part of our problem, and a savior of part of our problems.

The original eight-on-eight injector basically stayed the same from the first injector we put together in 1962. The valves improved. Scads of things changed. However, the Preliminary Flight Rating Test (PFRT) injector differed only from the qualification injector in flight units in the valve seat materials. We were having difficulty with the high temperature soak back after long runs. We decided it would be a good thing to strengthen the Teflon valve seat. In order to do that, we put fiberglass into the Teflon valve seat, and it really stayed together, except when the engine heat soaked back; the Teflon grew and grew and grew, and the oxidizer didn't get through the oxidizer side, if it got too hot. We flew two successful missions around the moon with that PFRT engine. Boeing made that particular device. We held our breath all the way because it was used as the brake engine and an apogee engine both; we were really worried about the valve seats getting too big. In the middle of the chamber of the basic R-4D engine as it evolved into the engine that flew on all the missions, there was a little tube sticking down, and that was a magic thing called the pre-igniter. It was both part of our problem, and a savior of part of our problems. The thing was a cooled molybdenum chamber with an L-605 nozzle. The reason we stuck the L-605 on was that it was a high temperature material. The ribs had to be on there to keep it round. It also had one other nice feature on the service module, they stuck out in all directions. The flight engines all ended up with a no-step design on the nozzles because they turned out to be convenient. (See Slide 3-5, Appendix E)

On the lunar orbiter, the 100-pound engines faced down. They used cold gas for attitude control. That was a pre-qualification test engine. We did have some technical difficulties. The first one was high heat transfer burning. Today, I can confess it was first-tangential combustion instability mode, but at the time this happened, it was really an interesting thing because in the Apollo mission duty cycle,[5] it had to perform a ten-second run followed by a very specific off time, then a three-second run followed by another thirty seconds, and then ten seconds of continuous burn. The characteristic was they would go through the first two very nicely, and on the third burn, in about one and one-quarter seconds, the temperature on the chamber wall would pass 3,100 degrees Fahrenheit. Shortly before that happened, the fire would come in a thrust vector mode, which wasn't planned. Actually, we compromised with NASA on that one. We just decided that was probably not a good duty cycle because nobody quite knew what it was or how to cure it. We compromised and went through a different duty cycle to get around that particular problem, which was the only place that it really occurred on that engine. (See Slide 6, Appendix E)

It took years for us to figure out what a good thing we had done without planning it.

We had a series of difficulties with spikes. That engine had some neat things to get through. It was generally operated in ten milliseconds on-time duty cycle. Thermal control was something we thought about, but the combustor in that mission had to sit there and, characteristically, it would go down to minus-100 degrees Fahrenheit. When the engine shut off in short pulse duty cycle in that kind of a radiative environment, the oxidizer entered the manifold first because it had gotten a very high vapor pressure relative to the fuel, and it went to the closest cold spot, which was at the chamber wall, and the fuel would come dribbling out. It also looked for a place to stop. It would freeze right on top of the oxidizer. We would build multiple layers of fuel oxidizer, and then, we would get a run long enough up to really do something. We'd get a really exciting event. I deemed it "pre-unplanned disassembly" at the time. That problem really went away when we learned a little bit about fuel control and kept injectors and propellant temperatures a little warmer. Aerozine-50 (A-50) propellant was the original propellant we selected because the big engines that had to be used to get us to the moon all used A-50, so that had to be the propellant of choice for us. (See Slides 7 and 8, Appendix E)

Carl Stechman didn't think the pre-igniter did something, but someone else did, and the NASA folks kind of agreed. The pre-igniter really was a good thing, but the serendipitous thing it did was the hot phase or first tangential instability went away because we had changed the interior configuration of the chamber a little bit. It took years for us to figure out what a good thing we had done without planning it.

The other major technical issue was the inner manifold explosions resulting from monomethyl hydrazine (MMH) evaporating and depositing like dew in the cool spot in the engine. That

[5] A parameter referring to time-varying, on-off cycling of any rocket thruster or engine (also to intermediate states of thrust, if needed).

was a recurrent problem, and it was the reason the space shuttle has a limit of 70,000 feet operation today. In space, it can't happen because there is no way to get the phenomena to occur because the pressure is inside the chamber and injector after engine firing, and it is less than the thermodynamic triple point of the fuel. We did a lot of premature disassembly (i.e. failures). The chamber would disintegrate during pulse mode firings in ten-millisecond pulses. The thing that really convinced us to drive to the pre-igniter was the program manager's data plot. After a night of testing, he had drawn a plot that showed chamber wall thickness across the bottom. The ordinate was the peak value of the measured pressure. He had infinity drawn both directions. It seemed like that might be a wise thing to change. Later, the pre-igniter really did alleviate the spike problem to a high degree. When we changed to warmer operating conditions, like a 70-degree Fahrenheit propellant, the problem went away and never came back.

In later developments, we put in a columbium chamber, which was a lot more tolerant. A-50 going away was also a good deal because it was more sensitive to that chamber. There was a lot of resistance going to the niobium chamber (niobium and columbium are the same material) because we had a molybdenum chamber that worked. If it was good enough and if it ain't broke, don't fix it. Stechman wrote an article about this feature in the *Journal of Spacecraft and Rockets*. It was not a real detailed discussion, but there is some discussion there. (See Slide 8, Appendix E.)

Another problem we ran into was a thing called a ZOT. There used to be cartoon called *BC*. A couple of the key characters were an anteater, who was always getting after ants in the ant hill, and a snake, who always got struck by lightning when he would do something inane. The ZOT was something like that snake. We didn't really understand it too well, but it sure was something. It wasn't called the ZOT originally. It was called, "What the hell caused that?" (See Slide 9 and 10, Appendix E)

If you could picture the oxidizer valve off in one of the early Apollo engines after it disassembled itself from the engine, there was a little squirrel thing running around in there; that was the seal between the injector and the valve. We thought something happened; after it happened a couple of times, we began calling it a ZOT, because, like that cartoon snake's observation, something was really interesting. Its characteristics were pretty definable. Ordinarily, when you opened a valve, you got a smooth pressure decay. Instead, what would happen was the pressure at the instant of the valve opening would disappear off the chart. We finally associated that with high pressure. That was the clue that we were looking for, and we finally figured it out after somebody asked us to run some vertical, facing-up engine tests. We discovered that it really was kind of an interesting phenomena confined to a relatively small operation area. We made a ZOT plot written by Stanley Mitten, who was one of the better engineers that I dealt with in the science part of the world over the years. Basically, it said that at very low pressure, there were no ZOTs because the fuel emptied the manifold and evaporated really quickly and was gone from the chamber almost instantly. (See Slide 10, Appendix E)

We were just getting into the qualification program, and we had this small task to make 700 engines.

