ALL ABOUT ROCKET ENGINES

by

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This book is dedicated to teenagers around the world
who dream of things to come
while their elders dream of how things were.

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FOREWORD

My fascination with rockets began when, at the age of eight, I began to carve soft pine rockets like the spacecraft in the comic strip of my hero, Buck Rogers. Upon leaving college in 1950 with a degree in chemical engineering, I seized an opportunity to work for Bell Aircraft Corporation in Niagara Falls, New York, where rocket engines for Rascal and Hustler air-to ground missiles were under development, and where Larry Bell developed the first American rocket powered airplane, the Bell X-1. One of my jobs was to construct a full scale model of the production model Rascal three barreled engine. I was hooked. I later moved to San Diego, California with my family, where at General Dynamics I worked for many years on missiles and rockets.

My purpose in writing this book is to encourage the emerging generation of scientists and engineers to get interested in rocketry, including the power plants that make travel into space possible. The engineers and scientists of my generation who worked on rockets during the 1950's and 1960's are either retired or no longer living. We developed an array of ballistic missiles to counter similar developments in the Soviet Union. Eventually these vehicles morphed into carriers of payloads to space for communications systems and Earth monitoring, exploratory flights to the moon, to the planets, and even to the outer reaches of the solar system. I was fortunate to be one of them, working on the propulsions systems on Atlas and Centaur rockets. Propulsion engineer on John Glenn's famous flight! Eventually ending up in preliminary design, defining future space systems.

New minds must now take over if America is to continue dominance in space exploration. Although the current state of events can largely be characterized as routine operations, and thus perhaps not too interesting, the truth is that rocketry, space exploration and space exploitation are still in infancy.

In 2009, America's space program has the appearance of approaching a hiatus, mainly as a result of closing out the Space Shuttle and in a few years shutting down the International Space Station. NASA has as yet no credible large program on the table. That is yet to be defined.

It is important to examine the drivers for non-defense space missions to gain assurance that we are not hunkering down - that an exciting future still lies ahead. Probably the single most effective driver is at the presidential level. A president can strong-arm an ambitious space mission into place, as President Kennedy did in 1962 when he called for placing men on the moon within the decade. In 1993 Vice President Al Gore and Russian Prime Minister Victor Chermomydin announced joint plans for a new space station, to become, eventually, the International Space Station, with multination participation. The runout cost of this project is estimated as high as $130 B, considerably higher than any estimate of a manned mission to Mars. In January, 2004, President George W. Bush outlined an ambitious plan to return to the moon and thence to Mars, but incredibly failed to provide funding and followup drive. But presidents don't think up missions. They are presented to them, with justifications, by dreamers. Curious and forward-thinking presidents will act in response to the challenges that space exploration offers.

A second driver is within the United States Congress. When it is perceived that another nation has upstaged the United States with a major achievement, as the Soviet Union did with Sputnik, the resulting furor is bound to stimulate space spending. Though this is not a desirable situation, it is destined to occur again as other nations (i.e. China achieves a manned moon landing, or Japan constructs the first Solar Power Satellite for beaming power from space to Earth) achieve their already publicized goals.

A third driver is commercial exploitation, as has already occurred with communications satellites and Earth mapping. This is manifested only when there is reasonable assurance of profit. Were Russia to orbit the first tourist hotel (Russia is the only nation transporting tourists to the International Space Station), there would likely be an instant burgeoning of that activity, heavily funded by the hotel and tourist industries in the United States.

But it is the lure of the galaxy that should excite you. The galaxy is our playground. Buttressed by the knowledge that humanity is capable of stupendous deeds, you can carry on in directions far beyond anything described above. In 1992 my son Jon and I formed an organization called the Interstellar Propulsion Society. The purpose was to being to begin drawing together thinkers around the world to share information on advanced propulsion. The idea was that if the propulsion problem were solved, everything else would fall into place to make interstellar travel possible. We had advisers and board members like Sir Arthur C. Clarke, James Arnold, Bob Forward, Marc Millis. That activity was short lived, as it grew to be too much to handle. Marc Millis, a dedicated space scientist from NASA, carried on. He is now Chairman of the Tau Zero Foundation (tauzero.aero), dedicated in a more formal manner to the same ends.

