Source Data for
NMUSAF History of Rocketry Tour

Initial Release – Redacted Edition**
4 March, 2024

This is NOT a NMUSAF document, nor is it endorsed by the NMUSAF in any way.

This is an informal training document for Docents giving the "History and Evolution of Rocketry" Tours, which was approved in November 2022 by the NMUSAF (National Museum of the USAF, Dayton OH). Current Tour Guides are Mike Ries, Ralph Taylor, and Jeff Robeson.

This document was written by Jeff Robeson, with considerable assistance by Jeff Smith, a former Docent who worked on the Atlas, Titan, and Minuteman missiles during his career in the USAF. Although he left the area for Montana during this long project, by email he provided significant editorial comments and remained committed to this project.

Two other individuals contributed to this effort:

- Harmon Withee, a Volunteer with prior USAF experience on the Titan II, added significant material on the Titan II.
- West Robeson, my son and an accomplished historian, contributed to the material on "Evolution of USAF Leadership in Space"

Most sections in this document started with the existing Gallery Guides at that time (usually identical to current signage and available online from the NMUSAF website) but were considerably expanded in detail for background reference on this tour. Sections that were totally new material were:

- Introduction: Solid and Liquid Rockets
- Evolution of USAF Leadership in Space
- Boeing LGM-30G Minuteman III (Supplemental Material)
- Lockheed Martin Titan IVB Rocket (Supplemental Material)
- Bell Aerospace Textron Model 8096
- Boeing Inertial Upper Stage
- Appendix A: Optional handout for tour

** Note that three sections from the original document have been redacted from this edition:

- Lockheed Martin Titan IVB Rocket
- Boeing LGM-30G Minuteman III
- North American X-15A-2

These three sections include material beyond the descriptions available on the NMUSAF website and were written under the auspices NMUSAF personnel for training in Gallery tours. I have retained "supplements" of the Titan IVB and Minuteman III articles in the original document since they are original material, and I apologize that in this edition they "provide supplementary material" to articles not included herein.

Any comments, corrections, or suggestions are welcome and should be directed to jeff.robeson@gmail.com

Contents

Introduction: Solid and Liquid Rockets

V-2 with Meillerwagen

Dr. Robert H. Goddard

V-2 Rocket Components

Rocket Engine Evolution in the United States

Evolution of USAF Leadership in Space

Douglas SM-75/PGM-17A Thor

Chrysler SM-78/PGM-19A Jupiter

Martin Marietta SM-68A/HGM-25A Titan I

Martin Marietta SM-68B/LGM-25C Titan II

Boeing LGM-30A Minuteman IA

~~Boeing LGM-30G Minuteman III~~ redacted from this edition – see note on cover page

Boeing LGM-30G Minuteman III Supplement

Martin Marietta LGM-118A Peacekeeper

Thor Agena A

Minuteman III Second Stage Rocket

Bell Model 8048

Reaction Motors XLR11 Rocket

Reaction Motors XLR99 Rocket

~~North American X-15A-2~~ redacted from this edition – see note on cover page

~~Lockheed Martin Titan IVB Rocket~~ redacted from this edition – see note on cover page

Martin Titan IVB Rocket Supplement

Rocketdyne LR79

Bell X-1B

Convair SM-65 Atlas

Vought ASM-135A Anti-Satellite Missile

Aerojet-General LR87

Boeing Inertial Upper Stage Space Payload Booster

APPENDICES: MISCELLANEOUS REFERENCE DATA:

Appendix A: Optional handout for tour

Introduction: Solid and Liquid Rockets

Rockets have been in use for hundreds of years. The first historical reference to the military use of rockets describes the battle of Kai-Feng, China, in the year 1232 A.D. "when the city's defenders used them with telling effect against invading Mongol hordes led by the son of Genghis Khan".[1] In the national anthem of the United States, "the rockets' red glare" refers to Congreve rockets used by the British in the War of 1812 to bombard Fort McHenry. All rockets were solid rockets until Robert H. Goddard flew the first liquid rocket in 1926. Solid rockets developed somewhat in the 20th century, but at the end of World War II measured only inches in diameter with ranges of no more than a few miles. It was the development of the liquid rocket that enabled dramatic increases in the capability of rockets: in 1944, Nazi Germany was launching thousands of V-2 rockets each carrying a ton of high explosives over 200 miles.

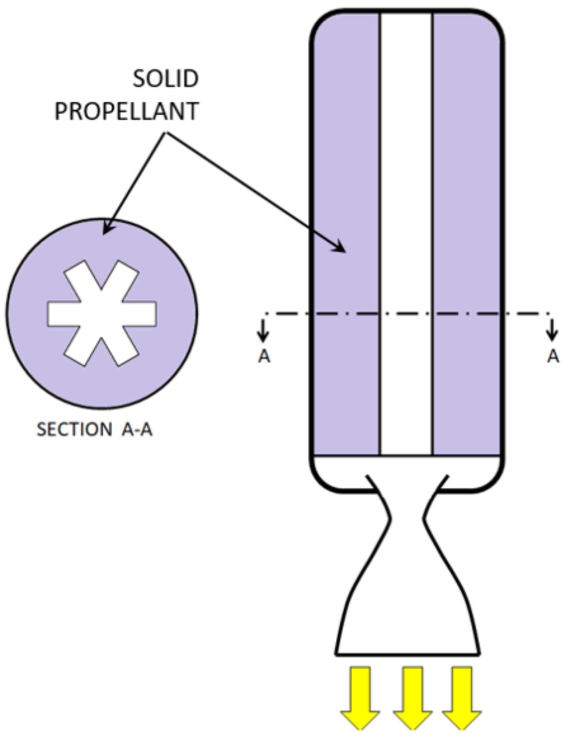
It is interesting that rockets were utilized for hundreds of years before anybody understood how they worked. Rocket engines operate according to Newton's laws. His second law states that a force applied to a body is equal to the mass of the body times its acceleration ($F = ma$), and his third law states that for every action, there is an equal and opposite reaction. In a chemical rocket, combustion energy accelerates propellant mass, and the force that accelerates the propellant mass is reacted by a force that pushes the rocket in the opposite direction of its exhaust. From this summary, it is clear why the first rocket company incorporated in the United States took the name Reaction Motors, Inc. Another outcome of Newton's laws is that rockets don't need anything (such as the atmosphere) to "push" against; in fact, rocket performance is improved in a vacuum.

Many people think that rockets are somehow more exotic than jet turbine engines, but actually both are reaction engines that rely on Newton's laws. Both burn a fuel to accelerate a mass of exhaust gasses, but jets use oxygen from the atmosphere to support that combustion. Rockets, however, must carry the oxidizer (typically oxygen) onboard so that it may operate outside the earth's atmosphere.

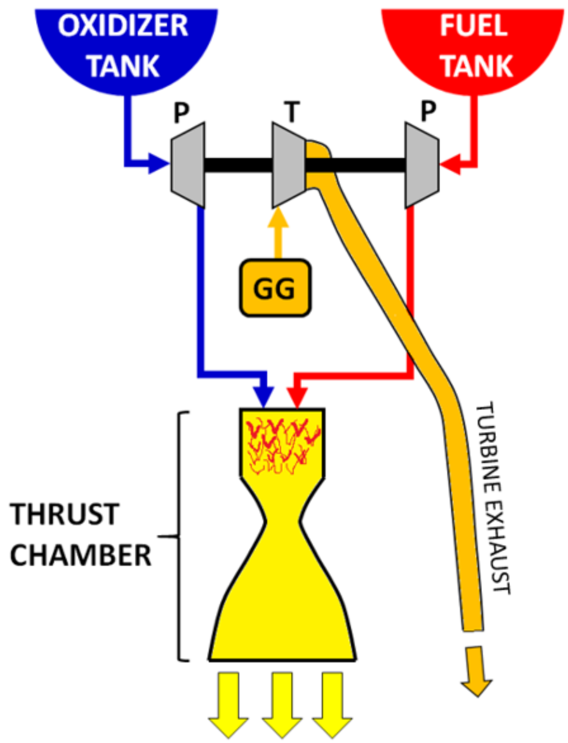
The rockets we will discuss on this tour are chemical rockets, which fall into two distinct categories: solid rocket motors and liquid rocket engines. As can be seen in the figure below, both solid and liquid rockets incorporate a unique nozzle shape. Called a De Laval, or converging-diverging (C-D) nozzle, it is the heart of a rocket and accelerates the exhaust gases to maximum velocities. In a De Laval or C-D nozzle, gasses accelerate to the speed of sound or Mach 1 at the throat or minimum nozzle area, and then in the divergent section continue to accelerate to higher, supersonic speeds. It should be noted that the speed of sound here is not the 761 mph we recognize for the speed of sound in air at standard sea level conditions, but instead, the speed of sound of hot combustion gasses, which is considerably higher.

The solid rocket is very simple, and similar to simple fireworks rockets, in which a black powder charge is ignited by a fuse, and the black powder burns until it is exhausted. Modern solid rockets are illustrated in the diagram below on the left. Solid propellants are compounds that include both the fuel and oxidizer mixed together, and are typically poured into the rocket casing and allowed to "cure" or solidify. It is important that thrust of a solid rocket is a direct function of the surface area burning, and the volume available for combustion. Thus earlier rockets were cylindrical masses of propellant that burned at the aft end and continued burning from aft to front, with thrust dropping as the combustion volume increased. Typically a star-shaped mandrel is left in the center of the casing during the casting process, and after removal, leaves a void in the center that is star-shaped. With different shaped centers, the burning rate of the propellant can be tailored to yield a more optimum thrust versus time curve.

A typical liquid rocket is illustrated in the diagram below on the right. A liquid fuel and liquid oxidizer are kept in separate tanks and then brought into a combustion chamber, or thrust chamber, where combustion takes place. In order to bring the fuel and oxidizer into the thrust chamber at high flow rates and very high pressures, propellant pumps (P in diagram) are used. The propellant pumps are driven by a turbine (T in diagram) mounted on a common shaft. To drive the turbine, a gas generator (GG in diagram) is employed to produce hot, high-pressure gas. The gas generator may use the primary fuel and oxidizer, or separately packaged chemicals (not shown in diagram). The gas from the gas generator is typically exhausted overboard after leaving the turbine.



Typical solid rocket motor



Typical liquid rocket engine

Solid and liquid rockets each have their own advantages and disadvantages. Solid rockets offer simplicity, high reliability, and low costs both for development and production. Liquid rockets provide higher performance, the ability to regulate thrust, a simple means of terminating thrust, and the ability to be restarted multiple times.

Despite spectacular failures and huge development delays and costs, the early liquid rockets, all descendants of the V-2, powered our world into space. It was not until the late 1950s that solid rocket technology was able to produce thrust levels comparable to the liquid rocket engines. Today large solid rockets are used exclusively for nuclear ballistic missiles because of minimal maintenance, high reliability, and the ability to launch almost instantly. For space boosters, large solid rockets are often used as “strap-on” boosters to augment (or replace) liquid engines at launch. While the choice or mix of solid and liquid rockets for space boosters varies widely depending on many factors, liquid rockets are predominantly used for upper stages because of their higher efficiencies and ability to modulate thrust and restart.

TOUR POINTS:

- Explain rockets provide thrust as reaction motors obeying newton's third law (F equal M x A)
- Oldest rockets were solid propellants (Chinese, Congreve rockets)
- Liquid rockets use separate fuel and oxidizers, gave us thrust to get into space more efficient and controllable than solids

SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

[1] Esther C Goddard and G Edward Pendray, *Robert H. Goddard - Diary of the Space Age Pioneer*, (Prentice-Hall, 1948)

Introduction: Solid and Liquid Rockets back to Table of Contents

V-2 with Meillerwagen

The German army developed the V-2, known also as the A4 missile, as an alternative to super-long-range artillery, which the Treaty of Versailles prohibited after World War I. Designed by rocket pioneer Wernher von Braun, the V-2 was a breakthrough in missile technology but failed to prevent Germany's defeat in World War II. The rocket was inaccurate, which made it a poor military weapon but an effective terror device. Though the rocket was destructive, killing almost 3,000 people in England and more in Belgium in the last year of the war, the German forced-labor system could not produce enough V-2s to affect the outcome of the war. In any case, the comparatively small power of V-2 attacks could not match the massive effect of Allied strategic bombing.

After the war, the German rocket team and many captured missiles were brought to the United States, the Soviet Union, and the United Kingdom, where V-2 technology helped to build the technological base for human spaceflight and advanced strategic missiles.

V-2 Missile Operations

The V-2 was the first practical modern ballistic missile. The technical name, the Aggregat 4 (A4), simply indicated that it was 4th in the Aggregat (German for "mechanism") series of rockets. The name it is more commonly known by, V-2, indicates that it was Germany's 2nd Vergeltungswaffe ("Retribution Weapon" or "Vengeance Weapon").[2] Its operation was complex and involved specialized transport and launching equipment. Unlike the V-1 flying bomb operated by the Luftwaffe, the German army operated the V-2 rocket. Erecting, servicing and launching a V-2 took from four to six hours and required some 32 different trailers and vehicles carrying fuel, batteries, pumps, spare parts, radios and other equipment. The entire operation required hundreds of soldiers, with the launch team alone needing more than 100 people to service and test the rocket, survey the site, run the support equipment and command the process. In all, more than 10,000 people and 3,000 vehicles were devoted to V-2 activities. Although over 300 V-2s were built at the Peenemunde development site, German records show that the vast majority of V-2s (5,797 missiles) were built at the Mittelwerk underground factory at Nordhausen, by slave laborers at the Dora concentration camp nearby, and overseen by the SS.[3] Some have estimated that as many as 12,000 forced laborers and concentration camp inmates died in the production of the V-2.[2]

After rail transport to the launching vicinity, large mobile cranes loaded rockets onto trailers, which took them to the actual launch site. The V-2 on display is on such a trailer, called a Meillerwagen.

The best launch sites were flat, wooded areas with clearings big enough to operate the missile and with ground or pavement firm enough to hold it. At the launch site, crews raised the rocket vertically with the Meillerwagen, then fueled it with alcohol and liquid oxygen. After several tests and adjustments, the rocket could be fired from the safety of an armored control car some distance away. The V-2's rocket engine burned for about a minute. The missile then continued in a ballistic, unpowered trajectory to its target. During operational flights, the V-2 reached an altitude of 50-60 miles, and its top speed was around 3,400 mph. During development testing, the Germans launched some vertically, one of which reached 117 miles, making the V-2 the first man-made object to reach space.[3]

The V-2, once launched, could not be stopped - it was too fast and flew too high. Since the V-2 arrived at several times the speed of sound, there could be no warning to its approach. The missiles impacted before the sonic boom they created was heard. Allied efforts to prevent rocket attacks depended on bombing production facilities and attacking rail transit with fighters. Allied air power destroyed many V-2s before they reached launch sites; the V-2 on display was damaged in an air attack.

Germany produced approximately 6,400 V-2s in 1944-1945[1]. Like the V-1, the V-2 was inaccurate. It could only be aimed at a large area, like a city. Together, the V-1 and V-2 missed their aim points by an average of more than nine miles. The first operational V-2 launch took place on Sept. 8, 1944, and the last on March 30, 1945. During this seven-month period, 1,115 V-2s hit England, and 1,524 fell on continental Europe. Many V-2s broke up or exploded in the air, and around 15 percent were never launched due to ground malfunctions. The total damage done in England by the rockets included 2,754 killed and 6,523 severely wounded. Some of the worst V-2 attacks included the destruction of a cinema in Antwerp (561 killed), and an impact on a crowded Antwerp street that killed 128 people.

The rocket engine for the V-2 along with a sectioned thrust chamber and turbopump is on display in the Missile Gallery.

TECHNICAL NOTES:

Warhead:	2,152 or 2,205 lbs. Amatol 39A explosive
Maximum speed:	3,400 mph
Range:	180-220 miles
Maximum altitude:	50-60 miles
Weight:	28,000 lbs. fueled

TOUR POINTS:

- Developed as an alternate to long-range artillery which had been prohibited by treaty of Versailles
- Wernher von Braun led design team
- Approximately 6,400 produced in last two years of war
- Poor military weapon but an effective terror device
- Range approximately 200 miles, warhead about 2,100 pounds
- Although 3,000 killed in England alone (9,000 military and civilians total), it was insignificant compared to the massive allied strategic bombing
- Meillerwagen trailer used for both transport & erection for launching
- Aerodynamic vanes and (connected) jet vanes in exhaust used for flight control
- Germany resorted to V-weapons as last hope to influence the war, to "punish" their enemies, and most importantly, to build German morale with their “wonder weapons”; the V-2 had no effect on the outcome of WWII, but led to Cold War ICBMs, which in turn were key to early space exploration.[2]

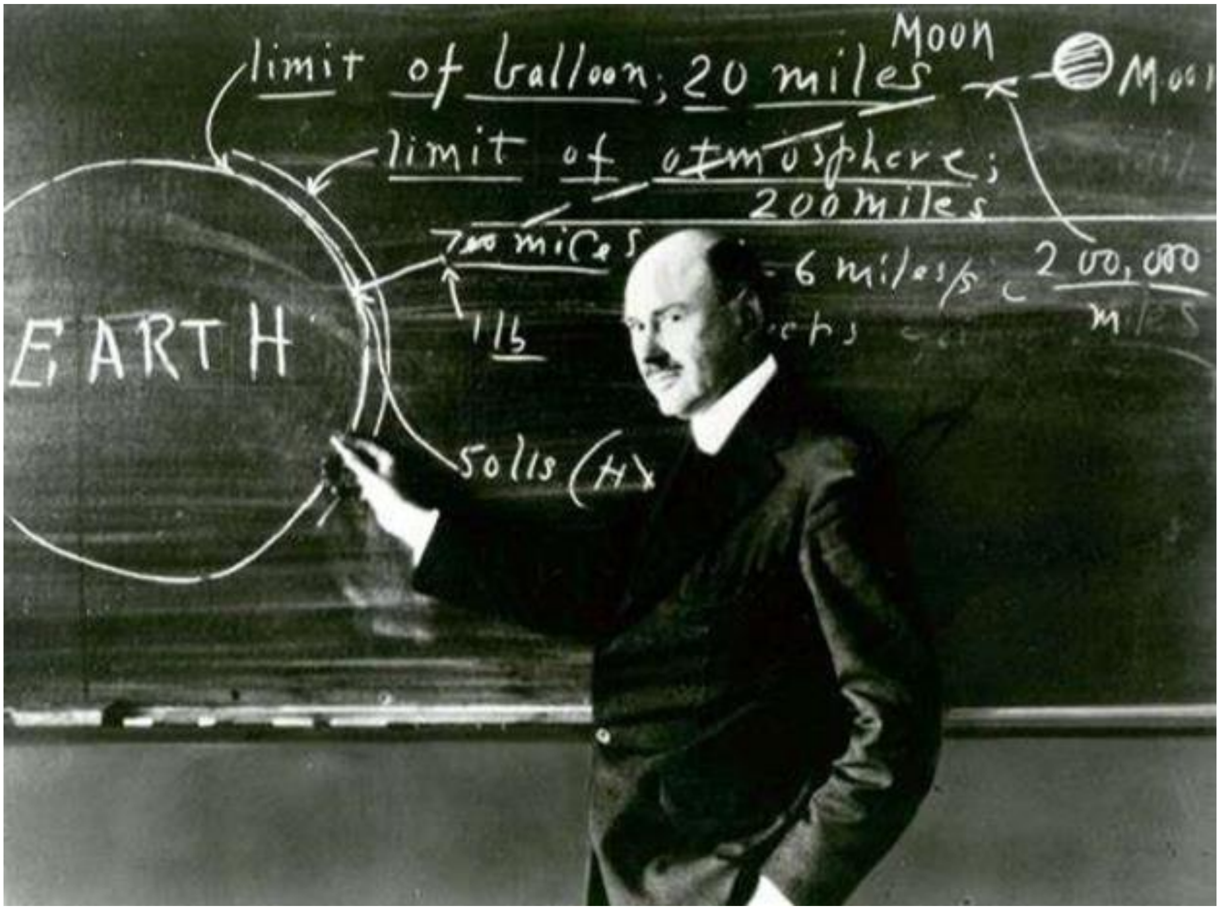
SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

[1] David Baker, *Rocket 1942 Onwards Owners Workshop Manual*, (Sparkford, UK: Haynes publishing, 2015)
[2] Wikipedia Article, https://en.wikipedia.org/wiki/V-2_rocket
[3] Encyclopedia Astronautica, http://www.astronautix.com/v/v-2.html

V-2 with Meillerwagen

back to Table of Contents

Dr. Robert H. Goddard



"The Father of Modern Rocketry"
"It is difficult to say what is impossible, for the dream of yesterday is the hope of today and the reality of tomorrow." - Robert Hutchings Goddard (1882-1945)

Physicist and inventor Dr. Robert H. Goddard is usually referred to in the U.S. as the father of modern rocketry and space flight. Historians would probably say that Goddard was certainly one of the fathers of modern rocketry and space flight. Konstantin Tsiolkovsky of Russia established the theoretical basis of rocket propulsion by 1896, and in France, Robert Esnault-Pelterie independently derived the same theories by 1913. Goddard's unique contributions were turning theory into practice, building the first liquid propellant rocket in 1926 and continuing to build and test innovative rocket components for the rest of his life. Shortly after Goddard, Hermann Oberth and Wernher von Braun in Germany took the final steps of pushing Goddard's innovations from the laboratory and experimental tests into production designs, culminating in the world's first ballistic missile, the V-2.

