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Chapter 6

From Peenemünde to the United States: A Classic Case of Technology Transfer*

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Abstract

This chapter traces the development of rocket technology in Germany, from the 1930s and 1940s, that led to the massive, and historically unprecedented, transfer of rocket, missile, launch-vehicle, and related technologies to the post–World War II United States. This achievement was made possible by an initial group of 118 German rocket specialists to which others were gradually

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‡ Peenemünde, Germany; U.S. Army Fort Bliss/White Sands/Redstone Arsenal; NASA Marshall Space Flight Center, U.S.A. [Editor's Note: Werner Dahm passed away in January 2008; Konrad Dannenberg passed away in February 2009; Walter Haeussermann passed away in December 2010; Gerhard Reisig passed away in March 2005; Ernst Stuhlinger passed away in May 2008].

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added. The contributions to rocketry, upper atmosphere, and space research, and eventually human space travel provided by Germany's Wernher von Braun and his team of engineers, scientists, technicians, and support personnel are, in particular, described, and the ongoing influence of the innovations they introduced is considered.

Introduction

A review is given of the massive, historic mid-1940s transfer of rocket, missile, launch-vehicle and related technologies, and an initial group of 118 rocket specialists, from wartime Germany to postwar United States. This chapter examines the contributions to rocketry, upper atmosphere, and space research, and eventually human space travel of Wernher von Braun[1] and his missile development team of engineers, scientists, technicians, and support personnel backed up by copious documentation and hardware.

Among the topics covered are the establishment of static and launch test facilities in Germany for a series of "Aggregate" rockets designated A1, A2, A3, A5, and A4. During pre–World War II and wartime periods, impressive progress was made in the development of rocket motors, guidance and control systems, supersonic aerodynamics, surface-to-air guided missiles, and also in studies of potential extensions of A4 technologies.

After the war, some 70 A4 (by then called V-2) rockets that had been shipped to the United States from Germany were converted for upper atmosphere and other research purposes and were launched principally from the U.S. Army's White Sands Proving Ground, New Mexico. From 1950 to 1960, the von Braun team worked at the Army's Redstone Arsenal in Huntsville, Alabama. There, Redstone, Jupiter, Pershing, and a variety of battlefield rockets were developed in addition to adaptations of the first two as Juno I and Juno II multistage space launch vehicles. In 1960, the team transferred to the new NASA Marshall Space Flight Center, where the Saturn series of launch vehicles was developed and placed into service. The team later played a major role in the development of three HEAOs (High Energy Astronomy Observatory satellites), the Skylab space station, the Space Shuttle, the International Space Station, the Hubble Space Telescope, and the Chandra X-ray Observatory.

Technology Development

Throughout the year 2003, the aerospace community celebrated the 100th anniversary of the Wright Brothers pioneering airplane flight near the small village of Kitty Hawk, North Carolina. There began aviation as it is known today.
In Germany, a little more than 60 years ago, the first rocket to reach the frontier of space took off near another historic site, Peenemünde, initiating spaceflight as known today. The counterpart to the Wright Brothers "Flyer" was the A4, developed by Wernher von Braun and his rocket team.

In contrast to airplanes, rockets have been known and used—mainly as military weapons—for almost 1,000 years. Their basic technology is far simpler than that of airplanes, as long as high efficiency, flight control, and target accuracy are not required. Because rockets do not need an ambient atmosphere for lift forces and for oxygen, they are able to fly beyond Earth's atmosphere.

In the late-19th and early-20th centuries, several men began to study the detailed physics of rocket propulsion and to ponder its potential for spaceflight. Principal among them were Konstantin Tsiolkovsky in Russia, Robert Esnault-Pelterie in France, Robert H. Goddard in the United States, and Hermann Oberth in Germany. This period witnessed the derivation of the pertinent rocket equations and pointed the direction in which a rocket development program might proceed. Rockets of the future, these pioneers concluded, should use liquid instead of solid propellants, perhaps liquid hydrogen and liquid oxygen; high combustion temperatures and pressures; liquid cooling for chamber and nozzle; tank pressurization with gas or turbo-pumps for propellant feed; gyroscopes for attitude stabilization; and a guidance and control system for target accuracy. Each of the four pioneers offered a wealth of ideas, working quietly with a small number of assistants. None was prepared to try to build a team of technical and scientific coworkers who could help transfer their ideas and relatively modest experimental efforts into realistic, large-scale engineering systems.

It was left to Wernher von Braun to take the next major step in the history of rocketry: the systematic building of a powerful, long-range, precision rocket.

Early Rocket Development in Germany

To trace how rocket technology got started in Germany, we first consider early development in the 1930s. Of several early amateur rocket and spaceflight societies in Germany and elsewhere, one at Reinickendorf near Berlin was the most successful (Verein für Raumschiffahrt, VfR). Among its members were spaceflight pioneer Hermann Oberth and the young Wernher von Braun, who soon recognized that the development of large rockets would require test and development facilities well beyond the reach of amateur groups.

Around 1928, the German Army (Reichswehr at that time) had started a small rocket development program under Colonel (later General) Karl Becker and Captain (later General) Walter Dornberger.[2] When they learned of Oberth's and von Braun's rocket club, they paid a visit to the rocketeers and promptly offered a contract to the latter. Recognizing that the development of a large precision rocket capable of flight into outer space would require development work and test facilities far beyond the reach of an amateur group, von Braun accepted the Army's offer and began working for the Reichswehr at Kummersdorf near Berlin in September 1932.

There, a series of A (for Aggregate) rockets were designed: the A1, which was ground-tested but never flown; the A2 (two units were built and successfully flown in 1934, "Max and Moritz," from the island of Borkum in the North Sea); the larger A3, which had major innovations (three-axis gyro control, jet vanes) but suffered from severe stability and control problems that called for a thorough redesign; and the beginning of the A5 design (the designation A4 had already been given to a larger rocket whose design specifications—225 kilometers distance, 1 metric ton warhead capability—had been prescribed by the Army). See Figures 1–3.

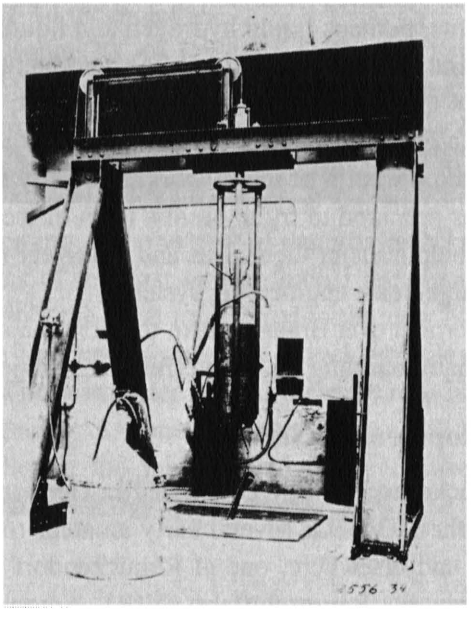


Figure 1: A2 on its test stand in Kummersdorf, December 1934. Credit: All images in this chapter are from authors' and U.S. Space & Rocket Center's archives. Hereafter listed as Authors/USS&RC.

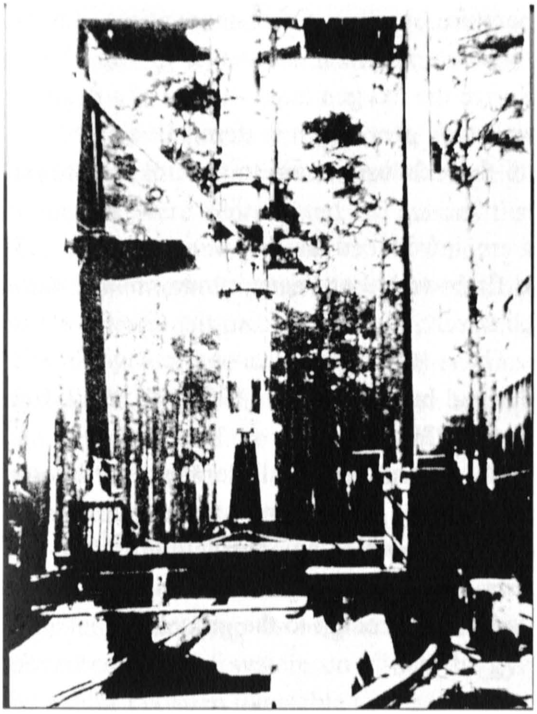


Figure 2: A3 on test stand, Kummersdorf, 1936. Credit: Authors/USS&RC.

