

NASA'S HYDROGEN OUTPOST

The Rocket Systems Area at Plum Brook Station

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Image 1: Testing of a hydrogen flow system for a nuclear engine in the High Energy Rocket Engine Research Facility (B-1 Stand) in June 1965 (GRC-1965-P-02327).

◆ Preface ◆

“There was pretty much a general knowledge about hydrogen and its capabilities,” recalled former researcher Robert Graham. “The question was, could you use it in a rocket engine? Do we have the technology to handle it? How will it cool? Will it produce so much heat release that we can’t cool the engine? These were the questions that we had to address.”¹

The National Aeronautics and Space Administration’s (NASA) Glenn Research Center, referred to historically as the Lewis Research Center,^a made a concerted effort to answer these and related questions in the 1950s and 1960s. The center played a critical role transforming hydrogen’s theoretical potential into a flight-ready propellant. Since then NASA has utilized liquid hydrogen to send humans and robots to the Moon, propel dozens of spacecraft across the universe, orbit scores of satellite systems, and power 135 space shuttle flights.

Rocket pioneers had recognized hydrogen’s potential early on, but its extremely low boiling temperature and low density made it impracticable as a fuel. The Lewis laboratory first demonstrated that liquid hydrogen could be safely utilized in rocket and aircraft propulsion systems, then perfected techniques to store, pump, and cleanly burn the fuel, as well as use it to cool the engine. The Rocket Systems Area at Lewis’s remote testing area, Plum Brook Station, played a little known, but important role in the center’s hydrogen research efforts.

This publication focuses on the activities at the Rocket Systems Area, but it also discusses hydrogen’s role in NASA’s space program and Lewis’s overall hydrogen work. The Rocket Systems Area included nine physically modest test sites and three test stands dedicated to liquid-hydrogen-related research. In 1962 *Cleveland Plain Dealer* reporter Karl Abram claimed, “The rocket facility looks more like a petroleum refinery. Its test rigs sprout pipes, valves and tanks. During the night test runs, excess hydrogen is burned from special stacks in the best Oklahoma oil field tradition.”² Besides the Rocket Systems Area, Plum Brook Station also included a nuclear test reactor, a large vacuum tank, a hypersonic wind tunnel, and a full-scale upper-stage rocket stand.

The Rocket Systems Area operated from 1961 until NASA shut down all of Plum Brook in 1974. The center reopened Plum Brook in the late 1980s and continues to use several test facilities. The Rocket Systems Area, however, was not restored. Today Plum Brook resembles a nature preserve more than an oil refinery. Lush fields and forests separate the large test facilities. Until recently, the abandoned Rocket Systems Area structures and equipment were visible amongst the greenery. These space-age ruins, particularly the three towers, stood as silent sentinels over the sparsely populated reservation. Few knew the story of these mysterious facilities when NASA removed them in the late 2000s.

^aThe Glenn Research Center is referred by its historical name, Lewis, throughout this book. The Cleveland laboratory began operation in 1942 as the NACA Aircraft Engine Research Laboratory (AERL). In 1947 it was renamed the NACA Flight Propulsion Laboratory to reflect the expansion of the research. In September 1948, following the death of the NACA’s Director of Aeronautics, George Lewis, the name was changed to the NACA Lewis Flight Propulsion Laboratory. On October 1, 1958, the lab was incorporated into the new NASA space agency, and it was renamed the NASA Lewis Research Center. Following John Glenn’s flight on the space shuttle, the center name was changed again on 1 March 1999 to the NASA Glenn Research Center.

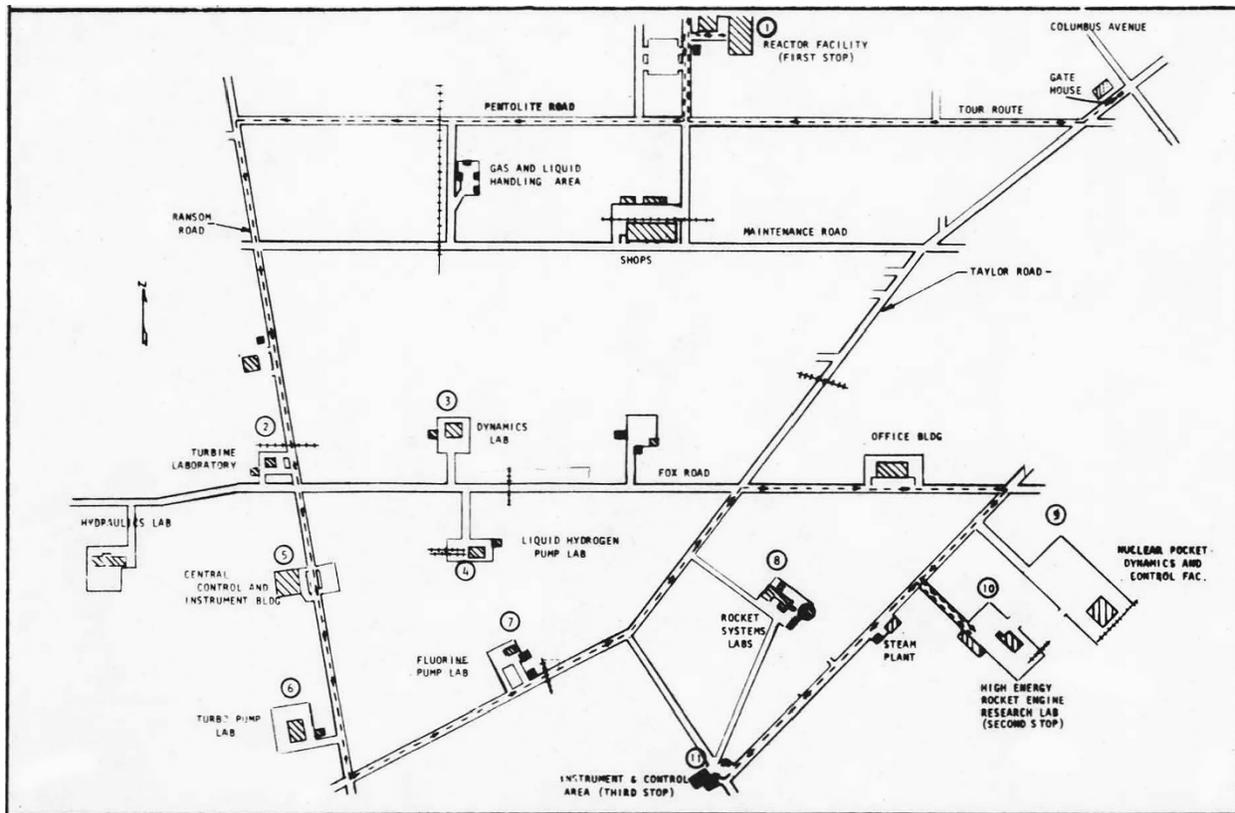


Image 2: Rocket Systems Area layout as it appeared in 1964. The dotted line denotes the route for a public driving tour of Plum Brook that October (NASA).

In an effort to mitigate the loss of these sites, the Glenn Historic Preservation Officer and the Ohio State Historic Preservation Officer developed a plan to document the Rocket Systems Area and distribute that information. The Glenn History Office supported this mitigation by collecting relevant documents and photographs, researching the development and testing at the sites, and conducting oral histories with former staff members. The collected information was used to create this publication and a Web site (<http://pbhistoryrsa.grc.nasa.gov>) to be shared with the public and NASA employees.

Glenn has established a tradition of documenting the operations and research related to its historic facilities, particularly those which have been eliminated from its campus. Histories of the Icing Research Tunnel, Plum Brook Reactor Facility, Rocket Engine Test Facility, Altitude Wind Tunnel, and Propulsion Systems Laboratory No. 1 and 2 have been published.^b

There are a number of excellent books that explore Glenn's history, liquid-hydrogen technology, the Centaur rocket, and the nation's nuclear propulsion efforts. The Rocket Systems Area and its esoteric hydrogen investigations, however, are rarely mentioned, let alone covered in depth in these previous histories. It is hoped that this publication will provide a rare view into the subterranean world of a federal

^bWilliam M. Leary, *We Freeze to Please: A History of NASA's Icing Research Tunnel* (NASA/SP—2002-4226, 2002); Virginia Dawson, *Ideas into Hardware: A History of the Rocket Engine Test Facility at the NASA Glenn Research Center* (NASA: Washington DC, 2004); Mark D. Bowles, *Science in Flux: NASA's Nuclear Program at Plum Brook Station, 1955-2005* (NASA/SP—2006-4317, 2006); Robert Arrighi, *Revolutionary Atmosphere: The Story of the Altitude Wind Tunnel and Space Power Chambers* (NASA/SP—2010-4319: Washington DC, 2010); and Robert Arrighi, *Pursuit of Power: The Propulsion Systems Laboratory No. 1 and 2* (NASA/SP—2012-4548: Washington DC, 2012).

research institution while providing the larger context of hydrogen's impact, explaining and sharing the stories of some of the Rocket Systems Area participants.