In the early 20th century, Goddard conceived and developed many key concepts for later development of ballistic missiles, earth-orbiting satellites and interplanetary exploration. The U.S. Air Force's strategic missile and space launch capabilities are built on the foundations laid by this American pioneer.
As a young man, Goddard was inspired by science fiction, and he became convinced that space travel was possible with rockets. In 1914 Goddard patented the concept of multi-stage rockets and liquid-fueled rockets. In 1916 he wrote about the possibility of a rocket going fast enough to leave the earth's atmosphere, and even reaching the moon. This paper was later published in 1919.[1] The press ridiculed Goddard's ideas and the government paid little attention to his work. Ironically, after developing improved military rockets including a prototype of the later bazooka, he demonstrated his products in November

1918 to the Army, Navy, and Army Air Corps at Aberdeen Proving Ground, Maryland. Although his audience was very impressed, the end of WWI less than a week later removed any incentive to capitalize on his work.[2]

His ideas, however, found a following in Germany, which later took many of Goddard's ideas to develop the V-2 rocket, the only operational ballistic missile used during World War II.

Pioneering Rocket Work

Goddard's paper titled "A Method of Reaching Extreme Altitudes" was published by the Smithsonian Institution in 1919 and not only derived the theory of rocketry but boldly projected the possibility of launching payloads even beyond the earth's gravity. Beyond the theory and new speculation, it also documented significant experiments with solid rockets, applying his theory to physical results. He boldly proclaimed "Experiments will be described below which show that, by application of the above principles, it is possible to convert the rocket from a very inefficient heat engine into the most efficient heat engine that ever has been devised." By using higher energy propellant, steel cases to increase combustion pressure, and incorporating the De Laval (converging-diverging) exhaust nozzle, he demonstrated that while rockets of his day produced about 1000 ft./sec. exhaust velocity at 2% efficiency, his improvements yielded exhaust velocities of about 8000 ft./sec. at up to 64% efficiency! With a goal of lofting scientific payloads high above the 20 mile limit imposed by balloons of the day, he realized that rockets could easily reach earth escape velocity (about 25,000 mph) and thus reach "any altitude".[1]

Goddard registered 83 patents related to rockets during his lifetime, and his executors registered 131 more based on his diaries and comprehensive research notes.[2] His most important experimental breakthrough came in 1926, when he built and tested the first successful liquid-fueled rocket. On March 16, in a field near Worcester, Massachusetts, his rocket flew for just 2.5 seconds and rose to a height of only 41 feet, but it proved that liquid-fueled rockets worked. Eventually he needed a less populated area to safely launch rockets, and Goddard moved his research to Roswell, N.M., in 1930.

There, Goddard and a small team of assistants built rockets which used high-speed pumps to deliver fuel to rocket engines, another fundamental idea still in use today. His most significant achievement in New Mexico came in 1941, when one of his rockets rose to a height of 9,000 feet. After the U.S. entered WWII, Goddard tried to convince the military of the potential value of rockets, but the government saw no usefulness to the war effort in his research. Disappointed, Goddard instead went to the U.S. Navy to work on jet-assisted takeoff rockets for aircraft, and to develop a "throttleable" rocket engine.

Influence on Space and Missiles

Goddard's ideas established several fundamentals of modern rocketry and space flight. Along with his mathematical calculations establishing the idea of "escape velocity" (the speed required to break away from earth's gravitational pull), Goddard proved that rockets would provide thrust in a vacuum, that is, they would work outside of the earth's atmosphere.

In addition to building and launching the first liquid-fueled rocket, Goddard also was the first to put cameras and scientific instruments on a rocket and use a parachute to protect the payload on landing.[2] Among his other inventions was the concept of using gyroscopes to stabilize rockets, and steering rockets by using moveable vanes for steering both in the airstream and to deflect exhaust gas. Goddard also pioneered "film cooling" using a rocket's liquid fuel to cool the thrust chamber and keep it from melting. This feature can be seen today in the German V-2 engine. Other innovations included propellant turbopumps, a gas generator to drive the turbopump, clustered engines, and a "movable tailpiece" (gimballed engine) for more efficient steering.[2]

Belated Honors

Goddard was not credited for his pioneering work until after his death in 1945 at age 62. In 1959 Congress recognized him with a gold medal, and only then was he rightly honored as the "father of space flight." That same year, the National Aeronautics and Space Administration (NASA), named the Goddard Space Flight Center, Md., in his honor. In 1960 the government awarded his estate $1 million for the use of his many rocket patents.

Finally, the New York Times -- having famously ridiculed Goddard's intellect in 1920 -- admitted it was wrong after Apollo 11 lifted off on its way to the moon in 1969.

TOUR POINTS:

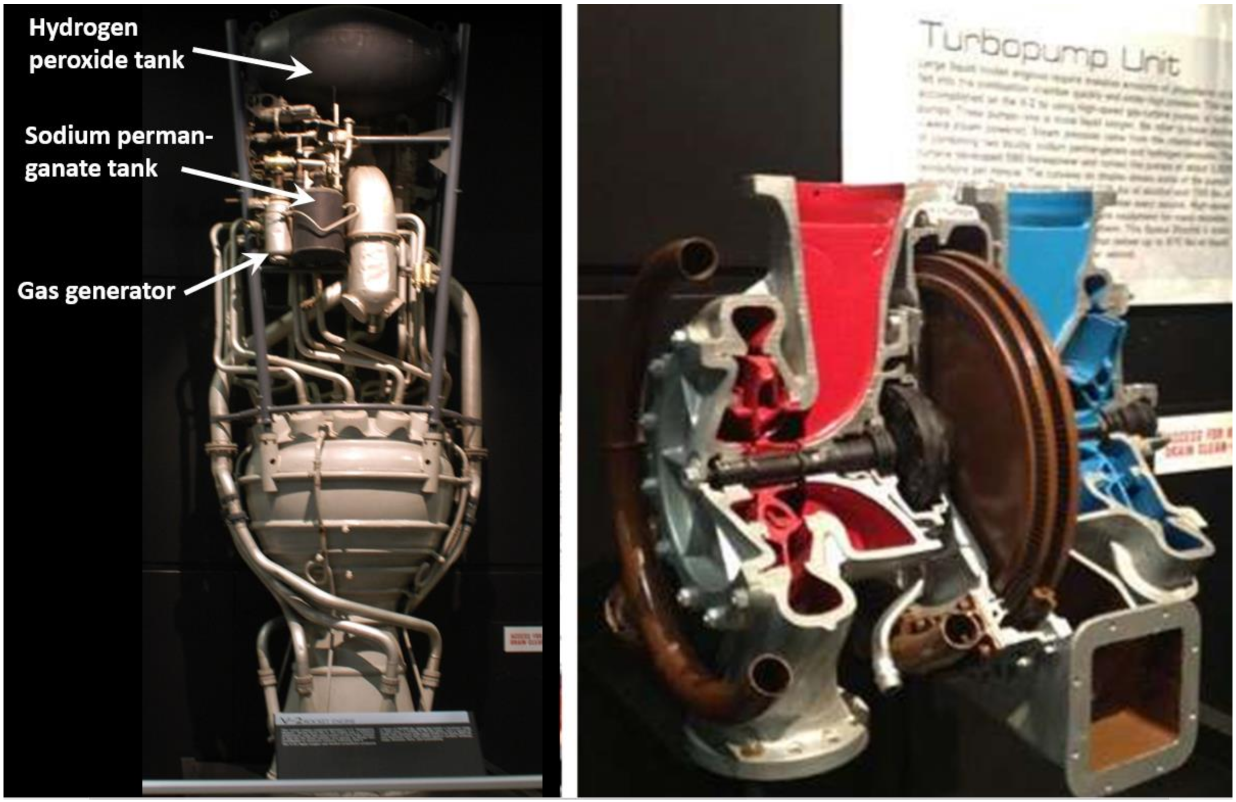
- Inspired by science fiction, Goddard was convinced that space travel was possible with rockets and patented multistage rockets and liquid fueled rockets. In 1926 he demonstrated the first successful liquid rocket in Massachusetts.
- He and his executors registered more than 200 patents related to rockets
- Tested significantly larger rockets in New Mexico reaching speeds of 600 mph and heights of nearly two miles. Demonstrated high-speed turbopumps, gyroscopic stabilization, parachute recovery, steering by jet vanes and gimballed nozzles.
- Although his work was not embraced by the US military, those in Germany were anxious to learn from his many innovations - many of which were incorporated in the V-2.
- The New York Times apologized in 1969 after ridiculing his theories in 1920

SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

[1] A Method of Reaching Extreme Altitudes, RH Goddard, published by the Smithsonian in 1919
[2] Esther C Goddard and G Edward Pendray, *Robert H. Goddard - Diary of the Space Age Pioneer*, (Prentice-Hall, 1948)

Dr. Robert H. Goddard   back to Table of Contents

V-2 Rocket Components



V-2 Turbopump Unit cutaway on display shows some of the pumps' moving parts. The turbopumps forced 128 pounds of alcohol and 159 pounds of liquid oxygen into the V-2's combustion chamber every second. (U.S. Air Force photo)

This rocket engine powered Germany's V-2 "Vengeance Weapon" during World War II. The engine was a technical achievement, using high-speed pumps to move large volumes of propellants into the thrust chamber very quickly. Its design also contributed directly to American and Soviet rocketry following WWII.

The V-2's liquid oxygen and alcohol propellants produced a thrust of 56,000 pounds, giving the rocket a maximum range of 220 miles, an typical ceiling of 50-60 miles, and a speed of 3,400 mph. Germany made over 6,000 V-2s during 1944-1945 and launched more than 2,600 against London, Antwerp, Liege, Brussels, Paris and Luxembourg.

Powering the V-2 Rocket

The German V-2 of WWII featured the largest and most powerful rocket engine up to that time. Very advanced for the 1940s, it paved the way toward more powerful rockets developed in the 1950s and later. Two critical engine parts -- the turbopump assembly and the thrust chamber -- are components of the complete engine on display in the museum's Missile Gallery. An entire V-2 rocket is on display in the World War II Gallery.

Turbopump Unit

Large liquid rocket engines require massive amounts of propellants to be fed into the combustion chamber quickly and under high pressure. This was accomplished on the V-2 by using propellant pumps driven by a steam turbine. These pumps -- one to move liquid oxygen, the other to move alcohol/water -- were driven by a steam turbine, with the pumps and turbine integrated into an assembly called a turbopump. Steam pressure came from the chemical reaction of combining two liquids, hydrogen peroxide and sodium permanganate in a device called a gas generator. The turbine developed 580 horsepower and turned the pumps at about 3,800 revolutions per minute. The cutaway on display shows some of the turbopumps' moving parts. The turbopumps forced 128 pounds of alcohol and 159 pounds of liquid oxygen into the V-2's combustion chamber every second.

High-speed turbopumps have been critical rocket engine equipment for many decades, and even the most recent rockets use them. The space shuttle's main engines, for example, used turbopumps that delivered up to 970 pounds of liquid oxygen and 162 pounds of liquid hydrogen per second.

Thrust Chamber

Another important component in the V-2 design was its thrust chamber, which had three important features: its propellant-mixing system, its cooling method and its shape.

Mixing: The twin turbopumps forced alcohol and liquid oxygen through small nozzles under high pressure into mixing "cups" at the top of the chamber. These innovative nozzles sprayed a mist of tiny droplets, making the mixture burn efficiently and with tremendous force.

Cooling: The temperature inside the thrust chamber was about 4,800 degrees Fahrenheit, hot enough to melt steel. Cooling the chamber, therefore, was critical to preventing the engine from destroying itself. The V-2's designers used two methods to cool the engine: regenerative cooling and film cooling. Regenerative cooling used the rocket's water/ethyl alcohol fuel to remove excess heat. This liquid circulated between the thrust chamber's double walls, cooling them before being forced through the injector nozzles. At the same time, film cooling used a thin layer of alcohol to cool the inner chamber walls. This alcohol film was injected through small holes in the chamber wall and formed a barrier between the rocket's flame and the chamber structure.

Shape: The chamber's short, round shape made the engine more efficient than older designs which were longer and thinner. The round upper part mixed and burned propellants effectively, and the wide opening at the bottom allowed rapidly expanding gasses to escape with minimal friction. Careful design of thrust chambers is important to liquid rocket engines because the power and stability of fuel combustion depends largely on the shape and size of the chamber.

TOUR POINTS:

- The V-2 not only was historically significant as the first ballistic missile, but its design (and designers) jump-started development of large rockets in the U.S. and the Soviet Union.
- The V-2 rocket burned alcohol and liquid oxygen, and produced 56,000 pounds thrust. At launch it weighed 29,000 pounds.
- Features visible that might be highlighted:
  - Hydrogen peroxide and sodium permanganate tanks and gas generator to power the turbopump
  - Turbopump with centrifugal pumps and turbine on common shaft
  - Propellant lines to thrust chamber:
    - Oxidizer lines split out to feed cups on top of thrust chamber
    - Fuel (alcohol) lines used to cool thrust chamber by both regenerative and film cooling

V-2 Rocket Components back to Table of Contents

Rocket Engine Evolution in the United States

As WWII drew to a close, under Operation Paperclip the American Army brought back German scientists involved in developing technically advanced weapons, including about 130 rocket scientists including Wernher von Braun, who had led the development of the V-2. Over 100 V-2 rockets and spares were also captured and became the basis of large rocket development in the U.S. V-2's with various improvements were tested by both the British and the Americans, and 78 V-2's were launched in the U.S. between 1946 and 1952. These tests included the world's first two-stage rocket (1949), using a new liquid-fueled upper stage developed by the CalTech's Jet Propulsion Laboratory and the first rocket launched at Cape Canaveral (1950).[1]

The first American rocket engine to produce more thrust than the 56,000 pounds delivered by the German V-2 (A-4) engine was the Rocketdyne XLR43-NA-1, first tested in 1950. The XLR43 was originally developed for the USAF Navaho supersonic cruise missile booster, but the Navaho was never produced. Initially, this engine developed 75,000 pounds static thrust, and was adopted as the powerplant for the Army Redstone missile, the booster that launched the first American space satellite. The Redstone engine retained obvious similarities to the V-2 engine with the same throat area, same cone angle on the nozzle, same propellants, same hydrogen peroxide system for the gas generator, and the same arrangement of aerodynamic fins connected to jet vanes in the exhaust.[2] Later, modified Redstones served as the launch vehicles that lifted Navy Commander Alan B. Shepard Jr. and USAF Capt. Virgil I. Grissom into space in 1961 on their separate suborbital missions aboard Mercury spacecraft.

Increased requirements for the Navaho led to the XLR43-NA-3 in 1952 with its power output improved to 120,000 pounds and two significant improvements:

1. The double-wall construction of the thrust chamber was replaced with thin tubular walls (called "spaghetti tubes"). The spaghetti tubes cut the weight of thrust chambers by 50% and allowed elimination of inefficient film cooling.
2. The gas generator now used the same propellants as the main thrust chamber, eliminating a subsystem for separate chemicals such as hydrogen peroxide.[2]

The next development (XLR-71-NA-1, 1953) was a two-chamber version of the "120K" engine above, and another major improvement was added – the Mark 3 turbopump. Unlike previous single-shaft versions of the turbopump, the Mark 3 turbopump included a gearbox so that the turbine could operate at much higher speeds, increasing efficiency and reducing size and weight.[2]

The final development (XLR-83-NA-1, 1956) of this remarkable engine was again motivated by increased Navaho requirements, with a three-chamber version. Improvements in thrust chamber cooling allowed the engine to switch from alcohol fuel to hydrocarbon fuel (kerosene) with thrust per chamber rising to 135,000 lb.[2]

Long before the Navaho program was cancelled in 1958 the "120K" engine developed for Navaho became the starting point for the booster engines on the new Atlas ICBM. The Atlas booster engine benefited from the later Navaho engine improvements including hydrocarbon fuels and growth to 135,000 lb. thrust, and by the time it settled as the LR89, it had been boosted to 150,000 lb. thrust. The final significant improvement for the LR89 was transition from the traditional conical nozzle to a "bell nozzle" that guides all of the exhaust's momentum to one direction (parallel flow) instead of spreading it across 15 degrees – improving thrust nearly 2%. In parallel with the Atlas development, the Thor and Jupiter IRBM's inherited the Rocketdyne experience and both used the LR79 engine, similar to the LR89 in all significant features and differing only slightly in configuration details dictated by different airframe applications.[2]

The XLR43 then evolved into the Rocketdyne S-3D engine that powered the Jupiter launch vehicle. Following the S-3D was a further development leading to the LR79 rocket engine. It powered the workhorse Thor launch vehicles that, since 1962, have put many payloads into orbit or deep space.

Two more rocket engine combinations contributed much to the nation's space program. The Rocketdyne LR89 booster and the LR105 sustainer engines for the Atlas launch vehicle were used in the Mercury orbital program. The Aerojet-General XLR87 engine powered the first stage of the Titan II booster that put the Gemini spacecraft into orbit. The Titan II was also the booster planned for the abortive Dyna-Soar and Manned Orbiting Laboratory programs.

The Apollo astronauts were launched to the moon atop the gigantic Saturn launch vehicle powered by the 1.5 million pounds thrust F-1 engine. Initial development of the F-1 was begun by the USAF Rocket Propulsion Laboratory in 1955, but in 1958 the project was turned over to NASA, where it continued with great success.

TOUR POINTS:

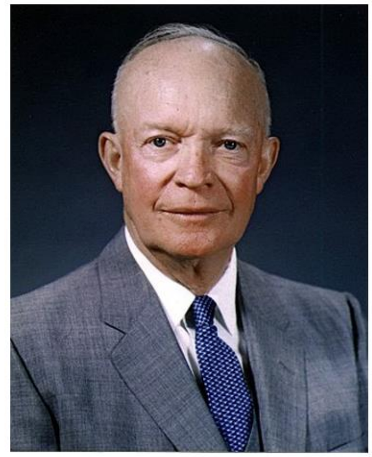
- Most early USAF liquid rockets trace their lineage directly to the V-2 and rapid technological evolution by Rocketdyne
- The Redstone used a 75,000 lb. thrust Rocketdyne engine (NAA 75-110), which was a very "short putt" from the V-2 engine
- The first U.S. astronauts went up (suborbital) on the Army Redstone rocket
- United States Air Force's first ICBM was the Atlas
- New 150,000 pound thrust booster engines developed for Atlas were adapted with little change for the Thor and Jupiter IRBM's

SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

[1] David Baker, *Rocket 1942 Onwards Owners Workshop Manual*, (Sparkford, UK: Haynes publishing, 2015)
[2] Robert S. Kraemer, *Rocketdyne: Powering Humans Into Space*, (American Institute of Aeronautics and Astronautics, 2006)

Rocket Engine Evolution back to Table of Contents

Evolution of USAF Leadership in Space


President Dwight D. Eisenhower

Shortly after WWII, many clamored to exploit the rocket technology that had made the V-2 possible. In the United States, the Army Ordnance Department, the Army Air Forces, the Navy, and various civilian organizations competed for priority and funding. When the US Air Force was created in 1947, one of its early goals was to extend its responsibilities from the stratosphere into space. Various programs were started without an overarching strategy or policy, often duplicating each other's goals, with the Truman administration never acknowledging the new space frontier. After taking office in January 1953, Dwight David Eisenhower took a personal lead in shaping the first American policies involving space. By the end of his administration the roles of all government entities including the Air Force and NASA had been established relative to space. The process was not smooth or without controversy, but these roles are largely unchanged sixty years later.

End of the 1940's

Captured V-2 technology and the technologists behind it became the starting point for serious rocket development by the Americans, British, and Russians. Under Operation Paperclip, the US Army rounded up over 200 German scientists involved in high technology programs. About 130 of them, including Dr. Wernher von Braun, agreed to work on rockets for the US Army. Work started at Ft. Bliss, TX, but soon relocated to Huntsville, AL, developing ballistic missiles initially for the Army and eventually the Saturn rockets for NASA. Col. Toftoy, Chief of the Army Ordnance Enemy Equipment Intelligence Section, had acquired enough parts to make over 100 V-2 rockets and invited scientists from various organizations to participate by providing test payloads and instrumentation. These relationships set a precedent for civilian/government scientist's participation in payload development and began a US space science community,[5] and by the end of 1945, Gen. Bernard Schriever had begun a four year tour at the Pentagon in a new role of scientific liason.[3] The contacts he nurtured would prove invaluable in his future and central role in Intercontinental Ballistic Missile (ICBM) and Intermediate Range Ballistic Missile (IRBM) development.

Significant programs involving rocket development and research into orbiting platforms were initiated within a year after Japan's surrender. The RAND corporation was initiated by Gen. Hap Arnold - initially as a special study contract under Douglas Aircraft.[3] Its first report, commissioned by Gen. Curtis LeMay, concluded that a satellite was feasible with then-current technology, could serve a variety of military missions, and would be essentially immune to enemy intervention.[5] Dozens of study contracts were issued for missiles, both jet and rocket powered, and the Navy proposed its own satellite program. In 1946 the Army Air Forces issued contracts for the Navaho and Rascal missiles, both rocket powered.[7]

In 1947 the National Security Act created the US Air Force, largely from the Army Air Forces, under the National Military Establishment (soon to be renamed the Department of Defense). It also created the Central Intelligence Agency. These new organizations would soon compete for space leadership. The National Security Act divided responsibilities relative to missiles between the Army and Air Force (basically assigning USAF control over strategic missiles and the Army having tactical and air defense missiles), but was silent relative to future satellites.[7] The USAF however, stepped out early to assert its claim for space - in January 1948 Gen. Hoyt Vandenberg, new Chief of Staff of the USAF, signed a "statement of policy for a satellite vehicle", which declared that the Air Force "as the service dealing primarily with air weapons - especially strategic - has logical responsibility for the satellite".[5] It would be several years before such responsibility stabilized, and after several iterations.