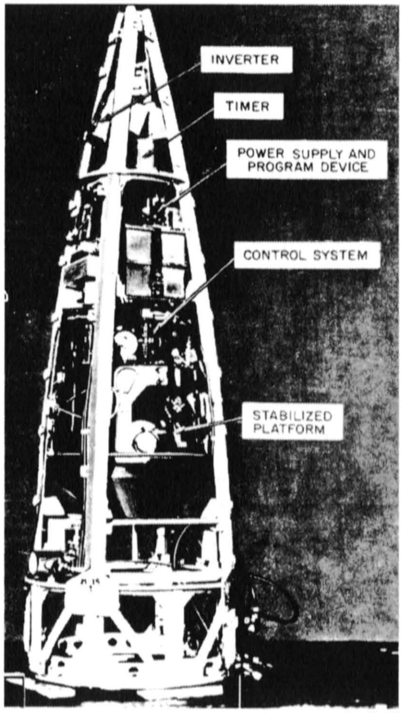


Figure 3: The forward compartment of an experimental A5 rocket with call-outs of major elements. Credit: Authors/USS&RC.

Realizing that large rockets could not be built and tested, and certainly not be launched, near the city of Berlin, in 1936 the Army began construction of a large rocket development center at a remote site on the island of Usedom in the Baltic Sea near the little fishing village of Peenemünde; it would be called Peenemünde East. The Air Force also established a base there, Peenemünde West, for the testing of Fi103 (V-1) flying bombs and rocket-powered airplanes.

At Peenemünde East, the Army built facilities for the testing and manufacturing of pumps, turbines, turbo-pump assemblies, and gas generators for rocket engines of varying sizes, and also of entire propulsion systems and of complete rockets. Among the advances in propulsion technologies made at Peenemünde were the design, development, manufacturing, and testing of several types of rocket motors, all leading to the A4 motor with its 25.4 metric tons of thrust, each with a regenerative cooling system for combustion chamber and nozzle, with proper injection heads for fuel and oxidizer, with a hydrogen peroxide power source to drive the turbine that in turn drove the two propellant pumps, and with the provision of "flexible" connectors in the oxygen and fuel lines to allow for changes in length in response to temperature changes. Other innovations developed and tested at that time included the use of a heat exchanger to vaporize a small amount of liquid oxygen to pressurize the oxygen tank; the use of a central, high-pressure nitrogen system to pressurize all propulsion system valves; and the use of carbon vanes that protruded into the exhaust stream to control the rocket during propelled flight.

Several of these innovations were introduced in the design of the A5 rocket, which was designed, built, and flight-tested at Peenemünde, mostly during 1938. A number of successful flights were conducted from the Greifswalder Oie, a small island near Peenemünde. These A5 flights cleared the way for the final design of the A4 rocket; its layout had been started in 1936 and 1937, but systematic work didn't get under way until 1939.

Von Braun insisted that all rockets would undergo full-duration static tests before launch, at that time the only certain means to detect possible system shortcomings. In those days, should problems occur during an actual flight, it was almost impossible to determine the cause, telemetry being limited to only seven channels through which to transmit data from the rocket to the ground.

Guidance and Control

Von Braun quickly and systematically identified the most important activities for the team beyond the A4 rocket's propulsion system. Among these were the development of a system to maintain stability during flight; of a guidance and control system to make it possible for the A4 to reach its target; the solving of aerodynamic problems for subsonic, transonic, and supersonic flight; and providing a remote measuring system for as many rocket flight functions and movements as possible. Also, elaborate test facilities had to be designed and built to permit the simulation and testing of all aspects of the flight of a rocket from launch through the atmosphere and into the frontier of space. Overall responsibility for the development of the rocket guidance and control system was assigned to Walter Haeussermann.[3]

The rocket's motions during flight are governed by a number of forces and factors: motor thrust, aerodynamic forces, gravity, wind, wind shear, atmospheric friction, decrease of the rocket's mass resulting from the consumption of propellants during flight, the movement of the center of gravity during that process, and forces generated by air rudders and jet vanes. The group charged with solving this complex guidance and control problem consisted of several professors of mathematics and a number of young engineers from technical universities who had specialized in electro-mechanical control systems for earthbound machinery and for airplanes. They soon came to the conclusion that rocket control problems could only be solved by building electro-mechanical systems, to be operated in the laboratory, which could simulate all the varying forces that acted on a rocket during flight.

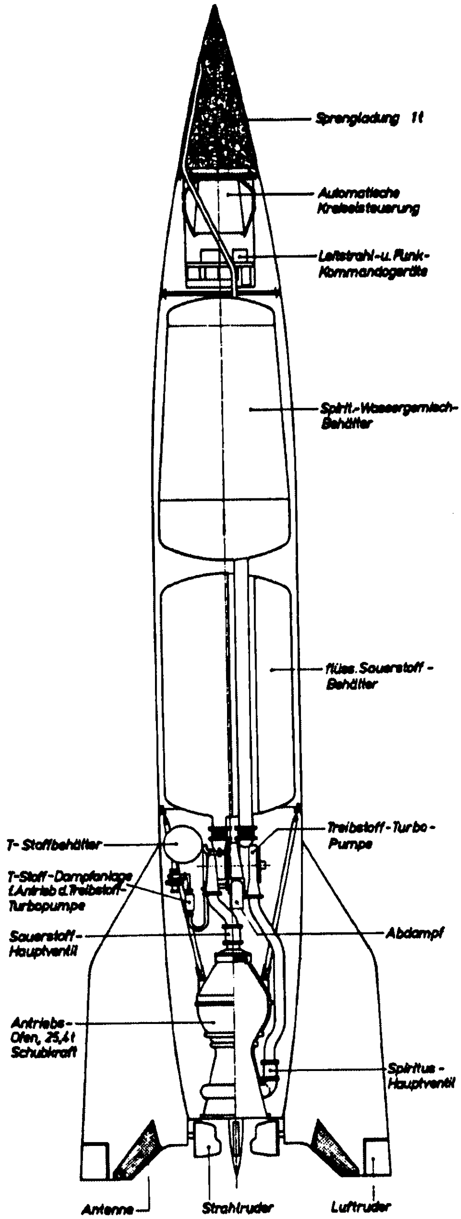
External forces acting on the A4 were simulated by controlled springs and electric actuators on systems called "swing tables." Forces caused by the inertia of masses were represented by masses that were mounted on shafts and connected with torque generators. Pendulums with variable proper frequencies and angular momentum generators showed whether a system capable of oscillations was properly damped. Such an elaborate electro-mechanical system, combined with a considerable amount of mathematics, was at the time called a "trajectory model" or "flight simulator"—later scientists would refer to it as an "analog computer." One of the originators of that simulator system, Helmut Hoelzer, decades later would receive an award "for having developed and operated the first analog computer."

The angular motions of A4s were measured by gyroscopes. If mounted in a cardanic system that allowed all three axes to move freely, the spin axis of a gyro rotor tended to keep its original direction constant irrespective of the rotational movements of the system on which the gyroscope was mounted. By measuring the angles between the stable spin axis and the rest of the rocket with potentiometer pickups, the instantaneous direction of the rocket can be determined.

A4s used two "position" gyroscopes of that kind, each with two degrees of freedom. Initially, the A4 also employed a "rate" gyro that did not indicate directional changes but, rather, angular velocities, that is, rocket turning rates. The rate gyro was later replaced by a resistor-capacitor network for differentiation of the position gyro signals (Figure 4).

Besides attitude control, the measurement of velocity and distance covered by the A4 rocket were of utmost importance to ensure controlled flight and target accuracy. Two different means were developed for effecting these measurements: a radio frequency link to the rocket and an onboard accelerometer and integrator to continuously measure acceleration, velocity, and distance. The radio method, also known as the Doppler system, was simpler than the "inertial" system, and, at Peenemünde, was used mainly during flight testing. Gerhard Reisig[4] and Otto Hoberg were responsible for the development of radio guidance systems.

In parallel, the development of accelerometers and integrators was started early, and three different systems were finally built and tested. One used an electrolytic cell system for integration; one used a capacitor; while the third, a gyroscope-type accelerometer, furnished the integration of acceleration directly by gyroscopic action. To obtain distance traveled, a second integration of the measured acceleration was necessary. Various methods were developed, but many test flights were carried out with one integration, providing a target accuracy of 1 to 2 kilometers.



GERMAN A-4 ROCKET

Figure 4: Cutaway of an A4 rocket noting, in the forward compartment, the location of gyroscopic elements and guidance beam. Credit: Authors/USS&RC.

The range of a rocket is controlled by providing a Brennschluss or burning cut-off signal at the proper moment. When radio guidance was employed at Peenemünde, the cut-off signal was transmitted from the ground station. Inertially guided rockets produced their cut-off signal onboard and had the advantage over radio systems that they could not be interrupted or disturbed from the ground.

For the lateral (yaw) flight control of a rocket, two methods were available and both were developed and used during flight tests at Peenemünde: a radio system, which used a "guide beam" (the intersection of two parallel radio beams of slightly different frequencies), and an inertial system, which relied on an accelerometer and an integrator in the lateral directions.