The Rocket Systems Division's Test Operations Reports were the backbone of this book. These reports, generated monthly for each facility, describe in detail the work performed at Rocket Systems Area sites. Through these reports one can trace the determined efforts of the Rocket Systems Division staff to install and test experimental items. In addition, the reports frequently made it possible to track down the technical reports describing the research programs.

Interviews with Plum Brook retirees and an email interview with Lewis researcher Robert Hendricks were invaluable. Participants included Henry Pfanner, Robert "Bucky" Walter, Richard Heath, Thorvald Brink, Donald Perdue, William Brown, James Cairelli, Gordon MacKay, and Harold McKune. These interviews provided perspectives on the Rocket Systems Area from staff members holding a variety of positions—including an electrician, facility engineer, civil engineer, controls specialist, and researcher. They were involved with different sites and had their own stories to relate. These interviews were complemented with transcripts of historical interviews with Glen Hennings, Abe Silverstein, Walter Olson, Robert Kozar, and others.

In the midst of this project, NASA Headquarters archivists offered to permanently transfer the John Sloop Collection to Glenn. These materials included the documents used to write *Liquid Hydrogen as a Propulsion Fuel, 1945-1959*, working papers from his tenure at headquarters, speeches, and cassettes of interviews that were conducted during his research. The Sloop materials, particularly the interviews, significantly aided my research.

Jan Vonkamp's Records Room at Plum Brook provided a significant portion of the photographs in this publication. The remainder came from Glenn's Imaging Technology Center's archive. The photographs were helpful not only in illustrating the book but in dating events and describing the facilities.

The Glenn History Collection includes copies of Directors' correspondence, the complete run of center newspapers, and substantial collections of Plum Brook Ordnance Works, Plum Brook Station, Centaur, and Nuclear Rocket for Rocket Vehicle Application (NERVA) materials that were used to support this effort. Glenn Historic Preservation Officer Les Main provided much of the information regarding NASA's historic properties and the demolition project.

A number of secondary resources were consulted for contextual information. These include John Sloop's *Liquid Hydrogen as a Propulsion Fuel, 1945-1959* and "NACA High Energy Rocket Propellant Research in the Fifties," Virginia Dawson's *Engines and Innovation: Lewis Laboratory and American Propulsion Technology*, Mark Bowles's *Science in Flux: NASA's Nuclear Program at Plum Brook Station*, James Dewar's *To the End of the Solar System: The Story of the Nuclear Rocket*, Dawson and Bowles's *Taming Liquid Hydrogen: The Centaur Upper Stage Rocket*, and Roderick Spence's "Nuclear Rockets" articles. The *Sandusky Register* newspaper archive was also very useful.

References

1. Robert Graham interview, Cleveland, OH, by Tom Farmer, 1991, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
2. Karl Abraham, "Moon-Landing Rocket Is in Our Back Yard," *Cleveland Plain Dealer* (5 March 1962).



Image 3: The Rocket Systems Test Site (J Site) at Plum Brook Station's Rocket Systems Area (GRC-2016-C-05182).

◆ Introduction ◆

“I looked out the next day and every window in that beautiful building was gone,” recalled former Lewis rocket researcher John Sloop. “We told them not to build it there.”³ On 16 November 1956, just months after Lewis’s newest and most powerful tunnel facility, the 10- by 10-Foot Supersonic Wind Tunnel, became operational, its special-ordered green-tinted windows lay in shards inside empty offices. The previous evening researchers had been running an experimental hydrogen-fluorine rocket engine across the street at a smaller facility referred to as the Rocket Lab. They decided to measure the gas levels in the facility’s exhaust scrubber several minutes after the run. Normally the operators would have purged the highly flammable gases immediately. Former NASA engineer Glen Hennings explained, “So we sat there and waited and shuddered for a while and pretty soon it came time for the sample; and the sample and the boom came together.”⁴

There were no injuries during the incident and damage to the wind tunnel was mostly cosmetic, but Associate Director Abe Silverstein, who had personally selected the high-pressure windows to withstand moderate explosions from the Rocket Lab, was not pleased. Lewis engineers were in the midst of planning a group of new test sites to complement the Rocket Lab’s high-energy rocket propellant work. They intended to place this new complex nearby along the edge of Lewis’s campus in Cleveland, now known as “Lewis Field.” The increased number of Rocket Lab explosions and the delays inherent in running the dangerous tests only at night or on the weekends resulted in the selection of an alternate location for the new sites—55 miles to the west in Sandusky, Ohio.

On 22 January 1958 the National Advisory Committee for Aeronautics’s (NACA’s) Lewis laboratory leased 2,712 acres of land at the Plum Brook Ordnance Works to construct the new Rocket Systems Area. By 1963 Lewis permanently acquired the entire 6,400 acres at the site and renamed it Plum Brook Station. At its peak Plum Brook contained 15 different facilities with at least 24 test rigs and cells, most of which fell under the Rocket Systems Area umbrella. The Plum Brook sites had official names, which often morphed over the years, but were more commonly referred to by their site designation or acronym: for example, D Site, B-1, and HHTF.



Image 4: Workers replace windows in the 10- by 10-Foot Supersonic Wind Tunnel Office Building. The windows had been blown out by an explosion at the Rocket Lab on 16 November 1956 (GRC-1956-C-43363).

The Rocket Systems Area contained the Liquid Hydrogen Pump Facility (A Site), the Turbopump Facility (C Site), the Controls and Turbine Test Facility (D Site), the Dynamics Stand (E Stand), the Hydraulics Laboratory (F Site), the Pilot Plant (G Site), the Hydrogen Heat Transfer Facility (HHTF), the Fluorine Pump Facility (I Site), the Rocket Systems Test Site (J Site), the Cryogenic Propellant Tank Facility (K Site), and two larger test stands: the High Energy Rocket Engine Research Facility (B–1 Stand) and the Nuclear Rocket Dynamics and Control Facility (B–3 Stand). There are descriptions of each site in Appendix A, and technical terms are defined in Appendix B.

These sites were dedicated to perfecting methods of handling and storing liquid hydrogen and oxidizers such as fluorine and oxygen. Lewis engineers designed the smaller Rocket Systems Area facilities to study rocket engine components independently before testing full engine systems at one of the larger test facilities located at Lewis Field or at industry sites. Many of the Plum Brook sites included multiple test rigs, so there was some duplication of capabilities. The staff used F Site, J Site, and K Site to investigate issues relating to propellant tanks; and used A Site, C Site, D Site, the Pilot Plant, and I Site for fuel pumping matters. F Site and J Site handled rocket engine cooling and combustion investigations. Researchers could also test full-scale engines and propellant systems in the B–1 and B–3 stands and subject missiles to simulated launch forces and vibrations at E Stand.

The NASA Glenn Research Center, formerly Lewis, is 1 of 10 NASA field centers. It originated in 1941 as the third NACA research laboratory. Congress created the NACA in 1915 to coordinate the nation's aeronautical research efforts. By 1917 this advisory panel had begun to build its own research laboratory at Langley Field in Virginia. Langley innovations such as the NACA engine cowl and the standardization of airfoils contributed to the preeminence of U.S. aircraft industry in the ensuing years.⁵

Lewis, then known as the Aircraft Engine Research laboratory, resolved engine and fuels issues for military aircraft during World War II and made critical contributions to the development of the jet engine in the 1940s. After the war, a small group of fuels researchers began analyzing high-energy propellants for rocket engines. They increased their activities in the early 1950s and soon came to a consensus that liquid hydrogen offered the best potential performance with the fewest hazards. Although military-sponsored research at other institutions had previously demonstrated that hydrogen could be used for propulsion, Lewis's testing of larger engines and the number of resulting research reports provided the impetus for the future hydrogen development. This coincided with a resurgence of military interest in liquid hydrogen. In the mid-1950s Lewis initiated plans to construct the Rocket Systems Area to expand its hydrogen efforts.

The Soviet Union's launch of *Sputnik* in October 1957 spurred the transition of the NACA into NASA, and led to a host of new space programs. The three most pertinent to the Rocket Systems Area were human exploration of Mars, the Apollo Program, and the Surveyor lunar missions. NASA established three rocket systems to accomplish these efforts—Saturn, Atlas/Centaur, and the Nuclear Rocket for Rocket Vehicle Application (NERVA). Liquid hydrogen was the key to all three of these new vehicles.