The Soviet Union's first atomic bomb was successfully detonated in August 1949, ending the American monopoly on nuclear weapons and fueling Cold War suspicions regarding nuclear capabilities and intentions. Faced with pressing gaps in intelligence, President Truman and British Prime Minister Atlee agreed the next year to cooperate in overflights of Soviet territory.[8] This preoccupation with obtaining intelligence from overflights would continue with the next administration and would shape fundamental policy decisions.

The Early 1950's

The ICBM program went from optimistic studies to a major funded program in 1954 when USAF created the Western Development Division (WDD) in Inglewood, CA, commanded by Brig. Gen. Bernard Schriever. The impetus for this commitment was a 1954 report the by the USAF Scientific Advisory Board (SAB) that asserted a breakthrough in "dry thermonuclear warhead" technology should enable a one megaton warhead by 1960 weighing about 1500 lb.[3] As a result, the Convair design for the first ICBM was pared down from five 150,000 lb. thrust engines to three, and soon became known as the Atlas. Only weeks after creation of the WDD, the SAB recommended a second design for an ICBM airframe be initiated, and this subsequently became known as the Titan.[4] Priority for the ICBM and the many technical challenges led Schriever to duplicate development of the rocket engines, the guidance system, and the reentry vehicles to assure success. USAF responsibility for land-based nuclear ballistic missiles was never challenged thereafter, but the contest over responsibility for satellites was just beginning.

General Bernard A. Schriever

In 1954 Eisenhower chartered a special study group headed by James Killian, then President of MIT and later Eisenhower's science advisor.[5] Eisenhower also established a secret peacetime strategy that made reconnaissance a national priority, and approved the highly classified U-2 reconnaissance aircraft that year, designed to fly high enough over the Soviets to obtain pictures without risk of being shot down by systems then available. Such unauthorized overflights were forbidden under international law, and the new CIA was given responsibility to make it officially a civilian, and not a military program. The Killian group was to assess the possibilities of a Soviet surprise attack, and the report the following February recommended the National Security Council (NSC) and the President recognize the ICBM program as the highest priority. Further, because of the pace of ICBM development, the group also urged concurrent development of IRBMs that could be remotely based within striking distance of the USSR.[3] Both recommendations were approved, and the Thor and Jupiter IRBMs were fielded by the USAF before the first ICBMs. The Killian final report also recommended launching a scientific satellite, which might establish the right of overflight in the regions "above" a nation's airspace and with it the precedent for the free passage of any reconnaissance satellite to follow.[3] Unaware of these secret deliberations between Eisenhower and the NSC, only months later, the USAF issued a General Operational Requirement for a reconnaissance satellite, which later became known as WS-117L, and established a Project Office at Wright-Patterson AFB.[3,5] This complexity resumes after the first satellite story.

As a result of the secrecy regarding national reconnaissance with the Eisenhower administration, the first attempts by the US to orbit a satellite were maneuvered to a non-military platform. In early 1955 Assistant SecDef Donald Quarles privately urged the US National Committee for the International Geophysical Year (IGY) to formally request a scientific satellite through the National Science Foundation. That summer Eisenhower announced the United States' intention to launch such a satellite for IGY,[3] and in August the DoD announced that the American satellite would be directed by the National Science Foundation, using a Vanguard rocket developed by the Naval Research Laboratory.[3] The Navy Vanguard had been developed from the earlier Viking research rocket and had no military application, while the Army proposal had been a modified Redstone SRBM.

Sputnik Changed Everything

The launch of the world's first artificial satellite on October 4, 1957 truly ushered in the space age, but also sent shockwaves through the free world's science, military, and intelligence communities. Not only had the Soviets surprised all with the ability to power and guide a payload into space, but the size of the payload of the 2nd Sputnik less than a month later had disturbing implications. Sputnik 2 weighed just over 1100 lb., while the satellites contemplated by Vanguard and Redstone were only 3 to 20 pounds. The Soviets had just announced the successful launch of their first ICBM that August[4], but the Sputniks had now validated real capability and their previous announcement could no longer be dismissed as just propaganda. The only plus that Eisenhower associated with Sputnik is that it set the precedent for unauthorized overflights for everybody. Only a month after Sputnik 2, the long-awaited Vanguard failed in spectacular and humiliating fashion before the international press. Together, Sputniks' success and Vanguard's failure precipitated convulsive changes in US space policy, including two total overhauls in responsibilities in less than one year.

Radical changes came quickly. Eisenhower suggested that a fourth military service might be established to handle missile activities and in November 1957, SecDef McElroy proposed centralizing control of the various American space projects along with advanced ballistic missile development. They would all be placed into a Defense Special Projects Agency. The same day that Vanguard became known as "Kaputnik", the Joint Chiefs of Staff formally stated their opposition to the new agency.[5] By January, the Defense Special Projects Agency had been renamed ARPA (Advanced Research Projects Agency) and the President's Science Advisory Committee concurred with the proposed role of ARPA except they recommended advanced ICBM research stay with the USAF.[5] The next month, ARPA was created with responsibility for all military and civilian space projects.[3]

While it seemed that ARPA had taken over "everything in American space" there were many exceptions and sidebar agreements that led to confusion and frustration among all participants. For example, USAF retained ballistic missiles (non-space but suborbital) and the Dyna-Soar program, but lost the "manned ballistic capsule project" which later morphed into Project Mercury. The USAF WS-117L reconnaissance satellite was given to ARPA, but the film-return option of WS-117L was split out as Corona and given to the CIA.[5] At the end of February, USAF's ownership of ballistic missiles was confirmed when they were given the go-ahead to start development of an advanced solid propellant ICBM and with the capability of being launched from hardened underground silos (soon to be known as Minuteman).[4]

ARPA's role as the new space agency was short-lived. Consistent with recommendations from many quarters, Killian and Nixon persuaded Eisenhower to transfer non-military space development to a new civilian agency. That agency, known as NASA, was signed into law in July 1958, but the legislation left significant latitude to the President to assign specific program responsibilities. The following month Eisenhower assigned the (non-military) role of human spaceflight to NASA.[5] Again, USAF retained responsibility for its Dyna-Soar Program. While some additional confusion resulted from the ARPA-to-NASA handoff, responsibilities were fairly clear in the unclassified world until the Space Shuttle came into use.

Classified Reconnaissance Programs

While USAF initiated its own reconnaissance program as far back as 1955, other agencies (both military and civilian) had their own priorities for intelligence gathering and thus unique requirements that spawned different platforms. This competition and the sensitivity in the early days over possible provocation from unauthorized overflights brought about a cloak of secrecy. The USAF program known as WS-117L started with three possible versions:

1- An electronic intelligence version (later SAMOS, or Satellite and Missile Observation System)
2- An imaging intelligence version that would use television to record images and download them later (found to be beyond technology of the day), and
3- An imaging intelligence version that would record images on film and return the film from orbit for processing and analysis.

During the 1958 convulsions involving ARPA, the third option was officially killed as a USAF program and then secretly resurrected as the heavily classified Corona Program. Lockheed retained design responsibility for the vehicle, including the Agena upper stage but program responsibility shifted over to the CIA. USAF retained launch responsibility using the Thor-Agena. Another early example of USAF launching a spy satellite that was not theirs was the GRAB satellite. GRAB stood for Galactic Radiation and Background, which referred only to its cover story as a research satellite. In reality, it was an electronic intelligence satellite developed by the Naval Research Laboratory to map Soviet air defense radar capability. It was successfully launched by an Air Force Thor-Able-Star in June 1960, becoming the first successful reconnaissance satellite.[8] Corona succeeded with its first film recovery mission two months later.

By 1960 Eisenhower had concluded that the diverse requirements of multiple agencies argued for centralized control. In August, Eisenhower agreed with the NSC to create a civilian agency reporting to the Secretary of the Air Force to coordinate all intelligence operations in space. The following year SecDef Robert McNamara formalized the formation of the NRO (National Reconnaissance Office), jointly directed by civilians in the DoD and the CIA. Although emphasis between DoD and the CIA shifted multiple times in the 1960's, joint management remained over the following four areas: USAF satellites, CIA satellites, Navy satellites, and CIA/USAF aircraft systems (U-2, A-12, and SR-71). The NRO remained a classified and unacknowledged program until 1992 and public notification of NRO launches did not begin until 1996. [8]

The Shuttle Years and The Present

The Space Shuttle was a complex program that significantly affected both responsibilities and working relationships of NASA and USAF, and only a brief overview is attempted in this article. The joint evolution of the Space Shuttle started with requirements negotiated between NASA and USAF concluding in 1972. USAF requirements significantly increased the size, capability, and cost of the Shuttle with payloads driven by the latest USAF reconnaissance satellite (the KH-11) and requirements for polar orbit capability and 1100 mile cross-range landing capability. The Shuttle cost model argued that all American payloads be shifted to the Shuttle, but fortunately back-up capabilities using expendable launch vehicles were maintained.[8]

While the Shuttle was unquestionably a technical marvel, it failed significantly relative to its goals of reliable and economic access to space. Its first classified payload for the NRO came four years after its first flight, launch rate was a tiny fraction of predictions, and two catastrophic failures resulted in delays of approximately three years before launches resumed. Even before the Challenger disaster in 1986, the writing was on the wall that the Shuttle would never approach the launch rates needed by the military. In 1984, USAF began development of its Titan IV launch vehicle and commercial expendable launch vehicles were being put back into the mix.

Early in the Shuttle era, the Space Command was established to consolidate launch operations, missile warning operations, and manage assets once in orbit. It was subsequently renamed Air Force Space Command (AFSPC) in 1985, and in 1993 assumed command and control over the intercontinental ballistic missiles formerly assigned to the Air Combat Command.[1] In December 2019, the Space Command was designated the United States Space Force, creating the first new military service since USAF was created in 1947.[2]

Since the retirement of the Shuttle in 2011 and the Titan IV years earlier, all government assets have been launched on commercial expendable vehicles and managed by the AFSPC. As of 2022, NRO launches are using the last of the Lockheed Martin Atlas Vs, the United Launch Alliance Delta IV Heavy, and the SpaceX Falcon.

SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

[1] https://www.afhra.af.mil/About-Us/Fact-Sheets/Display/Article/433549/air-force-space-command-usaf/

[2] https://www.cnn.com/2019/12/20/politics/trump-creates-space-force/index.html

[3] R Cargill Hall and Jacob Neufeld, editors, *The US Air Force in Space 1945 to the 21st century*, (Washington, DC: U.S. Air Force History and Museums Program, 1998)

[4] Office of the Historian, *SAC Missile Chronology, 1939-1988*, (Offutt AFB, Nebraska: HQ Strategic Air Command, 1990)

[5] John M Logsdon, editor, *Exploring the Unknown - Selected Documents in the History of the US Civilian Space Program*, (Washington DC: NASA History Office, 1996). The NASA History Series, Volume II: External Relationships

[7] Joseph T Page, *Rockets & Missiles of Vandenberg AFB* (Atglen, PA: Schiffer Military, 2019)

[8] Bruce Berkowitz, *The National Reconnaissance Office at 50 Years: A Brief History* (Chantilly, VA: Center for the Study of National Reconnaissance, 2011)

Evolution of USAF Leadership in Space   back to Table of Contents

Douglas SM-75/PGM-17A Thor

The SM-75/PGM-17A Thor intermediate range ballistic missile (IRBM) was the product of the early Cold War race to deploy nuclear armed missiles before the Soviets. Thor was designed to be an interim nuclear deterrent while the U.S. Air Force developed long-range intercontinental ballistic missiles (ICBMs) as a top national priority. The IRBM concept called for a missile with a range of about 1,500 miles that would be based in Europe. Great Britain agreed to host four IRBM bases, and 60 Thors were operational in England from June 1959 to August 1963. The first Thor was delivered to RAF Lakenheath in a C-124 in August 1958.[1] Royal Air Force crews operated the missiles, but USAF personnel controlled their nuclear warheads. Honoring a secret agreement with the Russians after the Cuban missile crisis of October 1962, withdrawal of Thors from the UK was completed by 27 September 1963.[1]

The USAF developed the SM-75 quickly. Douglas was selected in December 1955 and the first flight took place only 13 months later in January 1957.[1] Interservice competition to control the emerging strategic missile mission meant that the U.S. Army developed its Jupiter missile, which was ultimately assigned to the Air Force, at the same time. Thor's rapid design and deployment resulted from having much in common with the Atlas ICBM, which was then still in the planning stages. Thor's engines, guidance, and warhead came from the Atlas program, and only its airframe was new. Thor was the first major rocket built for operational use outside the cadre of German rocket scientists at the Army Ballistic Missile Agency in Huntsville.[1] After three failed test flights, Thor's first fully successful flight took place in September 1957. The following month, the USSR launched its Sputnik satellite - proving Soviet rocket capability and generating much anxiety in the U.S. - and President Dwight Eisenhower rushed Thor into production as a result.

The SM-75 was a single stage liquid-fueled rocket. Powered by liquid oxygen and kerosene, the vehicle could reach an altitude of about 280 miles before releasing its warhead on a ballistic (unpowered) trajectory toward its target. The missile required about 15 minutes to prepare for launch from its aboveground shelter, and could reach its target after about 18 minutes of flight.

Following its withdrawal as an IRBM when the Atlas ICBM became available, the Air Force used Thor as a nuclear atmospheric test vehicle and an antisatellite weapon.* The USAF and NASA adapted the Thor design to a very successful variety of space launch roles using upper stages (for example, see the Thor-Agena in this gallery). Thor was further developed into the Delta family of space launchers, and while the latest versions no longer use the LR79 engine or resemble the original Thor, they have continued the workhorse tradition for nearly 60 years.

**For an overview of antisatellite weapon programs, see "Vought ASM-135A Anti-Satellite Missile".*

Engine development and features

The Thor and Jupiter engines started development in 1953, about a year after Rocketdyne had started development of the Atlas ICBM engines. Seeing the challenges of ICBM development, the IRBM program was launched to provide interim nuclear deterrent earlier. Despite the later start, both IRBMs made their first flights and went operational before the first ICBM. Because of the decisions above, Thor and Jupiter inherited the same technological advancements that the Atlas ICBM engine enjoyed.[2] See the article "Rocketdyne LR79" for additional information.

A significant difference between the Thor and Jupiter LR79 was that the Thor inherited the two small 1000 lb. thrust vernier engines directly from the Atlas ICBM for roll control and precise velocity adjustments after the main engine was shutdown. On the Jupiter, the turbine exhaust was used as a roll thruster and separate verniers were not required. The Thor engine began flight test at 135,000 lb. sea level thrust, but for production as an IRBM, the thrust was 150,000 lb. at sea level.[2]

TECHNICAL NOTES

Warhead: Single W-49 in the megaton range
Engines: One Rocketdyne LR79-NA-9 of 150,000 lbs. thrust; two Rocketdyne LR101-NA vernier engines (for small velocity adjustments and roll control) of 1,000 lbs. thrust each
Guidance: All-inertial
Range: 1,500 miles
Length: 65 ft.
Diameter: 8 ft.
Weight: 110,000 lbs. (fully fueled)

TOUR POINTS:

- First operational IRBM, deployed in 1958 with the last retired in 1963
- Utilized the same 150,000 pound thrust Rocketdyne LR79 engine as the Jupiter IRBM, both developed in parallel with the Atlas ICBM engines
- Used 2 small vernier engines (from Atlas) for roll control and final velocity adjustment
- Sixty missiles were deployed in Great Britain
- US Air Force crews were responsible for the nuclear weapons and the RAF were responsible for missile operations

SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

[1] David Baker, *Rocket 1942 Onwards Owners Workshop Manual*, (Sparkford, UK: Haynes publishing, 2015)
[2] George P. Sutton, *The History of Liquid Propellant Rocket Engines*, (American Institute of Aeronautics and Astronautics, 2006)

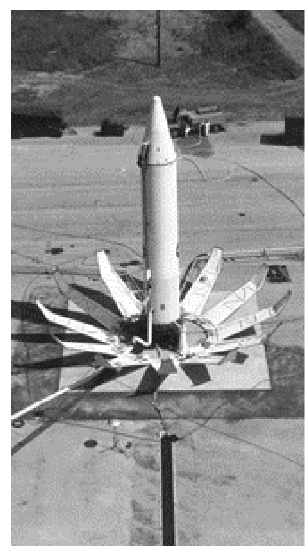
Douglas SM-75/PGM-17A Thor back to Table of Contents

Chrysler SM-78/PGM-19A Jupiter

The Jupiter Intermediate Range Ballistic Missile (IRBM), in service from 1960 to 1963, was an important link between early, short-range rockets and later weapons that could reach any point on Earth. Jupiter was a close relative of the Army's Redstone missile, and its development began in 1956 as a joint U.S. Army and U.S. Navy project. Rocket pioneer Wernher von Braun conceived the Jupiter after the Redstone proved successful, and rockets with a range of up to 1,500 miles seemed possible. Soviet development of similar missiles around the same time underscored the need for Jupiter. President Dwight Eisenhower gave the IRBM high priority in weapons development, second only to the Intercontinental Ballistic Missile (ICBM).

Originally designed for shipboard use, (hence the squat proportions to minimize height), Jupiter was a compromise between Army and Navy designs. In 1956, the Department of Defense gave the USAF responsibility for building and operating all IRBMs, and limited the range of any missiles deployed by the Army to less than 200-miles, but the Army continued developing Jupiter in case the Air Force's Thor IRBM program failed. The Navy dropped out of the Jupiter program in December 1956, shifting their focus on the solid propellant Polaris missile.[1] The first successful Jupiter launch took place in May 1957.

In October 1957, the USSR launched Sputnik, the first satellite - an event that caused the U.S. to greatly speed up missile development to counter the Soviet threat. As Jupiter was quickly made ready, the U.S. explored basing options. The single-stage missile's range of 1,500 miles required bases on the periphery of the USSR. Negotiations with France proved unsuccessful, and finally Italy and Turkey accepted IRBM bases. Italian and Turkish crews trained to operate the missiles, but Americans controlled the nuclear warheads. Two squadrons with a total of 30 missiles were operational at Gioia del Colle, Italy, by 1961; a single squadron of 15 Jupiters became operational at Cigli Air Base, Turkey, in 1962. Due in part to the Cuban Missile Crisis of 1962, the U.S. removed its Jupiter missiles from Italy and Turkey by July 1963.



The Jupiter was launched from an austere and unprotected pad. A "petal enclosure" was used to provide maintenance personnel some protection from the elements, but there was no protection from possible attack (such as silos used by later ICBMs). A Jupiter based in Turkey is shown at right with the petal enclosure in place. It is not surprising that some of the locals mistook the Jupiters for minarets. The second picture show the enclosure in the open or launch configuration.

While the Thor, Atlas, and Titan II all resulted in derivative designs that served for many decades as space launch vehicles, Jupiter's space launch career was brief. With solid propellant upper stages similar to those used on the Army Juno I (modified Redstone) that launched America's first satellite, the Jupiter launch vehicle took the name Juno II. Its first mission (a failure) in December 1958 came under the auspices of NASA, which had just been created that year. It had only four successful missions in ten tries over three years, but its second mission successfully launched Pioneer IV. Pioneer IV was a lunar probe that went beyond the moon to become the first man-made object to escape earth's gravitational attraction.[1]

Engine development and features

The Jupiter and Thor engines started development in 1953, about a year after Rocketdyne had started development of the Atlas ICBM engines. Seeing the challenges of ICBM development, the IRBM program was initiated to produce interim nuclear deterrent earlier. Despite the later start, both IRBMs made their first flights and went operational before the first ICBM. Because of these decisions, Jupiter and Thor inherited the same technological advancements that the Atlas ICBM engine enjoyed.[2] See the article "Rocketdyne LR79" for additional information.

While the Thor used two small vernier engines for roll control and precision in final velocity, the Jupiter instead used the turbine exhaust as a roll thruster by controlling the angle of the exhaust.[2]

Other subsystems on the engine included electrical, pneumatic and hydraulic systems and a lubrication system for the turbopump. Electrical and hydraulic power were provided from ground sources until liftoff. Engine hydraulic pressure after liftoff was supplied by a pump mounted on the turbopump gearbox. Hydraulics powered the gimbal actuators, roll actuator, and the thrust control valve. Gas spheres in the missile were replenished by ground supplies until liftoff. Starting propellants for both the gas generator and main thrust chamber were kept in spherical, pneumatically pressurized, ground-mounted tanks. Ignition was provided by pyrotechnic igniters. An early requirement to observe a 10g limit on the airframe led to the need for throttling capability on the engine, but the 10g limit was dropped and throttling capability was never implemented.[3]

TECHNICAL NOTES

Warhead: Single W-49 in the megaton range
Engine: One Rocketdyne S-3D of 150,000 lbs. sea level thrust, burned approximately 3 minutes[3]
Guidance: All-inertial
Range: 1,500 miles
Length: 60 ft.
Diameter: 8 ft. 9 in
Weight: 108,804 lbs. (fully fueled)

TOUR POINTS:

- America's second IRBM (after Thor), deployed in 1961 and retired in 1963 as a result of the Cuban missile crisis resolution
- Originally developed by the Army and Navy, it was turned over to the Air Force in 1956 following a Secretary of Defense decision that weapons with ranges of greater than 200 miles would belong to the Air Force
- Utilized the same 150,000 pound thrust Rocketdyne LR79 engine as the Jupiter IRBM, both developed in parallel with the Atlas ICBM engines
- Instead of verniers for roll (like Thor), the Jupiter used the turbine exhaust for roll control - it could swivel +/- 25^{o} from the vertical
- A total of 45 missiles were deployed in Italy and Turkey
- Italian and Turkish air force crews were responsible for operating the missile and the USAF personnel retained responsibility for the nuclear weapons

SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

[1] David Baker, *Rocket 1942 Onwards Owners Workshop Manual*, (Sparkford, UK: Haynes publishing, 2015)
[2] George P. Sutton, *The History of Liquid Propellant Rocket Engines*, (American Institute of Aeronautics and Astronautics, 2006)
[3] JD Hunley, editor , "History of Rocketry and Astronautics", AAS History Series, Volume 20, IAA History Symposia, Volume 12, and the American Astronomical Society Publication, 1991)

Chrysler SM-78/PGM-19A Jupiter back to Table of Contents

Martin Marietta SM-68A/HGM-25A Titan I

Entering operational service in 1962, Titan I was the United States' first multistage ICBM (Intercontinental Ballistic Missile). Incorporating the latest design technology, Titan provided an additional nuclear deterrent to complement the U.S. Air Force's Atlas missile. Though the Titan I was operational for only three years, it was an important step in building the Air Force' s strategic nuclear forces.