While gyroscopes and accelerometers were "body-mounted" during A4 test flights, planning and design work for a more accurate method were started even in the early years at Peenemünde. If three gyroscopes are mounted on a common platform that is free to turn around its three axes, the gyroscopes work together to keep platform orientation constant, irrespective of the angular and linear motions of the rocket. If the accelerometers are also mounted on this platform, they will always measure accelerations and velocity in the same original direction, resulting in far greater target accuracy.

During the early 1940s, some tests with stabilized platforms were successfully carried out at Peenemünde. When this technology was transferred to the United States in the mid-1940s, members of the von Braun team and their new American industrial colleagues developed the stabilized platform to considerable perfection and widespread use not only in rockets, but also in airplanes and submarines. The platform initially built for the U.S. Army Pershing guided missile was later used, with slight modifications, for the Saturn V launch vehicle that propelled Apollo astronauts to the Moon.

Aerodynamic Studies

The designers of the early long-range rockets faced a peculiar situation; aerodynamic design technology existed only for vehicles moving at subsonic speed. This, at the time, meant airplanes whose maximum velocity was approximately 250 meters per second. In contrast, rockets were designed to travel at 1,500 meters per second or even more, in other words, at supersonic velocities—beyond even those of bullets and artillery shells.

The sparse academic data then available revealed that supersonic flow behaves differently from subsonic flow. Thus, rocket designers found themselves in a situation similar to that of the early airplane designers from the Wright Brothers well into World War I: design by guesswork and intuition!

The few early wind tunnels that deserved this designation were bedeviled by mysterious x-shocks in the nozzle that falsified their data output. These shocks were eventually traced by Rudolf Hermann,[5] the future designer and head of Peenemünde's wind-tunnel facility, to condensation of moisture in the tunnels' air ducts. Knowing the cause made elimination a short step to take.

His two, 40 by 40–centimeter tunnels at Peenemünde, built for a rapid sequence of experiments and quick data reduction, were designed during the late 1930s. They were free of such shocks and became the backbone of the rocket-research center's aerodynamic programs. In fact, they were the largest supersonic tunnels of their time and were able to produce force data, pressure distributions, and even some heat-transfer data. The pressure distributions provided considerable insight into the workings of supersonic flow. After World War II, the Peenemünde tunnels and key personnel ended up at the U.S. Navy's Ordnance Laboratory at Silver Spring, Maryland, where they became the nucleus of naval missile aerodynamics research and development.

The aerodynamic design of a ballistic missile, typified by the A4, was relatively simple: fins of proper shape and size were used to maintain the center of pressure behind the center of gravity. How far behind was less important. It was planned to equip the A9, a potential successor to the A4, with wings to permit it to glide and thereby increase its range. This, in effect, meant building a supersonic airplane during World War II!

Airplanes have to have their centers of pressure and gravity close together to be controllable. Wind-tunnel tests revealed that, going supersonic, the A9's center of pressure moved so far to the rear that the rocket could no longer be controlled at supersonic speeds. More than 20 drastically modified shapes were tried in the tunnel, and none turned out to be flyable. Scientists now know that this transonic center-of-pressure shift is a fairly general feature of supersonic designs. At an altitude of about 8,000 meters and Mach 0.75, planes, such as the Concorde, had to pump fuel back and forth to compensate for the shift.

All rules, however, have their exceptions. The Wasserfall antiaircraft rocket had a fuselage, short wings, and fins fitted with air vanes. It had to fly in an airplane-like fashion at Mach numbers up to 4. Its shape was developed in the wind tunnel by trial-and-error and had a fixed center of pressure through its whole Mach-number range.

"Regener Tonne"

Among the early problems faced by researchers at Peenemünde was whether radio connection among ground stations and high-flying rockets could be maintained despite the ionized layers of the stratosphere. To shed light on the question, von Braun contacted Professor Erich Regener of the Technical University of Stuttgart, who had already developed balloons to carry stratospheric-physics-measuring instruments to altitudes up to about 30 kilometers.

Working with the Peenemünde team in the early 1940s, Regener carried out field-strength measurements of short-wave signals from transmitters carried aloft by his balloons. He soon became convinced that A4 rockets would be ideal to carry his instruments to even higher altitudes, 50 kilometers and more. This led to a meeting between von Braun and Regener in July 1942 to discuss plans for placing Regener instruments onboard an A4.

Regener provided an aluminum container, later called "Regener Tonne" ("Regener Barrel") that could carry an assembly of instruments, including a quartz spectrometer to register solar ultraviolet radiation, temperature and pressure gauges, batteries, and receivers and transmitters for command and data transmission and the reconstruction of the entire A4 flight trajectory.

The mission called for the container, which was air- and water-tight and light enough to float, to be ejected from the ascending rocket at an altitude of about 50 kilometers. From there, it would descend slowly by parachute while measurements were taken and, finally, would settle down on the waters of the Baltic Sea, where it would be recovered. After two non-instrumented test flights, an instrumented Regener Tonne was ready by late 1944 with flight testing scheduled for January 1945. By then, however, Soviet troops had come so close to Peenemünde that the SchutzStaffel (SS) ordered immediate evacuation, thereby terminating the Regener project.

The launching of scientifically instrumented A4s would have to wait. A4s shipped to New Mexico, after the war ended, started carrying scientific instruments to high altitudes as early as 1946. White Sands was just around the corner.

Extension of the A4 Project

Within a short time after its establishment, the Peenemünde development center grew at a rapid pace. During the 1940s, its work force included thousands of resident employees, and a similar number of engineers and scientists worked for the rocket project at universities and industrial firms. Von Braun personally was fully immersed in the daily effort to produce a reliable long-range precision rocket. However, his lifelong dream of building rockets for spaceflight never left him. He maintained a small, almost invisible, group of advance planners, who studied possibilities of extending the capabilities of the A4 toward rocket systems that could achieve orbital flight, round trips to the Moon, and eventually even voyages to Mars.

Around 1940, planning began for the A9, actually an A4 equipped with wings for a gliding descent. Officially, it was called an "A4 with extended range" (600 kilometers), but to some of his closest coworkers, von Braun remarked that, sometime in the future, "we will want to bring space travelers safely back from space, so we had better begin thinking of methods how this can be done." There were plans for a modification of the A9, the A4b, which had a cockpit for a pilot and wheels for landing on a runway.

Next to the A9, plans were made for the A10, which was propelled by six A4 motors in parallel; with nitric acid and kerosene as propellants, it would develop a thrust of 183 tons. Combining an A9 with an A10 would result in a two-stage rocket, with a range of 5,200 kilometers. (It may be noted that the principle of multistage rockets had been described for the first time 400 years earlier, in 1529, by Konrad Haas in Romania!). See Figure 5.

As the planners at Peenemünde pointed out, the next logical step would be the development of the A11 with 1,600 tons of thrust. As a booster for the A9/A10 combination, the three-stage rocket would have provided orbital capability, opening the human-in-space era.

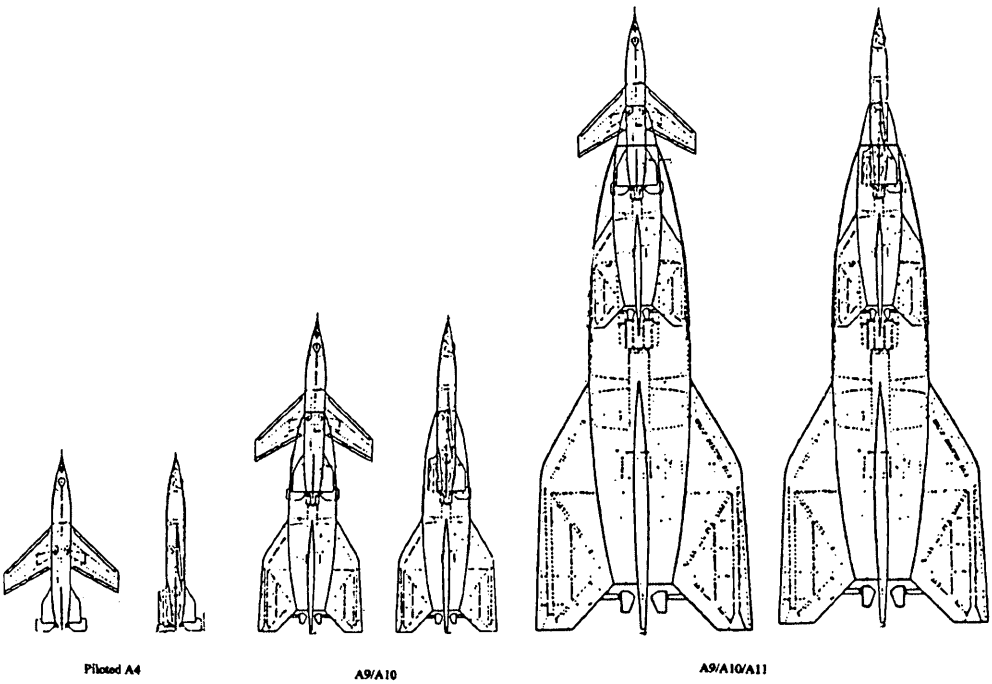


Figure 5: Proposed extensions of the A4 rocket through the A9/A10/A11 configuration. Credit: Authors/USS&RC.