It is my hope that the information in this book, especially the advanced concepts in the final chapters, will spark your interest. Perhaps some among you will be charting the first interstellar missions.

CHAPTER 1

A Thousand Years of Rocketry

1-1 Early History

Rockets owe their origin to the invention of gunpowder by the Chinese, perhaps as early as the tenth century a.d. The formula for gunpowder that reached the Near East, and then Europe, consisted of one part charcoal, one part sulphur, and six parts potassium nitrate (saltpeter). One can guess that its main use in China was for celebrations, due to its spectacular burning when ignited. No doubt rockets were then devised by the Chinese to add aerial splendor to their celebrations. Records dating back to 1252 a.d. show that the Chinese eventually created and fired war rockets. Without guidance systems such instruments of war would have been used more to terrorize enemies than to slaughter them. Not much has changed.While this book is being written, Palestinians are randomly lobbing crude rockets from Gaza into Israel, as part of an ongoing conflict between two tiny nations.

Manuscripts describing the fabrication of rockets appeared in English, German, Italian and Arabic between the years 1249 and 1280 a.d. Thus it is believed that as early as 1200 a.d. knowledge about gunpowder had travelled west along the trade routes from China.

Something interesting occurred in Europe around the fourteenth century. Experimenters discovered that if the ingredients for gunpowder were finely ground together, the resulting mixture would explode when ignited. You can imagine that considerable personal injury accompanied this discovery. Later, an even more powerful substance was produced by adding water to the mixture and then drying it. Charcoal, especially in its activated form, is very porous and therefore exhibits a very high surface area beyond what is visible on the exterior. In the process of fine grinding, the sulphur and oxygen source (saltpeter) are worked into the pores, coating much of the surface. Such an intimately mixed substance will burn more rapidly. Indeed, it will detonate when ignited.

With this new power, inventors forgot about rockets and turned to devising pistols, muskets and cannon, thus revolutionizing warfare. Guns are closely related to rockets, but the propulsive force is near instantaneous and is contained inside the gun barrel. Here's an interesting question: Since there were no guns before this time, what did they call the material?

It was not until 1688 that the first brief records appeared, documenting actual scientific research on rockets by a German named Christopher Geisler. These records indcate that propellants and flight characteristics had been evaluated on rockets weighing fifty-five pounds and one-hundred thirty-two pounds. Geisler's experiments were revived forty-two years later by German ordnance personnel on one-hundred pound rockets.

European interest in rockets finally came to life in the late 1700's as a result of severe losses experienced by British troops in India, who were routed by an opposing force of five-thousand Indian soldiers armed with rockets. Several investigators then undertook experiments, the most successful being Sir William Congreve with his invention of the war rocket shown in Figure 1-1. His rockets were first used by the British in devastating attacks on Boulogne in 1806, Copenhagen in 1807, and Danzig in 1813. The rockets were fired from tubes mounted on tripods. Sir William sought other applications for rockets. Among his other inventions was a rocket for killing whales.

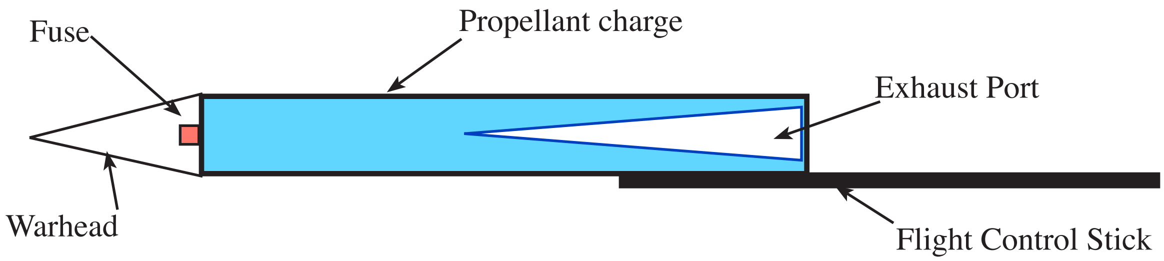

Figure 1-1 The Congreve war rocket.