Lewis, which had previously concentrated on hydrogen's combustion and cooling, now also explored pumping, tankage, and heat transfer issues. In addition, the center managed the fuel system for the nuclear rocket program and the overall Centaur vehicle. The center also undertook a wide array of liquid-hydrogen research for the advanced long-duration space missions of the future. Plum Brook's Rocket Systems Area was an important contributor to each of these endeavors throughout the 1960s—particularly pumping and storage.



Image 5: View of Plum Brook and the Sandusky area in 1965. The site is surrounded by farmland, and Lake Erie is visible in the background (GRC-2016-C-05786).

Plum Brook’s sprawling 6,400-acre property provides an ideal location for testing rocket systems with high-energy propellants. The test sites, the control buildings, and the neighboring community are all located at safe distances from one another. The open spaces negated the need for scrubber equipment to remove toxins from the rocket engine exhaust and afforded the engineers greater latitude in scheduling their test runs. This ability to work safely and remotely with large quantities of rocket propellants accelerated the development of liquid rocket engine components in the 1960s. The studies provided basic research for NASA and the aerospace industry as well as specific developmental testing for particular missions or rocket systems.

NASA’s budget reductions in the early 1970s, however, resulted in the cancellation of the nuclear rocket program and the closure of Plum Brook. The test facilities were mothballed for possible use in the future, and Plum Brook remained essentially vacant for nearly 15 years. In the late 1980s NASA began reactivating K Site and three large facilities that had just commenced operations in Plum Brook’s final years—the Spacecraft Propulsion Research Facility (B-2 Stand), the Space Power Facility (SPF), and the Hypersonic Tunnel Facility (HTF). Plum Brook continues to support a variety of NASA missions today.

The Rocket Systems Area and the reactor facility, however, were not among the sites resurrected. In 2009 the center began to remove the small, abandoned rocket systems sites. The Rocket Systems Area story gives insight into some of the basic efforts that were required to transform liquid hydrogen into a reliable rocket propellant. It also provides a unique view into the workings of a clandestine, but important, NASA testing facility and the often mercurial nature of federal research activities.

References

3. Howard Douglass interview, Cleveland, OH, by John Sloop, 28 May 1975, Glenn History Collection, Oral History Collection, Cleveland, OH.
4. John Gibb, Glen Hennings, Harold Christianson, and Dave Fenn interview, Cleveland, OH, by John Sloop, May 1974, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
5. Alex Roland, *Model Research* (Washington, DC: NASA SP-4103, 1985), <http://ntrs.nasa.gov>

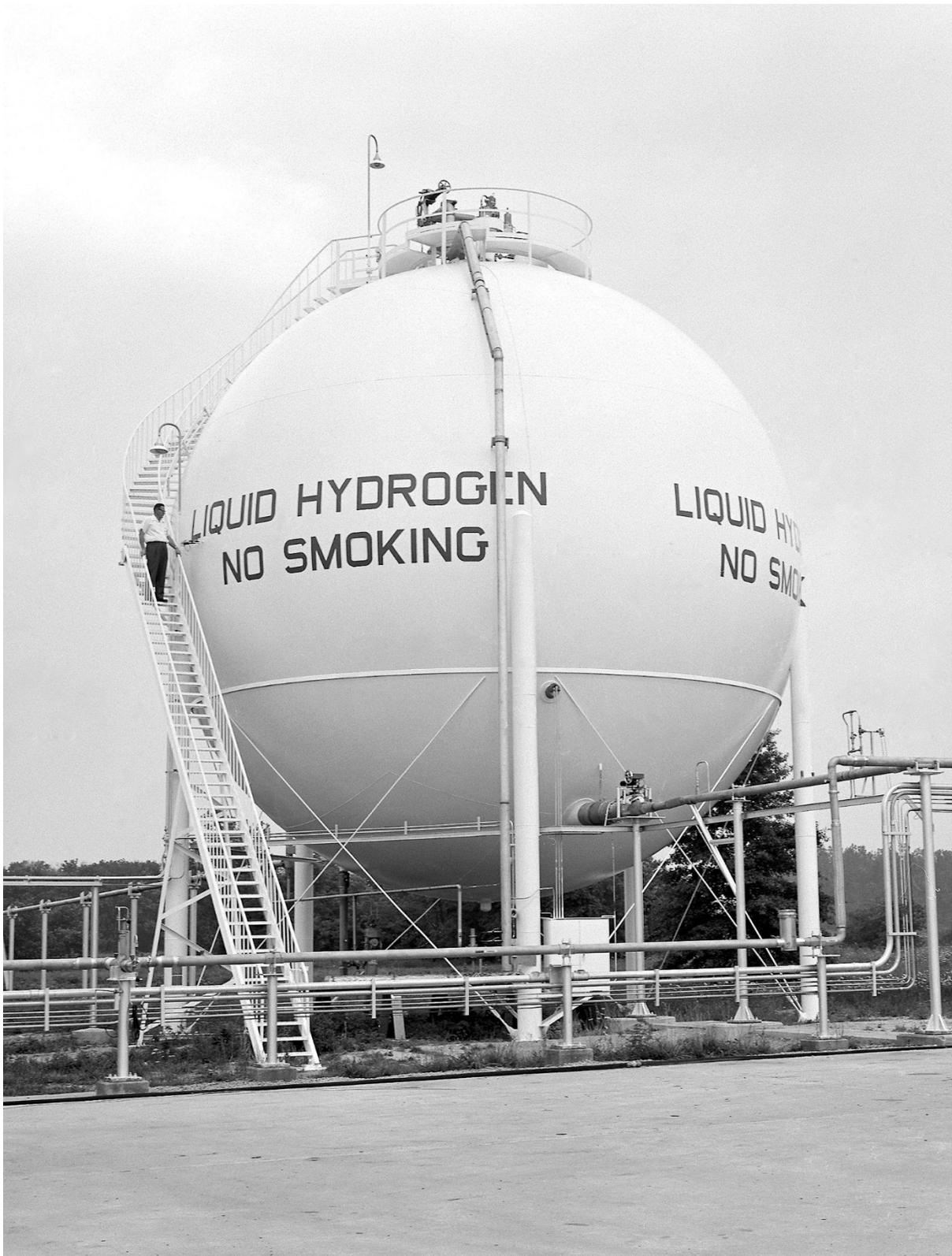


Image 6: A 200,000-gallon hydrogen Dewar, the largest in the world at the time, at Plum Brook's B Complex (GRC-1965-P-02438).

◆ Chapter 1 ◆

Laying the Foundation

On 13 September 1814 the British Navy rained thousands of 32-pound shells on Fort McHenry from the Baltimore harbor. The attack, which inspired the “Star Spangled Banner,” was the most significant demonstration of rocket technology in the United States to date. On 17 October 1997 a Titan IV/Centaur rocket sent the 12,500-pound Cassini-Huygens spacecraft on a seven-year journey to Saturn. It remains the heaviest interplanetary spacecraft ever launched. The development of high-energy liquid propellants, particularly liquid hydrogen, is perhaps the most significant factor in the dramatic increase in rocket performance, from launching small projectiles across the bay to sending large spacecraft on 2-billion-mile flights to the outer solar system.

Gun-powder-based rockets have been in use since ancient times, but it was the introduction of liquid-fueled engines in the 1920s that led to the breakthrough of the V–2 missile during World War II. Although modern rocket pioneers identified the cryogenic liquid hydrogen as an optimal propellant, for decades it was considered more of a laboratory curiosity than a viable fuel option. After the war, the merger of rocket-engine and liquid-hydrogen technology seemed possible for the first time. The military sponsored several short-lived studies in this area. As the military’s interest began to wane in the late 1940s, the NACA’s Lewis laboratory began its multidecadal effort to advance high-energy propellants.