Another advanced rocket system considered by the planners was the A60. With a more powerful 60-ton rocket motor, and with integral propellant tanks (in contrast to the tank-in-shell design of the A4 and A9), the A60 would have a range of 750 kilometers.

By 1942 Allied bombing raids had intensified, to the point that combined German Air Force and antiaircraft artillery proved unable to counter the attacks. The need for an antiaircraft guided missile thus became obvious. Von Braun offered plans for three different designs. Of them, a liquid-propelled version, called the Wasserfall, was accepted. This design had been studied in his Future Projects Office since 1941. The rocket was to be propelled by an eight-ton motor and guided by a combination of two radar systems, one to track the target, the other to guide the missile. The two radar systems were to be connected using a computing system. In its first version, successfully flight tested in February 1944, the missile was guided from the ground by radio, while the ground operator followed the target and the missile visually. Basically, the performance of Wasserfall met with the following specifications: target velocity 865 kilometers per hour, 30 kilometers altitude, 50 kilometers range, and 90 kilograms of explosives. However, the deteriorating war conditions in Germany at that time allowed only modest technical progress. Wasserfall never reached deployment status during World War II.

A historical footnote at Peenemünde was a project suggested in late 1943 by the German Navy. It called for a submarine to tow five cylindrical containers, each carrying an A4 rocket with propellants, instrumentation, and warhead. After a four-week crossing of the Atlantic Ocean, the containers would be positioned upright, their front lids would open, and their rockets, fitted with 1-metric-ton warheads, would be launched toward the eastern seaboard of the United States. Even within Peenemünde, the project was top secret: few people knew about it. Later, when details became known, grave doubts were raised concerning the military effectiveness of this seemingly farfetched project.

After the war, rumors began to circulate that Peenemünde had been close to building an "America rocket." There were two sources of this rumor. First, when plans were discussed for the two-stage A9/A10 rocket, someone remarked that its range would about equal the distance from Europe to America. From then on, the A9/A10 configuration was sometimes referred to as the "America rocket." However, because its trajectory would have ended with a long, low-altitude, subsonic glide, it would never have become a serious weapon of war. The second source of the rumor was the submarine project described previously.

Technology Transfer

At the initiative of U.S. Army Colonel Holger Toftoy, with the assistance of Major James Hamill and others, a group of 118 Germans was transferred from Germany to Fort Bliss, Texas, between autumn 1945 and mid-1946. Sporadically, others followed later. Most of the group worked on future projects at Fort Bliss, with some 30 specialists being assigned to help train military personnel and the U.S. Army's General Electric contractor in the handling and launching of A4 rockets and in converting them for research flights from the White Sands Proving Ground, about 100 kilometers to the north in the state of New Mexico.

The V-2 at White Sands

As early as February 1944, the U.S. Army began looking for a site suitable to flight test rockets and missiles. Ordnance Department, Corps of Engineers, and civilian engineers eventually zeroed in on a site some 50 kilometers east of Las Cruces, New Mexico, in the Tularosa Basin between the Sacramento Mountains to the east and the San Andreas Mountains to the west. Some small rockets were tested at the site, which was given the name White Sands Proving Ground. Thus, when captured German rocket components began to arrive at the new range in mid-August 1945 followed by the first group of Germans that October, the Army was more or less prepared for what followed.

Of the many rocket components shipped to the United States from Germany, 70 complete A4s—by then widely referred to as V-2s—were assembled and taken to the launch pad. Of these, 67 were launched successfully, and 47 reached altitudes of between 100 and 167 kilometers. Instead of explosive warheads, each carried, in converted nose cones, an assembly of scientific research instruments. Several young scientists at Johns Hopkins University and the Naval Research Laboratory, among them Ernst Krause and Milton Rosen, established a V-2 Upper Atmosphere Research Panel that organized, for interested scientists, the distribution and assignment of research space within the V-2 nosecones (Figure 6).

Soon, an active program of high-altitude research was underway in atmospheric physics, cosmic radiation, astronomy, astrophysics, infrared and ultraviolet spectroscopy, ionospheric studies, X-rays from space, and other experiments. This proved to be a marvelous opportunity for scientists of many specialties to carry out productive and pioneering research.

The General Electric Company was chosen by the U. S. Army to repair defective and build missing V-2 parts, install scientific instruments in the dummy warhead space, and conduct such modifications as might be required. Most of the rockets were used for upper atmosphere research, while others plowed new ground by serving as the first stage of the two-stage Bumper—the second stage a liquid-propellant rocket-powered WAC-Corporal provided by the Jet Propulsion Laboratory (Figure 7). A record altitude of 390 kilometers was achieved by a Bumper at White Sands on 24 February 1949.

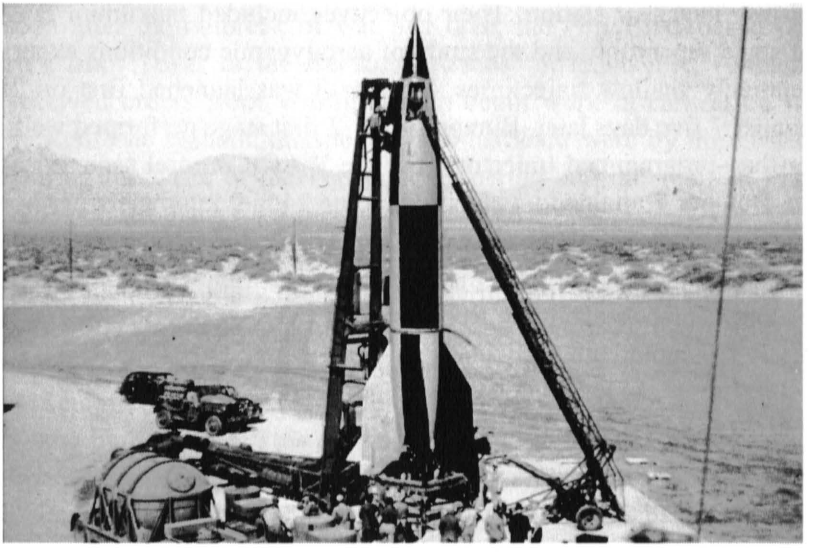


Figure 6: An A4, later called V-2, being serviced at the White Sands Proving Ground in New Mexico. Credit: Authors/USS&RC.

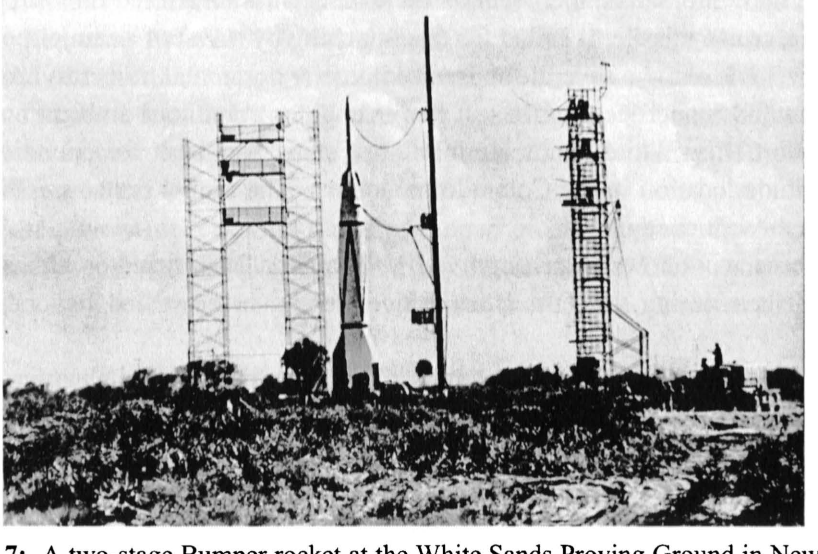


Figure 7: A two-stage Bumper rocket at the White Sands Proving Ground in New Mexico, 1949. Credit: Authors/USS&RC.

The Proving Ground was only about 160 kilometers in length, while the reach of a V-2 fired along a flat ballistic trajectory was about 320 kilometers, so clearly the rocket had to be fired straight up. This was an acceptable option in that the V-2s were primarily to be used for high-altitude research.