Titan began as a recommendation from Gen. Schriever in October 1954 for a more conservative backup to Atlas, which some engineers suspected of being too radical to succeed. Schriever also sought a second contractor as a hedge against placing too much work with a limited number of companies. The Air Force approved the program on 2 May 1955, four months after the Western Development Division had awarded Aerojet a contract for development of a LOX/hydrocarbon engines that might be required as backup to the Rocketdyne engines for Atlas.[2] It is no coincidence that the thrust chambers of both the Titan I first stage and Atlas boosters each started out at 150,000 lb. sea level thrust.

The first American ICBM based in underground silos, Titan I gave USAF managers, contractors and missile crews valuable experience building and working in vast bunkers containing everything the missiles and crews needed for operation and survival. These early silos, however, had certain drawbacks. First, the missiles took about 15 minutes to fuel, and then had to be lifted to the surface on huge elevators for launching, which further slowed their reaction time. Rapid launching was crucial to avoid possible destruction by incoming missiles, even though Titan silos were designed to withstand nuclear blasts. Second, the missiles' placement close together in groups of three - necessary because they shared a single ground-based radio guidance system - made them vulnerable to enemy attack. An all-inertial guidance system, which does not depend on ground computers, was not yet perfected.

In its brief career, Titan I equipped six squadrons of nine missiles each, in Colorado, Idaho, California, Washington state and South Dakota. Although Titan I's two stages gave it true intercontinental range and foreshadowed future multistage rockets, its propellants were dangerous and hard to handle. Super-chilled liquid oxygen oxidizer had to be pumped aboard the missile just before launch, and complex equipment was required to store and move this liquid. Kerosene fuel also was pumped aboard just before launch.

Titan I allowed USAF missileers to perfect techniques for efficiently operating strategic missile facilities spread across several states and requiring great coordination and skill. Still, the Titan I was a transitional missile. Even as the USAF deployed 54 Titan Is on operational alert from 1963-1965, it prepared to deploy more advanced Titan IIs in their place. Later missiles, like Titan II, used safer fuels and more advanced guidance, but followed the Titan I example of underground basing and multiple stages.

Engines

The Stage I rocket engine, designated LR87-AJ-3, consists of two engine subassemblies. The two subassemblies develop a total of 300,000 pounds of thrust (at sea level) and are mounted on a common engine frame that transfers the thrust to the missile airframe. The subassemblies are similar and are interconnected by instrumentation and electrical components. The subassemblies are started and shut down simultaneously, by a common control system. Each engine subassembly includes a thrust chamber assembly, a turbopump assembly (TPA), a gas generator assembly, and propellant lines and valves. One subassembly also contains a helium heat exchanger in the exhaust of the #2 gas generator to provide pressurization for both propellant tanks. The engines are started by a bank of nitrogen bottles (ground support equipment) which start the turbopump assembly spinning until the gas generator takes over. Both the main thrust chambers and the gas generators use electrical ignitors to start combustion. Both chambers are gimballed to provide pitch, yaw and roll control.[1]

The stage 2 rocket engine, the LR91-AJ-3, consists of a single thrust chamber rated at 80,000 lbs. thrust at altitude, and basic operation is similar to each of the two subassemblies in the stage 1 engine. The thrust chamber is gimballed to provide pitch and yaw, but for roll, four vernier nozzles are arranged around the main thrust chamber, and each can be rotated for roll control. After the main thrust chamber is shut down, the verniers operate in a "vernier solo mode" for stage final velocity trimming and separating from the warhead. With the main turbopump assembly shut down, a smaller auxiliary turbopump assembly provides propellants to the gas generator, whose hot gasses are diverted to the auxiliary turbopump and the vernier nozzles.[1] Because the 2nd stage engine does not operate at low altitudes, its nozzle incorporates a large expansion ratio. Although the thrust chamber was fuel-cooled as far as the throat, the large diverging section was not actively cooled, but incorporated an ablative liner.[3]

TECHNICAL NOTES:

Warhead:	Single nuclear warhead in the megaton range
Re-entry vehicle:	Avco Mark 4, ablative
Engines:	(1st stage) Aerojet LR87-AJ-3 of 300,000 lbs. thrust; (2nd stage) Aerojet LR91-AJ-3 of 80,000 lbs. thrust
Propellants:	RP-1 kerosene fuel and liquid oxygen oxidizer
Range:	6,300 miles
Length:	98 ft.
Diameter:	10 ft.
Weight:	223,000 lbs.[2]

TOUR POINTS:

- While the Atlas was our first ICBM and lit all its engines at launch, Titan was the first U.S. truly multistage ICBM, operational in 1962
- Used kerosene and liquid oxygen, requiring nearly 30 minutes to raise the missile from its silo to surface for launch and load the propellants
- Radio guidance system required missiles to be clustered in groups of 3
- 54 missiles, operational for only three years
- First stage Aerojet General LR87 300,000 pounds thrust; second stage Aerojet general LR91 80,000 pounds thrust

SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

[1] T.O. 21M-HGM25A-1.1, *Technical Manual - Operational and Organization Maintenance USAF Model HGM-25A Missile Weapon System Operation* (USAF)

[2] David Baker, *Rocket 1942 Onwards Owners Workshop Manual*, (Sparkford, UK: Haynes publishing, 2015)

[3] George P. Sutton, *The History of Liquid Propellant Rocket Engines*, (American Institute of Aeronautics and Astronautics, 2006)

Martin Marietta SM-68A/HGM-25A Titan I back to Table of Contents

Martin Marietta SM-68B/LGM-25C Titan II

The Titan II, developed from the Titan I ICBM, was on operational alert from 1963-1987 and was the largest and most powerful American nuclear-armed missile. The Titan II also enjoyed a long career as a space launch vehicle, sending satellites and manned spacecraft into earth orbit.

While the Titan I system was becoming operational, the USAF recognized that it could be simplified to reduce costs and improve reliability. The genesis of the improved Titan II can be dated to July 1958 when the Air Force examined a variety of possible changes that included more powerful engines, a larger second stage, storable propellants, in-silo launch and an all inertial navigation system.[1] Using the same manufacturing and test facilities, the Titan II took shape as a major step forward in ICBM technology. Perhaps Titan IIs most important feature was its quick-launch capability. It could be launched in about 60 seconds from inside its underground silo. (Titan I fuel (RP-1) was loaded in the silo, and the missile was raised to the surface to load the oxidizer (LOX). It took nearly 30 minutes to prepare Titan I for launch.). This speed was crucial in responding to a preemptive nuclear attack before incoming missiles arrived.

New "hypergolic" liquid fuels made Titan II's quick launches possible. Hypergolic fuels ignite on contact with one another, eliminating the need for an ignition system, and they can be stored indefinitely near room temperature inside the missile. Partly as a result of using these new propellants, the Titan II had fewer parts and a simpler design than the Titan I. Reliability was considerably enhanced by simplifying and reducing parts count. Relative to the Titan I, the Titan II reduced: 125 active control components to 30; 245 moving parts to 111, and 172 relays, valves & regulators to 27. Stored supplies of helium or nitrogen were eliminated using cooled gases from the turbine exhaust to maintain propellant tank pressures.[1] Also, a new silo design vented the tremendous blast of Titan II's improved engines away from the missile, allowing in-silo launching and eliminating the need to elevate the Titan II to ground level before launch.

Another innovation of the Titan II relates to the various gaps and holes between the first and second stage. During staging the delays traditionally associated with shutting down the first stage and allowing the stages to separate a safe distance could allow the second stage to decelerate over 100 ft./sec. On the Titan II a "hot separation" reduces the transition to a minimum by allowing the second stage to fire while it is still attached to the first stage. The holes and gaps allow the exhaust gases to safely vent during the transition and when the second stage thrust assures clean separation, explosive bolts free the second stage to proceed.[3]

Titan II's advanced "all-inertial" guidance system made the missile less vulnerable to enemy attack. Each Titan II carried its own self-contained guidance equipment and no longer relied on ground computers. This improvement made widely dispersed bases possible, and Titan II sites were typically several miles apart, enhancing survivability during a potential nuclear strike. At the height of Titan II operations, the USAF deployed 54 Titan IIs at three bases in Arizona, Kansas and Arkansas. Each base had two squadrons of nine missiles each. The combat crew for a single missile included two officers and two enlisted personnel, but many support troops were required to maintain the missiles, train crews, and provide security.

In 1981 the USAF undertook a missile modernization program, and Titan II ICBM operations ceased in 1987. Spare Titan IIs were converted to space boosters and used to launch satellites. This role was not new for Titan II, since this powerful and reliable rocket had been used for many years in civil and military space programs. Titan IIs launched manned Gemini missions for NASA in the mid-1960s, and later Titans evolved into more powerful space boosters with the addition of "strap-on" solid rockets, launching some of the most important U.S. military satellites.

Engines

The Stage 1 rocket engine, designated LR87-AJ-5, was very similar to the -3 version used on the Titan I. The most significant change was from LOX/RP-1 to nitrogen tetroxide oxidizer and Aerozine 50 fuel, a 50/50 mix of monomethyl hydrazine and unsymmetrical dimethylhydrazine (UDMH) developed by Aerojet General. These hypergolic fuels enabled long term storage without cryogenic boil-off and eliminated ignition components (because they ignite spontaneously on contact). Thrust was uprated 43% through higher propellant mass flow and a slight increase in chamber pressure. Solid propellant starter cartridges were added to pre-spin the turbopump turbine, further simplifying the start sequence.

Tank pressurization, a critical component to maintaining airframe rigidity, was accomplished on the Titan I using liquid helium carried on board and heated in the turbine exhaust. On Titan II, the helium pressurization system was eliminated. Oxidizer was bled off and heated in the turbine exhaust and used to pressurize the oxidizer tank, and a small amount of turbine exhaust was bled off, cooled with fuel, and used to pressurize the fuel tank.[3]

A Coded Switch System (CSS) prevented an unauthorized or inadvertent missile launch. The Stage 1 engine oxidizer valve was locked in the closed position. A valid operator code had to be entered into the CSS, removing the launch-disable signal and providing a launch-enable signal that unlocked the valve. The status of each valve lock in the missile wing was monitored at the wing command post.[2]

The stage 2 rocket engine, the LR91-AJ-5, shared similar improvements from Titan I. The same hypergolic fuels were used as on stage 1, thrust increased 25%, and starter cartridges simplified the start sequence. Roll control on stage 2 was simplified considerably from the four vernier nozzles used on Titan I. Turbine exhaust was routed to a single nozzle controlled by a hydraulic actuator. Pressurization of the stage 2 oxidizer tank was not required in flight, and the fuel tank was pressurized by utilizing cooled exhaust gas as with stage 1.[2]

Additional details extracted from Reference 2 below:

> ROCKET ENGINE SYSTEM
> The Stage 1 rocket engine consists of two independent subassemblies mounted on a single engine frame. Each subassembly contains a thrust chamber assembly, a turbopump assembly, a gas generator, and an engine start system. The two subassemblies have an integrated electrical system for simultaneous operation.
>
> Prior to Stage 1 rocket engine operation, the missile prevalves are opened to allow propellant to flow through the suction lines to the rocket engine. At countdown T-zero, a 28 vdc signal is applied to the two solid-propellant starter cartridge initiators. Ignition and burning of the gas pressure generator produces hot gases which are directed through an inlet nozzle to the turbopump assembly turbine for initial acceleration and running of the turbine. The turbine, through a gear train, drives the fuel and oxidizer pumps. The fuel and oxidizer pumps deliver propellants through discharge lines to the thrust chamber valves. When fuel discharge pressure within the fuel discharge lines reaches 310 psi, thrust chamber valve pressure sequencing valve opens. Through mechanical coupling, the thrust chamber fuel and oxidizer valves open, fuel flows down the thrust chamber coolant tubes, back up into the injector, and is emitted into the combustion chamber. Oxidizer flow is directly through the injector into the combustion chamber. The propellants ignite hypergolically and the flow of expanding gases from the nozzle produces thrust. Rocket engine sustained operation is dependent upon bootstrap operation involving the turbopump assembly and the gas generator. Simultaneously with the flow of propellants to the thrust chamber, a small amount of fuel and oxidizer is drawn off below the thrust chamber valves into gas generator fuel and oxidizer lines. Cavitating venturis, located in the gas generator lines, control propellant flow to the gas generator. Propellant pressures open the check valves installed in the lines, allowing propellant to enter the gas generator. The propellants ignite hypergolically and a fuel-rich gas is produced which enters the turbine inlet, drives the turbine, and thereby sustains turbopump assembly

operation. An autogenous pressurization system is used for inflight propellant tank pressurization. The system utilizes a small portion of cooled exhaust gas to pressurize the fuel tank.

The oxidizer tank is pressurized by directing a small amount of oxidizer into an autogenous system super-heater where the oxidizer is heated and converted to a gas. The expanding gas is directed to the oxidizer tank for inflight tank pressurization. Stage 1 engine shutdown occurs when either oxidizer or fuel is depleted, causing a subsequent drop in thrust chamber pressure which is detected by the thrust chamber pressure switch. When this lower pressure is sensed, a signal is sent to the thrust chamber pressure sequencing valve to initiate closing of the thrust chamber valves, thereby terminating rocket engine operation. Simultaneously a signal is sent to the Stage 2 separation nut squibs and gas pressure generator to initiate Stage 2 separation and rocket engine start.

The Stage 2 rocket engine consists of a thrust chamber assembly with ablative skirt, turbopump assembly, gas generator, fuel tank autogenous pressurization system, roll control assembly, and engine control system.

Except for minor differences, the Stage 2 rocket engine operates the same as the Stage 1 rocket engine. The initial start signal for the Stage 2 rocket engine is transmitted from the thrust chamber pressure switches located on the Stage 1 rocket engine. At Stage 1 engine shutdown, a signal is transmitted from the Stage 1 pressure switches to initiate the Stage 2 solid propellant starter cartridge and separation nut squibs. The rocket engine self-sustaining and shutdown operations are similar to those of Stage 1; however, the shutdown signal for Stage 2 is initiated by the missile guidance set. A roll control nozzle, utilizing exhaust gas from the gas generator, is incorporated in the system to provide roll control of the missile during Stage 2 operation. The roll control nozzle is connected to a hydraulic actuator installed between the missile and the roll control assembly. The flight control system receives guidance signals from the missile guidance set and sends control signals to the actuator. Pressurization of the Stage 2 oxidizer tank is not required in flight. The Stage 2 fuel tank is pressurized by utilizing cooled exhaust gas.

AIRBORNE PROPELLANT SYSTEM

The airborne propellant system consists of fuel and oxidizer tanks, disconnects, pressure transducers, storage valves, and pressurization and vent piping. The Stage 1 fuel and oxidizer fill-drain and storage valve No. 2 drain disconnects are located in the Stage 1 engine compartment. The remaining Stage 1 disconnects are located at various points on the outer skin of the missile. The disconnect ground halves are connected to these disconnects to direct the flow of propellants and gases to and from the missile tanks. The disconnects are self-sealing and must be manually connected and disconnected.

There are six storage valves: four in the Stage 1 engine compartment and two in the Stage 2 engine compartment. These valves are gas pressure (squib) actuated, butterfly valves with zero-leak diaphragms. The diaphragms prevent propellants stored in the missile tanks from entering the engines. Each valve has a positive locking device that automatically locks the valve in the open position when the valve is actuated.

The pressurization and vent piping for the Stage 1 fuel and oxidizer tanks consists of flex hose between the top of each tank and disconnects on the skin of the missile. The Stage 2 tank pressurization and vent piping is a flex hose between the bottom of the tank and a disconnect on the missile skin. These systems are used to safely vent gases away from the missile during loading operations and pressurize the missile tanks to flight pressure after loading. They are also used to pressurize the missile for leak check, purging, blanketing, and propellant unloading.

AUTOGENOUS PRESSURIZATION SYSTEM

Autogenous pressurization systems are used for the inflight propellant tank pressurization of both stages of the LGM-25C missile. Stage 2 incorporates a fuel tank autogenous pressurization system only. Immediately after propellant loading of the missile, the Stage 2 oxidizer tank is pressurized with nitrogen and sealed. No additional inflight pressurization is required. The Stage 1 autogenous pressurization system consists of a fuel tank pressurization system and an oxidizer tank pressurization system. After loading, the Stage 1 fuel and oxidizer tanks and the Stage 2 fuel tank are pressurized and sealed. The fuel tank pressurization system consists of a gas cooler, hot gas bypass orifice, flow control orifice, sonic nozzle, burst diaphragm, and connecting tubing. The oxidizer tank pressurization system consists of a superheater, oxidizer bypass orifice, cavitating venturi and filter, flow control orifice, burst diaphragm, and connecting tubing.

FUEL TANK PRESSURIZATION SYSTEMS.
The fuel tank autogenous pressurization systems used on both stages of the LGM-25C missile are identical. Both systems cool the hot exhaust gas from the gas generator from +1600 degrees F to +200 degrees F in the gas cooler. The cooled exhaust gas is used to maintain the required fuel tank pressure of 24 to 29 psia on Stage 1 and 49 to 54 psia on Stage 2. Gas enthalpy control is provided by installing orifices of proper size in the bypass lines of the gas cooler. The amount of gas fed to the fuel tank is regulated by the use of a sonic flow control nozzle installed in the line between the gas cooler and the fuel tank. When pressure within the system reaches approximately 300 psig, the burst diaphragm, installed upstream of the gas cooler, ruptures allowing flow of cooled exhaust gases to the missile fuel tank.

TECHNICAL NOTES:

Warhead:	Single nuclear warhead in the megaton range
Re-entry vehicle:	General Electric Mark 6, ablative
Engines:	(1st stage) Aerojet LR87-AJ-5 of 430,000 lbs. thrust (sea level); (2nd stage) Aerojet LR91-AJ-5 of 100,000 lbs. thrust (altitude)
Propellants:	Aerozine 50 fuel and nitrogen tetroxide oxidizer
Range:	9,000 miles
Length:	108 ft.
Diameter:	10 ft.
Weight:	330,000 lbs. fueled

TOUR POINTS:

- Significant improvement over Titan I, with hypergolic propellants that could remain in tanks for extended periods
- Largest and most powerful of America's nuclear armed missiles
- With storable propellants and ability to launch from within silo, could be launched in about 60 seconds
- Inertial guidance system reduced vulnerability to jamming and allowed widely dispersed bases
- 54 missiles operational from 1963 to 1987
- Special man-rated Titan IIs were used to launch ten manned Gemini capsules, and after their operational career as ICBMs, surplus Titan IIs were converted to space boosters and used to launch satellites. Further development included the Titan III and Titan IV with large solid strap-on boosters attached to Titan IIs to significantly increase payload capability
- Same engines as Titan I but upgraded to 430,000 pounds thrust for first stage and 100,000 pounds thrust for second stage

SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

[1] David Baker, *Rocket 1942 Onwards Owners Workshop Manual*, (Sparkford, UK: Haynes publishing, 2015)

[2] T.O. 21M-LGM-25C-1, *Technical Manual - Operation, USAF Model LGM-25C, Missile Weapons System Operation*, (USAF)

[3] George P. Sutton, *The History of Liquid Propellant Rocket Engines*, (American Institute of Aeronautics and Astronautics, 2006)

Martin Marietta SM-68B/LGM-25C Titan II back to Table of Contents

Boeing LGM-30A Minuteman IA

The Minuteman missile concept pushed rocket technology to a new level and it vastly improved U.S. nuclear strategic deterrence. Minuteman was the first U.S. intercontinental ballistic missile (ICBM) to use solid fuel, permitting quick response launches in case of attack. The first Minuteman missiles became operational in October 1962.

Minuteman IA missiles like the one on display were the first generation of a revolutionary new family of ICBMs. The use of solid rather than liquid fuel created a system with a response time of less than one minute from key-turn to launch - hence the "Minuteman" name, referring to colonial American patriots who could be ready to defend their homes at a moment's notice. In contrast to Minuteman, older missiles like Atlas and Titan I took up to half an hour to fuel and launch. Atlas and Titan I were also complex and costly, requiring close monitoring and constant maintenance, and their cryogenic oxidizer could be dangerous. Moreover, they both had reliability challenges associated with complex plumbing and control needed in liquid rockets.

Minuteman's advantages combined speed, low maintenance, high reliability, high "survivability" from attack, and low cost. The U.S. Air Force had been studying solid fuels since the early 1950s, and using solid fuel was important because it meant that the missile could be stored unattended for long periods. (While long-term storage unattended is a significant benefit, many solid propellants gradually deteriorate over time, such that Minuteman stages are periodically refurbished or replaced.)[2] In addition, Minuteman was small enough to be housed in very strong, unmanned underground silos, able to survive nuclear attack.