At very low pressures, it wasn't such a good deal – particularly in the pulse duty cycle, which was pretty hardware dependent. If there was a place in the engine between the valve seat and the injector face, that could be cold. Guess how it got cold. When the oxidizer evacuated the injector, all these small engines had the valves separated from the injector face by a thermal standoff. If the valves seats could be kept cool, while the injector face was running very hot, the little thin standoffs in between the valve seat and the injector could get very cold when the oxidizer was evaporating and emptying the manifold. The fuel came out after, and if the ambient pressure was just right and the ambient pressure was above the triple point pressure, dew would develop inside the oxidizer manifold. If enough dew collected, on the next pulse, liquid fuel would develop inside the oxidizer manifold, and it would generate some horrendous pressures. We'd get premature disassemblies[6] again. It wasn't a problem for Apollo because that particular engine never ran in real life in its missions until it was well out in space. This wasn't a space problem; it was purely a ground problem. It was a problem for the space shuttle because the shuttle engines operated for attitude control during the early phases of reentry. There was a big concern because through stage down to 70,000 feet, there is the risk of having a ZOT occur and a valve leak or too much condensed fuel in the oxidizer manifold harming the hardware pretty severely. The ZOT story, today, is probably still a problem that people need to think about for the upcoming vehicles, because the shuttle engine is going to be, with any probability, one of the attitude control engines for the new large vehicles. The 870-pound thruster is the ideal size for intermediate control. This is one of those problems now that we recognize, we know what it is, and we know how to deal with it. In the current shuttle engine, that is an easy thing to fix. (See Slides 11 and 12, Appendix E)

People often wonder about schedules. Marquardt had no schedule problems at all. Our task was really pretty easy. We just had to do a little development, which happened in the 1962-1963 time frame, and then, we did a little more development. Then, we got the R-4D, and we did some more development. By the time we got out to the 1965 time frame – and that is a September 1965 schedule as a matter of fact – we had managed to make a little bit of hardware and break quite a bit of it. We were just getting into the qualification program, and we had this small task to make 700 engines. Interestingly enough, once we decided we had the problems

[6] Meaning that the thruster exploded.

behind us and were pretty well along the path of making hardware that we believed was okay to support manned flight, we geared up and produced about ten engines a week out of that little factory, which had grown from 500 to about 800 people during the Apollo Program. There wasn't a straight-forward acceptance test that consisted of four pulse-firing test series. There were two ten-second runs to get good performance data. Then, we had to run sixty-second durations, so we could demonstrate engine life margin. On average, we ran two of those engines a day for two years to get all of that hardware out of there. It was an interesting time. (See Slide 13, Appendix E)

The cost was always an issue. The hardware evolved up to be an Aerojet product today. That same R-4D heritage resides up at Aerojet Redmond now. Carl Stechman is their corporate knowledge of what the history of that engine is and really knowledgeable about what makes those engines work. In 1960, the price of an engine was about $30,000 each. If you take the Consumer Price Index and the ratio of that – just taking cost of living adjustments – it would be up to about a factor of six. I'm absolutely sure they would have liked to produce 2,000 more. I'm pretty well convinced they would have been just as happy as clams to make another couple thousand of these things. We made about 650 engines. That was 650 production units. We actually flew 469 of them during the Apollo Program, which is an astounding number of little rocket engines that actually fly in space all on one program. In all that time, and the millions of cycles that were put on during that whole program, there was not one R-4D valve or engine failure. We were really kind of tickled that we may have done something good. (See Slides 14 and 15, Appendix E)

In all that time, and the millions of cycles that were put on during that whole program, there was not one R-4D valve or engine failure.

What happened to the other 200 engines? NASA had this requirement that you had to keep both the hardware and the documentation around for at least ten years after the conclusion of the program. We had a storage spot. We tested the original lunar module qualification unit with the four engines, which on both the service module and the lunar module were stored structures. That unit sat in the back of a storage room for about forty years before the company downsized; they were throwing stuff away, and Carl Stechman managed to recover one. I know where one other one is for sure – in my office. A bunch of them were sold to Rocketdyne for some classified program. They sold eleven of them for another program. NASA's Jet Propulsion Laboratory got a bunch of them, primarily to be taken apart and used for valve testing. There are some in the Smithsonian, a few in the space museum down in Alamogordo, New Mexico. There are some in NASA's Kennedy Space Center museum. There are some in other museums somewhere in the South. There is some facility that has quite a number still sitting in the original containers. Last I heard, there were still a number of them in storage down at Johnson Space Center, waiting to find a home. (See Slide 16, Appendix E)

I was running a 200-pound thrust development program at Marquardt in about 1992. I actually took one of those engines off a particular module because we were having a data problem in our test stand. We couldn't seem to get data to repeat, or we couldn't get anyone to believe that we could repeat data anyway. We actually pulled a logbook for one of those engines out of its original dead storage, took one of those engines off of that module, put it into the test stand, and re-fired the thing. It repeated its original acceptance test within two seconds of specific impulse and about one-half pound of thrust. They seemed to have stood the test of time fairly well. There was some documentation still around up until a couple of years ago; I had a copy of the original PFRT report and the qualification report I wrote. Carl Stechman is a good source because he kept a lot of the original stuff from a historical standpoint. The thing has really gone a long way from where it started. It started as an injector. The basic injector was the R-4D that is still sold today. It was the same one that we developed just before the pre-igniter was incorporated because we got some thermal control. We got a little smarter. We turned that one with a large area nozzle made out of niobium into one with a 311-second engine. I left Marquardt at about that time. Then, they decided, "Gee, if a little is good, more must be better." It had more nozzles and some reductions in film cooling. (See Slide 17, Appendix E)

Today, the engine marketed by Aerojet is still that basic eight-on-eight configuration with the changes that they have made into it. It has a current specific impulse of about 323 seconds. From where it started out in the good old days at 292 seconds to where it is today, it's come a long way. (See Slide 18, Appendix E)

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

QUESTION: Give us a sense, if you would, of where all these different articles were tested – the ones that were to fly as well as the ones that were part of the development activity. Were there multiple facilities up and down the West Coast or were they all contractor? Were they altitude as well as ambient?