Pioneers

Eastern civilizations have used rocket-propelled arrows as weapons for centuries. Performance increased over time, but it was the quantities of these devices that made them advantageous, not their accuracy. The West took up rocketry in earnest only after India used small iron-clad missiles to rout British troops in 1792. The use of rockets increased during the 1800s as new applications were identified. Early rockets burned a mixture of gunpowder and oxidizer^c to create the thrust for propulsion. These solid propellant rockets were stable enough to stockpile for long durations. Their limited, but reliable, performance continues to make solid rockets preferable for some applications today.⁶

As part of an unrelated effort, European scientists began liquefying gases in the mid-1800s by compressing the vapor until liquid formed. Permanent gases such as hydrogen, oxygen, carbon dioxide, and nitrogen, however, were initially thought to be impossible to liquefy. In 1877 two Frenchmen working independently, Raoul-Pierre Pictet and Louis Cailletet, produced the first liquid oxygen by compressing the gas, significantly reducing its temperature, then expanding it into atmospheric pressure levels.⁷ This was the beginning of cryogenics—the study of the behavior and creation of extremely low temperature materials.⁸

The next breakthroughs in cryogenics came in the 1890s when German engineer Carl von Linde industrialized the liquefaction^d process. Scottish scientist James Dewar employed Linde’s system to create the first liquid hydrogen in 1898. Dewar also designed an insulated storage container, known as the “Dewar flask,” that could store liquids at cryogenic temperatures. These Dewars, which consist of a glass liner inside a steel container with a vacuum space between the layers, are still employed today.⁹ Despite a better

^cFuels require oxygen to burn. Engines operating in the upper atmosphere or space must carry oxygen with them to burn. Liquid oxygen is the most common oxidizer, but others such as fluorine have been considered. Oxygen in requires smaller tanks when it is a liquid than when it is a gas.

^dLiquefaction is the process of converting a solid or gas into liquid.

understanding of the properties of liquid hydrogen and improvements to the liquefaction technique, demand for liquid hydrogen remained relatively light for decades. It was not until the United States became interested in the hydrogen bomb during the 1950s that the infrastructure to produce larger quantities emerged.



Meanwhile, others were interested in utilizing rocket engines to power fantastical space vehicles that would transport humans to the Moon or Mars. These missions would require greater performance that could only be provided by liquid fuels. In 1903 Russian scientist Konstantin Tsiolkovsky conceived a theoretical rocket that combined the new entities of liquid hydrogen and liquid oxygen as a propellant.

Hydrogen is the lightest, most prevalent, and simplest element on the periodic table. In 1776 British scientist Henry Cavendish was the first to identify hydrogen, which is always bound to other elements in nature, as a unique element.¹⁰ Hydrogen's light weight and inherent ability to easily transfer its energy made it appealing for rocket propulsion. Large, heavy tanks are required to store the low-density chemical in its gaseous form, but the volume can be significantly reduced if the hydrogen is converted from gas to liquid. Hydrogen, however, must be kept at -423°F to retain its liquid form. This introduces a host of handling issues. In addition, liquid hydrogen was relatively difficult to produce in the early 20th century.

The scarcity and handling problems eventually caused Tsiolkovsky to eliminate liquid hydrogen from his conceptual rocketship. The first flight-ready liquid-hydrogen-fueled engine would not appear for nearly 50 years. (A complete history of the development of liquid hydrogen is contained in *Liquid Hydrogen as a Propulsion Fuel, 1945-1959*.¹¹) Nonetheless, Tsiolkovsky had provided the vision for modern rocket propulsion and space travel.¹² American rocketeer Robert Goddard also considered liquid hydrogen and liquid oxygen for his rocket experiments and proposed that a rocket vehicle could eventually reach the Moon. Goddard ultimately settled on a combination of gasoline and liquid-oxygen because of the difficulty in procuring and handling liquid hydrogen. On 16 March 1926 Goddard launched the first liquid-fueled rocket in Auburn, Massachusetts. The 41-foot vertical flight was the first physical demonstration of Tsiolkovsky's concepts and the birth of modern rocketry.¹³

That same year, German professor Herman Oberth claimed in his *The Rocket into Interplanetary Space* that space travel could be achieved using an alcohol and oxygen booster rocket with a liquid-hydrogen and liquid-oxygen upper stage. Again, the practicality of using liquid hydrogen was prohibitive. Oberth continued designing liquid rocket engines and advocating space missions in the 1930s. In 1941 he became a member of Wernher von Braun's rocket team at Peenemunde that produced liquid-fueled missiles during World War II.



Image 7: Tsiolkovsky photograph in a Russian shrine aboard the International Space Station in 2002 (NASA s113e05368).

Unlike their German counterparts, U.S. rocketeers did not receive government support during this period. Instead, they relied on private donations and formed amateur rocket societies that took inspiration from science fiction, not weaponry. Goddard continued to improve his liquid rockets throughout the 1920s and 1930s. NACA management was aware of Goddard's work but did not believe that it would contribute to the group's aeronautical objectives. The NACA was, however, impressed by the potential of using small solid propellant rockets for jet-assisted takeoff (JATO) applications.¹⁴

Ohio War Contributions

As World War II broke out in Europe during the fall of 1939, the United States began preparing for its possible involvement. Insufficient airpower and delays in mobilizing the industrial base had impacted the U.S. military's effectiveness during World War I. To prevent these problems from occurring again, the NACA created a new laboratory in Cleveland and the military established a munitions manufacturing complex in Sandusky in January 1941.

It became apparent in the late 1930s that Germany was designing aircraft that flew higher and faster than U.S. models. In response, the NACA expanded its efforts and built two new research laboratories—the Ames Aeronautics Laboratory in California and the Lewis Flight Propulsion Laboratory in Cleveland. The Cleveland laboratory, which began operation in 1942, was dedicated to engines. The NACA laboratories were fairly autonomous and thrived on basic research. They generally conveyed their findings to industry through technical publications and conferences, but did not develop their own products. During the war Lewis researchers concentrated their efforts on engine cooling, turbochargers, fuels, and deicing systems for existing military aircraft. In late 1943 the laboratory also began testing early U.S. turbojet engines. The lab would later apply its aeropropulsion expertise to rocket engines.



In 1940 and 1941 the War Department seized roughly 44 million acres of land across the Midwest to create 77 new munitions plants.¹⁵ One plant, the Plum Brook Ordnance Works (PBOW), was built on roughly 9,000 acres of farmland near Sandusky, Ohio. The proximity to two ports, five railway lines, and five highways made this location particularly appealing to the War Department.¹⁶

On 7 January 1941, two weeks before ground was broken in Cleveland for the NACA lab, members of the 153 households affected by the Sandusky land seizure assembled in a local hall to meet with military representatives. The agents informed them that they had two months to sell their properties to the government and approximately another month to vacate the area. The military relocated the local cemetery, town hall, and several businesses from the site.¹⁷ Ardent protests from community leaders and legal appeals from disgruntled property owners could not stop the actions.

Beginning in April 1941 the property was fenced in, plowed over, and built upon. In just nine months the farmlands gave way to a decent-sized industrial town with 8 manufacturing structures, 99 concrete bunkers to store the explosives, and numerous temporary wooden buildings. The first trinitrotoluene (TNT) manufacturing line began operation in mid-December, one week after the Pearl Harbor attack.¹⁸

The PBOW operated continuously around the clock throughout the war to produce TNT, dinitrotoluene (DNT), and pentolite. The explosives were crated and shipped 90 miles to the Ravenna Arsenal where they were packed into shells and dispatched to Allied forces overseas. The PBOW was the nation's third largest producer of TNT during World War II and significantly exceeded its production quotas. The PBOW ceased operations immediately after the war ended in August 1945 and released its 5,800 employees from duty.¹⁹