In 1958, guided by the Air Force Ballistic Missile Division, industry began work on the new three-stage missile. Boeing was the overall contractor, and important parts of the missile came from the firms Autonetics (guidance); Aerojet, Hercules and Thiokol (rocket stages); and Avco (re-entry vehicles). The USAF planned to deploy up to 1,600 Minutemen - later revised to 1,000 and then 950 - making the system a very strong nuclear deterrent.

Advent of Solid Propellants
For the first decade of modern large rockets, liquid propellant systems predominated. Despite promise of higher reliability, lower costs (development, procurement, and maintenance), and the ability to launch without lengthy fueling and checkout, large solids had significant drawbacks – notably vastly inferior efficiency, and difficulties in building large solids that were not susceptible to mechanical cracking.

Efficiency in rockets is usually reflected in a term called specific impulse or I_{SP}. Specific impulse is simply the amount of thrust produced by one pound of propellant burned for one second. The early IRBMs and ICBMs (all liquid) had I_{SP} in the 240-250 range while solids in the mid 1950's were typically below 200. Mechanical cracking of solid rocket propellants was a significant concern up through the early 1940's. Solid propellants were basically powders that were either in cartridges or packed to maintain their shapes. Cracks were easily induced through transportation and handling or storage in cold temperatures. A crack in a solid propellant opens additional burning surface area and can easily lead to overpressure with catastrophic results. In the mid 1940's, Jack Parsons at Aerojet Engineering Corp. introduced a castable mixture of asphalt and potassium perchlorate that provided some resilience and resistance to cracking but also bonded the propellant securely to the motor case.[1]
"This case bonding idea became the fundamental basis for almost all of the modern rocket motor designs". The asphalt-perchlorate also improved I_{SP} to nearly 200.[2]

Improved solid propellants evolved rapidly in the 1950's including synthetic polymers, polysulfides, and polyurethane, gradually improving I_{SP} and mechanical properties. Two significant discoveries basically made the USAF Minuteman

ICBM and the USN Polaris SLBM (submarine-launched ballistic missile) feasible. First, the Jet Propulsion Laboratory developed the internal star-shaped burning grain design that allowed burn rates and thus thrust variation over time to be tailored. Second was the discovery at the Atlantic Research Corporation that addition of powdered aluminum in castable composite components significantly increased I_{SP}.[1]

A challenge to solid rockets that was solved on the Minuteman involved shutdown of a solid motor. Thrust of liquid rocket engines can be terminated precisely simply by closing propellant valves, but solid rockets traditionally burn until the propellant is exhausted, leaving significant uncertainty of the final velocity, which directly impacts range and accuracy. On the third stage, four elliptical "blow-out ports" are visible. At the proper velocity determined by the guidance system, shaped pyrotechnic charges cut out these ports, and the sudden venting of combustion pressure to the vacuum of space immediately terminates combustion and thrust.

"One very significant feature of the [study funded circa 1955 by USAF] was the realization that solid rockets could be flown over a trajectory that was drastically different from that of the existing liquid propellant ICBMs and IRBMs. Solids (because of their very strong chamber structure) could accelerate out of the silo at more than 2 g's, pitch over toward the target very rapidly, and go through the regime of maximum dynamic pressure at a significant pitch angle. Since this increased its range almost 20% compared to the liquid trajectory, this concept was used in all subsequent systems."[2] This discovery not only offset the slightly lower I_{SP} of solids relative to liquids, but also resulted in shorter time to target.

Minuteman Basing

After a series of successful test launches, the USAF began rapidly deploying Minuteman missiles. Minuteman IA missiles like the one on display were based at Malmstrom Air Force Base, Mont., in the 341st Strategic Missile Wing, the first of six Minuteman wings. Malmstrom's first flight of 10 missiles went on operational alert on Oct. 22, 1962. Later models would be deployed at Malmstrom and five other bases in western states including South Dakota, North Dakota, Wyoming and Missouri. These states had thousands of square miles of open space surrounding the bases, making them ideal for Minuteman operations.

Each Minuteman wing contained three or four 50-missile squadrons divided into 10-missile flights, each with a single launch control center. The Minuteman force grew very quickly as the US Army Corps of Engineers constructed the relatively small, easy to build silos using prefabricated sections. By 1966, 1,000 silos were complete, and all their missiles were operational by mid-1967.

Minuteman Operations

Each underground launch control center, with two USAF officers on constant alert, controlled ten missiles typically separated from one another by at least three miles of open land. The launch crews rotated regularly, and they maintain very high proficiency in the awesome responsibility of operating nuclear weapons. The crews, missiles and silos receive support from technical, administrative, service, security and many other personnel at the wings' parent bases.

An Evolving System

The Minuteman IA on display (designation LGM-30A) represents one of 150 deployed at Malmstrom AFB between 1962 and 1969. Improved range and accuracy in later models enabled their deployment at U.S. bases farther from their targets in the former Soviet Union.

Like any ICBM, Minuteman IA was a complex system. The rocket's three powerful stages burned one after the other to send a single nuclear warhead on a free-falling or ballistic path to its target. To hit a target thousands of miles away, Minuteman used a precise guidance system of gyroscopes, accelerometers, and a computer that was powerful for its time.

Sensing the missile's movement, the guidance unit swiveled rocket motor nozzles to keep the missile on course. It also told the three stages when to fire and separate, and determined the right moment to release the re-entry vehicle containing the nuclear warhead.

The re-entry vehicle at the tip of the missile free-fell to its target using gravity alone. To protect the warhead inside from the heat of atmospheric re-entry, the vehicle was covered with special materials called "ablative" coatings that carried away heat by burning and charring away as the vehicle streaked earthward.

The missile on display came to the museum in 1971. Later Minuteman models included Minuteman IB (LGM-30B), II (LGM-30F) and III (LGM-30G). Over the years, the Minuteman series received various upgrades with improved motors, guidance, re-entry vehicles, and warheads. Minuteman III, also on display in this gallery, is still in service and is projected to be America's primary land-based strategic nuclear deterrent well into the future.

TECHNICAL NOTES:

Height:	53.8 ft. Weight: 65,000 lbs.
Range:	Designed for 5,000+ miles Speed: 15,000 mph
Propulsion:	Stage 1--Thiokol, 210,000 lbs. thrust; Stage 2--Aerojet, 60,000 lbs. thrust; Stage 3-- Hercules, 35,000 lbs. thrust
Guidance:	All inertial, Autonetics Division of Rockwell
Warhead:	Nuclear, re-entry vehicle by Avco

TOUR POINTS:

- First U.S. ICBM to use solid fuel, operational 1962
- Solid fuel enabled the launch in one minute - hence name Minuteman
- Advantages: launch speed, low maintenance, high reliability, high survivability, low-cost
- The Minuteman began a trend of reduced warhead weights and yields. RV's went from about a ton on the IRBM's to about four tons on the Titan II. The Minuteman I reentry vehicle was less than 1000 pounds, but Minuteman brought significantly larger numbers of missiles with increased reliability and accuracy.
- Housed in hardened, unmanned underground silos
- 1000 silos completed

SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

[1] JD Hunley, "The History of Solid Propellant Rocketry - What We Do And Do Not Know", a AIAA 99-2925 Invited Paper at the 35th AIAA, ASME, SAE, ASEE Joint Propulsion Conference and Exhibit, June 20-24, 1999

[2] Philip D. Umholtz, *The History of Solid Rocket Propulsion and Aerojet*, (Edwards AFB, CA: Air Force Research Laboratory, 1999)

Boeing LGM-30A Minuteman IA back to Table of Contents

Boeing LGM-30G Minuteman III (Supplemental Material for Rocket Tour)

Minuteman Technology

"The discovery that adding large amounts of aluminum significantly increased the specific impulse [efficiency] of a castable composite propellant further aided large missile technology".[1]

The first stage motor is manufactured by Thiokol Corp., produces about 200,000 lb. thrust at sea level, and has four mechanically actuated nozzles for pitch, yaw, and roll control. The second stage is manufactured by Aerojet - its sea level thrust would be about 60,000 lb., and pitch and yaw are controlled though Liquid Injection Thrust Vector Control (LITVC) using Freon, which is injected into the exhaust flow from ports around the nozzle to "steer" the exhaust flow and vector the thrust. The injected fluid locally disrupts the exhaust flow at the injection point, and the resulting asymmetry in the exhaust plume results in a small side load at the nozzle. The third stage, made by either Thiokol Corp. or Chemical Systems Division of UTC, would produce about 35,000 lb. thrust at sea level, and employs liquid strontium perchlorates for the fluid in a LITVC system. A separate small solid fuel rocket provides roll control through valves that direct the flow. All three stages burn approximately 60 seconds each and the propellant fraction (propellant weight divided by stage launch weight) is approximately 90% for all three.[2]

Above the third stage a small post-boost vehicle (PBV) incorporating liquid rockets was developed to individually adjust the velocity (speed and direction) of each warhead before it is released into a purely ballistic trajectory. This vehicle uses eleven small rocket engines that operate off pressure-fed hypergolic propellants (nitrogen tetroxide and monomethyl hydrazine). The main engine of 332 lb. thrust is in the center and gimballed for pitch and yaw control. The ten remaining thrusters provide attitude control in all three axes and are 20 to 25 lb. thrust.[2]

TOUR POINTS:

- Minuteman III ICBM was deployed in 1970 and currently is United States' only operational land-based strategic nuclear missile
- Worlds first missile to carry more than one warhead using a "multiple independently targetable reentry vehicle" (MIRV) system. Originally 3 warheads were carried, but since 2005 one warhead is used due to treaty limitations. A PBV guides each RV, using small liquid rockets
- Precise velocity control of stage 3 uses "thrust termination ports" to snuff out the burning

SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

[1] JD Hunley, "The History of Solid Propellant Rocketry - What We Do And Do Not Know", a AIAA 99-2925 Invited Paper at the 35th AIAA, ASME, SAE, ASEE Joint Propulsion Conference and Exhibit, June 20-24, 1999

[2] *Minuteman III ICBM Weapon System, A History and Description*, (Colorado Springs, Colorado, 2004). Prepared by the Systems Engineering and Technical Analysis Staff, Northrop Grumman Mission Systems

Boeing LGM-30G Minuteman III Supplement back to Table of Contents

Martin Marietta LGM-118A Peacekeeper

The Peacekeeper (pictured at right as displayed in the Missile Gallery of the NMUSAF) was the USAF's most powerful, accurate and technologically advanced Intercontinental Ballistic Missile (ICBM) deterrent from 1986 to 2005. Conceived to replace the Minuteman ICBMs, its development began in the early 1970s as the "Missile, Experimental," or MX. Later, it received the official name "Peacekeeper," and the first test flight took place in 1983 at Vandenberg AFB, California. It became operational in 1986, when 10 missiles were deployed at F.E. Warren AFB, Wyoming. By 1988, the USAF had 50 missiles in service there.

Whether to base the missiles inside stationary, hardened silos or on mobile railways to keep the Soviets guessing at the missiles' true location was a major issue during Peacekeeper's development. More extreme ideas also were considered, including dropping the missile from a cargo aircraft (after which it would "launch" from the air) and "dense packing" the missiles in silos located so close together as to induce fratricide among attacking warheads.[1] Funding problems and competing ideas about the wisdom of each basing solution delayed Peacekeeper production and deployment. Eventually, the USAF decided to place all LGM-118As into hardened, underground silos previously used by Minuteman ICBMs, using a heavily modified version of the Minuteman Command Data Buffer command and control system. Many contractors worked on the Peacekeeper, but Martin Marietta and Denver Aerospace (now Lockheed Martin) assembled and tested the Peacekeepers.

Constructed with an airframe made of a Kevlar epoxy composite, the Peacekeeper was much lighter than previous ICBMs, and it could carry more warheads. It used an advanced ring laser gyro guidance system for increased reliability and accuracy. When combined with new Multiple Independently-targeted Re-entry Vehicle (MIRV) technology, one Peacekeeper could accurately deliver as many as ten nuclear warheads on different targets at the same time.

A three-stage solid-propellant missile with a liquid propellant post boost vehicle, (sometimes referred to as a "fourth stage"), Peacekeeper was the first Air Force ICBM to use the "cold launch" technique similar to the system used to launch missiles from submarines. This procedure shot the missile out of a modified Minuteman underground silo with a massive burst of high-pressure steam, and its first-stage solid-rocket motor ignited only after the missile cleared the silo. The next two stages, also solid-fuel rockets, boosted the missile's payload into space. The post-boost vehicle was liquid-fueled, and it contained the missile's guidance and re-entry systems. After maneuvering in space to properly orient the re-entry system, the fourth stage activated and released up to ten nuclear warheads. Each warhead—contained in a small, unpowered MK-21 reentry vehicle—descended on an independent ballistic path to its target. Accuracy depended on the warheads' being released at the correct position and velocity.

The Peacekeeper modernized and improved the United States' nuclear deterrence, but the end of the Cold War made its mission less crucial. In accordance with the Strategic Arms Reduction Treaty (START) II, signed in 1993 with Russia, and other arms control treaties, the United States decided to remove all multiple-warhead ICBMs and to deactivate all 50 LGM-

118As between 2003 and 2005. (After a variety of delays, the START II Treaty was abandoned, never having actually gone into effect.) Some Peacekeepers were eventually used as satellite launch vehicles.

TECHNICAL NOTES:

Height: 71 feet
Weight: 195,000 lbs.
Engines: Three-stage solid-fuel rocket motors; liquid-fuel "fourth stage" post-boost vehicle
Payload: Up to 10 Avco Mk-21 reentry vehicles
Guidance: Inertial
Range: 6,000+ miles
Max Speed: Approx. 15,000 mph

TOUR POINTS:

- USAF's most powerful, accurate, and advanced ICBM deterrent from 1986 to 2005
- Developed to address perceived "window of vulnerability" in nuclear forces in the 1970s and 80s
- Kevlar epoxy composite airframe made Peacekeeper very light
- Could deliver up to 10 warheads to dispersed targets
- Used "cold launch" system similar to SLBMs; ejected from launcher by steam, then ignited
- Ring laser gyros made guidance much more reliable and accurate than that of previous systems
- Retired in accordance with START II (1993), although START II never went into effect

SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

NMUSAF Fact Sheets
Docent Expert: Jeff Smith
Colonel, USAF (ret)
BS & MS, Astronautical Engineering
Former Commander
320th Missile Squadron, 90th Space Wing (now Missile Wing)

[1] https://www.nytimes.com/1982/11/23/world/reagan-proposes-dense-pack-100-mx-missiles-wyoming-seeks-arms-pacts-with-soviet-051579.html
https://minutemanmissile.com/peacekeeper.html
https://www.nti.org/gsn/article/us-pulls-multiple-warheads-all-nuclear-missiles/
https://www.armscontrol.org/act/2005_10/OCT-MX
https://www.armscontrol.org/factsheets/USRussiaNuclearAgreements
https://www.greatfallstribune.com/story/news/local/2014/06/18/last-malmstrom-icbm-reconfigured-treaty/10773351/

LGM-118A Peacekeeper back to Table of Contents

Thor Agena A

The U.S. Air Force launched the world's first space photo reconnaissance satellites using a rocket like the Thor Agena A on display. These satellites, secretly code-named Corona, took pictures of the Soviet Union's bomber and missile bases during the Cold War. The USAF and the Central Intelligence Agency jointly managed Corona, which was known to the public as the Discoverer research satellite program.

Launch System

The Thor Agena A launch vehicle combined a Thor ballistic missile (similar to the nuclear-armed version on display in the museum's Missile Gallery, but designated SLV-2 or Space Launch Vehicle-2) with an Agena upper stage. At first, the Agena vehicle was meant to be launched by Atlas boosters, but the 1957 Soviet launch of Sputnik - the first satellite - sped up the U.S. Discoverer program. Thor was the first vehicle available to carry Agenas. To accommodate the heavier payload, the Thor LR79 engine was uprated from 150,000 to 170,000 lb. thrust.[1]

Originally, Thor was designed as an intermediate-range nuclear ballistic missile (IRBM) in 1956. It borrowed engine and guidance technology from the developing Atlas program, and Thor IRBMs were operational in Great Britain from 1959 to 1963. Though Thor was created quickly as an interim nuclear deterrent, it later became a very successful satellite launch vehicle. The long-lived Delta rocket series, based on refinements of the original Thor design, operated through the end of the Cold War and beyond.

The Corona satellites consisted of the Agena "stage" and the reconnaissance payload as one single assembly. The only portion that would separate later was a small reentry package with a film canister. The Thor (first stage) boosted the Agena-Corona satellite for the first two and a half minutes, and the Agena engine would then fire as a second stage to complete acceleration to orbital speed. The Agena-Corona satellites were placed into elliptical orbits that ranged as far as 1,049 miles and as close as 61 miles to the earth.

For additional information on the Thor first stage, refer to either "Douglas SM-75/PGM-17A Thor" or "Rocketdyne LR79".

Agena

For the CIA/USAF reconnaissance programs such as Corona, the Agena was an integral part of the orbiting satellite. After boosting itself into orbit, the Agena provided 3-axis stabilization for the sensors. The propulsion system for the Agena stage came from the rocket motor which had been developed by Bell Aerospace for the Powered Disposable Bomb Pod (PDBP), a standoff weapon designed to be carried under the fuselage of the supersonic Convair B-58 Hustler. Initially fueled with IRFNA (Inhibited red fuming nitric acid) and JP-4 jet fuel, the engine delivered a thrust of 15,000 pounds. After the first Thor Agena A the JP-4 fuel was changed to UDMH (unsymmetrical dimethyl hydrazine), providing a hypergolic propellant combination that no longer required an ignition system. In late 1960 Agena B's were employed, which had dual start capability and an extended tank for additional propellant.[1] Like Thor, Agena underwent several changes over its lifetime, and it proved to be one of the most successful U.S. upper stages of the Cold War era.

Corona Satellites

The Discoverer satellites' secret identity as Corona intelligence imaging platforms was closely guarded. As boosters like Thor Agena became operational, satellites gave the United States a new capability to see from space what the USSR and other communist nations were doing. Unlike reconnaissance aircraft, an orbiting satellite placed no crew members in harm's way and was immune to enemy air defenses. Developing dependable satellite imaging systems, though, was difficult. Not only did the boosters have to place satellites in precise orbits, the satellites' cameras had to function perfectly and the film had to be recovered after the satellites successfully re-entered the atmosphere. The first Discover I payload was launched by a Thor-Agena A on 23 February 1959. Launched from Vandenberg AFB, it was the first payload placed in polar orbit by any rocket anywhere.[1] On Aug. 19, 1960, following several earlier attempts, Discoverer XIV was the first U.S. reconnaissance satellite to finally return intelligence imagery after successful recovery from orbit. The aircraft that recovered the payload, C-119J (S/N 51- 8037) is on display at the museum.

TECHNICAL NOTES:

Stage 1 (Thor):
Engine: Rocketdyne* LR-79-7 of 170,000 lbs. thrust[1]
Weight: 109,000 lbs. loaded (102,000 lbs. propellant)
Stage 2 (Agena):
Engine: Bell XLR81-BA-5 of 15,500 lbs. thrust
Weight: 8,400 lbs. (6,400 lbs. propellant)

TOUR POINTS:

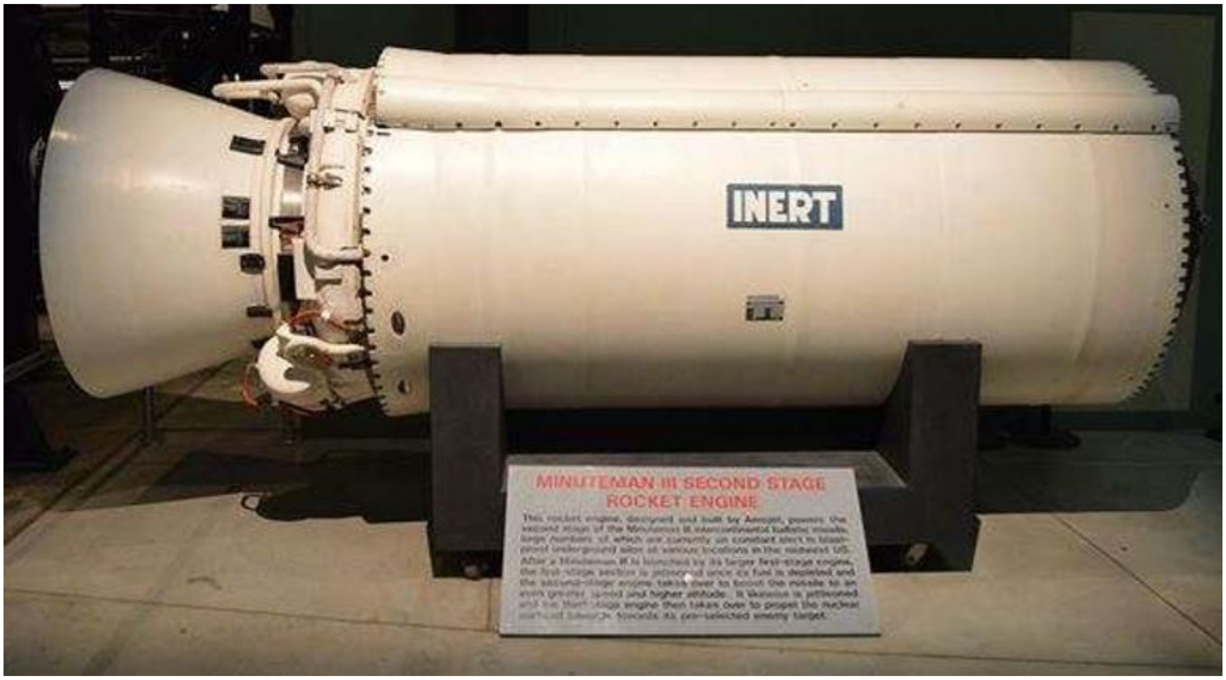
- Similar to Thor missile we saw earlier but with Agena upper stage replacing the original warhead this vehicle launched the world's first spy satellites
- Secretly code-named Corona, they were known to the public as the "Discoverer" research satellite
- Discoverer XIV was the first U.S. spy satellite to successfully return film after recovery from orbit. The film canister was retrieved with its parachute by a C-119 Flying Boxcar (on display in Gallery four)
- The basic Thor vehicle was developed into the long-lived Delta rocket series which has operated as recently as 2021

SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

[1] David Baker, *Rocket 1942 Onwards Owners Workshop Manual*, (Sparkford, UK: Haynes publishing, 2015)

Thor Agena A back to Table of Contents

Minuteman III Second Stage Rocket



This rocket motor, designed and built by Aerojet, powers the second stage of the Minuteman III Intercontinental Ballistic Missile, large numbers of which are currently on constant alert in blast-proof underground silos at various locations in the United States.