Because of range limitations at White Sands, the last two Bumpers were sent to the newly established Long-Range Proving Ground in Florida on the site of an existing naval air station. Their objectives included maximum range, the testing of stage separation, and the study of aerodynamic conditions experienced during relatively shallow trajectories. Bumper 8 was launched first on 24 July 1950, Bumper 7 five days later. Bumper 8's V-2 first stage performed well over a shallower-than-programmed trajectory, but the WAC-Corporal second stage did not ignite. Bumper 7 attained a velocity of some 14,500 kilometers per hour and impacted nearly 250 kilometers down range. These Bumpers were handled by U.S. Army personnel; at the time the German team was being transferred from Fort Bliss and White Sands to the Redstone Arsenal in Huntsville, Alabama, and consequently they could not participate.

Studies at Fort Bliss and White Sands

Much to their disappointment and frustration, members of the Peenemünde rocket team stationed at Fort Bliss and White Sands were not assigned a project worthy of their 12 years of experience in Germany. In effect, they were "put on ice" for an uncertain future.

But they weren't completely idle. Other than supporting the V-2 research program at White Sands, members based at Fort Bliss embarked on a project to develop a cruise missile. It called for the launching by a V-2 of a ramjet-powered winged vehicle along a several-thousand-kilometer horizontal trajectory. As there were no wind-tunnel facilities to test ramjet engines at reduced ambient air pressure at Fort Bliss/White Sands, a mobile test stand was built for operation at a high-altitude location in the Colorado mountains. The ramjet cruise-missile project was discontinued in 1949.

Some work toward an improved V-2—called Major and/or Ursus—was accomplished during the Fort Bliss period but never advanced beyond paper studies.

Then there was a quietly conducted, preliminary, study of electric propulsion for spacecraft. Von Braun recalled reading about the concept in Hermann Oberth's treatise on spaceflight published in 1929 and asked one of his coworkers, Ernst Stuhlinger,[6] to look into its feasibility. In 1964, he published the results of his studies in the book *Ion Propulsion for Space Flight.*

And, it was at Fort Bliss, during 1948 and 1949, that von Braun wrote *The Mars Project*, a 90-page booklet first published in German in 1952 and the following year in the United States. His studies showed that humans could reach Mars using chemically propelled rockets.

Redstone and Jupiter Missiles

Soon after the outbreak of war in Korea, the Fort Bliss–based team was transferred from Texas to the Redstone Arsenal in Huntsville, Alabama. Von Braun received orders from Washington to begin work in earnest on what became the Redstone ballistic missile. He and his team were by no means unprepared. During the close of the Peenemünde period and the years at Fort Bliss, they had developed plans for a successor to the A4/V-2.

The A4 had been plagued by reentry problems. These were avoided in the Redstone by incorporating terminal guidance in the following manner: after engine cut-off, the tip of the missile was separated from the propulsion unit and guided down to the target by active air vanes. This required designing an entry-body configuration whose center of pressure moved little throughout its 1 to 5 flight-Mach-number range. This new design made it feasible to use integral tankage and fuselage constructed of aluminum.

The problem faced at the time stemmed from the fact that it would be several years before supersonic wind-tunnel data became available. Consequently, design shapes had to be based on estimated aerodynamics, on experience gained at Peenemünde, on recently developed cone-lift theory, and on extrapolations over the conical segments of the body derived from similarity concepts developed at Redstone Arsenal. For this reason, the tip of the Redstone missile was composed of conical elements. As it turned out, the first wind-tunnel data became available about a month before Redstone's first flight. Fortunately, the results were close to estimates and hence no modifications of the entry body were required (Figure 8).

A relatively modest wind tunnel was soon included among facilities at the Redstone Arsenal and is still operating, after all these years! It has a sister facility that deals with internal flow problems from rocket-engine elements to gas turbines.

Another difficulty with the V-2 was its complicated 18-unit rocket engine injector design. In Peenemünde, tests had led to a much simpler mixing nozzle injector, but original vibration problems and a freeze against further design changes prevented its production. The use of a silver screen as catalyst in the hydrogen peroxide steam generator for the pump steam turbine did improve steam-plant operation by avoiding the use of liquefied potassium permanganate. Many other improvements were under examination toward the end of the war. At Fort Bliss, more improvements had been studied that eventually would lead to a more efficient turbo-pump system.

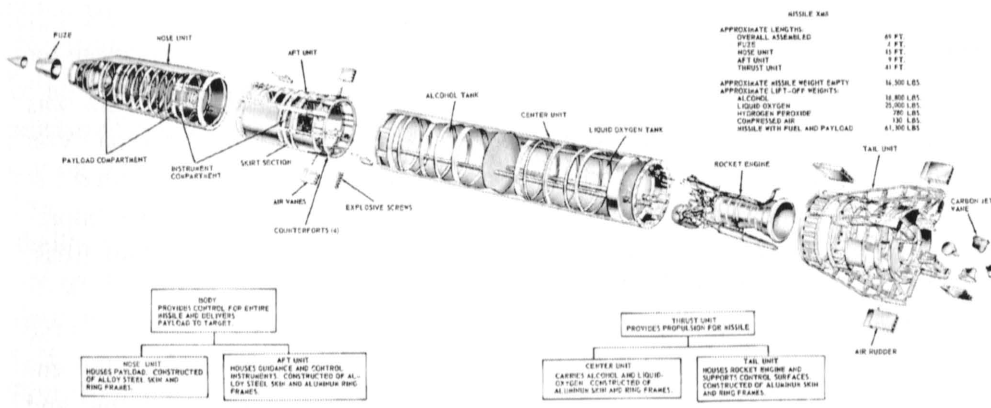


Figure 8: Cutaway with call-outs of the Redstone ballistic missile. Credit: Authors/ USS&RC.

When the team was relocated from Fort Bliss to Huntsville, its development director, Walter Riedel III, decided to join William Bollay at North American Aviation's Aerophysics Laboratory, where he helped in the development of rocket engines for the U.S. Air Force Navaho I missile. The engine that emerged from this work developed 35 metric tons of thrust and used the same propellants as the V-2's liquid oxygen and alcohol. It had the same burning time and shared other similar characteristics. More advanced Navaho III engines developed more than 60 metric tons on liquid oxygen and kerosene propellants. This development led von Braun to decide against starting an engine-development program at Redstone Arsenal, preferring rather to purchase directly from North American the Navaho engine. By 1953, the Redstone had achieved operational readiness, but it was not until 1958 that it was finally deployed in Europe.

The Redstone experience set up a long-term relationship between North American and the von Braun team that lasted through the Space Shuttle period. Among other advantages, the collaboration led to the Jupiter intermediate range ballistic missile (IRBM) engine with its superior cooling system, often referred to as "spaghetti cooling." The engine burned kerosene and liquid oxygen, and its turbo-pump unit was moved to the side of the rocket engine, thus permitting engine swiveling for flight control. Early Jupiters were produced at the Army Ballistic Missile Agency on the Redstone Arsenal, later ones at the Warren Michigan plant of the Chrysler Corporation. In 1958, the Jupiter was turned over to the

U.S. Air Force for operational use, and, during that year and into 1959, its personnel trained at Redstone Arsenal. Then in early 1960, some 60 Jupiters were finally deployed in Italy and Turkey. Much later, clusters of eight Jupiter engines would propel the first vehicles of the Saturn I and Saturn IB types into space.

The final military missile project undertaken by the von Braun team was the Pershing. When the von Braun team transferred to NASA in mid-1960, project director Arthur Rudolph remained with the Army to assure development continuity. He later rejoined the von Braun team to manage the Saturn V program.

Coincidentally, the development of the U.S. Air Force's own IRBM, the Thor, was directed by former Peenemünder Adolf K. Thiel, who left the von Braun Army team in 1955 to join the Space Technology Laboratories in California (STL later became TRW, Inc., Space Division). The missile was manufactured by the Douglas Aircraft Company and deployed in the United Kingdom.

Redstone and Jupiter Space-Launch Derivatives

As early as 1952, von Braun visualized the possibility of orbiting a small Earth satellite—he hoped it would be the world's first—with a Redstone rocket modified by adding three solid-propellant upper stages. Shortly thereafter, as the Jupiter IRBM development cycle was beginning, he made plans to use the Redstone to flight test models of warheads covered with heat-protecting ablation surfaces, a technique that would be necessary for Jupiter and, in fact, for all long-range missiles of the IRBM and intercontinental ballistic missile (ICBM) types. This warhead test vehicle became known as the Jupiter-C (for composite) in that it was developed to support the Jupiter IRBM program, which then enjoyed high national priority (Figures 9 and 10).