For a few years most European armies had a rocket corps. Further experimentation improved the weapons' range and accuracy. Much of the experimental work centered on getting rid of the stick that trailed the rocket, which gave it stability during flight. Stick controlled rockets probably originated in China. Even today the rockets that are used in fireworks use this design for flight control.

Dutch investigators attempted to use vanes for stabilizing flight, but the idea never caught on (Figure 1-2). Still, the Dutch rocket is a close cousin to the rockets favored by amateur experimenters today.

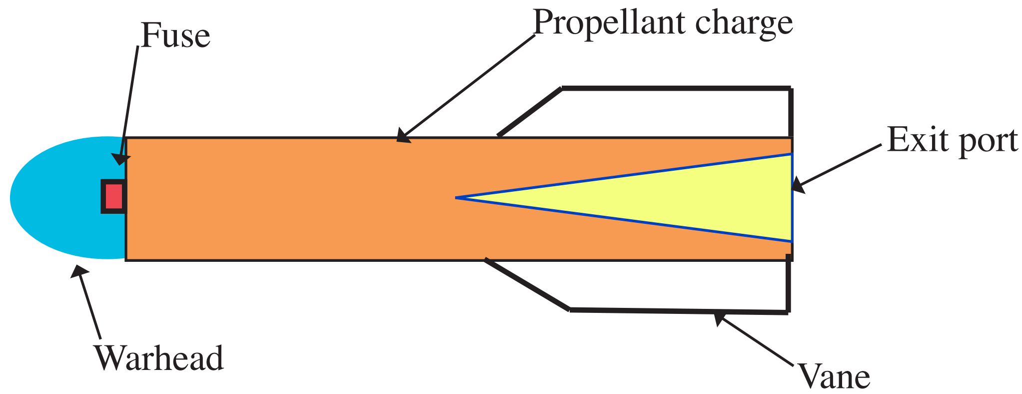

Figure 1-2 Dutch experimenters were the first to try control vanes.

About the middle of the nineteenth century an Englishman named William Hale discovered that a rocket's flight could be stabilized by spinning it at high speed, much like a quarterback spins a football to achieve the optimum throw. He accomplished this by installing a screw vane in the rocket's exhaust, as shown in Figure 1-3. Oddly, at about this time, the usage of rockets was abandoned across Europe, so Hale's invention found little application (As the story goes, the casualties among the rocket corps exceeded those of the enemy).

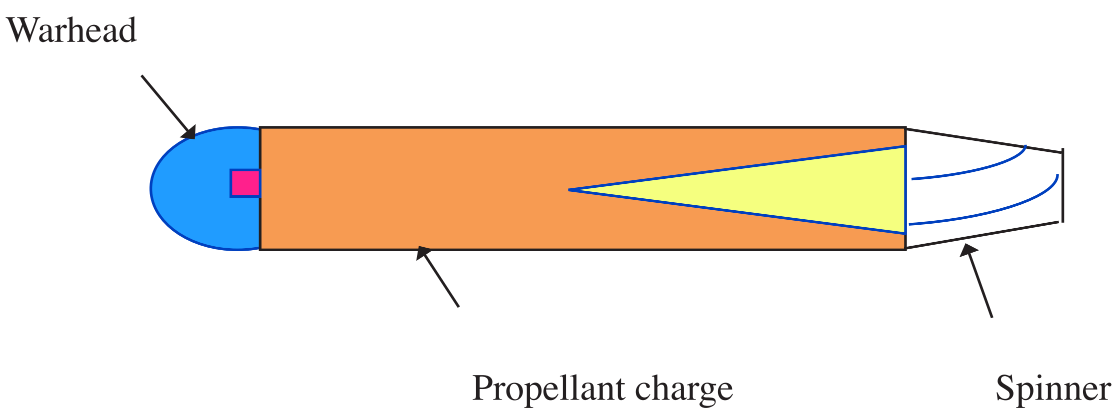

Figure 1-3 Diagram of William Hale's spinning rocket.