PFEIFER: All the engines were both qualification and acceptance tested at Marquardt's facilities. After we won the Apollo Program contract, we went off and built two vacuum test facilities, which simulated altitude continuous firing for as long as we wanted to run an engine. They would run days and days with the same capability we had on steam ejection. We did all of the testing in both for the qualification and the acceptance test. One of them was a large ball, which was an eighteen-foot diameter sphere, evacuated again with a big steam ejector system that could be used for system testing; that's where we did the Lunar Excursion Module testing. We put the whole cluster in there and tested the entire cluster at the simulated altitude conditions. The lowest altitude we tested at – typically an acceptance test – was 105,000 feet simulated altitude. The big ball – because people were interested in what they called goop formation, which is an unburned hydrazine product migrating to cold surfaces on different parts of spacecraft – was built to address those kinds of issues. We ran long-life tests in a simulated space environment with the entire inside of the test cell around the test article, liquid nitrogen cooled, so it could act as getter for any of the exhaust products. That particular facility could pull down to about 350,000 feet (atmosphere) equivalent altitude, which was pushing pretty close to the thermodynamic triple point of the MMH. It was a good test facility. Those facilities are no longer there. When the guys at Marquardt sold the company to what eventually became part of Aerojet, all those test facilities were cut off at the roots. I think they have a movie studio there at this point. That part of it is truly not recoverable, but it did some excellent high-altitude, space-equivalent testing at the time.

STEVE FISHER[7]: Regarding your facilities, and probably more so towards the end of Marquardt, how did you guys test in the San Fernando Valley with all the leaks and the stuff you had? How did you guys manage the Environmental Protection Agency (EPA)?

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

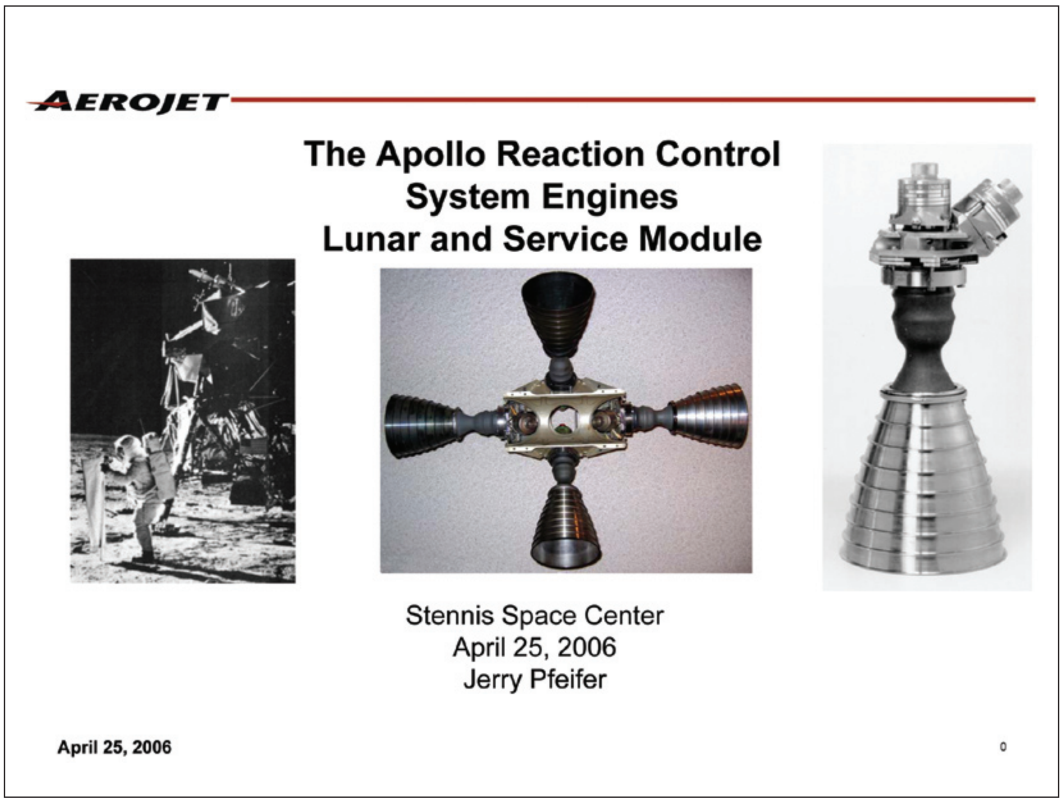
PFEIFER: Surprisingly, we had very few problems while testing in the San Fernando Valley. In the early 1960s, nobody had ever seen dinitrogen tetroxide (N_2O_4), so that wasn't too big a deal. We really did only make small, red clouds. In all the hundreds of thousands of tests and probably well over one million firings that I was around that place for, in all that thirty-something years, we had a total of one serious injury associated with rocket engine testing and propellants. Because we were trying to figure out what propellants would really be good, we tried all of the fun stuff like the carbon tetrafluoride, chlorine pentafluoride, and pure fluorine. The materials knowledge wasn't all that great at the time. On one test, the fluorine we had didn't react well with the copper they were using for tubing, and it managed to cause another *unscheduled disassembly* of the facility. It was very serious. It's like one of those Korean War stories. The technician happened to be walking past the test facility when it decided to blow itself up. A piece of copper tubing pierced one cheek and came out the other. That was the only serious accident in all of the engines handled in all those years.

Now, we did have a problem with the EPA later because they figured out what the brown clouds were about. We built a whole bunch of exhaust mitigation scrubbers to take care of engine testing in the daytime. In general, we operated the big shuttle (RCS) engine, the 870-pounder at nominal conditions; they scrubbed the effluents pretty well. If you operated that same 870-pound force engine at a level where you get a lot of excess oxidizer, yeah, there's a brown cloud. But, you know, it doesn't show up well in the dark. They did do some of that. But, that's gone; it was addressed one way or another.

Saturn S IV B Stage Ullage & Apollo Command Module Reaction Control Engines

Appendix E

G. R. "Jerry" Pfeifer's Presentation Viewgraphs



Origin of Apollo RCS 100 Lbf Thruster

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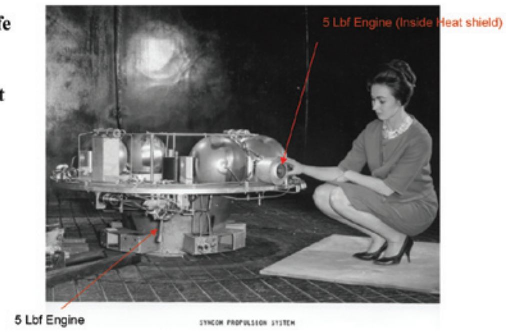
- Based on IR&D work performed by Warren Boardman (retired), Jerry Pfeifer (Boeing Rocketdyne) et.al starting in the 1960 time period.
  - Two thrust levels (5 and 25 Lbf)
  - single unlike impinging injector doublet
  - Molybdenum combustion chamber (Durak ($MoSi_2$ Coating)
  - Eckel fast response solenoid valves

Advent 25 lbf engine was life tested using Molybdenum chamber in 1962.
•Single unlike doublet Injector
•Bolted assembly