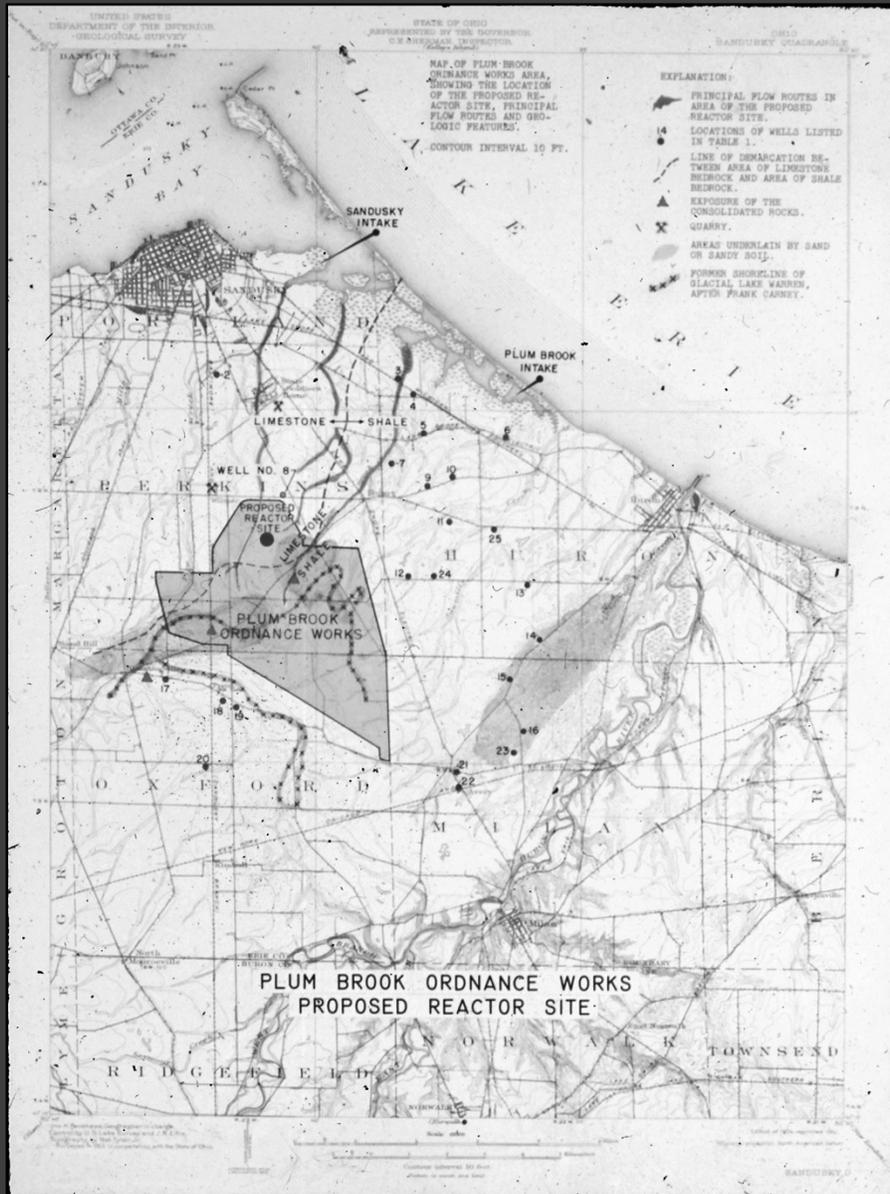


Image 8: Map showing the location of the PBOW in relation to Sandusky and Lake Erie (NASA CS-123748).

The swath of land for the PBOW was part of a larger 500,000-acre parcel in north-central Ohio, known as the Firelands. In 1792, the state of Connecticut, which then had rights to the area, set aside the vacant land as recompense for families who lost their homes or property during the Revolutionary War. The new settlers began arriving at the Firelands in 1814 and steadily converted the densely wooded area into a sprawling patchwork of farms and townships. The area possessed some of the most fertile farmlands in the state.



Image 9: A typical Firelands farm seen in 1941 near the future site of the PBOW. In addition to being forced off the land, the landowners had to accept low offers from government land agents (GRC-2016-C-05138).



Image 10: Construction crews clearing the land to build the PBOW in the summer of 1941. Construction was slowed somewhat by lawsuits from property owners, but a complex manufacturing facility complete with offices, dormitories, and storage bunkers was built in less than a year (GRC-2016-C-05136).



Image 11: An Acid Area at the PBOW. The acid was used to manufacture TNT and DNT. The waxlike chemicals were scraped into flakes and stored in the PBOW's concrete bunkers until shipment to the Ravenna Arsenal for incorporation into shells (GRC-2016-C-05097).



Image 12: Female staff in the PBOW drafting area during 1941. Women played an essential role in the activities at the PBOW and the NACA's Lewis laboratory during the war (GRC-2016-C-05135).

German Advances

Allied dominance of the skies was a decisive contributor to the defeat of Germany in Western Europe. Although the United States employed a limited number of unguided and unpowered solid rocket missiles, the primary weapon was aircraft powered by large piston engines.²⁰ It was Germany, however, that developed the war's most significant aerospace advancements—the axial-flow turbojet engine and the liquid-fueled guided missile. The former significantly affected the research at the NACA's Cleveland laboratory, but is only tangentially related to the Rocket Systems Area story. The liquid-fueled missiles, however, are directly related to the work that would be done at Plum Brook and the Rocket Systems Area in the coming years.

Germany introduced the first cruise missile, referred to as the V-1, in June 1944. Because these winged “buzz bombs” required atmospheric air to operate, they traveled at low altitudes, making them susceptible to traditional air defenses. Wernher von Braun was simultaneously developing a significantly more advanced weapon known as the V-2. In September 1944 the Germans began launching V-2s, the first ballistic missiles, at Great Britain. The V-2's liquid-alcohol and liquid-oxygen rocket engine propelled the missile at supersonic velocities out of the atmosphere until it descended without warning on its target a minute later. There was no defense.²¹

The Germans launched thousands of V-2 missiles during the final year of the war, but they were too late to change the outcome. Nonetheless the V-2 provided the first sustained demonstration of liquid-fueled missile technology. The missile's potential as a weapon spurred the United States and Soviet Union to race across the German countryside in the spring of 1945 to capture engineers and technology on their way to Berlin. The Peenemunde group surrendered to the U.S. Army en masse.

Turbopumps were an essential element of the V-2 success. Turbopumps are high-speed pumps that draw large quantities of liquid fuel and oxidizer from the tank and pump it quickly into the engine's combustion chamber. Researchers in several countries began using turbopumps in experimental liquid rockets during the 1930s, but the V-2 pumps were exponentially more powerful. In addition, the V-2 pumps were individually powered to permit specific flow levels for the oxidizer and the fuel.²²

New Tools for the Cold War

The emergence of the jet engine during World War II offered the potential for tremendous performance gains, including the breaking of the sound barrier. In October 1945 the NACA's Cleveland laboratory completely reorganized to concentrate its efforts on variations of the turbojet and the ramjet engines.²³ This work would consume most of the lab's resources for the next decade. The other NACA laboratories studied aerodynamic issues of high-speed flight. In 1946 the NACA established a remote base in the southern California desert to operate its new rocket-powered X-plane aircraft. The experimental X-planes provided crucial transonic aerodynamic data that were difficult to obtain in contemporary wind tunnels.²⁴

During the war, the NACA had tested unguided bombs and missiles in its wind tunnels, but the Agency wrestled with the best way to approach guided missiles in the postwar era. Were they unpiloted aircraft or simply high-tech artillery systems. The former was within the NACA's mandate, whereas the latter would fall under the military's purview. The NACA played it both ways. In 1945 the Agency established the Special Committee on Guided Missiles and created a missile range on Wallops Island to study transonic aerodynamics by launching small experimental research rockets,²⁵ yet the NACA left it to the military take the lead in developing missile propulsion systems.²⁶

In the postwar years both the army and navy pursued the development of ballistic missiles to deliver nuclear warheads, but others foresaw alternative applications. Von Braun, who had long saw rockets providing access to space, kindled military interest in reaching space to orbit reconnaissance satellites and

missile platforms.²⁷ Civilian scientists proposed using rockets to study the upper atmosphere.²⁸ During this period the Peenemunde team continued its development of V-2 derived missiles at the White Sands military base in New Mexico, and a rocket research and manufacturing mecca took hold in Southern California. It included North American Aviation, Aerojet, Marquardt, and the Jet Propulsion Laboratory (JPL).²⁹



Although most of the rocket development focused on the kerosene-oxygen propellant system, the military was also interested in alternative fuels, including liquid hydrogen. In 1945 the navy supported a research effort at Aerojet that led to the first U.S. hydrogen-oxygen rocket—a small gaseous-hydrogen and liquid-oxygen engine—run on 15 October 1945. The navy contracted JPL to study the logistics of using liquid hydrogen as a propellant.³⁰

Meanwhile the U.S. Air Force sponsored the creation of a Cryogenics Laboratory at Ohio State University which included its own liquefaction equipment. In 1947 students and faculty began testing small experimental turbojet, rocket, and ramjet engines with both gaseous and liquid hydrogen. On 14 June 1947 the Ohio State researchers operated the nation's very first liquid-hydrogen/liquid-oxygen rocket engine. The group tested variations of the 100-pound-thrust engine over 100 times during the next four years. The effort included investigations of regenerative cooling,^e turbopumps, and use of fluorine as an oxidizer.³¹

Researchers at JPL operated their own liquid-hydrogen/liquid-oxygen rocket in the fall of 1948 and became the first to operate a regeneratively cooled liquid-hydrogen engine the following year. In 1949 Aerojet began testing increasingly large gaseous hydrogen and oxygen engines with varying success, culminating with a 3000-pound-thrust version. In the mid to-late 1940s Aerojet, JPL, and Ohio State demonstrated that liquid hydrogen, which had previously been only a theoretical fuel, could be used in turbojet, ramjet, and rocket engines. In addition, they had developed the first coaxial injector, high-pressure pump, and regenerative cooling system for liquid hydrogen.³²

Transitions

The Cleveland laboratory's postwar emphasis on high-speed flight and its shift from piston engines to turbojets had an unintended effect on its future rocket work. Because jet engines did not employ



Image 13: Launch of a V-2/WAC (Without Any Control) Corporal rocket in 1950 (NASA 66P-0631).