During 1956 and 1957, Jupiter-C rockets successfully launched warheads with protective ablative-type surfaces, and, in so doing, resolved the complex reentry problem for IRBM-class missiles. In September 1956, a Jupiter-C—with all stages performing flawlessly—reached an altitude of 1,090 kilometers and the amazing range of 5,440 kilometers. By adding a fourth stage, a Jupiter-C (in such a configuration it became known as Juno I) would have been able to orbit a small artificial Earth satellite a full year before the launch of the first Soviet Sputnik (Figure 11).

For von Braun, this golden opportunity for an American "first" was obvious, even at a modest cost and with flight-proven components. In September 1954, he wrote a proposal for an American satellite project, which was based on the multistage rocket system, developed for Jupiter reentry tests, and submitted it to his military superiors. In it he pointed out that launching an American satellite would be possible in the autumn of 1956. However, the decision in Washington was that a satellite project should be assigned to the Navy, where a competitive project, the Vanguard, had been proposed and approved.

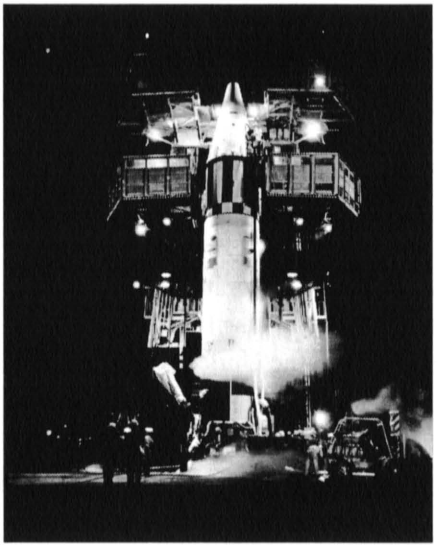


Figure 9: The Jupiter IRBM on its service tower at Cape Canaveral, Florida, 1966.
Credit: Authors/USS&RC.

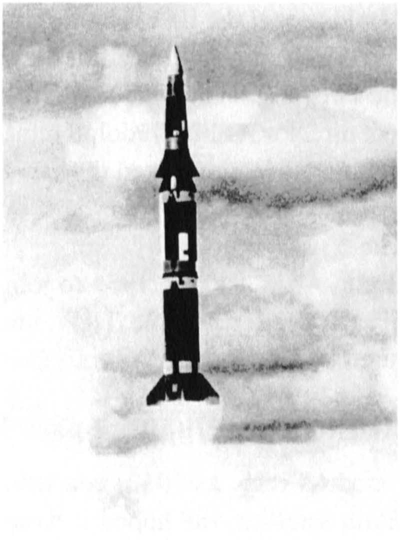


Figure 10: A Pershing ballistic missile in flight.
Credit: Authors/USS&RC.

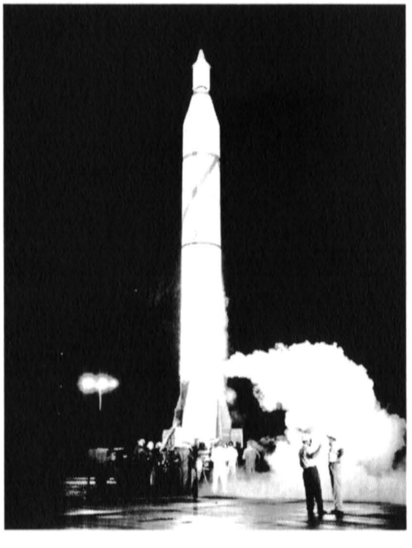


Figure 11: The Jupiter-C reentry test rocket at Cape Canaveral, Florida.
Credit: Authors/USS&RC.

Figure 12: A Redstone rocket boosts the Mercury MR-3 capsule in America's first human suborbital flight, Cape Canaveral, Florida, May 1961.
Credit: Authors/USS&RC.

Officially, von Braun's team in Huntsville was not permitted to work on a satellite project. Only after the launching of Sputnik in early October 1957, and after repeated failures of the Vanguard launcher, the team finally received a go-ahead order to launch von Braun's proposed Army satellite. Three months later, on 31 January 1958, Explorer 1 was in orbit.

Solid-propellant upper staging added to the Jupiter IRBM gave rise to the Juno II configuration, which was used to orbit Earth satellites and to propel instrumented probes on deep-space trajectories.

The Saturn Launch Vehicles

In mid-1960, the rocket team was transferred from the U.S. Army Ballistic Missile Agency to NASA's newly established George C. Marshall Space Flight Center with von Braun as its first director. Freed from responsibility for developing military missiles, the team could now devote its full time to peaceful, space-related endeavors.

Even before Kummersdorf and Peenemünde, von Braun had been pondering how a human mission to the Moon might be undertaken. He continued developing his ideas during the Fort Bliss/White Sands and Redstone Arsenal years. As Marshall's director, he could do something about them.

The first component, he concluded, would be a powerful, three-stage rocket to transport into Earth orbit the spacecraft that would then travel to the Moon, land there or dispatch a suitable lunar lander and return-to-orbit vehicle, and then return to Earth with the astronauts. He figured that the basic rocket would require a payload-lifting capability of some 120 metric tons, in turn meaning that multiple engines would be needed to provide a thrust force of approximately 3,500 metric tons. He also considered that, for maximum propulsive efficiency, the upper stages should be powered by liquid hydrogen, the same fuel that the pioneers of spaceflight had described decades earlier. The first rocket motor using liquid hydrogen and liquid oxygen had been built around 1958 by Abraham Silverstein at NASA in cooperation with the Pratt and Whitney Corporation. In addition, there was the launch vehicle's structure to be designed and built, staging problems to be solved, decisions to be made as to the type of guidance and control system to be employed, and much more. Then there was the spacecraft itself with its structure, propulsion, control system, and myriad other elements to be designed, developed, and built.

NASA eventually decided to separate what became the prodigious Apollo lunar exploration project between von Braun's Marshall Space Flight Center and Robert R. Gilruth's Manned Spacecraft (later Johnson Space) Center in Houston, Texas. Von Braun would be responsible for developing the booster rocket (which became the Saturn V) and injecting the lunar-bound spacecraft (which became Apollo) onto the transfer trajectory. Meanwhile, the Gilruth team would handle the actual lunar transfer, landing on the Moon, return from the Moon, and all the necessary accommodations involving the astronaut crew (Figure 12).

Work on the motor for the giant booster rocket had started quietly in 1958 with a contract between the Marshall Space Flight Center and North American Aviation's Rocketdyne Division in California. Among the novel technical problems to be resolved was the liquid hydrogen technology for Saturn V's second and third stages, the clustering of rocket engines for parallel operation, the swiveling of these engines for guidance and control, and the in-flight separation of the three stages (Figures 13–15).

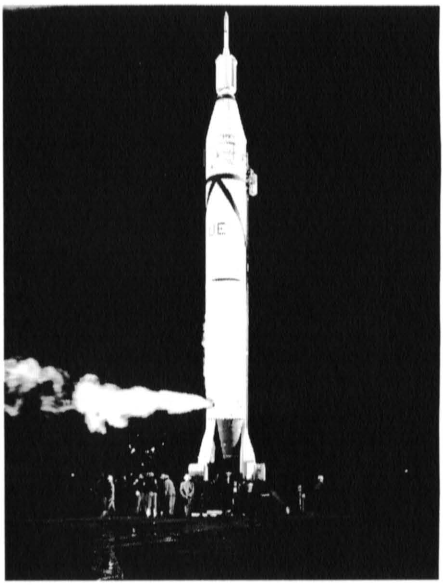


Figure 13: A Juno I rocket at Cape Canaveral, Florida, being prepared to launch the Explorer 1 satellite, January 1958. Credit: Authors/USS&RC.

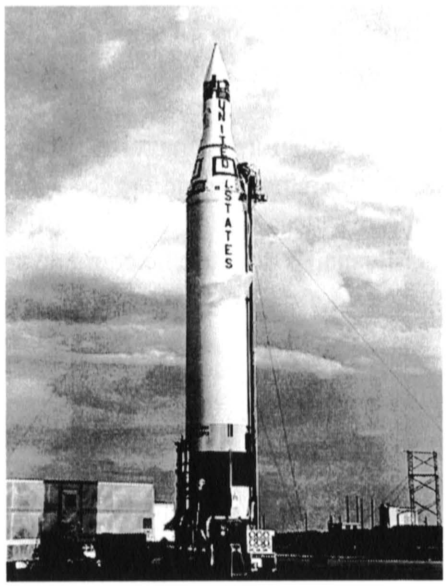


Figure 14: Juno II rocket that sent the Pioneer 4 lunar bypass probe on its journey in March 1959. Credit: Authors/USS&RC.