Apparently, rockets were used during the War of 1814 when rockets were fired on Ft. McHenry. The phrase, "and the rockets' red glare" in the National Anthem comes to mind. But it was not until World War II that solid propellant rockets appeared again on a large scale, when the Soviet Union unleashed its multibarreled Katusha rockets against German forces, and Americans fired bazookas against armored vehicles and tanks. Subsequently, development of solid propellant rockets proceeded along many lines, including anti-aircraft rockets and propulsion for spacecraft.

1-2 Twentieth Century Developments

Dr. Robert Goddard (Figure 1-4) is known as the father of modern rocketry. He was a professor of physics at Clark University in Massachusetts and was devoted to studying and applying rockets as a method of reaching high altitudes for collecting weather data. The idea of using rockets for this purpose, as well as travel into space and to other planets, was already old, dating back to the seventeenth century. Dr. Goddard was the first to conduct scientific experiments with supporting calculations. He produced two important papers on rocketry which were published by the Smithsonian Institution. The first paper, which appeared in 1919, covered his work with solid propellant rockets. Subsequently he became convinced that the only practical way to achieve reliable, extended operation of large rocket engines was to use liquid propellants. The balance of his investigations dealt with liquid propellant rockets.

Figure 1-4 Modern rocketry owes its beginnings to Dr. Robert Goddard.

After several years of research in Massachusetts, where he worked on small rockets, Dr. Goddard obtained a leave of absence and moved to a desert site in New Mexico, where he could work in relative secrecy. Figure 1-5 is a photo from the Smithsonian collection showing an oxygen-gasoline powered rocket in the frame from which it was launched on March 26, 1926 in Auburn, Massachusetts. Figure 1-6 from the same collection shows a rocket mounted in a sixty foot tower at the New Mexico facility.

Figure 1-5 Dr. Robert Goddard with an early liquid fueled rocket.

Funding was limited to small grants from the Guggenheim, the Carnegie Institution, and the Smithsonian. By 1926 Goddard had demonstrated the feasibility of liquid propellant rockets. Dr. Goddard published very little, but two important papers and a summary of his work were published by the Smithsonian and subsequently the American Rocket Society in 1946, in a slim book, titled "Rockets."