^eRegeneratively cooled engines use cryogenic liquid hydrogen as both the propellant and the coolant to prevent the engine from burning up. The fuel was fed through rows of narrow passages that surrounded the combustion chamber and nozzle before being ignited inside the combustion chamber.

superchargers or require the high-octane fuels used in piston engines, the laboratory shifted the employees in those fields to turbomachinery and combustion activities, respectively.

Lewis established the massive Compressor and Turbine Division in 1945 to study and improve the complex compressor-turbine systems employed by turbojet engines. Axial-flow compressors consist of several fan-like stages driven by a gas-powered turbine. Each stage increases the air pressure incrementally before the compressed flow mixes with fuel and ignites in the combustion chamber. Most of the expanding air is expelled as thrust through the nozzle, but a portion is passed through the turbine blades, which power the compressor stages.³³ Lewis researchers refined compressor blade designs, improved turbine cooling, and developed new high-strength, high-temperature alloys and composite materials.³⁴ In the 1960s Lewis applied its turbomachinery expertise to cryogenic fuel pumping systems for rockets.



After the war, Lewis moved its fuels researchers to Walter Olson's Fuels and Thermodynamics Division. One group in this division, John Dietrich's Combustion Branch, included roughly a dozen researchers that became interested in analyzing small rocket engines. They viewed rocket engines as a natural extension of aircraft propulsion. NACA leaders in Washington, DC, however, were still struggling with the NACA's official position on missiles. To prevent any attention, Lewis management assigned the rocket group the esoteric name, the "High Pressure Combustion Section" and placed them in a small facility at the far edge of the campus.³⁵ Olson gave the men a large degree of freedom to develop and conduct their own tests.³⁶

Lewis's new rocket researchers reviewed the work performed at Peenemunde and JPL. Investigators from JPL and its partner, the California Institute of Technology, had cut their teeth in the late 1930s and early 1940s experimenting with solid propellant rockets, including those used for JATO applications. Olson visited JPL during the final year of the war and witnessed the rocket testing. The Lewis researchers realized that they were far behind the Germans in traditional liquid rockets and JPL in solid rockets. They decided to focus instead on high-energy liquid propellants, combustion, and cooling.³⁷

Paul Ordin and several colleagues began the program by determining the theoretical performance of a variety of high-energy propellants.³⁸ Because no single fuel possesses all of the desirable characteristics for rocket propulsion—such as specific impulse,^f density, reaction rates, thermal stability, and availability—designers must compromise. Olson, who encouraged the merger of academic research with physical testing, had his staff calculate the theoretical performance of high-energy fuels with different oxidizers and then test the best combinations at the High Pressure Combustion Laboratory, better known as the Rocket Lab.³⁹



Image 14: Paul Ordin (left) and colleague Vearl Huff in October 1950. In 1948 Huff developed a simplified method for calculating theoretical rocket performance data that worked well with the lab's initial computer systems. Huff's method proved to be Lewis's first major contribution to rocketry (GRC-1950-C-26558).

^fA measure of engine efficiency that measures the change in momentum for a unit of propellant consumption. It is equal to the thrust in pounds divided by the weight flow rate in pounds per second.



Image 15: Rocket Lab shortly after Lewis's trades apprentices were enlisted to quickly construct protective earthen mounds around the facility in preparation for the 1949 Inspection (GRC-1949-C-24935).

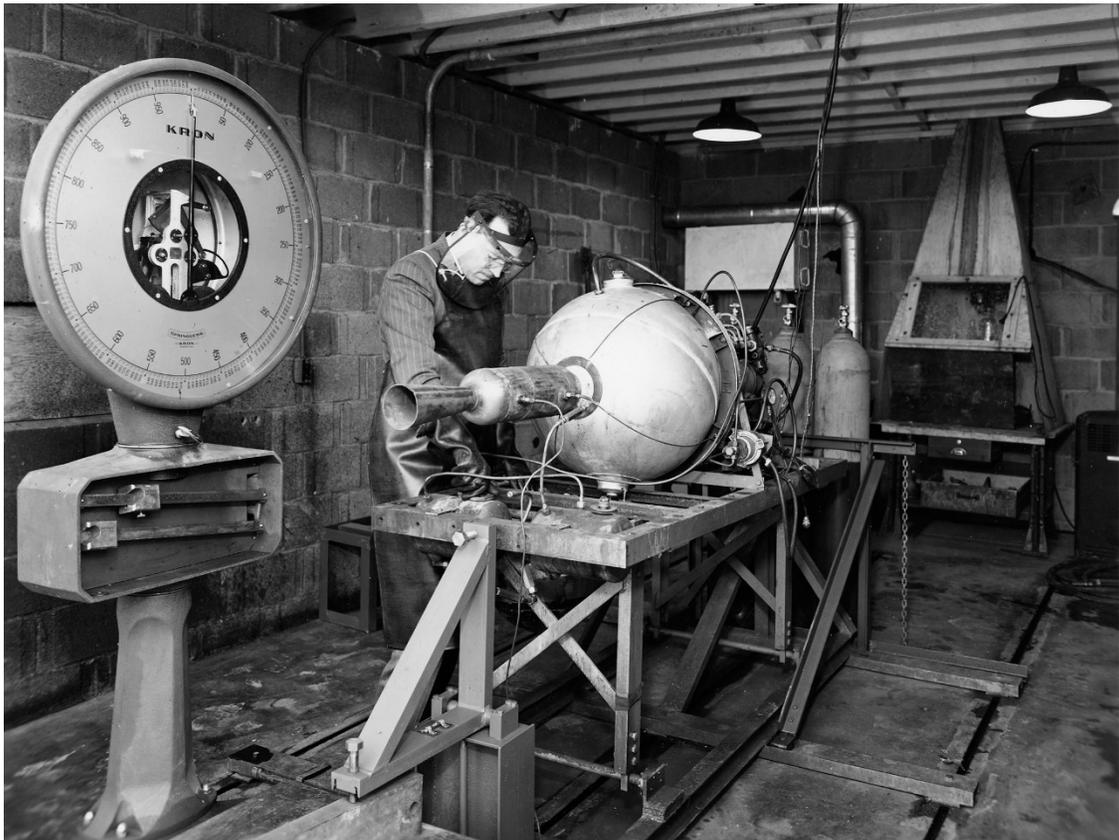


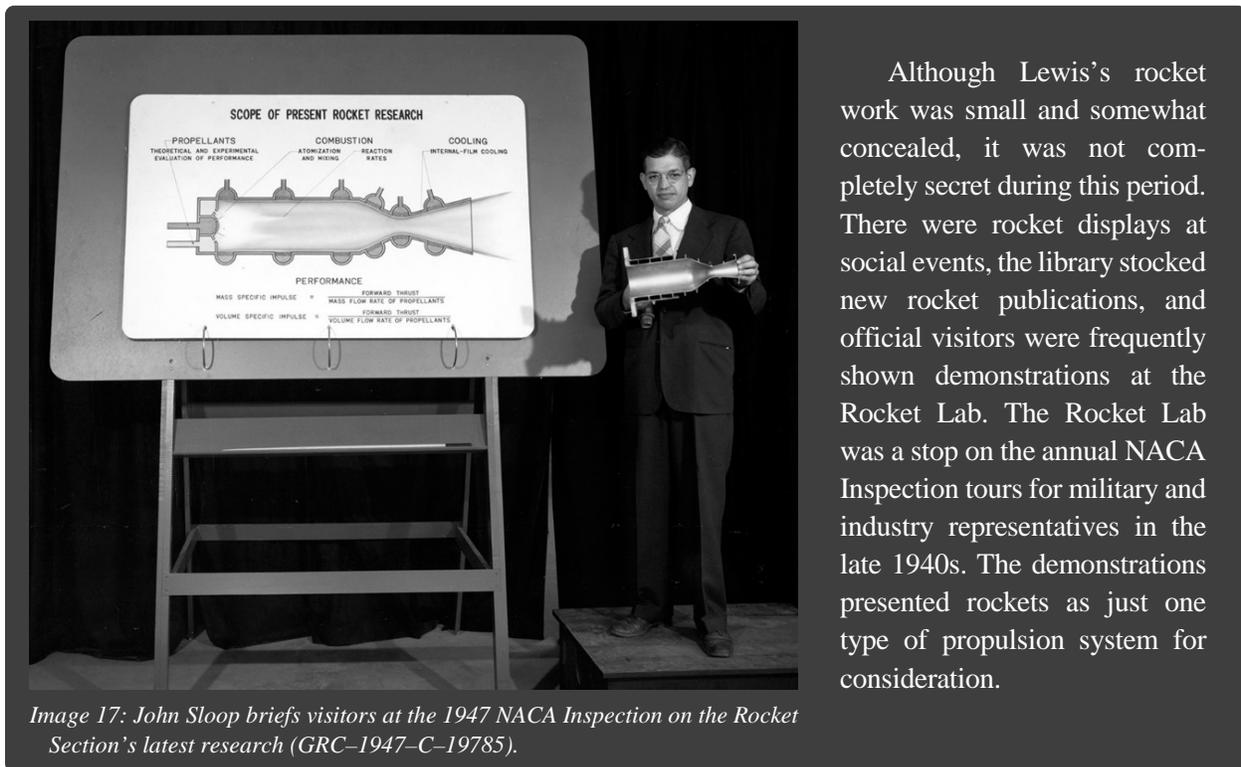
Image 16: A Rocket Section researcher prepares a rocket engine for testing at the Rocket Lab with the hypergolic combination of nitric acid and aniline in March 1946 (GRC-1946-C-14482).