R-1E-1 (Without Valves)



April 25, 2006

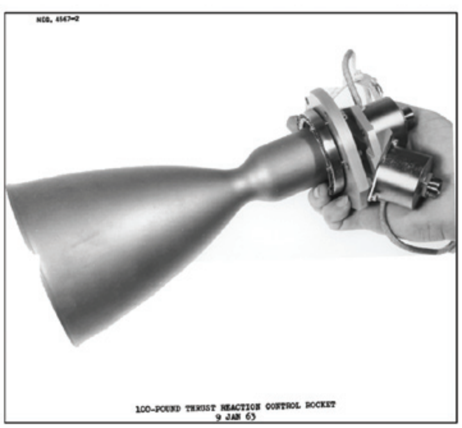
1

Original Apollo Configurations

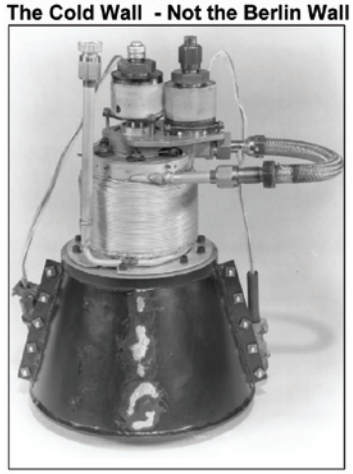
AEROJET

- NASA/Rockwell funded Marquardt for a “Common” engine to be used on the Service Module, Lunar Module and Command Module (buried)

Early Model R-4 100 lbf Engine
One Piece Molybdenum Chamber



A R-4D Concept that never Flew
A Good Idea that Lost to Politics
The Cold Wall - Not the Berlin Wall



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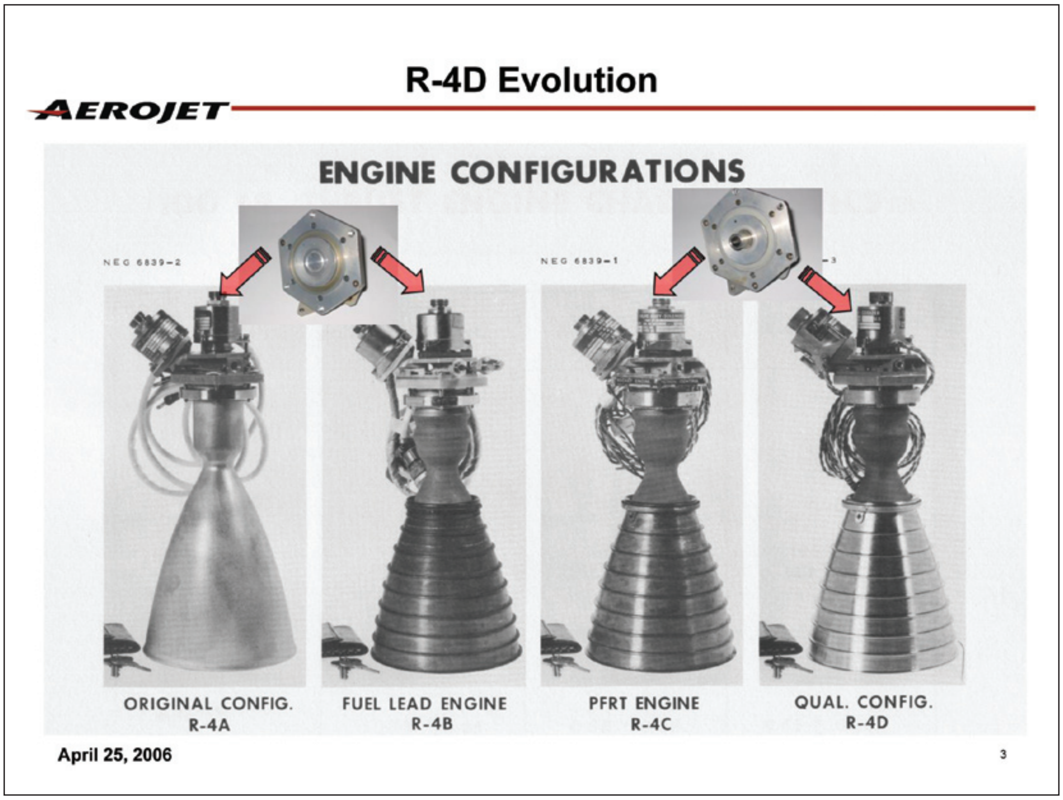
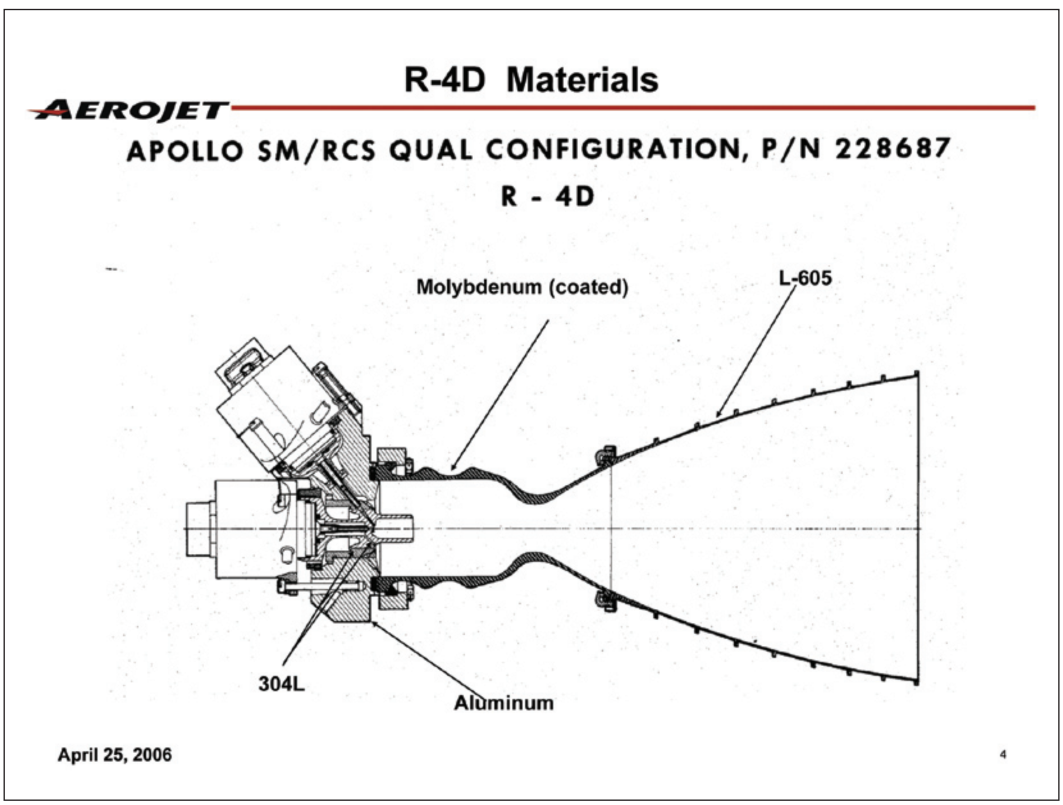