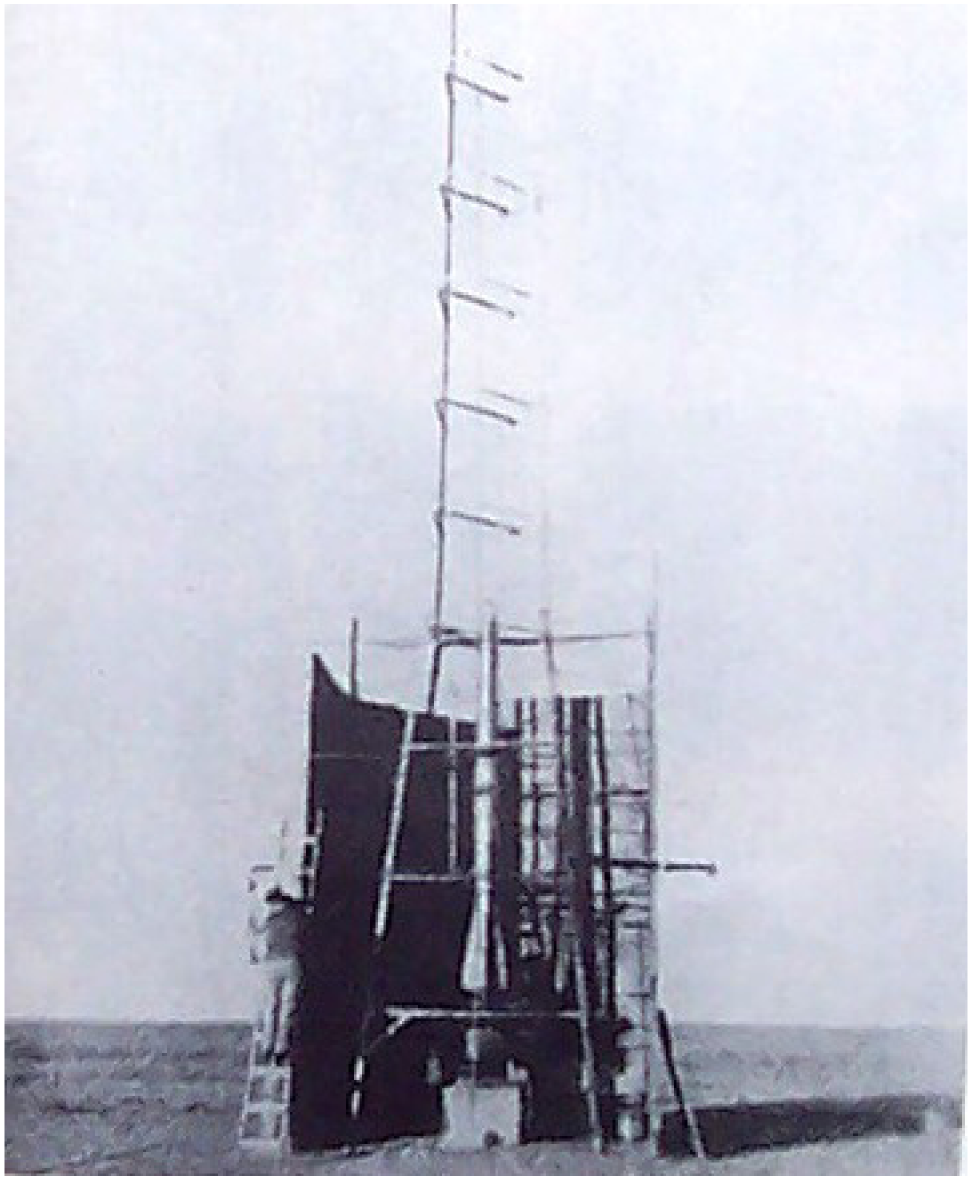

Figure 1-6 A liquid fueled rocket in a sixty-foot tower in New Mexico.

Dr. Goddard's pioneering work inevitably attracted the interest of other parties, especially societies interested in furthering rocket technology to the point where space travel might be possible. Experimental work on liquid fueled rockets was undertaken between 1932 and 1941 by the American Rocket Society. In 1936 the California Institute of Technology (Cal Tech) began serious rocket study under private funding. Government funding appeared in 1939 with the founding of the Army Air Corps Jet Propulsion Research Project at Cal Tech. The purpose of this research was to develop propulsion devices for jet-assisted takeoff of aircraft. By 1941 the project was able to successfully demonstrate a solid propellant motor for assisted takeoff.

Subsequent work with liquid propellants led to successful demonstration of liquid fueled rocket motors, a natural outgrowth of Dr. Goddard's pioneering feasibility demonstrations.

Shortly, it was determined that while research work should continue at Cal Tech, a production facility was needed to manufacture quantities of jet takeoff rockets, as well as other rockets that were seen to be needed for World War II. Thus, Aerojet Engineering Corporation, located in Azusa, California was born. This company later moved its operations to Sacramento, California. Another company, Reaction Motors, was organized in New Jersey. This company evenutally built rocket motors to power the first US experimental rocket plane, the Bell X-1 (Figure 1-7).

Figure 1-7 "Glamourous Glennis," the Nation's first rocket plane, had its first flight on January 16, 1946.

Other companies, including General Electric, North American Aircraft and Consolidated Vultee also began programs concerned with various aspects of rocket hardware and applications. Cal Tech eventually separated the rocket research project from the institute. The new organization, located in Pasadena California, became the famous Jet Propulsion Laboratory.

Meanwhile, several rocket development projects emerged in Europe, notably work in England on anti-aircraft rockets, in Italy a short-lived program on liquid fueled rocket motors, and in Germany, rocket motor development by the Walter

Company, BMW, and the upstart Verein fur Raumschiffahrt (VfR). VfR was a society of rocket enthusiasts dedicated to developing a space rocket. The organization carried out experimental work at their test area near Berlin, named *Raketenflugplatz,* or “rocket launch site.”

With respect to influence on future space launches, the work conducted by VfR was by far the most significant being performed during the 1930’s. The members of the society were inspired by Dr. Robert Goddard’s experimental results, as well as the work of Hermann Oberth in Germany, who demonstrated a small rocket motor that operated on liquid oxygen and kerosene in 1930.