To prepare for what became the Saturn V, it was decided first to build a smaller, simpler Saturn I using existing rocket engines. Already on 15 August 1958, the Advanced Research Projects Agency (ARPA) of the U.S. Department of Defense had issued ARPA Order 14-59 backed by an initial payment of U.S. $2 million. The Army Ballistic Missile Agency was authorized to proceed with what was then called the Juno V Booster Program. This soon evolved into the Saturn I booster, based on existing Redstone and Jupiter missile components. By

1959, the Department of Defense realized that it had no military requirement for Saturn-class vehicles and urged their transfer to NASA. By October, NASA had officially taken over responsibility for all booster systems larger and more powerful than those based on the existing IRBM and ICBM systems then in inventory (Figure 16).

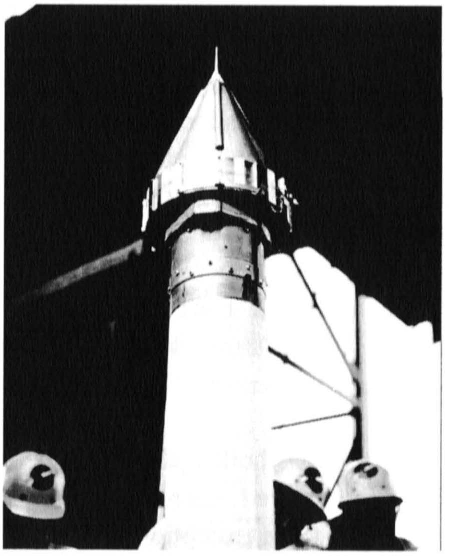


Figure 15: The Pioneer 4 lunar bypass probe being fitted to its Juno II launch vehicle at Cape Canaveral, Florida. Credit: Authors/USS&RC.

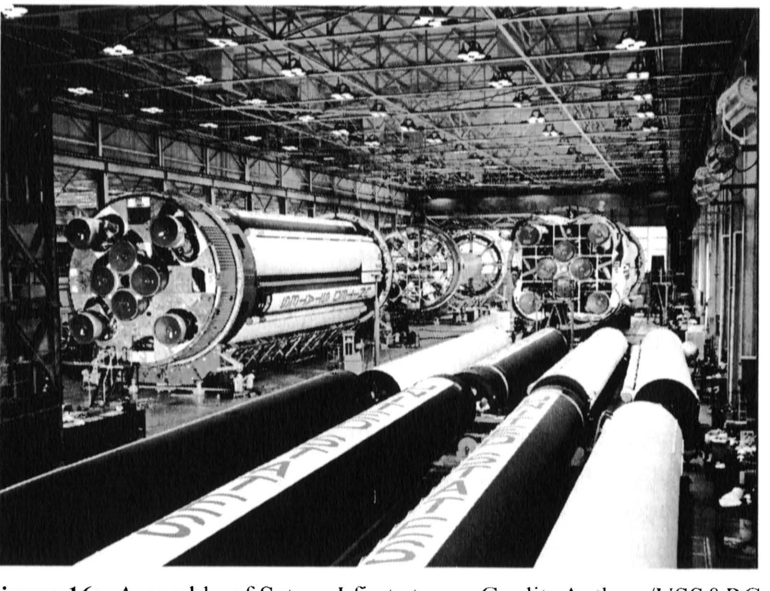


Figure 16: Assembly of Saturn I first stages. Credit: Authors/USS&RC.

Ten Saturn I's were eventually built and successfully flown between October 1961 and July 1965. Saturn I SA-1 through SA-4 used clusters of eight Rocketdyne H-1 engines, while the remaining six added a new S-IV second stage powered by six RL-10 engines burning liquid hydrogen and liquid oxygen.

The Saturn IB followed in 1966 with an upgraded Saturn I first stage and a modified S-IVB second stage, then under development for Saturn V. It was powered, not by RL-10 engines, but by a new J-2, which also operated on liquid oxygen–liquid hydrogen. Saturn IBs were used for testing engine operation and stage separation, to monitor and check-out Apollo spacecraft in Earth orbit, and later to rotate crews for the Skylab space station. The first four, launched between 1966 and 1968, tested unmanned Apollo command and service module (CSM) performance, including reentry into Earth's atmosphere, and lunar module descent and ascent engine performance. In October 1968 a Saturn IB lifted the manned Apollo 7 CSM mission into Earth orbit. During 1973, three more Saturn IBs serviced Skylab, and finally, in July 1975, a single one was used for the Apollo–Soyuz Test Project, a cooperative American–Soviet rendezvous and docking success.

Finally, the huge Saturn V was built and tested. The SI-C first stages of the initial two rockets were manufactured entirely at the NASA Marshall Space Flight Center in Huntsville, with the exception of their F-1 engines that were provided by the Rocketdyne Division of North American Aviation in California. These engines, five in number, burned kerosene (RP-1) and liquid oxygen and produced a thrust of 680 metric tons for a total S-IC stage thrust of 3,400 metric tons. Subsequent S-IC stages were manufactured by Boeing.

The two upper stages of Saturn V were powered by Rocketdyne Division's J-2 engines that burned liquid hydrogen and liquid oxygen, five in the S-II second stage with a total thrust of 454 metric tons, and a single one in the S-IVB third stage producing over 90 tons of thrust. The second stage was built by North American Aviation and the third by Douglas Aircraft.

The first complete Saturn V, assembled and tested at the Marshall Space Flight Center, was used as a dynamic test vehicle (called "the shop queen"). It was hung vertically in a huge test tower and checked for vibrational resonances. It was later sent to Cape Canaveral where it was the first Saturn V to be stacked in the Vertical Assembly Building, the first to ride the crawler to the launch site, and the first to test fueling and checkout procedures. This same Saturn V rocket has found a permanent resting place at the U.S. Space & Rocket Center in Huntsville, located adjacent to Marshall Space Flight Center. The rocket is to be refurbished and placed in a protective structure for public viewing.

The powerful engines, single and in their clusters, were tested by the manufacturers and also on huge test stands at the Marshall Space Flight Center. Heavy components of Saturn V, including the transfer vehicle to the Moon (CSM) and the Lunar Module (LM), were tested on Saturn Is and Saturn IBs and also on a single Saturn V on near-Earth flights. In November 1967, the first complete Saturn V, carrying the unmanned Apollo 4, was launched to an altitude of 16,000 kilometers. Three manned Saturn V's (Apollo 8, 10, and 13) traveled around the Moon, and six additional manned Saturn V's (Apollo 11, 12, 14, 15, 16, and 17) enabled a total of 12 astronauts to walk on the Moon. The last Saturn V to be launched put the space station Skylab into its orbit, unmanned. Three Saturn IBs subsequently sent crews to operate the station and conduct scientific research (Figures 17 and 18).

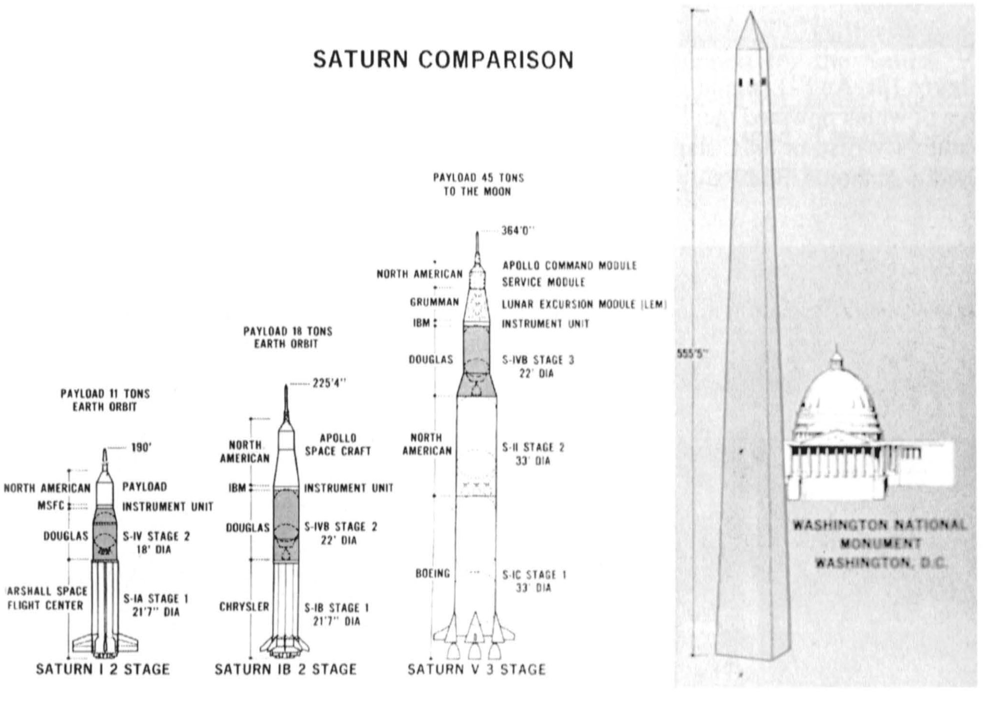
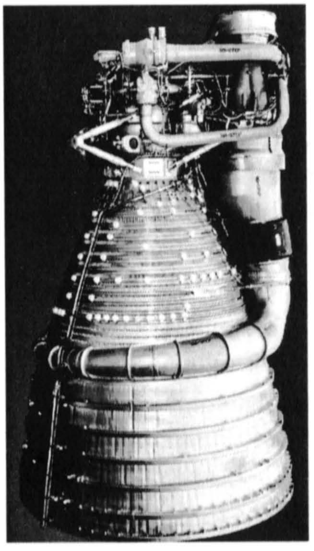


Figure 17: Comparison of the Saturn I, Saturn IB, and Saturn V launch vehicles. Credit: Authors/USS&RC.