The Rocket Lab was a collection of four single-story cinderblock test cells located at the remote western edge of Lewis Field. The staff could mount small engines in a test cell so that its fiery exhaust flowed horizontally out the open doors and into the atmosphere. Ordin and the others tested 100-pound-thrust rocket configurations with the most promising propellant combinations and different injectors and nozzles. They were particularly interested in the high specific impulse of hydrazine and diborane.⁴⁰ Lewis researchers, who were present in May 1947 when representatives from Ohio State, Aerojet, and JPL presented papers on their hydrogen efforts at a symposium at Wright Field, forwent hydrogen to avoid duplicating their efforts.⁴¹



On 26 May 1948 Lewis hosted approximately 100 guests for a special conference on fuels. The conference covered the entirety of Lewis fuels research, but notably included a paper on the rocketeers' difficulty working with diborane.⁴² The fuels conference led to the laboratory's first official rocket research project. In 1949 the U.S. Navy requested that Lewis test a 220-pound-thrust rocket engine for possible use on a new high-altitude fighter aircraft and the Lark missile. The navy was concerned about the reliability of liquid rockets at high altitudes and asked Lewis to test the engine in a new altitude chamber. They found that the engine operated well in the thin air but that the low temperatures impaired the hydraulic fluid performance.⁴³ Although small in scope, the navy project added legitimacy to Lewis's fledgling rocket program.

In February 1949 Lewis management briefed NACA Headquarters on the survey of the basic properties of several high-energy fuels by researcher John Sloop. Three months later the committee members visited Cleveland and toured the Rocket Lab. Afterward they recommended expanding the combustion research and investigations of nitric acid and alternative oxidizers such as fluorine.⁴⁴



Although Lewis's rocket work was small and somewhat concealed, it was not completely secret during this period. There were rocket displays at social events, the library stocked new rocket publications, and official visitors were frequently shown demonstrations at the Rocket Lab. The Rocket Lab was a stop on the annual NACA Inspection tours for military and industry representatives in the late 1940s. The demonstrations presented rockets as just one type of propulsion system for consideration.

Image 17: John Sloop briefs visitors at the 1947 NACA Inspection on the Rocket Section's latest research (GRC-1947-C-19785).

Fluorine's Potential

Robert Goddard's first liquid rocket launch in 1926 used liquid oxygen as the oxidizer, and by the 1940s liquid oxygen had proven itself as a stable, clean-burning entity. Lewis researchers however, were interested in the potential of several unproven oxidizers with higher energy levels, particularly fluorine.⁸

Fluorine has two advantages over oxygen: it does not require a spark to ignite, and a smaller quantity is required to produce the same amount of energy as oxygen. This offered the potential for more reliable combustion and smaller propellant tanks. Fluorine's severe volatility and toxicity, however, presented engine designers with substantial hurdles to overcome. There are only a limited number of materials that can withstand fluorine—a minute amount of friction or contamination causes catastrophic explosions, and its noxiousness poses environmental concerns.⁴⁵ Any length of exposure or concentration of fluorine can be extremely damaging and inhalation can often be deadly.⁴⁶

In 1948 Ordin began calculating fluorine's theoretical performance when paired with several different fuels, then began testing the combinations in engines in the Rocket Lab. The rocket staff procured the fluorine for their runs from a chemical company in downtown Cleveland and personally brought the fluorine to Lewis. The early morning transport of the chemical required approval from numerous local communities, and a police escort.⁴⁷ In the early 1950s the researchers tested fluorine with jet fuel, ammonia, or hydrazine in small rocket engines.⁴⁸ The experience improved the method for safely handling fluorine, and by 1955 Lewis researchers were able run JP-4 and fluorine in engines with up to 10,000 pounds of thrust.⁴⁹ Lewis's fluorine development would continue well into the 1960s.

Atomic Awareness

The concept of using energy from radioactive decay for propulsion dates back to the turn of the century, but the actual implementation was implausible until the first controlled atomic fission took place in 1939.⁵⁰ During World War II Lewis researchers became intrigued by the potential of using nuclear energy to power aircraft, but NACA Headquarters refused to approve the research because all available personnel in the atomic field were engaged in the top secret Manhattan Project.⁵¹ The atomic bombing of Hiroshima and Nagasaki in August 1945 brought the war in the Pacific to an end and signaled the beginning of a nuclear arms race. Scientific minds across the nation, however, also realized that the atom's massive energy offered great potential for an array of military and civilian applications including aircraft and missile propulsion.

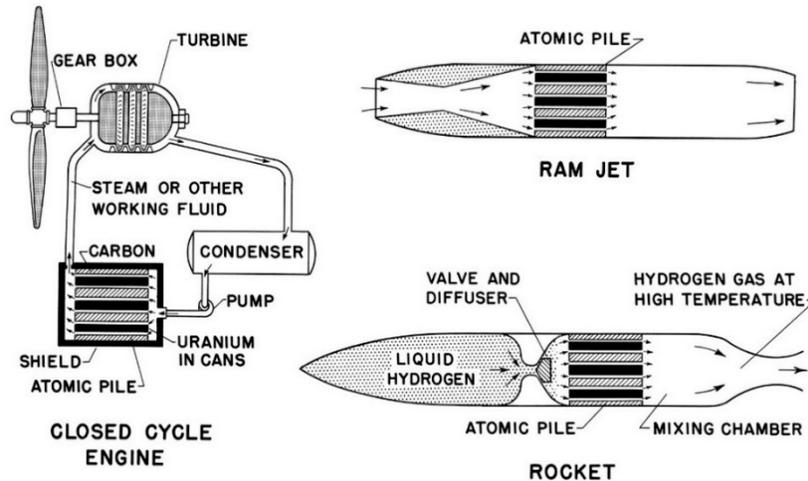
The morning after the Hiroshima bombing, Lewis researchers briefed Lewis management on a possible role that the lab could have in the nascent field of nuclear propulsion,⁵² and they created a research order proposal to investigate the use of atomic energy for aircraft propulsion.⁵³ A few Lewis researchers reviewed available nuclear physics literature, but they were limited by the lack of access to secret Manhattan Project data.⁵⁴ They concentrated their efforts on high-temperature materials, heat transfer issues, and theoretical atomic aircraft and missile concepts.⁵⁵ Although small in scope, it was the beginning of the laboratory's nearly 30-year interest in the development of nuclear propulsion systems.

The NACA was not the only group interested in the use of nuclear energy for propulsion. The military sponsored a number of nuclear aircraft studies in 1946 and 1947, most significantly the air force's Nuclear Energy for the Propulsion of Aircraft (NEPA) program.⁵⁶ The identification of shielding requirements and

⁸Fluorine was first produced in a French laboratory in 1886, but it was not manufactured in large quantities until it was employed in World War II weapons systems. Fluorine production methods were improved in the postwar years, and its applications spread. It was at this time that NACA Lewis researchers became interested in its use in rocket systems.

lightweight materials that could withstand high temperatures was an early priority. Lewis supported NEPA by constructing an underground cyclotron^h to study the effects of radiation on potential engine materials.⁵⁷

The military was also drawn to the possibility of using fission to power the upper stages of the emerging missile systems. North American Aviation conducted a study for the military in 1947 that concluded that nuclear rockets were feasible but that a number of serious technical issues would have to be overcome. These early studies identified liquid hydrogen as the optimal working fluid for nuclear vehicles.⁵⁸



SOME POSSIBLE FUTURE APPLICATIONS OF NUCLEAR ENERGY TO AIRCRAFT PROPULSION

FIGURE AERL -11-1

NACA
C-11561
8-15-46

Image 18: A 1946 Lewis chart outlining potential nuclear propulsion applications for gas turbine, ramjet, and rocket engines. Lewis management used the chart and others like it to lobby for funding for in the coming fiscal years (GRC-1946-C-15561).