While Dr. Goddard’s work was performed in secrecy, the VfR purposely worked to stimulate public interest. The society’s experiments led to construction of a small liquid propellant rocket that was demonstrated at the German army’s Kummersdorf testing ground. German officers were immediately caught up with the military possibilities of rocket propulsion. The papers of the society were seized by the German army in 1933, shortly after the demonstration. Wernher von Braun, a young VfR member, was hired by the German army to produce an experimental rocket, designated the A-1. In less than fifteen years, this man would be engaged in rocket development work in the United States, ultimately to take a lead role in America’s manned mission to the moon - the Apollo Program.

The A-1 development program was begun in 1933. It was a small rocket, measuring under five feet in length, about a foot in diameter, and weighing 330 pounds when loaded with propellants. It was limited to test stand firings. Fabrication of its successor, the A-2, was begun in 1934. This rocket delivered a thrust of 600 pounds and reached an altitude of 6500 feet with a burn time of 16 seconds.

Following the successful flight of the A-2, the German army initiated its plans to develop and manufacture rockets on a large scale. Von Braun’s next task was to develop the A-3, a much larger rocket than the A-2. It measured 25 feet in length, 2.5 feet in diameter, and weighed 1650 pounds. The thrust of the motor was 3300 pounds, with propellants fed by pressurized tanks. Completed in three years, the A-3 ascended to an altitude of 40,000 feet and covered a distance of eleven miles. The A-3 was the prelude to Germany’s next great leap in rocket technology.

The Peenemunde Research Institute was established in 1937 on the Baltic seacoast. Former VfR members were called to work at the site, which grew to employ

20,000 people in the production of the A-4, better known as the V-2 war rocket. The A-4, a museum model of which is shown in Figure 1-8, was much larger than the A-3, and required development far beyond what had been demonstrated in previous models.

Figure 1-8 A V-2 war rocket on display at a German museum.

The A-4 measured 47 feet in length, with a diameter of 5.5 feet. Fully loaded with its propellants, liquid oxygen and an alcohol/water mixture, it weighed more than 24,000 pounds and had an engine thrust of 56,000 pounds. Specifications called for a range of 150 miles and ability to hit a specific target - London. Additional details on the construction of the A-4 are shown in Figure 1-9.