R-4D Evolution
AEROJET
ENGINE CONFIGURATIONS
NEG 6839-2
NEG 6839-1
ORIGINAL CONFIG.
R-4A
FUEL LEAD ENGINE
R-4B
PFRT ENGINE
R-4C
QUAL. CONFIG.
R-4D
April 25, 2006
3


R-4D Materials
AEROJET
APOLLO SM/RCS QUAL CONFIGURATION, P/N 228687
R - 4D
Molybdenum (coated)
L-605
304L
Aluminum
April 25, 2006
4

First Use of R-4D Apollo engine -Lunar Orbiter

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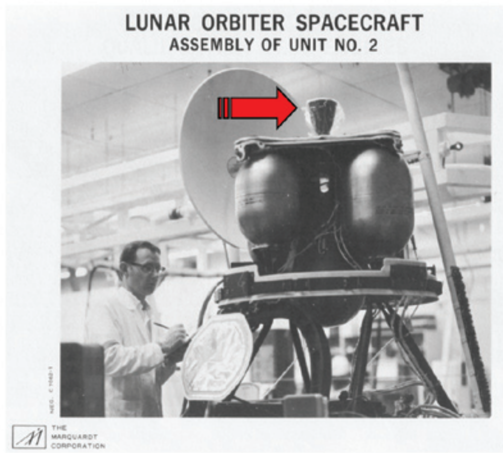

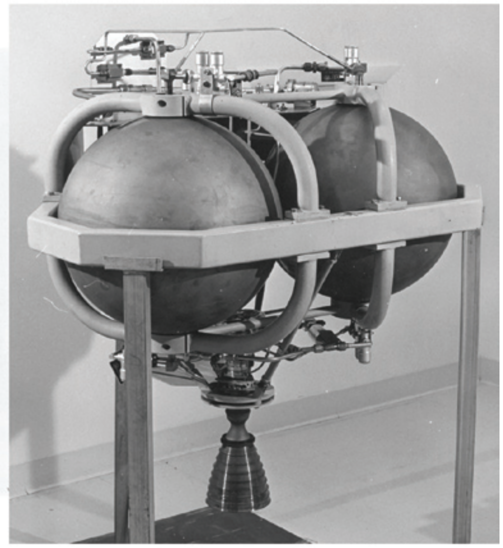

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Problems

AEROJET

- HHTB -High Heat Transfer Burning - a.k.a. 1st tangential combustion instability
  - Went away never to return - after the pre-ignition chamber was integrated.

- Spikes - The result of detonating (by a vapor phase ignition delay) residual unburned and partially reacted propellants that deposited on the chamber wall
  - At 0.010 Electrical pulse widths the chamber cooled down due to the propellant holdup in the manifold
  - Eliminated by heating the injector to 70°F (with MMH) and 125°F (with A-50)
  - SP-4205 statement that "Marquardt eliminated spiking by installing a small tubular "pre combustion" chamber inside the engine" is in error.

- ZOTS (inner-manifold explosions)
  - Resulting from operation in a pressure field above the triple point of MMH or A-50 and is aggravated by gravitational field.
    - It happens at sea level up to 70,000 ft or so.
    - Only occurs in space if there is a significant fuel leak that pressurizes the chamber between firings (pulse mode).

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AEROJET - Ignition characteristics – "Spikes"

- The development of the reaction control engines for the Apollo LM and SM resulted in additional development and testing because of premature disassembly of engines during extended duty cycle pulse mode testing at low temperatures.
- The molybdenum combustion chamber would disintegrate during pulse mode firings where the equivalent propellant mass contained in the injector manifold exceeded the operating time of the pulse (about 10 milliseconds)
- The emptying process included condensation of the partially reacted and unburned neat propellants on the interior walls of the combustion chamber (nitrates) .
- During the subsequent ignition (if the chamber was cold) the ignition delay could result in a "vapor phase detonation or "spike" that would act as an explosive source for the detonation of the nitrates
- The rest is history

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AEROJET Ignition characteristics – "Spikes"

- Elimination of this undesirable operational characteristics was accomplished by maintaining the injector heat above 70°F (120°F for Aerozine-50 fuel)
- Additional margin was subsequently accomplished by the incorporation of a niobium material combustion chamber which has low temperature ductility and can absorb the localized high strain rate detonations
- A detailed discussion of this phenomena is documented in:

"*Ignition Transients in Small Hypergolic Rockets*" **Juran and Stechman**

Journal of Spacecraft and Rockets, Volume 5, Number 3, Pages 288-292,

March 1968

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ZOTs

AEROJET

References:
1. Stechman and Sumpter "Development History of the Apollo Reaction Control System Rocket Engine" , AIAA-1989-2388, ASME, SAE, and ASEE, Joint Propulsion Conference, 25th, Monterey, CA, July 10-13, 1989. 6 p.
2. Hudson, AIAA-86-1632, "***The Apollo Reaction Control Thruster***"

Courtesy "B C Rides Again"
1988 Creato s Syndicate, I c

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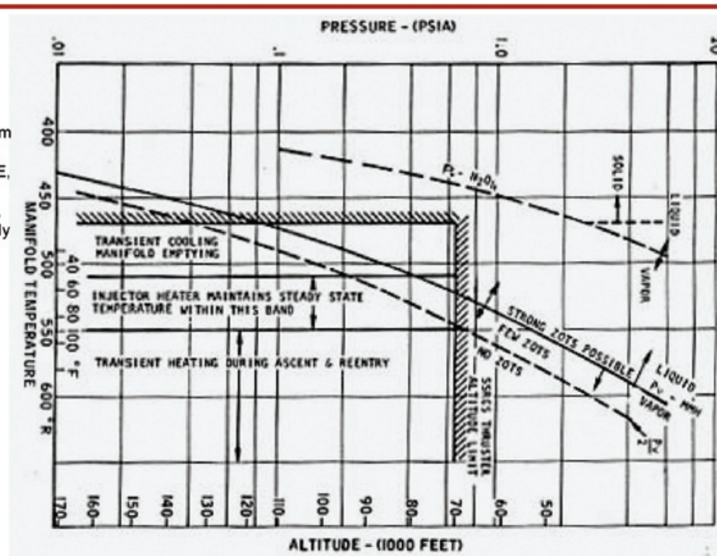
ZOT PLOT

AEROJET

Reference:
1. Stechman and Sumpter "Development History of the Apollo Reaction Control System Rocket Engine" , AIAA-1989-2388, ASME, SAE, and ASEE, Joint Propulsion Conference, 25th, Monterey, CA, July 10-13, 1989. 6 p.