In total, 32 Saturns were built and flown, 10 Saturn I's, 9 IB's, and 13 V's. All had a successful take-off, with a 100 percent flight-success rate. In some flights malfunctions did occur, such as the so-called "Pogo effect" (an oscillation in the propellant system of the second stage), but these malfunctions were cleared up and corrected; they did not reoccur (Figure 19).



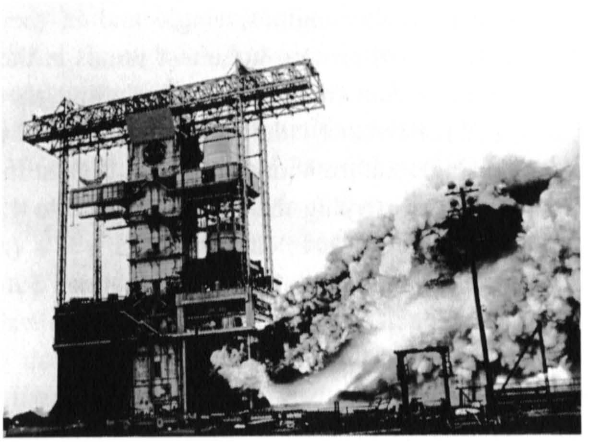


Figure 19: Testing the J-2 engine, five of which were used to power Saturn's V second, or SII Stage. Credit: Authors/USS&RC.

Figure 18: An F-1 engine, five of which powered the Saturn's V first, or S-1C stage. Credit: Authors/USS&RC.

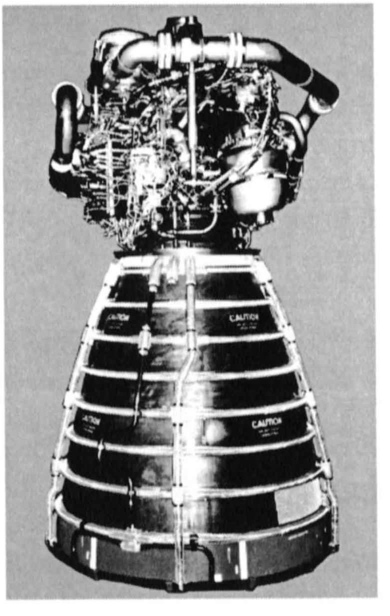


Figure 21: The Space Shuttle Main Engine (SSME). Credit: Authors/USS&RC.

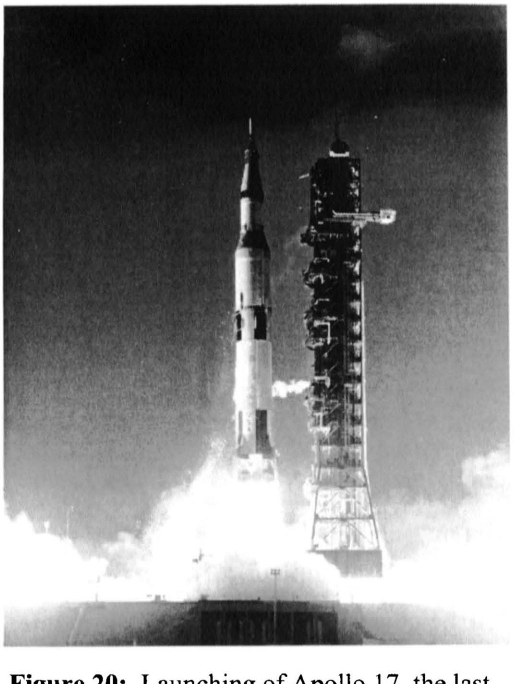


Figure 20: Launching of Apollo 17, the last Apollo flight to the Moon, 1972. Credit: Authors/USS&RC.

The Saturn–Apollo Project was terminated after Apollo 17. At that time, two more complete Saturn Vs were ready to be launched. They were mothballed. Later, one of the giants was restored and put on display at Kennedy Space Center in Florida. The other, located at NASA Johnson Space Center in Houston is being prepared for restoration (Figure 20).

Of course, there was more to the Saturn story than the launch vehicles themselves. At Cape Canaveral, Florida, an entire Saturn launch complex had to be designed and built. Three major elements were the crawler-transporter, the flame deflector, and the-hold-down arms.

Crawler-transporter—The Saturn V launch vehicle had to travel from the Vertical (later, Vehicle) Assembly Building to the distant Launch Complex 39 (LC 39), always in the vertical position. The late Olin Duren found the solution for what seemed an almost intractable problem: adapting surface-coal-mining-industry crawler transport technology to the delicate movement of enormous, highly complex rockets. Each crawler-transporter developed for the Saturn V weighed 1,720 tons and was powered by two, 2,750 horse-power, diesel engines that moved at a speed of 1.6 kilometers per hour under full load. The crawler's leveling system kept the platform vertical to within 10 minutes of arc on a 5 percent grade.

Flame deflector—It defined the design of the launch pad and is still in service with the Space Shuttle. Its two-way, wedge-type configuration measured 12 meters high, 15 meters wide, 23 meters long, and it weighed 635 tons.

Hold-down arms—Mechanically operated hold-down arms firmly secured the Saturn V during assembly; transport to the launch site; pre-launch preparations there; and, after ignition, up to the development of full engine thrust. At that point, the arms automatically and simultaneously released the giant rocket for lift-off. They worked flawlessly.

The Space Shuttle Main Engine

Before the Saturn–Apollo Project had come to its end, NASA started its next major project, the Space Shuttle. It was to be propelled by a combination of liquid-propellant rocket engines and solid-propellant boosters. Development of both systems was the responsibility of Marshall Space Flight Center. For the Space Shuttle Main Engine (SSME), Marshall joined forces with the Rocketdyne Division of North American Aviation (Figure 21).

The SSME uses liquid hydrogen and liquid oxygen as propellants. It develops 228 tons of thrust at a specific impulse of 453 seconds. The engine is based on "closed expander cycle" technology. Such engines channel propellants from the main rocket motor system, mix them in a preburner with an excess of one of the propellants, and burn the mixture at a relatively low temperature (600 degrees C). The hot gas, after driving the turbine for the propellant pumps, is not discharged overboard, but injected into the main combustion chamber of the rocket motor, where it is burned completely under high pressure and high temperature (3,000 degrees C), thus contributing to the rocket thrust.

Conclusion

The technology transfer from Germany to the United States is both unfinished and ongoing. Much of the same technology reached other shores also—the Soviet Union, the United Kingdom, France, Italy, and elsewhere. Later from and through the primary beneficiaries, it was absorbed by still other societies, notably China, India and Japan.

Then there is the story of projects and accomplishments made possible by the development of rocket-launch systems. As has been seen, modified and instrumented V-2s (from the mid-1940s to the early 1950s) came first. They were followed by ever larger, more powerful, and increasingly reliable launch vehicles that propelled artificial Earth satellites, lunar and planetary probes, and eventually manned spacecraft into space.

Innovative projects undertaken by the German–American rocket team under von Braun's direction were America's first artificial satellite, Explorer 1 orbited by a Juno I in January 1958; Pioneer 4, the first successful lunar flyby probe launched by a Juno II in March 1959; recovery, that May, of two monkeys from a Jupiter IRBM nosecone at the end of a 2,560 kilometer-long, 480-kilometer high trajectory; and the first American in space, Alan Shepard, aboard a Redstone-boosted Mercury capsule in May 1961.

From these modest beginnings, the Huntsville-based team went on to launch three Pegasus micrometeoroid satellites in 1965; a series of nine historic human Apollo expeditions to the Moon, including six landing missions, between 1968 and 1972; Skylab, the first U.S. space station that was occupied for 171 days by three sequential three-person crews between 1973 and 1974, and three High Energy Astronomical Observatories were orbited during 1977–1979. The team later became heavily involved with the Shuttle, the Hubble Space Telescope, the Chandra X-ray Telescope, the manufacturing and launching of the Probe B, and the International Space Station programs. The story is indeed ongoing, with no end in sight.

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