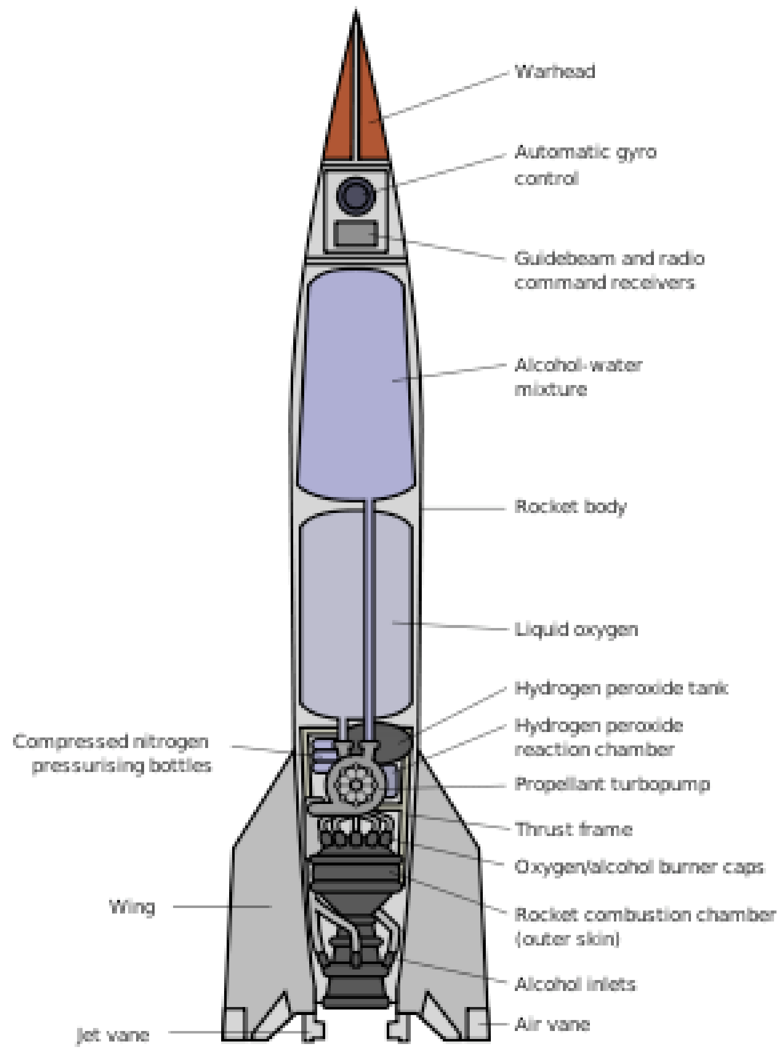

Figure 1-9 The V-2 was the forerunner of modern liquid propellant rockets.

It was obvious from the beginning to von Braun and his associates that it would not be possible to build such a vehicle with high pressure propellant tanks. At the pressures at which they would have to operate, several hundred pounds per square inch, they would be too heavy and the rocket would fall short of its mission. The solution was to build light weight tanks, pressurized only to the level needed to supply turbine driven pumps. The pumps then would deliver propellants to the thrust chambers at high pressure. Configuring such a pump had already been undertaken by Dr. Goddard and had been suggested by Hermann Oberth in the late 1920's. For the V-2, the pumps would have to deliver propellants at a rate of about fifty gallons per second. That's an oil drumful every second. Chapter 4 has more information on this subject.

On October 3, 1942, the first successful V-2 rocket was launched from No.7 test stand, proving the technical concept, but still requiring more development work. Meantime, British intelligence became aware of teeming operations at Peenemunde. On the nights of August 17-18, 1943, the British RAF bombed Peenemunde, causing substantial damage, but was unsuccessful in shutting down operations. Production of the V-2 was moved shortly thereafter to a huge underground tunnel system in the Harz mountains. Here the V-2 went into high rate production by a work force comprised of slave labor from across Europe. Thousands died, and thousands more were shipped to death camps when they became too ill to work. Reportedly, nearly 6,000 V-2's were produced, at a rate that sometimes reached twenty a day.

In September, 1944, the first V-2's crossed the English channel, targeting London. It was the beginning of an onslaught that continued until March, 1945. In just over a half year, thirteen hundred rockets had been aimed at London and an additional forty at Norwich. Antwerp was also targeted. Peenemunde was then captured by Soviet troops and the factories were destroyed. In the Bavarian factory American soldiers and then Russian soldiers removed tons of rockets and equipment for shipment to their respective countries. Facilities for production of V-2's were completely dismantled and shipped to the Soviet Union. German expertise contributed heavily to Russia's rapid progress in building rockets during the post-war era. The V-2 also became the starting point for ballistic missile development in the United States, under army sponsorship.

The number of rockets launched by the Germans in less than a year was phenomenal, about as many as were launched by the United States up to the year 2000.

1-3 Post World War II Developments

Following World War II, rocket development in the United States took place at the White Sands Proving Ground near Almogordo, New Mexico. By July, 1945, three hundred rail carloads of V-2 equipment had been received at the site. A cadre of German scientists and engineers, led by Wernher von Braun, was brought to the United States and billeted at Fort Bliss, Texas. Later, this group was relocated to Huntsville, Alabama, to pursue rocket development for the Army at Redstone Arsenal. Two programs were undertaken. The first was to learn about the V-2 through examination, tests and launchings. The program moved along rapidly, with early launchings as a goal. The culmination of this program came on January 20, 1950, when a V-2 rocket with a WAC Corporal upper stage was launched. It reached an altitude of 250 miles, a record that remained unbroken for ten years. The second program was directed toward more ominous ends. Through secret papers captured during the war, the Allies learned that the Germans had plans for rockets that were far more powerful than the V-2. One rocket, designated A-9 (Figure 1-10), had a planned range of 3000 miles, which would have enabled bombing of New York and Moscow from launch sites inside German borders.

Figure 1-10 Artist rendition of the A-9/A-10 intercontinental rocket.