After a Minuteman III is launched by its larger first-stage engine, the first-stage section is jettisoned once its fuel is depleted and the second-stage engine takes over to boost the missile to an even greater speed and higher altitude. It likewise is jettisoned and the third-stage engine then takes over to propel the nuclear warhead onward toward its pre-selected target.

Twelve holes can be seen in the nozzle just aft of the throat in four groups of three. A system called liquid injectant thrust vector control (LITVC) pumps liquid strontium perchlorate through those holes to deflect the exhaust nozzle stream, changing pitch and/or yaw in response to inputs from the guidance control. Two small liquid rockets are on each side of this stage, and firing tangentially in pairs, impart roll inputs as needed. These rockets use hypergolic propellants: monomethyl hydrazine and nitrogen tetroxide.

TOUR POINTS:

- Fluid injection slots in the nozzle (visible from left side) are used to vector thrust without physically moving the nozzle.

SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

[1] *Minuteman III ICBM Weapon System*, *A History and Description*, (Colorado Springs, Colorado, 2004). Prepared by the Systems Engineering and Technical Analysis Staff, Northrop Grumman Mission Systems

Minuteman III Second Stage Rocket back to Table of Contents

Bell Model 8048

This liquid-fueled rocket engine powered early Agena spacecraft that played a crucial role in putting the first reconnaissance and early warning satellites into orbit in the 1950s and 1960s. Used as a second stage to boost satellites into higher orbits, Agena upper stages transformed Air Force ballistic missiles into effective space launch vehicles.

The versatile Lockheed Agena upper stage had the unique ability to maneuver in orbit, carry a variety of heavy payloads, and eject reconnaissance film capsules for recovery on earth. Later Agenas carried probes to the moon and other planets, and one version served as a docking target in the Gemini manned space program. Different Agena models were carried as upper stages on Atlas, Thor and Titan rockets, and the Thor Agena A rocket on display in this gallery has an Agena upper stage. The Bell Model 8048 engine, also known as the XLR81, powered 20 Agena vehicles from 1959 to 1961.

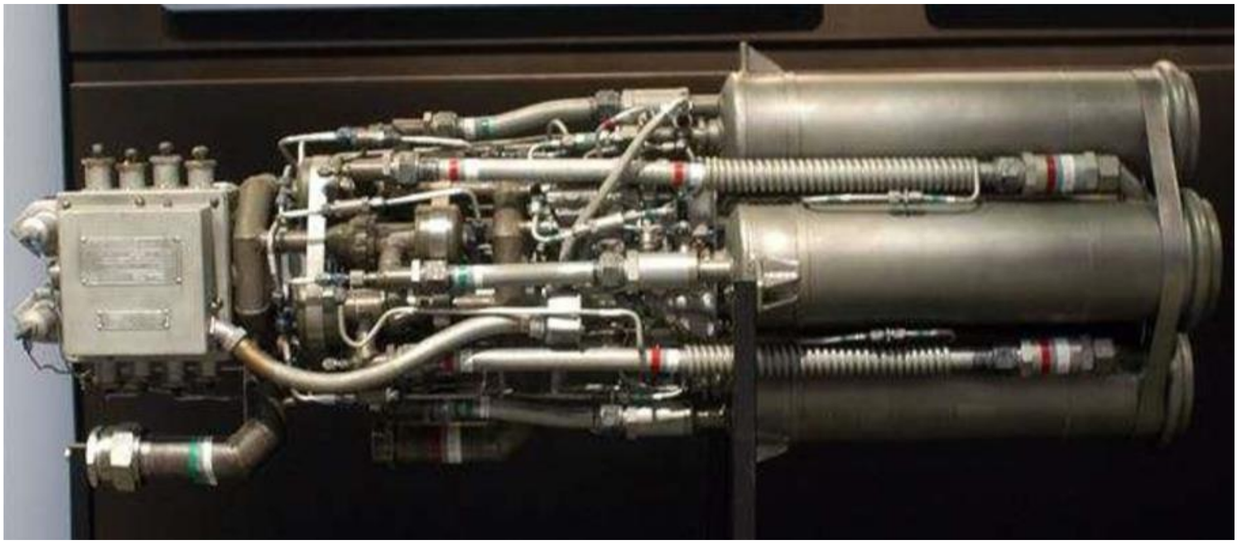
The engine is the first of a family of similar engines that powered Agena A, Agena B and Agena D spacecraft. This engine was "gimbaled," that is, its thrust nozzle could be pivoted to steer the rocket. The Model 8048 was also known briefly as the "Hustler" because it was originally designed to power a stand-off nuclear weapon to be carried under the B-58 Hustler bomber. Bell Aerospace donated the engine on display to the museum in 1963.

TECHNICAL NOTES:

Thrust:	15,489 lbs.
Weight:	279 lbs.
Propellants:	Nitric acid (oxidizer) and unsymmetrical dimethylhydrazine (fuel)
Burn time:	120 seconds

Bell Model 8048 back to Table of Contents

Reaction Motors XLR11 Rocket



The XLR11 was a liquid-fuel rocket engine developed in the United States for use on X-planes, and had a long career powering important research aircraft. An XLR11-RM-5 engine powered the first airplane to break the speed of sound, the Bell X-1, in 1947, and also powered other X-1 models, such as the X-1B on display in the Research & Development (R&D) Gallery. A variant known as the XLR8-RM-5 helped power the USN D-558-2 Douglas Skyrocket to be the world's first Mach 2 airplane.[4] Another early application was the Republic XF-91 Thunderceptor, which used the XLR11 to supplement its primary jet engine. It was later used in the the record-breaking X-15s, which used two XLR11 engines mounted together because the intended engine (the 50,000 lb. thrust XLR99) experienced significant development delays. In 1959 to 1961, the XLR11 pair powered 29 of the X-15 early flights, allowing it to reach Mach 3.5 and over 130,000 feet. XLR11s later flew in five different NASA lifting bodies between 1966 and 1975 at Edwards AFB. Yielding important data that supported the design of the Space Shuttle, the X-24A and X-24B lifting bodies are also on display in the Space Gallery. The XLR11 was pressed into service because it was the only suitable rocket already man-rated, and some engines had to be taken from museums and refurbished to support the program.

The XLR11, also known as the RMI 6000-C4, was developed by Reaction Motors, Inc. over a two-year period for the Bell X-1 aircraft and delivered a total of 5,900 pounds of thrust. The engine's propellants were liquid oxygen (LOX) and a mix of 25% water and 75% ethyl alcohol. The engine had four thrust chambers, using a double-wall construction for fuel cooling. The center of each injector plate had an electrical ignitor, and the controls gave the pilot the ability to stop and restart its four individual chambers. The individual chambers were only "on-off" and thus the engine was not throttleable like the later XLR99, but could be "stepped" in increments of about 1500 lb. Coils around the fuel lines leading to the base of each chamber warmed the LOX such that gaseous oxygen could simplify the ignition process.[1]

In the early versions, the propellants were pressure-fed without pumps. The thrust chamber pressure was 220 psi, and tank pressures in the aircraft were between 280 and 370 psi. In later versions a small turbopump assembly was added to enable higher chamber pressures and much lighter propellant tanks on the aircraft. For the turbopump versions a gas generator was fed by hydrogen peroxide and a solid catalyst.[1]

A significant development of the XLR11 was a turbopump-fed version developed for the MX-774 program known as the 8000-C4 or the XLR35-RM-1.[2] The MX-774 was an early classified program by Consolidated Vultee (later Convair) and one of the first contracts towards developing an Intercontinental Ballistic Missile (ICBM). Three test vehicles (also known as "Hiroc", for high-altitude rocket) were launched with partial success in 1948 and first incorporated a tank system that used nitrogen pressurization to stiffen the thin walls instead of conventional metal stiffeners. That feature was a key development later used by Convair in the Atlas missile, which became the first successful ICBM. The XLR35-RM-1 used a higher chamber pressure to attain 8000 lb. thrust and incorporated four chambers similar to the XLR11, but they were each mounted on hinges with actuators to control deflection angles.[3] These hinged or swiveled engines allowed control of pitch, yaw, and roll and presaged the gimballed engine, which later permitted tilting about two axes simultaneously.

TECHNICAL NOTES:

Thrust: 5,900 lbs. (1,475 lbs. in each of four chambers)
Propellants: Ethyl alcohol and water fuel and liquid oxygen oxidizer
Weight: 345 lbs.

TOUR POINTS:

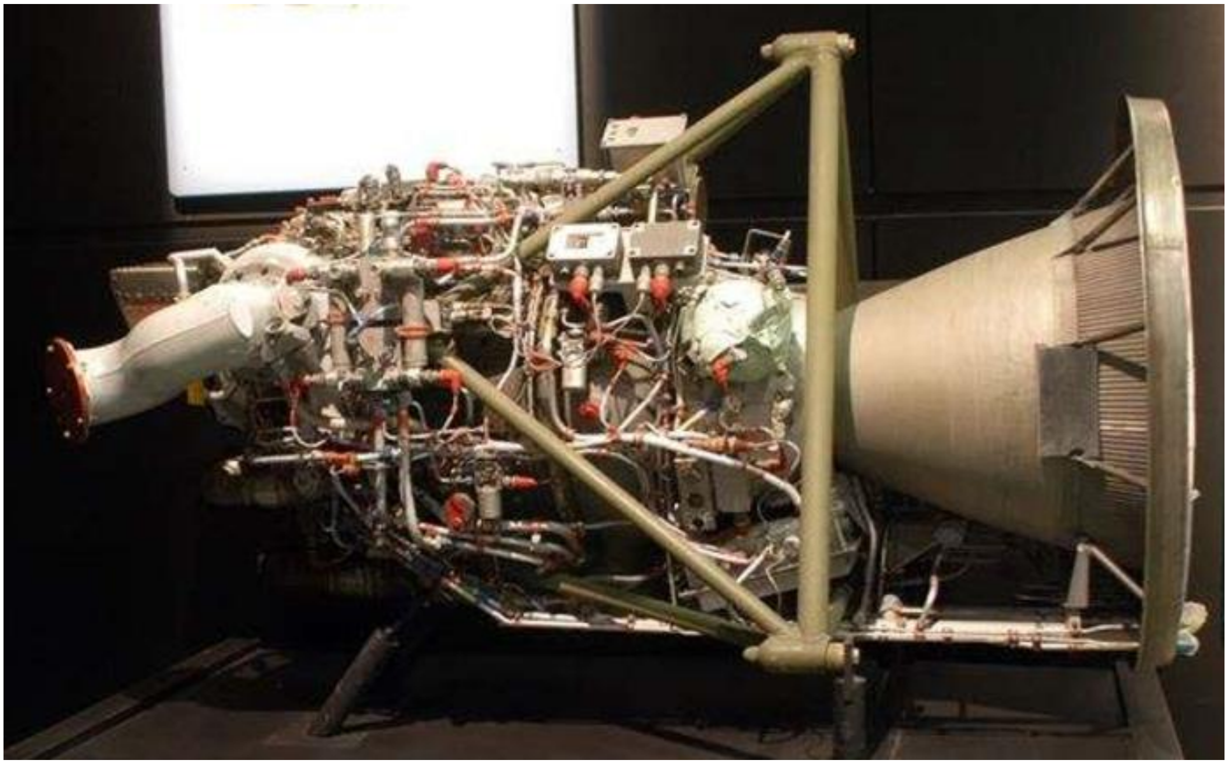
- Most famous for powering the bell X-1 in 1947 to break the speed of sound (Yeager)
- Also powered other X-1 aircraft including X-1B on display in this gallery
- Augmented the turbojet on the Douglas D-558-2 skyrocket, first aircraft to achieve Mach 2
- Two engines were used in the X-15 until the single, more powerful XLR99 engine was available. Even with the smaller XLR11's, the X-15 achieved Mach 3.5
- Used in numerous "lifting body" vehicles, such as X-24A and X-24B.
- Four separate chambers each produced approximately 1500 pounds thrust and could be turned on and off separately

SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

[1] George P. Sutton, *The History of Liquid Propellant Rocket Engines*, (American Institute of Aeronautics and Astronautics, 2006)
[2] National Air & Space Museum website, https://airandspace.si.edu/collection-objects/space-propusion-reaction-motors-lr35-8000c4-liquid-fuel-motor-mx-774-rtv-2
[3] John Chapman, *Atlas: The Story of a Missile*, (Harper & Brothers, 1960)
[4] https://en.wikipedia.org/wiki/Reaction_Motors_XLR11

Reaction Motors XLR11 back to Table of Contents

Reaction Motors XLR99 Rocket



The XLR99 powered the record-breaking X-15 on its fastest flights at nearly seven times the speed of sound. It was the first large, throttleable, restartable liquid propellant rocket engine to be used in a piloted vehicle. The engine was used only in the X-15 program, which rocketed humans to the edge of space. The X-15A-2 in this gallery has an XLR99 engine.

Developed and built by the Reaction Motors Division of Thiokol Chemical Corp., the XLR99 could deliver more than 57,000 pounds of thrust at altitude. The engine used liquid oxygen and anhydrous ammonia propellants fed into the engine by turbopumps at a flow rate of more than 10,000 pounds per minute. The XLR99 engine had an operating life of one hour, after which it could be overhauled and used again, though operating times twice that long were demonstrated in tests. The XLR99 was theoretically capable of between twenty and forty flights before overhaul. The basic X-15 carried propellants for about 83 seconds of full-power flight, and the X-15A-2 carried enough in its twin orange external tanks for up to 140 seconds of full-power flight[2].

Like other modern large liquid fueled rocket engines, the walls of the XLR99's thrust chamber included hollow tubing so that fuel could be routed through the tubes to cool the chamber walls before being burned in the engine. It was also one of the last large engines to retain film cooling, in which fuel was admitted through holes at the periphery of the injection plate at the front of the thrust chamber.[1]

Development and Design Features

Development of the XLR99 encountered significant challenges and led to delays such that the X-15 flew its first 25 flights with the lower thrust XLR11 engine. Because of the development problems, General Electric was contracted to start development of a backup engine, but eventually the GE contract was cancelled and the XLR99 served reliably through the program. The interior of the tubular thrust chamber was coated with a ceramic material known as Rokite and suffered from spalling and flaking, leading to tube damage. This issue was eventually resolved with an improved primer application.[1]

The ammonia fuel was unique among rockets that have flown[1] and was chosen in large part because of its high specific heat capacity. Ammonia is one of the few substances known with a higher specific heat than water, and roughly twice as high as alcohol and hydrocarbon fuels. This high specific heat meant that the ammonia fuel could remove more heat from the combustion chamber than other fuels.[3]

The XLR99 could be restarted up to six times and during development suffered from "hard starts" that led to a unique ignition arrangement. Prior to the main thrust chamber, there are two ignition chambers, each with its own igniter, propellant lines, and control functions. While ignition progresses through the 1st stage igniter, the 2nd stage igniter, and then the main chamber, both ignition chambers remain fueled and operating at normal operating levels. Each igniter stage included redundant spark plugs. On shutdown, helium was used to purge the propellants from the thrust chamber to improve lightoff if the engine were restarted. Throttling was possible between 30% and 100% thrust, but the range between 30% and 50% was rarely used because of instability issues. The engine also had an idle mode using only the two igniter stages, where roughly 90% of the valves and control components could be checked out at a lower, safer power setting. [1]

Another feature that may still be unique among large liquid rockets is the means by which the XLR99 was throttled. Unlike other turbopump assemblies, the XLR99 turbopump incorporated a speed governor to regulate turbine speed. The throttle in the cockpit provided an electrical signal to the engine control which changed the speed governor setting. The turbopump was driven by a gas generator which in turn was powered by hydrogen peroxide and a solid catalyst. [1]

The engine was designed to be not only restarted but re-usable after inspections and refurbishment in between flights. Only eight XLR99 engines were used during 169 flights and numerous ground runs. [1]

TECHNICAL NOTES:

Thrust: 50,000 lbs. at sea level; 57,000 lbs. at 45,000 ft.; 57,850 lbs. at 100,000 feet
Propellants: Liquid anhydrous ammonia fuel and liquid oxygen oxidizer
Weight: 915 lbs. including turbopump

TOUR POINTS:

- Powered the most famous and most significant rocket-powered aircraft, the X-15 with max speed of 4520 mph (Mach 6.7) and altitudes over 350,000 feet
- First large throttleable, restartable liquid propellant rocket engine to be used in manned vehicle
- Used anhydrous ammonia and liquid oxygen
- Three X-15 aircraft were built and accomplished 199 flights from 1959 to 1968
- One aircraft is in the National Air and Space Museum in DC, another was destroyed in a crash, and one is displayed here
- The X-15 on display was modified to accommodate external fuel tanks, extending full-thrust burn time from approximately 83 seconds to 140 seconds
- Eight pilots were awarded USAF astronaut wings for flying over 50 miles altitude
- The most famous pilot of the X-15 was Neil Armstrong

SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

[1] George P. Sutton, *The History of Liquid Propellant Rocket Engines*, (American Institute of Aeronautics and Astronautics, 2006)
[2] Michelle Evans, *The X-15 Rocket Plane - Flying the First Wings Into Space - Flight Log*, (Mach 25 Media, 2013)
[3] Robert W. Seaman and George Huson, "The Choice of NH3 to Fuel the X-15 Rocket Plane", 8th NH3 Fuel Assoc. Conference, Sept 19-20, 2011, https://nh3fuel.files.wordpress.com/2013/01/2011-seaman-huson.pdf

Reaction Motors XLR99 Rocket back to Table of Contents

Lockheed Martin Titan IVB Rocket (Supplemental Material for Rocket Tour)

The Titan IV emerged from concerns as early as 1984 (two years before the Challenger disaster) that NASA would not be able to assure large military payloads on the shuttle as initially claimed. The contract to produce the Titan IV was let on 28 February 1985 and based on the commercial Titan III with extended second stage and various upper stage options. The biggest change was the upgrade to the solid rocket boosters (SRB), with thrust increased to 1.6 million pounds.[2]

In 1987 the Challenger disaster and a spectacular failure of a USAF Titan 34D were both traced to SRB failures. In the wake of the Challenger, plans for shuttle launches from Vandenberg AFB for military programs were cancelled, denying USAF of its 60,000 lb. capability for low earth orbits. Also recognizing the Titan IVA would not be able to accommodate growth satellites then being planned, Martin Marietta proposed the Titan IVB which would incorporate new SRBs from Hercules with new technology and increased performance.[4] The Titan IVB version replaced the seven solid segments of the Titan IVA SRBs with three larger segments and a special filament-wound graphite epoxy case with a vectored nozzle to replace the liquid injection control employed by the previous Titan SRBs. The new motors (SRMU, or Solid Rocket Motor Upgrade) had a thrust of 1.7 million pounds thrust each.[2]

The new SRMUs suffered significant development problem, delaying the Titan IVB seven years and requiring extension of the Titan IVA flights. Even before the Titan IVB took flight in 1997 the USAF initiated the Evolved Expendable Launch Vehicle (EELV) program to plan for more economic and reliable launch vehicles and greater lift capability. A Titan V concept was not selected under EELV, and remaining Titan II core vehicles were scrapped.[4] Atlas V and later, Delta IV launch vehicles inherited USAF heavy lift missions.

The stage 1 engine, the LR87-AJ-11, has several changes since its Titan II configuration. Since the stage 1 engine no longer operates at sea level, the nozzle expansion ratio (exit area divided by throat area) was increased from 8:1 to 16:1 to improve efficiency. Because the twin thrust chambers of the LR87 are exposed for about two minutes to the intense heat load of the adjacent SRB nozzles, they are covered with protective thermal shielding. Vacuum thrust for the first stage was increased to 548,000 lb. versus 478,300 lb. for the Titan II, and the second stage LR91 engine was also increased from 80,000 on the Titan II to 105,000 on Titan IV.[3]

The new SRMU was developed by Hercules.