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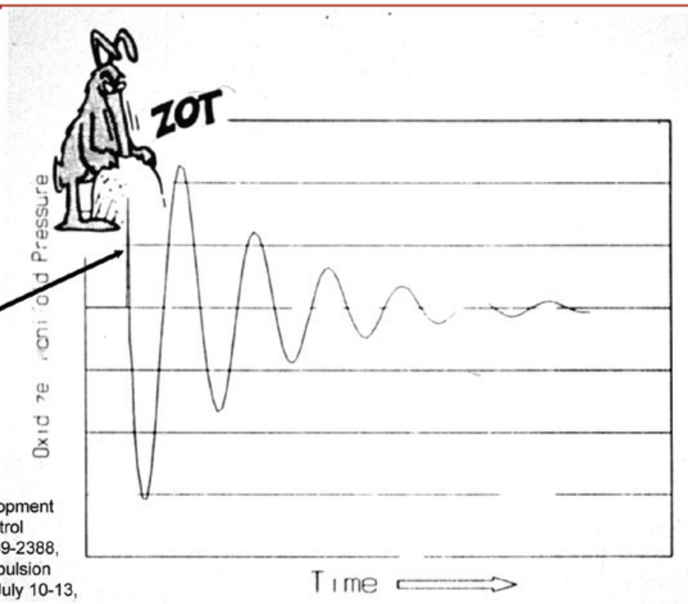
Identifying a ZOT from Test data

Manifold Pressure increases at ignition instead of decreasing due to overpressure at valve or in injector



Reference:
1. Stechman and Sumpter "Development History of the Apollo Reaction Control System Rocket Engne" , AIAA-1989-2388, ASME, SAE, and ASEE, Joint Propulsion Conference, 25th, Monterey, CA, July 10-13, 1989. 6 p.

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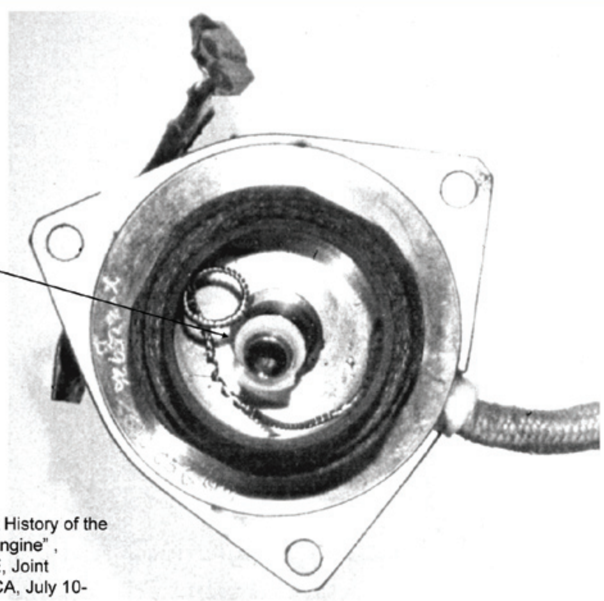
ZOT Damage

Valve Outlet



Reference:
1. Stechman and Sumpter "Development History of the Apollo Reaction Control System Rocket Engine" , AIAA-1989-2388, ASME, SAE, and ASEE, Joint Propulsion Conference, 25th, Monterey, CA, July 10-13, 1989. 6 p.