This was the first intercontinental missile (ICBM). The boost stage, designated the A-9, was to be a rocket similar to the A-4, but much larger, at a diameter of 13.5 feet. The second stage was to be a modified A-4 (V-2), fitted with wings. This rocket was comparable in size to future United States ICBM's Atlas and Titan.

At first glance, the A-9 would have been a prohibitively expensive weapon, since only conventional bomb materials were available for warheads. As a weapon of terror, though, it would have been difficult to match. There were additional difficulties. During that period, guidance systems for long range flights were limited. The system would have required siting radio stations along the flight path, or perhaps using spies in New York City buildings to send out homing signals to the weapon.

Development of the atomic bomb during the 1940's placed an entirely new face on the potential for this type of long range weapon. A single atomic warhead, transported by an ICBM, could destroy an entire city at a distance halfway around the world. It was this realization that spurred both the United States and the Soviet Union into urgent development of ICBM's as well as intermediate range missiles (IRBM's).

By the late 1940's a number of American aircraft manufacturers, as well as other companies, began to show an active interest in the field of rocketry. The world entered the atomic age when World War II ended. Within a short time the Soviet Union had matched U.S. achievements in developing an atomic bomb. The Soviet Union became the new enemy, and what came to be known as the Cold War, a standoff between western nations and communist countries, was destined to last for forty years. The United States and Russia armed themselves with thousands of guided missiles, equipped with atomic warheads, with a resulting capability to totally destroy each other many times over.

In the United States, the *Navaho* program was the first effort to develop a long range rocket based warhead delivery system. Intitial specifications called for a range of 500 miles. At the end of the program engineers were producing concepts that would travel 5000 miles. The program began with attempts to verify some of the German achievements and plans under designations Hermes IZ and Hermes II. Consolidated-Vultee produced the MX-774 under this program (Figure 1-11). It looked something like the V-2, and was part of a development in that company that ultimately led to production of the Atlas ICBM.

General Dynamics

Figure 1-11 MX774 experimental rocket, built by Consolidated-Vultee, on its launch pad.

A huge effort went into starting up rocket engine companies. Bell Aircraft, Reaction Motors, General Electric, Marquardt, Aerojet, Curtiss Wright and North American Aviation all vied for contracts with government agencies. Later, Pratt & Whitney, manufacturer of aircraft engines, also started up a rocket engine division.

The Navaho program was blanketed in secrecy. Even today some of the documentation remains classified. But it is certain that from this program came important developments that were key to successful production of future IRBM's and ICBM's including Redstone, Thor, Jupiter, Atlas and Titan. These developments included high thrust engines of U.S. design, advanced guidance systems that enabled precise targeting, and major advancements in strong, light weight materials that made the construction of high performance rockets possible.

Navaho itself went through several design iterations starting with boosters shaped like the V-2. As the program progressed, significant changes were made, until the configuration that finally entered serious testing consisted of an oxygen/RP-1 fueled booster with engines designed by North American Aviation, and a second stage powered by a ramjet. Navaho in flight is illustrated in Figure 1-12.

The program was a failure, but was considered worthwhile because of the technology that was gleaned from it. Out of 16 attempted flights, only three actually left the launch pad. The final flight as it appears in Figure 1-12 appears to be going great, but it failed at 42 seconds into flight due to a fire in the engine compartment. The program was cancelled in 1957. By that time other missiles like Atlas and Jupiter were already deep into flight testing.

Douglas Aircraft Company of Los Angeles, California, undertook development of the Thor IRBM. In San Diego, California, General Dynamics Convair division (no longer Consolidated-Vultee) was building the Atlas ICBM. In Denver, Colorado, the Martin Company began development of the Titan ICBM. At Redstone Arsenal in Huntsville, Alabama, the Army, together with Chrysler Corporation and a supporting staff of German scientists and engineers, undertook development of the Redstone, and subsequently the Jupiter IRBM's. In a few years the rockets developed by the United States and the Soviet Union were modified to carry spacecraft, and even humans into space - the beginning of a spectacular era of space exploration.

But that is another story. This book is about rocket engines, the remarkable power plants that make space travel possible.

Figure 1-12. Navaho's final flight (USAF photo archives).