TECHNICAL NOTES:

Engines: Two-stage liquid-fuel core vehicle with two solid rocket boosters
Stage 0: Two solid rocket motors of 1.7 million lbs. thrust each (sea level)[2]
Stage 1: LR87 engine of 548,000 lbs. thrust (vacuum)
Stage 2: LR91 engine of 105,000 lbs. thrust (vacuum)

TOUR POINTS:

- 12,000 pound payload capability to geosynchronous orbit (with Centaur upper stage).
- NASA's Cassini-Huygens spacecraft to Saturn was the only non-classified payload.
- Core vehicle is Titan II with engines uprated to 548,000 pounds thrust on the first stage and 105,000 pounds thrust on the second stage
- Two "strap-on" solid rocket boosters (similar to space shuttle) are called stage 0 and each produced 1.7 million pounds thrust

SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

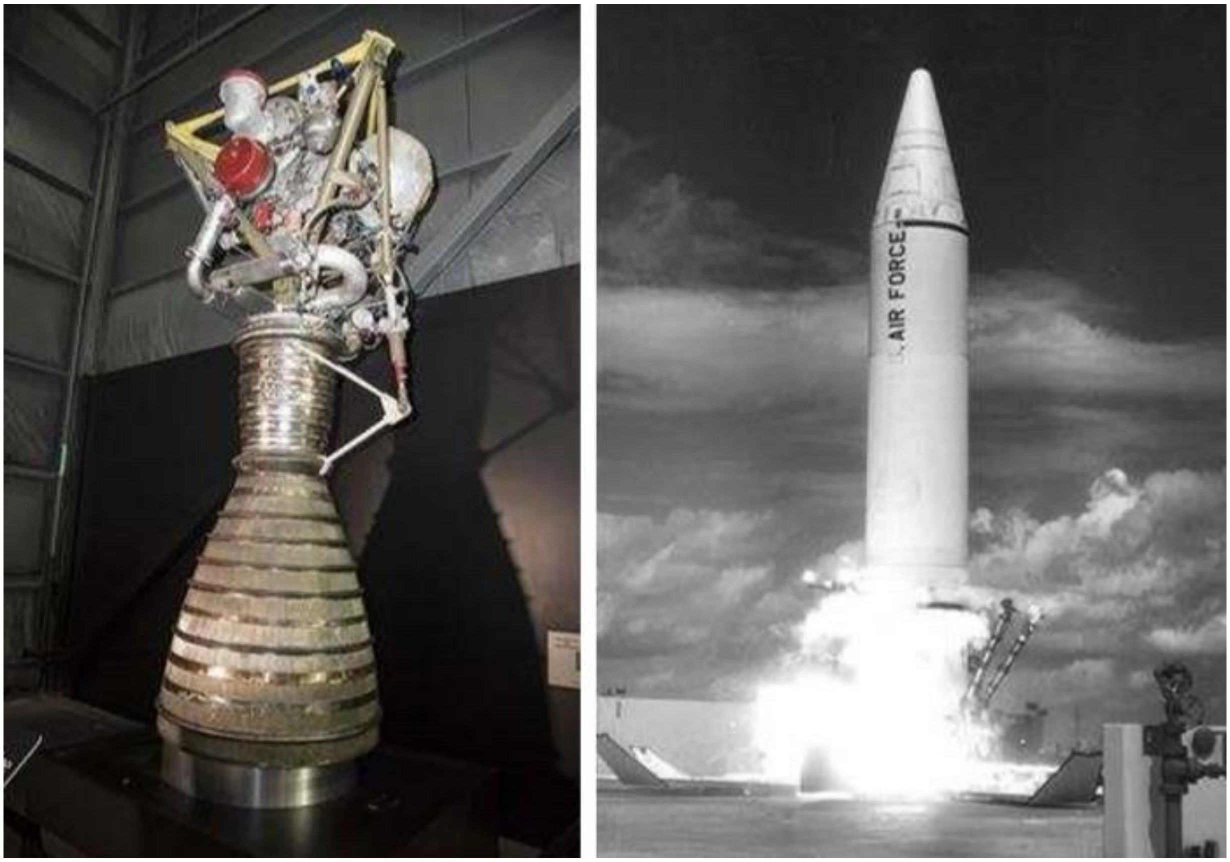
[2] David Baker, *Rocket 1942 Onwards Owners Workshop Manual*, (Sparkford, UK: Haynes publishing, 2015)

[3] George P. Sutton, *The History of Liquid Propellant Rocket Engines*, (American Institute of Aeronautics and Astronautics, 2006)

[4] Jeffrey L. Smith, “Building a better booster (part 2)”, The Space Review in association with Space News, February 18, 2019, http://www.thespacereview.com/article/3660/1

Lockheed Martin Titan IVB Rocket (Rocket Tour Supplement) back to Table of Contents

Rocketdyne LR79



Rocketdyne LR79 (S-3D) engine on display at NMUSAF, and ignites during a Jupiter test launch at Cape Canaveral, Florida, in 1960

The LR79 rocket engine was a reliable workhorse for U.S. Air Force space and missile launches between 1958 and 1980. Variants of this liquid-fueled engine powered Jupiter and Thor Intermediate Range Ballistic Missiles (IRBMs), Thor and Delta boosters, and Juno II satellite boosters. The Jupiter version was later developed into the H-1 engine for Saturn I and IB rockets used in the Apollo and Skylab programs, and the Apollo-Soyuz Test Project. The LR79 was also known by its civilian designation S-3E (Thor) and S-3D (Jupiter). Rocketdyne developed the engine in 1955-56 for the U.S. Army. In 1956, Jupiter became an important Air Force missile when the USAF gained responsibility for all ballistic missiles with ranges of more than 200 miles. An LR79 engine powered a Jupiter on the first successful American IRBM test flight on May 3, 1957. In 1959, a Jupiter rocket took two monkeys named Able and Baker on a 16-minute sub-orbital ride to an altitude of 300 miles, a prelude to human spaceflight.

Development

The Thor and Jupiter engines started development in 1953, about a year after Rocketdyne had started development of the Atlas ICBM engines. Seeing the challenges of ICBM development, the IRBM program was launched to produce interim nuclear deterrent earlier. Despite the later start, both IRBMs made their first flights and went operational before the first ICBM. Because of the decisions above, Thor and Jupiter inherited the same technological advancements that the Atlas ICBM engine enjoyed. These significant improvements from the V-2 technology of 1945 were developed in the early 1950's on the USAF Navaho cruise missile program and include:

- Replacing hydrogen peroxide systems for gas generators with those that used the primary propellants, reducing weight and complexity
- Incorporating thrust chambers made of thin "spaghetti tubes" rather than double walls, improving cooling performance and cutting weight roughly 50%

- Change from alcohol fuels to higher energy hydrocarbon fuels with increased performance
- Development of geared turbopump assemblies that allowed turbine speeds much higher than pump speeds, which improve efficiency, reduced gas generator power requirements, and reduced turbine wheel diameter. [2]

The mounting structure differed between the Thor and Jupiter according to the needs of the respective airframes, and there were minor differences in controls and piping. The Thor engine began flight test at 135,000 lb. sea level thrust and a conical nozzle, but for production as an IRBM the thrust was 150,000 lb. sea level and the nozzle had adapted a "bell shape" that aligned the exhaust momentum parallel with the direction of travel. Aligning the exhaust instead of letting it spread out from a conical nozzle added about 1.7% thrust. The bell shape was used on all production engines and has become a standard feature on modern rockets. A final improvement implemented on Jupiter and Thor (and Atlas) was mounting the thrust chamber to a gimbal block. With flexible sections in propellant lines and two hydraulic actuators mounted 90 degrees apart, this arrangement allowed vectoring the thrust and eliminating the previously used jet vanes and associate thrust losses.[2]

TECHNICAL NOTES:

Thrust: 150,000–205,000 lbs. (depending on model)
Weight: 1,417–2,003 lbs. (depending on model) Turbopump speed: 3,950–6,717 rpm (depending on model)
Propellants: RP-1 (kerosene) and liquid oxygen
Propellant flow: About 3,400 gallons liquid oxygen and 2,100 gallons kerosene per minute (depending on model)

TOUR POINTS:

- Developed from Atlas booster engine and used on Thor and Jupiter IRBMs
- Later developments used on Delta launch vehicles and first stage of Saturn I and IB
- Visible features:
  - Gimbal block and flex lines allowing nozzle movement
  - Spaghetti tubes for cooling thrust chamber
  - Actuators for vectoring
  - Gas generator
  - Turbine exhaust port

SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

[1] Robert S. Kraemer, *Rocketdyne: Powering Humans Into Space*, (American Institute of Aeronautics and Astronautics, 2006)
[2] George P. Sutton, *The History of Liquid Propellant Rocket Engines*, (American Institute of Aeronautics and Astronautics, 2006)

Rocketdyne LR79 back to Table of Contents

Bell X-1B

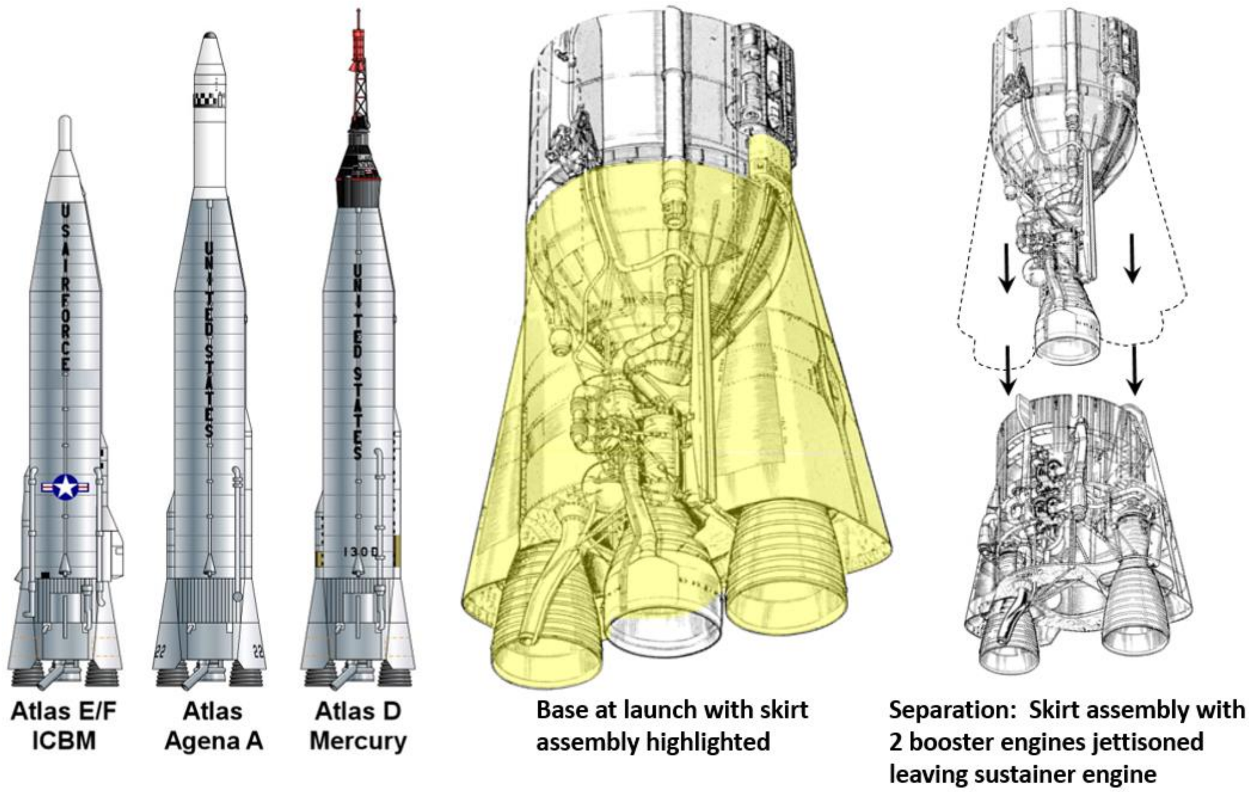
The X-1B was one of a series of rocket-powered experimental airplanes designed to investigate supersonic flight problems. The X-1B's flight research primarily related to aerodynamic heating and the use of small "reaction" rockets for directional control. The X-1B made its first powered flight in October 1954. A few months later, the U.S. Air Force transferred the X-1B to the NACA (National Advisory Committee for Aeronautics), predecessor to NASA (National Aeronautics and Space Administration), which conducted the heating and control tests. The X-1B tests played an important role in developing the control systems for the later X-15. On test missions, the X-1B was carried under a "mother" airplane and released between 25,000-35,000 feet. After release, the rocket engine fired under full throttle for less than five minutes. After all fuel (an alcohol-water mixture) and liquid oxygen had been consumed, the pilot glided the airplane to earth for a landing. The X-1B made its last flight in January 1958, and it was transferred to the museum a year later.

TECHNICAL NOTES:

Engine:	Reaction Motors XLR-11-RM-6 four-chamber rocket engine of 6,000 lbs. thrust
Maximum speed:	1,650 mph
Maximum altitude:	90,000 feet
Landing speed:	170 mph
Weight:	16,590 lbs. loaded

Bell X-1B back to Table of Contents

Convair SM-65 Atlas



Left: Three configurations addressed in this article. Right: Unique "stage and a half" concept.

The Atlas missile plays a pivotal role in the story of USAF ballistic missiles and space boosters but is not currently available for display. The Atlas was the Strategic Air Command's first Intercontinental Ballistic Missile (ICBM) (Convair B-65, later redesignated SM-65). Atlas A through Atlas C were development models and the Atlas D became the first operational ICBM. Atlas E and F (see left illustration above) comprised the bulk of the operational force. The Atlas became operational in 1959 and was phased out as an ICBM in 1965, being superseded by the Titan II ICBM. Before the Atlas was even retired as a ballistic missile, it began its career as a workhorse space booster. Soon the Able and Agena upper stages, which had been first developed for the Thor, were integrated with the Atlas. The Atlas Agena A (2nd illustration above) was first used to launch the first MIDAS (MIssile Defense Alarm System) satellite in 1960.[1] Familiar to most Americans, the Atlas D was modified for use in NASA's Project Mercury, propelling four Americans into orbit, beginning with Lt Col. John H. Glenn on February 22, 1962 (3rd illustration above). Later, for Project Gemini, Atlas missiles launched Agena B upper stages modified for use as docking targets for the Gemini capsule.

Initial Operation Configuration (IOC) Atlas D was a stop-gap intended to help address the perceived "missile gap" between the United States and the Soviet Union. As a weapon system, the Atlas D left much to be desired; it was based at first on vertical gantry-type launch "pads", and later in unhardened horizontal "coffin" launchers that provided little or no protection against attack. It had to be fueled immediately prior to launch - a nominally 15-minute process - and was radio-guided, raising the possibility that a strike on the guidance station could incapacitate multiple missiles. Additionally, Atlas Ds were grouped in complexes of 3 missiles controlled by a single launch control center, limiting the extent to which the force could be dispersed. Nonetheless, 30 Atlas Ds stood alert as our initial ballistic missile nuclear deterrent between January of 1959 and December of 1964.[4]

The Atlas E attempted to address some of these shortcomings. The missile was stored horizontally in an earth-covered "coffin" enclosure that theoretically provided protection against 25 psi overpressure, but the missile still had to be erected and fueled before launch. All-inertial guidance made each missile independent of any ground support after launch. And each missile had its own launch control center, a practice carried over to the Atlas F and Titan II. The follow-on system, the Atlas F, was stored vertically underground in a silo and an elevator raised it to ground-level for launching. Atlas F silos were hardened against 100 psi overpressure, and like the Atlas E, the Atlas F had all-inertial guidance. Ultimately, 28 Atlas Es and 74 Atlas Fs contributed to America's nuclear deterrent capability between December 1961 and June 1965.[4]

Both fully operational variants of the Atlas ICBM (Atlas E and Atlas F) suffered from two major drawbacks - hardness and response time. Because the missile had to be erected or elevated to be fueled and launched, there was a response time on the order of 15 minutes, during which it was vulnerable to being caught in the open when even a relatively inaccurate strike would have destroyed it. The Atlas ICBM could deliver a nuclear warhead more than 6,300 miles from its launch site.

Development of the Atlas and its engines

In 1948 Convair flight tested three missiles under the MX-774 program. A significant improvement over rockets of the day was to use internal pressurization of the tank structure to provide stiffness and strength instead of heavy internal stiffeners and bracing. This design, further developed on the Atlas, was sometimes called "the stainless steel balloon" because the tank structure was only 0.010 inches in thickness. Another significant innovation that Convair developed for the Atlas, when they were awarded the contract in 1957, was called the "one-and-a-half stage" (reference illustrations at right, above). At launch, three large rocket engines would provide thrust, but after about two minutes, the two large booster engines and the "skirt assembly" would drop away, shaving about 7000 lb. from the vehicle which would continue to be powered by a single sustainer engine in the center. The stage-and-a-half design allowed all rocket engines to be verified to be operating on the ground before releasing the missile and avoided the difficulty of starting an engine in flight.[2]

While the Atlas airframe leveraged Convair's experience on the MX-774, the Atlas engines were derived directly from Rocketdyne's experience on the Navaho cruise missile, which utilized three 135,000 lb. thrust rockets to boost the subsonic missile to cruise speed. The Navaho rocket engines utilized "spaghetti tube" construction of the thrust chamber to reduce weight relative to the previous double wall construction and had transitioned from alcohol as a fuel to hydrocarbons (kerosene). The version developed for the Atlas booster engines retained these features, boosted thrust to 150,000 lb. per thrust chamber, and were the first to use a bell-shaped nozzle instead of a conical nozzle, improving thrust efficiency. On the Atlas D the main engines were called the MA-2 drive system, and all three engines were gimballed for thrust vectoring. The two booster engines, called the L89-NA-5, shared a common gas generator. The center sustainer engine, called the LR105-NA-5, produced 57,000 lb. thrust at sea level and had a high nozzle expansion ratio for optimized performance at high altitudes. Two small vernier engines mounted on the side provided about 1000 lb. thrust each and were used for roll control after the boosters were jettisoned and for final velocity adjustment after the sustainer engine was shut down.[3]

Atlas legacy

Both IRBMs (Thor and Jupiter) benefitted from Atlas by using propulsion, guidance, and warhead technology developed for Atlas. The Atlas 150,000 lb. thrust booster engine (LR89) were modified as the LR79 engine in both, and the Atlas vernier engines were also used on the Thor. The LR89 was later developed into the H-1 engine used in the Apollo and Skylab programs, and the Apollo-Soyuz Test Project. The basic Atlas was developed into a stretched version called the Atlas II, which enjoyed success as a space booster. Atlas III followed and the Atlas V continues as an important booster, but the earlier Rocketdyne engines have been replaced by Russian engines.

SPECIFICATIONS (Atlas D):

Diameter:	10 ft. across tank (width 16 ft. across booster skirt assembly)
Length:	85 ft. 6 in. (in ICBM configuration)
Weight:	260,000 lbs. maximum at launch
Armament:	Nuclear warhead on ICBM, none on scientific or Mercury flights
Engines (ICBM/Atlas D):	One Rocketdyne LR89-NA-5 dual-chamber booster engine & one Rocketdyne LR105-NA-5 sustainer engine plus two small vernier rockets for attitude correction (steering)
Engine thrust at launch:	360,000 lbs.
Crew:	None (One on Atlas Mercury)

PERFORMANCE (Atlas D):

Maximum speed: Orbital velocity of about 17,500 mph. for Atlas Mercury. Approximately 16,000 mph as an ICBM.
Range: Over 6,300 miles as an ICBM (the Atlas D could achieve orbit with reduced payloads)
Maximum altitude: Approximately 900 miles as an ICBM

TOUR POINTS:

- The Atlas was USAF's first operational ICBM and deployed from 1959 to 1965
- The Atlas was used on Project Mercury to boost four American astronauts into orbit
- Use of liquid oxygen and the need to erect or elevate the missile prevented rapid launch capability
- Unique features included lightweight "stainless steel balloon" tanks and "stage-and-a-half" design to ensure all engines are lit on the ground before liftoff
- The 150,000 lb. thrust booster engines led directly to the Thor and Jupiter engines as well as derivatives for the Apollo Program

SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

[1] David Baker, *Rocket 1942 Onwards Owners Workshop Manual*, (Sparkford, UK: Haynes publishing, 2015)
[2] John Chapman, *Atlas: The Story of a Missile*, (Harper & Brothers, 1960)
[3] Robert S. Kraemer, *Rocketdyne: Powering Humans Into Space*, (American Institute of Aeronautics and Astronautics, 2006)
[4] Jacob Neufeld, *Ballistic Missiles in the United States Air Force, 1945-1960*, (Washington DC, Office of Air Force History, 1990)

Convair SM-65 Atlas back to Table of Contents

Vought ASM-135A Anti-Satellite Missile

The ASM-135A anti-satellite missile (ASAT) was the only U.S. air-launched missile ever to destroy a satellite. In the late 1970s, the U.S. anticipated Soviet development of "killer satellites" that could destroy vital U.S. reconnaissance and communication satellites. The anti-satellite missile countered this threat. Airborne tests with "captive" (not launched) ASAT missiles on modified F-15 fighters began in 1982. The ASM-135 was designed to be launched from an F-15A in a supersonic zoom climb.[5] In September 1985, an ASM-135A destroyed a real satellite in a pre-planned test. An F-15A launched the missile at 38,100 feet. Streaking into space, the missile homed in on the U.S. Solwind P78-1 satellite at 345 miles above the Earth, and impacted the one-ton spacecraft at about 15,000 mph. No warhead was necessary for this "kinetic kill".

The Solwind solar observation satellite was operational but several of its instruments had failed. This, along with other political and technical factors, led to its selection as a target for the ASM-135A. This test was the first time a U.S. missile destroyed a satellite.

Two solid-rocket stages propelled the missile into space, and a "miniature homing vehicle" (MHV) locked onto the satellite's infrared image with a telescopic seeker. The first stage was a modified Boeing AGM-69 SRAM missile using a Lockheed Propulsion Company LPC-415 solid propellant two pulse rocket engine. The LTV Aerospace Altair 3 using the Thiokol FW-4S solid propellant rocket engine was the second stage of the ASM-135. Hydrazine thrusters on the Altair helped point the missile towards the target.