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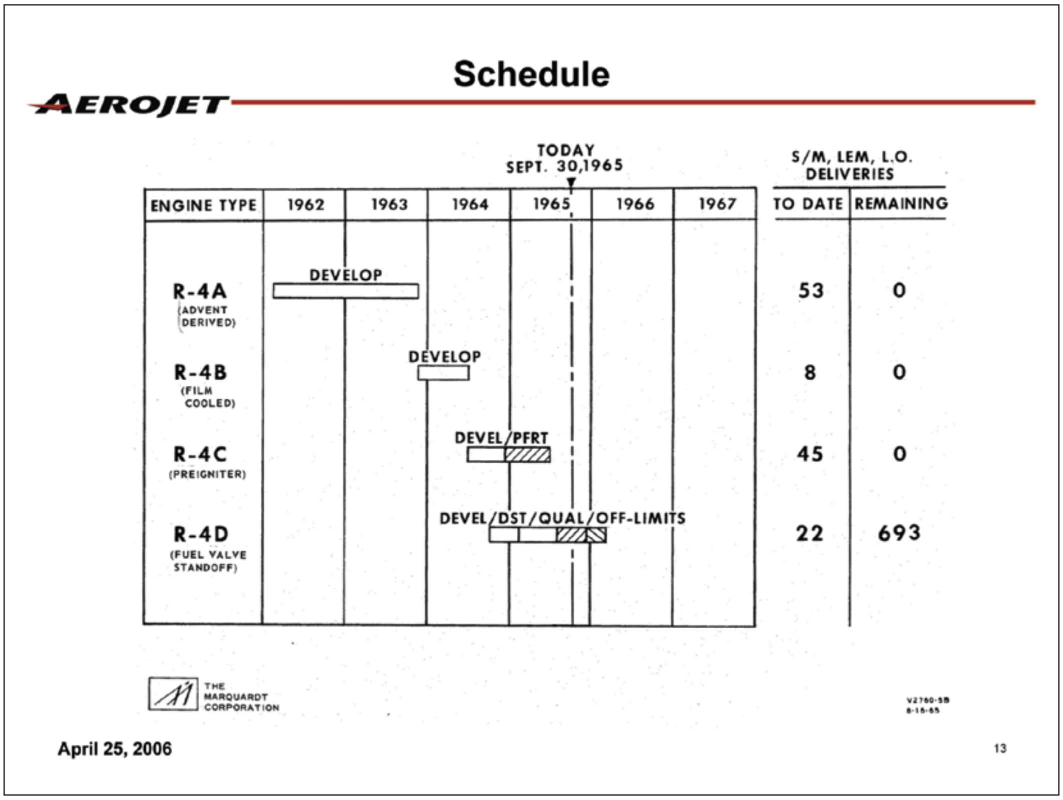
Schedule
AEROJET
TODAY
SEPT. 30,1965
S/M, LEM, L.O.
DELIVERIES
ENGINE TYPE
1962
1963
1964
1965
1966
1967
TO DATE
REMAINING
R-4A
(ADVENT DERIVED)
DEVELOP
53
0
R-4B
(FILM COOLED)
DEVELOP
8
0
R-4C
(PREIGNITER)
DEVEL/PFRT
45
0
R-4D
(FUEL VALVE STANDOFF)
DEVEL/DST/QUAL/OFF-LIMITS
22
693
THE MARQUARDT CORPORATION
April 25, 2006
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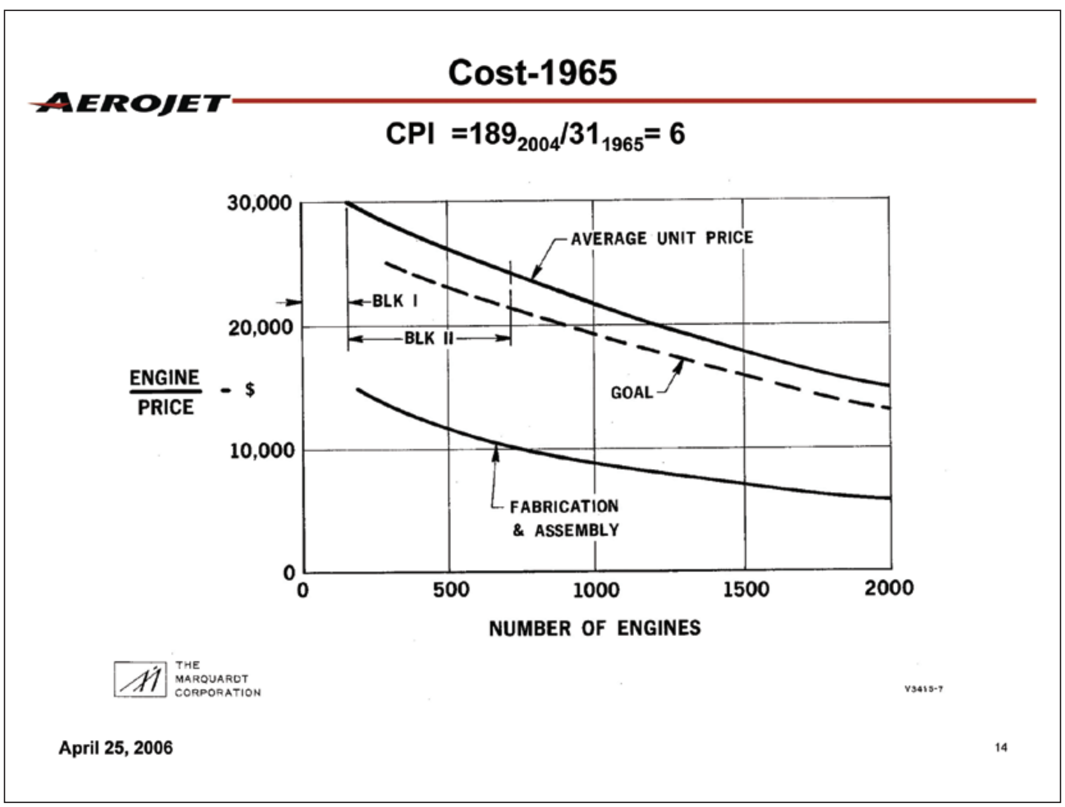
Cost-1965
AEROJET
CPI =189$_{2004}$/31$_{1965}$= 6
30,000
20,000
10,000
0
ENGINE PRICE - $
AVERAGE UNIT PRICE
BLK I
BLK II
GOAL
FABRICATION & ASSEMBLY
0
500
1000
1500
2000
NUMBER OF ENGINES
THE MARQUARDT CORPORATION
V3415-7
April 25, 2006
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History of Use

AEROJET

TABLE 1-2 UNOFFICIAL R-4D LAUNCH AND USAGE HISTORY

Revised by Carl Stechman (c.stechman@verizon.net) or (stechman@rocket.com)
10-0ct-02

L178.005	R-4D	(16)	1966	Feb	26	SM-009
1966-073	R-4D		1966	Aug	10	Lunar Orbiter
L178.006	R-4D	(16)	1966	Aug	25	SM-011
1966-100	R-4D		1966	Nov	6	Lunar Orbiter
1967-008	R-4D		1967	Feb	5	Lunar Orbiter
1967-041	R-4D		1967	May	4	Lunar Orbiter
1967-075	R-4D		1967	Aug	1	Lunar Orbiter
1967-113	R-4D	(16)	1967	Nov	9	SM-017
1968-007	R-4D	(16)	1968	Jan	22	LM 1 AS
1968-025	R-4D	(16)	1968	Apr	4	SM-014
1968-089	R-4D	(16)	1968	Oct	11	SM-101
1968-118	R-4D	(16)	1968	Dec	21	SM-103
1969-018	R-4D	(16)	1969	Mar	3	SM-104
1969-018	R-4D	(16)	1969	Mar	3	LM 3 AS
1969-043	R-4D	(16)	1969	May	18	SM-106
1969-043	R-4D	(16)	1969	May	18	LM 4 AS
1969-059	R-4D	(16)	1969	Jul	16	SM-107
1969-059	R-4D	(16)	1969	Jul	16	LM 5 AS
1969-099	R-4D	(16)	1969	Nov	14	SM-108
1969-099	R-4D	(16)	1969	Nov	14	LM 6 AS
1970-029	R-4D	(16)	1970	Apr	11	SM-109
1970-029	R-4D	(16)	1970	Apr	11	LM 7 AS
1971-008	R-4D	(16)	1971	Jan	31	SM-110
1971-008	R-4D	(16)	1971	Jan	31	LM 8 AS
1971-063	R-4D	(16)	1971	Jul	26	SM-112
1971-063	R-4D	(16)	1971	Jul	26	LM 10 AS
1972-031	R-4D	(16)	1972	Apr	16	SM-113
1972-031	R-4D	(16)	1972	Apr	16	LM 11 AS
1972-096	R-4D	(16)	1972	Dec	7	SM-114
1972-096	R-4D	(16)	1972	Dec	7	LM 12 AS
1973-032	R-4D	(16)	1973	May	25	SM-116
1973-050	R-4D	(16)	1973	Jul	28	SM-117
1973-090	R-4D	(16)	1973	Nov	16	SM-118
1975-066	R-4D	(16)	1975	Jul	15	SM-111
End Apollo Configuration						
Number units used			469			

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What happened to all of those Residual Apollo engines

AEROJET

- Sold to Rocketdyne for classified program (What?)
- 11 were used on the BSS LEASAT satellite
- NASA JPL where valves were used for projects
- Plume generators
- Smithsonian Air and Space Museum
- NASA Kennedy Space Museum
- Other museums
- a bunch were sold to junk dealers
- and 4 are here:

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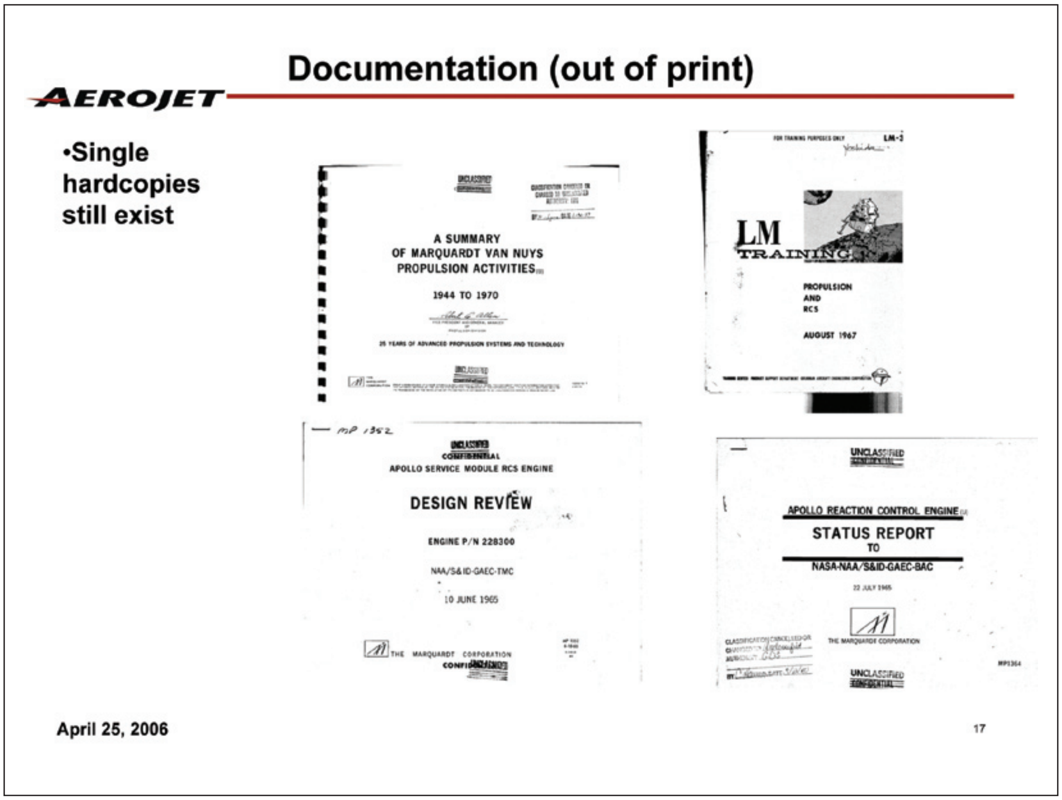
Documentation (out of print)
AEROJET
•Single hardcopies still exist
A SUMMARY
OF MARQUARDT VAN NUYS
PROPULSION ACTIVITIES
1944 TO 1970
LM
TRAINING
PROPULSION
AND
RCS
AUGUST 1967
APOLLO SERVICE MODULE RCS ENGINE
DESIGN REVIEW
ENGINE P/N 228300
NAA/S&ID-GAEC-TMC
10 JUNE 1965
THE MARQUARDT CORPORATION
APOLLO REACTION CONTROL ENGINE
STATUS REPORT
TO
NASA-NAA/S&ID-GAEC-BAC
THE MARQUARDT CORPORATION
April 25, 2006
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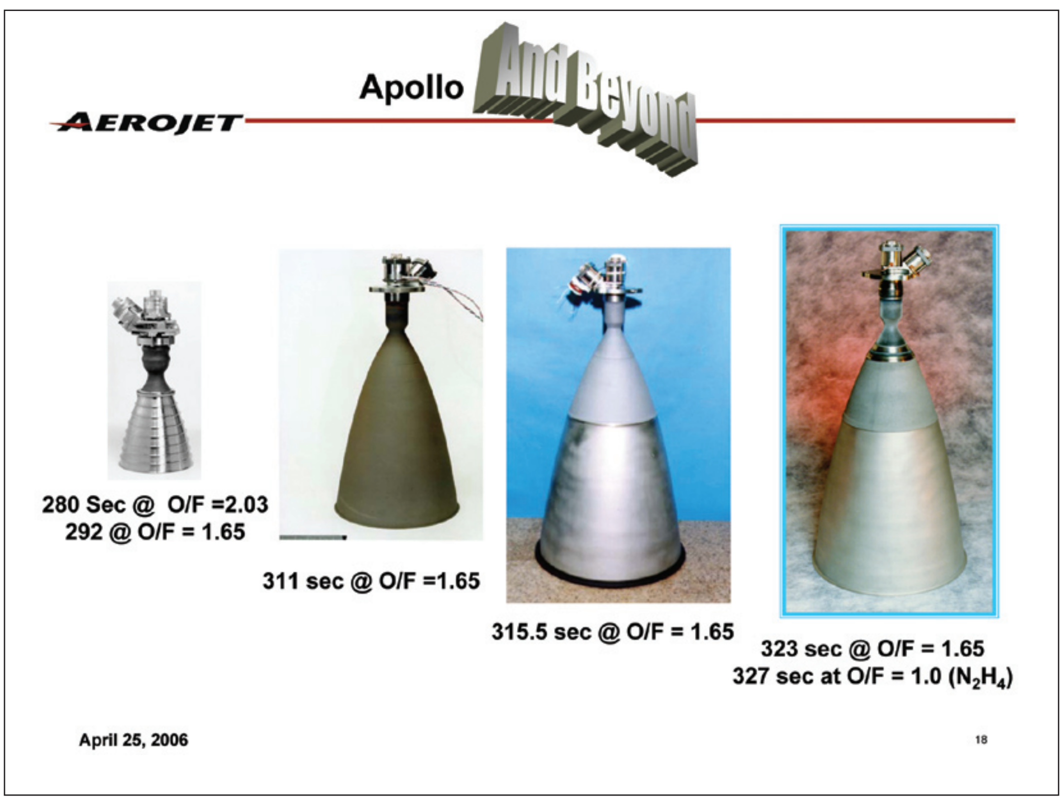
Apollo And Beyond
AEROJET
280 Sec @ O/F =2.03
292 @ O/F = 1.65
311 sec @ O/F =1.65
315.5 sec @ O/F = 1.65
323 sec @ O/F = 1.65
327 sec at O/F = 1.0 (N_2H_4)
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