LTV Aerospace also built the third stage, the Miniature Homing Vehicle (MHV). The second stage was used to spin the MHV up to approximately 30 revolutions per second and point the MHV towards the target. A ring laser gyroscope was used to determine the spin rate. The infrared sensor, developed by Hughes Research Laboratories, used a combination of strip and spiral infrared detectors to measure target's position as it crossed the strips in the sensor's field of view. The detector was cooled by liquid helium from a dewar installed in place of the F-15's gun ammunition drum and from a smaller dewar located in the second stage of the ASM-135.[5]

A "bang-bang" control system fired individual solid rocket motors (there were 56 full charge "divert" and eight lower thrust "end-game" solid rocket motors) arranged around the circumference of the MHV to keep the target in the sensor's field of view. The eight "end-game" motors were used to perform finer trajectory adjustments just prior to intercepting the target satellite. Small attitude control rocket motors at the rear of the MHV were used to damp off center rotation.[5]

Political and public concern about the Cold War arms race extending into space affected the program along with budget and development issues. The U.S. Air Force terminated the ASAT program in 1988. The missile on display is a captive version of the ASM-135A, designated CASM-135A.

Other Antisatellite Programs

The first interception of a satellite by an air-launched missile occurred on October 13, 1959, when the last USAF Bold Orion missile was tested in an ASAT mode. Built by Martin Aircraft as a prototype to demonstrate technologies for future air-launched ballistic missiles as part of Weapons System 199B (WS-199B), in the ASAT test it was launched by a B-47 aircraft and passed with 4 miles of the Explorer 6 satellite at 156 miles altitude. It was determined that the satellite would have been destroyed if it had been armed with a nuclear warhead.[1,2]

The Soviet Union developed the "Co-orbital interceptor", a killer satellite that intercepted seven targets and detonated five times between 1963 and 1972.[3]

Two ground-based ASAT systems were fielded by the US in the early 1960's, as summarized in a 2009 article in Air Force magazine:[3]

- Neither system depended on pinpoint accuracy—they employed the destructive power of nuclear warheads.
- The Army's Program 505 used Nike Zeus missiles originally developed as anti-ballistic missile weapons. Based on Kwajalein Atoll, it went operational in1963 and stood on alert for a year. It was then abandoned by SecDef Robert S. McNamara in favor of the Air Force's effort.
- The Air Force's Program 437 used Thor missiles as its base. Program 437 was based on Johnston Island in the Pacific. Three of four test flights (without live warheads) were successful, and the system was declared fully operational in 1964. After the system was up and running, US scientists began to learn more about the possible

deleterious effects of nuclear explosions in space. Tests demonstrated that the electromagnetic pulse from a nuclear explosion traveled a considerable distance. Any attempt to destroy an orbiting Soviet target thus risked unintended destruction of US satellites as well. In addition, the threat of USSR nuclear weapons in orbit had not materialized. In late 1970, Project 437 was downgraded from alert status to 30-day notice. In 1975, the launch facilities on Johnston Island were deactivated and Project 437 was abandoned.

ASAT technology continues to be developed but as of this writing no country has destroyed satellites from a different country. China destroyed its first satellite in 2007, and the next year the USN destroyed an orbiting satellite using a ship-launched Aegis missile. In March 2020, India became the fourth country demonstrating ASAT technology, destroying one of its own satellites with a ground-launched missile.[4]

TECHNICAL NOTES:

Launch:	From F-15A aircraft at 38,100 feet
Target altitude:	Approx. 350 miles (low earth orbit)
Maximum speed:	15,000 mph
Guidance:	Infrared heat seeking

SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

[1] Bill Yenne, *US Guided Missiles*, (Crecy Publishing Limited, 2012)
[2] https://en.wikipedia.org/wiki/Bold_Orion
[3] https://www.airforcemag.com/article/0209tomato/
[4] https://spacenews.com/why-we-need-to-avoid-more-anti-satellite-tests/
[5] https://en.wikipedia.org/wiki/ASM-135_ASAT

Vought ASM-135A Anti-Satellite Missile back to Table of Contents

Aerojet-General LR87 Liquid Rocket

The LR87 is a liquid-fueled rocket engine first used on Titan Intercontinental Ballistic Missiles (ICBMs). LR87 variants also powered the first stages of Titan space boosters in the Gemini manned spaceflight program and various Titan space launch vehicles. Though this powerful engine is in reality two engines working together, it is considered a single unit. The LR87 first flew in 1959.

The pipes around the top of the engine's two thrust chambers deliver fuel and oxidizer to high-speed turbopumps. The pumps then push these propellants to the bell-shaped thrust chambers, where the liquid mix becomes a mist and ignites, creating thrust. The machinery between the thrust chambers generates hot gas to drive the turbopumps.

LR87s came in several different models and used a variety of propellants. Early production LR87s used liquid oxygen and kerosene propellants on Titan I ICBMs. All later models used hypergolic fuels, which are liquids that ignite spontaneously when mixed together. The hypergolic propellants chosen for the LR87 (Aerozine 50 and Nitrogen Tetroxide) also had the advantage of being stored in the rocket tanks for long periods of time, making launches faster and simpler. The LR87 was also tested successfully with liquid hydrogen and liquid oxygen. The LH_2/LOX version was never carried forward to production.

The LR87 is a fixed thrust engine - it cannot be throttled, and it is not restartable in flight. Both of the engine's thrust chambers can gimbal, or tilt slightly, for steering.

The version on display is the LR87-AJ-5 and was used on the Titan II ICBM. The LR87 on the Titan I ICBM is similar but has minor differences in piping and the arrangement of some components. Both Titan ICBMs can be seen in the Missile Gallery. Further details on those versions of the LR87 can be found in the articles "Martin Marietta SM-68A/HGM-25A Titan I" and "Martin Marietta SM-68B/LGM-25C Titan II". The LR87 on the Titan IV here in the Space Gallery looks very different from this engine: on the Titan IV the LR87 engine is not lit until high altitude after the two solid rocket boosters have completed firing, so it is entirely covered by protective heat shielding and incorporates nozzle extensions to increase the expansion ratio, significantly increasing thrust at higher altitude.

TECHNICAL NOTES:

Burn time:	About 165-200 seconds depending on engine model and propellants
Propellants burned:	From about 1100 to 1800 lb. per second depending on engine model.
Turbopump speed:	24,000 rpm
Thrust:	300,000 to 430,000 lbs. (sea level) depending on engine model[1]

TOUR POINTS:

- Visible features:
    - Gimbal blocks and tube flex sections allowing nozzle movement
    - Spaghetti tubes for cooling thrust chamber
    - Solid propellant start cartridge

- Turbopump gearbox and propellant pumps
- Turbine exhausts (one bulged for heat exchanger)

SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

[1] George P. Sutton, *The History of Liquid Propellant Rocket Engines*, (American Institute of Aeronautics and Astronautics, 2006)

Aerojet-General LR87 back to Table of Contents

Boeing Inertial Upper Stage Space Payload Booster

The Inertial Upper Stage (IUS) is an unpiloted upper-stage booster rocket developed for the US Air Force and used from 1982-2004. They were carried aloft by Titan launch vehicles and the Space Shuttle. Once in space, IUS vehicles lifted satellites into high orbits or sent probes on interplanetary trajectories.

IUS/DSP in front of Titan IVB

Twenty-four IUS vehicles were launched. They flew with Defense Support Program (DSP) and other military satellites. Other IUS launches included the Magellan spacecraft to Venus (1988), the Galileo probe to Jupiter, and the Ulysses solar orbiter (both 1990). The Chandra X-ray observatory (1999) also used an IUS. When the Space Shuttle Challenger was lost in 1986, the accident also destroyed an IUS carrying a NASA Tracking and Data Relay (TDRS) Satellite.

The IUS is displayed attached to a DSP satellite. Seven IUS/DSP assemblies such as this were launched by Titan IVB vehicles similar to the one on display immediately behind them, being enclosed in the massive payload shroud. Separating from the Titan IVB about nine minutes after launch, the IUS would carry the DSP for 6-7 hours and then place it in a geosynchronous orbit about 22,300 miles above the earth.

Origins and Applications

During the development of the Space Shuttle, upper stage vehicles were explored to boost payloads from the Shuttle's low earth orbit to higher orbits or to escape velocity for planetary probes. In the longer range, NASA planned to develop a reusable "space tug", but the long development timeline argued for an interim upper stage (IUS) that could provide initial capability. USAF was tasked with developing the IUS and started with five contractors. USAF also added a requirement for the new IUS that it be compatible with the Titan 34D. Four contractors proposed modifications of existing liquid-fueled upper stages but USAF selected Boeing's new solid-fueled design, largely to reduce development time and costs for this interim vehicle. In 1975 NASA cancelled further work on the reusable space tug, and it became apparent that the IUS would have to serve longer than originally planned. The IUS name survived, but "Interim" was changed to "Inertial" (referring to its guidance system) and full scale development began the next year.[5]

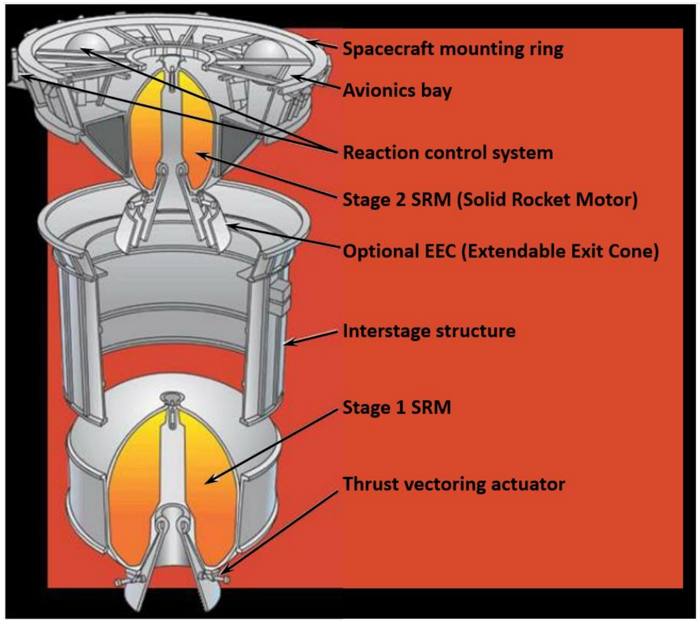
NASA was led by the unique requirements of their Galileo probe and ESA's Ulysses probe to develop a version of the Centaur upper stage for the Shuttle. The Centaur, which had been introduced in the 1960's, offered higher performance than the IUS (utilizing liquid hydrogen and liquid oxygen propellants), and flight hardware was ready for planned launch of both probes in mid-1986. After the Challenger disaster, the Centaur was reassessed as too dangerous for manned operations and never used on the Shuttle.[7] Both probes flew 3-4 years later with the IUS. For Galileo, instead of launching directly to Jupiter with the Centaur, the reduced IUS performance required the probe to conduct multiple gravitational assist maneuvers with Venus and then the Earth.

The IUS was used on Titan 34D and Titan IV vehicles as well as on the Space Shuttle. For Shuttle operations, the IUS would be deployed from the cargo bay, and not ignited until the Shuttle had moved a safe distance away.

Design[1]

The IUS contains two solid rocket motors (SRM) joined by a cylindrical interstage structure and topped with an equipment section that houses avionics and the reaction control system (RCS), which controls the attitude of the IUS and its attached payload. The payload is attached to a mounting ring at the top of the IUS.

The IUS stands 17 feet tall with a diameter of 9.25 feet, and with full propellant weighed 32,500 lb. The cross section at right illustrates primary components and layout.[4]



Since both SRMs burn until the propellants are fully consumed, propellant loads were varied depending on payload and trajectory to obtain the desired velocity increments. The first stage SRM produced 42,000 lb. thrust and with a full propellant load of 21,400 lb. would burn up to 150 seconds - the longest duration for an SRM in space. The second stage SRM produced 18,000 lb. thrust and could hold up to 6000 lb. of propellant. Both SRMs had nozzles that were mechanically vectored (+/- 4 deg. for stage 1 and +/- 7 deg. for stage 2). The first stage nozzle had an expansion ratio of 64:1. The second stage basic nozzle had an expansion ratio of 47:1 but an optional extendable exit cone would raise that to 181:1 when deployed.[2]

The two SRMs were provided for separate burns to raise a payload from low earth orbit to a geosynchronous orbit. (At 22,300 miles altitude, a geosynchronous orbit is a circular orbit whose orbital period matches the rotation of the earth, thus making the satellite to appear “fixed” above a designated point on the equator.) After the first burn, the stage 1 SRM and interstage structure were jettisoned and the remainder of the IUS and the payload would coast about six hours in an elliptical transfer orbit that peaks at 22,300 mile altitude. On reaching that altitude, the stage 2 SRM burned, further increasing the velocity to achieve a circular orbit. From a low earth orbit, the IUS could place a 5000 lb. payload into geosynchronous orbit. For a planetary probe, the two SRMs would be fired in succession without an extended coast period. In that mode of operation nearly 8000 lb. of payload could be boosted from low earth orbit to escape velocity.

The RCS could be loaded with one to three 120 lb. tanks of hydrazine for its twelve thrusters. The RCS was used for roll control during SRM burns, for attitude control during coast periods, to trim precise velocity prior to payload separation, and to finally provide a separation maneuver to keep the IUS from colliding with the payload. The RCS thrusters were oriented so that there was no forward-thrusting that might damage the payload.

The equipment support section avionics include guidance, navigation, control, telemetry, command and data management, and electrical power. Extensive redundancy included essentially all avionics plus SRM ignitors, thrust vector actuators, stage separation pyrotechnics and RCS elements, yielding 98% overall reliability. A unique feature of the IUS was that it could be controlled by ground command during flight.[6]

The IUS was developed and built by Boeing Aerospace, Seattle, under contract to the Air Force Systems Command's Space and Missile Systems Organization (later Space Division).

Operational History

From its first mission in 1982 until its final in 2004 the IUS launched a diverse range of civilian and military payloads into high-altitude orbits or off into space:

- NASA launched two planetary probes (Galileo to Jupiter and Magellan to Venus) using the Shuttle and IUS.
- NASA also launched two unique probes using the Shuttle and IUS. The Chandra X-Ray Observatory was placed in an oblong earth orbit ranging from 9000 to 84,000 miles altitude. The Ulysses probe (built by ESA) went far out of the ecliptic plane into a solar orbit taking it over the solar poles.

- All the remaining payloads of the IUS were placed into geosynchronous orbits:
  - Six Tracking and data relay satellites (TDRS) were launched by Shuttle/IUS. A seventh TDRS was on board Challenger on its final flight.
  - Six DSCS satellites (Defense Satellite Communications System) satellites were orbited in pairs using one Shuttle and two Titan 34Ds.
  - Eight DSP satellites (similar to the one attached to the IUS display) were launched - seven by Titan IVB and the other by Shuttle.
  - Finally, two classified DoD payloads were also launched by the Shuttle/IUS but further particulars were not provided.

TECHNICAL NOTES:

Weight:	32,500 lbs. (Vehicle 5,100 lbs., propellant 27,400 lbs.)
Propulsion:	Two solid-fuel rockets. First stage 45,600 lbs. thrust with 21,400 lbs. propellant; second stage 18,500 lbs. thrust with 6,000 lbs. propellant
Launch vehicles:	Space Shuttle, Titan 34D, Titan IVA, Titan IVB
Boost capability:	5,000 lb. payload to geosynchronous orbit or up to 8,000 lbs. beyond Earth's gravitational field

TOUR POINTS:

- The IUS changed its name from "Interim" to "Inertial" when the planned replacement (NASA's Space Tug) was cancelled.
- The two SRMs achieve higher efficiencies than most solid rockets because of high expansion ratios in the nozzle operating in the vacuum of space.
- Over 22 years, the IUS was launched 24 times, servicing a variety of civilian and DoD payloads.
- While most payloads were launched into a geosynchronous orbit, three payloads were sent beyond the earth's gravitational field (Magellan, Galileo, and Ulysses).

SOURCE DOCUMENTS and ADDITIONAL INFORMATION:

[1]https://science.ksc.nasa.gov/shuttle/missions/sts-30/sts-30-press-kit.txt (NASA Press Kit for Space Shuttle Mission STS-30 (Magellan))

[2] http://www.braeunig.us/space/specs/ius.htm ("Rocket and Space Technology" website

[3]https://www.slideserve.com/ziya/solid-rocket-engines-1

[4]https://en.wikipedia.org/wiki/Inertial_Upper_Stage

[5]https://fas.org/spp/military/program/cape/cape1-3.htm (Federation of American Scientists, Space Policy Project, Military Space Programs, "The Cape", Chapter I, Section 3)

[6]https://web.archive.org/web/20140417071751/http://www.aerospace.org/wp-content/uploads/crosslink/V4N1.pdf (*Crosslink*, Winter 2002/2003, "Evolution of the Inertial Upper Stage", W. Paul Dunn)

[7]https://arstechnica.com/science/2015/10/dispatches-from-the-death-star-the-rise-and-fall-of-nasas-shuttle-centaur/ ("A deathblow to th Death Star: The rise and fall of NASA's Shuttle-Centaur")

Boeing Inertial Upper Stage Space Payload Booster back to Table of Contents

APPENDICES: MISCELLANEOUS REFERENCE DATA:

Appendix A: Optional handout for tour
See following two pages.

Glossary/Notes for Rocket Engine Tour

RV – Reentry Vehicle. An RV contains and protects a warhead or film canister during the fiery atmospheric reentry following de-orbit.

MIRV – Multiple Independently-targetted Reentry Vehicle.

PBV – Post-boost vehicle. On the Minuteman III or Peacekeeper, the PBV was a vehicle with small liquid rockets that would accurately finalize the position and velocity of individual RV's.

SRB – Solid Rocket Boosters ("strap-on boosters") as used on Titan IV and the Space Shuttle

Hypergolic propellants – Liquid fuel and oxidizer combination that spontaneously combust when brought in contact with each other. Elimiantes need for ignition systems.

Thrust – The force that pushes an airframe forward in reaction to the acceleration of exhaust gasses. Applicable to rockets and jet engines.

Rocket Thrust Equation - thrust equals the mass flow rate of propellants time the velocity of the exhaust gasses plus the nozzle exit area times the nozzle exit pressure minus ambient pressure. The first term is basically Newton's famous F = ma, while the second term is a pressure-area term that adds thrust at altitude (since ambient pressue drops).

$$F = \dot{m}V_e + (P_e - P_a)A_e$$

F is thrust (force)
$\dot{m}$ is mass flow rate of propellants
V_e is exhaust velocity
P_e is pressure at nozzle exit
P_a is ambient pressue
A_e is nozzle exit area

Missile vs. Rocket - Terms are often used interchangeably, but there are nuances of meaning. "Rocket" is a type of propulsion based on chemical combustion and directing the hot exhaust to produce thrust. "Missile" is traditionally any weapon propelled or hurled (e.g., spears, guided missiles). Non-weapons are usually referred to as rockets.

Orbital terms:

Equatorial orbit - Stays in lower latitudes and alternates from below and above equator. Launches from lower latitudes to the East get a free "head start" from the rotation of the earth and thus require less launch energy than polar orbit.

Polar orbit - typical track from Vandenberg AFB in CA, vehicles launched south and orbit over polar areas. Obtains worldwide coverage under orbital track as earth rotates beneath.

LEO (low earth orbit) - typically ~100 to 300 miles above earth. Used for all manned operations to date (excepting moon missions).

Geosynchronous orbit - placing payloads about 23,000 miles above the earth and in the equatorial plane matches orbital speed with the earth's rotation. Result is objects in geosynchronous orbit (e.g., TV broadcasting satellites) appear to be "fixed" at same location in sky.

Terms on this page refer to figures below

Solid Rocket vs. Liquid Rocket – Both are reaction devices use chemical combustion to produce hot exhausts. In a solid rocket the propellant is a solid where fuel and oxidizer are pre-mixed, and once ignited, burns until the propellant is consumed. In a liquid rocket separate liquid propellants (fuel and oxidizer) are brought from separate tanks into a combustion chamber. A liquid rocket can often modulate thrust or stop and restart thrust.

Turbopump – On a liquid rocket, a turbopump is typically a fuel and oxidizer pump (P in Figure) integrated with a turbine (T in Figure) to drive the pumps and an integrated gearbox assembly.

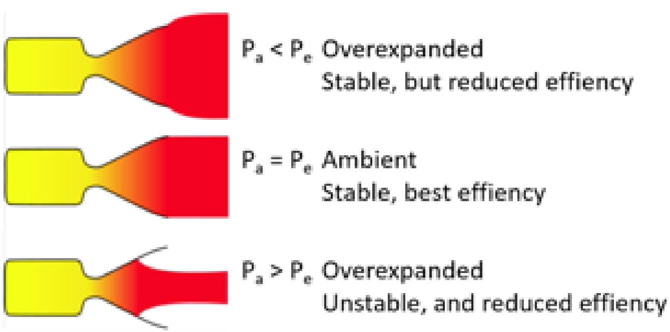
Gas Generator – (GG in Figure) A small combustion chamber that produces "warm" gasses to drive the turbine in a turbopump or power small thrusters for attitude control.

Combustion Chamber - a pressure vessel in which combustion takes place

de Laval nozzle or converging-diverging nozzle - rocket nozzle that directs exhaust from combustion chamber and accelerates exhaust gasses. Subsonic gasses accelerate in the converging portion, reach Mach 1 at the minimum area or throat, and continue to accelerate through the divergent portion of the nozzle supersonically

Thrust Chamber - the combustion chamber integrated with the nozzle

Expansion Ratio - Ratio of nozzle exit area (Ae) divided by throat area (At). Typically about 8 for SL rockets and 15 or much higher for high altitude or vacuum.



Above: impact of changing ambient pressure for constant expansion ratio.