In the late 1940s the military's interest in missiles, liquid hydrogen, and nuclear propulsion quickly declined as defense budgets tightened and enthusiasm for conceptual space missions faded. Liquid hydrogen appeared to be too wily and powerful for the intended missile missions, and engine performance and vehicle weight seemed to reduce the promise of rocket systems in general.⁵⁹ The use air-breathing ramjet engines appeared to be a more reliable option for missiles. In the meantime the military continued its reliance on bomber aircraft to deliver warheads.⁶⁰ Despite modest developmental advances, many felt that these technologies were more applicable to theoretical space applications than intercontinental missiles.⁶¹ The military also canceled NEPA in 1951 after the program failed to produce any breakthroughs for nuclear aircraft, although general nuclear propulsion research continued.⁶² Meanwhile the Lewis laboratory was poising itself to accelerate its efforts in these fields just as the military was getting out.

^hCyclotrons employ large magnets to accelerate charged particles from a radioactive source until they release high energy levels.

References

6. A. Bowdoin Van Riper, *Rockets & Missiles: The Life Story of a Technology* (Baltimore, MD: Johns Hopkins University Press, 2004).
7. Faidra Papanelopoulou, “Louis Paul Cailletet: The Liquefaction of Oxygen and the Emergence of Low-Temperature Research” *Notes & Records of the Royal Society* (2013), <http://rsnr.royalsocietypublishing.org/content/roynotesrec/early/2013/10/04/rsnr.2013.0047.full.pdf> (accessed 2 January 2015).
8. Michael T. Davis, Robert K. Allgeier, Jr., Thomas G. Rogers, and Gordon Rysavy, *The Development of Cryogenic Storage Systems for Space Flight* (Washington, DC: NASA SP–247, 1970), <http://ntrs.nasa.gov>
9. J. L. Heilbron, editor, “Low Temperature Physics,” *The Oxford Companion to the History of Modern Science* (New York, NY: Oxford University Press, 2003).
10. Los Alamos National Security, “Period Table of Elements: LANL, Hydrogen,” <http://periodic.lanl.gov/1.shtml> (accessed 15 September 2014).
11. John Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959* (Washington, DC: NASA SP–4404, 1977), <http://ntrs.nasa.gov>
12. John Sloop, “Technological Steps to Liquid Hydrogen Propulsion,” International History of Astronautics Symposium, 21–28 September 1980, NASA Glenn History Collection, Sloop Collection, Cleveland, OH.
13. Davis, *The Development of Cryogenic Storage Systems*.
14. Minutes of Meeting of Special Committee on Jet Propulsion, 10 April 1941, NASA Glenn History Collection, NACA Collection, Cleveland, OH.
15. Steve Gaither and Kimberley Kane, “The World War II Ordnance Department’s Government-Owned Contractor-Operated Industrial Facilities: Indiana Army Ammunition Plant Historic Investigation” (Fort Worth, TX: U.S. Army Corps of Engineers, 1995).
16. “Five Railroads Located in Plant Area,” *Sandusky Star-Journal* (6 January 1941).
17. “New Site for Perkins Cemetery,” *Sandusky Star-Journal* (17 January 1941).
18. “The Saga of Plum Brook Ordnance Works as a World War Two High-Explosives Facility Comes to a Close,” *The Plum Brook News* (18 August 1945).
19. “The Saga of Plum Brook Ordnance Works.”
20. John Adams Shortal, *A New Dimension: Wallops Island Flight Test Range: The First Fifteen Years* (Washington, DC: NASA RP–1028, 1978), <http://ntrs.nasa.gov>
21. Leslie Simon, *German Research in World War II* (New York, NY: John Wiley and Sons, 1948).
22. George Sutton, *History of Liquid Propellant Rocket Engines* (Reston, VA: American Institute of Aeronautics and Astronautics, 2006).
23. “Survey of Fundamental Problems Requiring Research at the Aircraft Engine Research Laboratory,” May 1946, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
24. Richard P. Hallion, *On the Frontier: Flight Research at Dryden, 1946–1981* (Washington, DC: NASA SP–4303, 1984), <http://ntrs.nasa.gov>
25. Shortal, *A New Dimension*.
26. Perry Pratt, Minutes of First Meeting of Subcommittee on Propulsion Systems, 23 October 1945, NASA Glenn History Collection, NACA Collection, Cleveland, OH.
27. Henry H. Arnold, “Air Power for Peace,” *National Geographic Magazine* 89, no. 2 (February 1946).
28. Constance McLaughlin Green and Milton Lomask, *Vanguard: A History* (Washington, DC: NASA SP–4202, 1970), <http://ntrs.nasa.gov>
29. Robert Kraemer, *Rocketdyne: Powering Humans Into Space* (Reston, VA: American Institute of Aeronautics and Astronautics, 2006).
30. Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959*.
31. Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959*.
32. Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959*.
33. George Gray, *Frontiers of Flight: The Story of NACA Research* (New York, NY: Alfred A. Knopf, 1948).
34. Compressor and Turbine Research Division, *Aerodynamic Design of Axial-Flow Compressors* (Washington, DC: NACA RM–E56BO3, 1958), <http://ntrs.nasa.gov>

35. Walter Olson interview, Cleveland, OH, by Virginia Dawson, 16 July 1984, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
36. John Sloop, “High-Energy Rocket Propellant Research at the NACA/NASA Lewis Research Center, 1945–60,” Seventh International History of Astronautics Symposium Proceedings, 8 October 1973, NASA Glenn History Collection, Sloop Collection, Cleveland, OH.
37. Virginia Dawson, *Engines and Innovation: Lewis Laboratory and American Propulsion Technology* (Washington, DC: NASA SP-4306, 1991), <http://ntrs.nasa.gov>
38. R .O. Miller and P. W. Ordín, *Theoretical Performance of Rocket Propellants Containing Hydrogen, Nitrogen, and Oxygen* (Washington, DC: NACA RM E8A30, 1948), <http://ntrs.nasa.gov>
39. John Sloop, “NACA High Energy Rocket Propellant Research in the Fifties” 28 October 1971, NASA Glenn History Collection, Dawson Collection, Cleveland, OH.
40. Miller, *Theoretical Performance of Rocket Propellants*.
41. John Sloop, “Aerojet Special Chronology,” undated, NASA Glenn History Collection, Sloop Collection, Cleveland, OH.
42. Sloop, “High-Energy Rocket Propellant Research.”
43. John Sloop Memorandum, “R.A. D-229, Altitude Ignition of Liquid Propellant Rocket Engines,” 11 July 1949, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
44. Robert Dietz Memorandum, “Recommendations of the NACA Subcommittee on Propulsion Systems Analysis Made During the February 2–3, 1949, Meeting,” 31 May 1949, NASA Glenn History Collection, NACA Collection, Cleveland, OH.
45. Walter M. Osborn, *Noncavitating and Cavitating Performance of a Liquid-Fluorine Pump Designed by Stream-Filament Method* (Washington, DC: NASA TM X-722, 1963), <http://ntrs.nasa.gov>
46. W. Clark Cooper to Gerald Morrell, 10 August 1956, NASA Glenn History Collection, Sloop Collection, Cleveland, OH.
47. Paul Ordín interview, Cleveland, OH, by John Sloop, 30 May 1974, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
48. Sloop, “High-Energy Rocket Propellant Research.”
49. Harold Schmidt and Jack Harper, *Handling and Use of Fluorine and Fluorine-Oxygen Mixtures in Rocket Systems* (Washington, DC: NASA SP-3037, 1967), <http://ntrs.nasa.gov>
50. Roger Launius, *To Reach the High Frontier: A History of U.S. Launch Vehicles* (Lexington, KY: University of Kentucky, 2003).
51. George Lewis to Cleveland, “Cleveland Memorandum for Director of Aeronautical Research, June 22, 1945,” 1 August 1945, NASA Glenn History Collection, Nuclear Propulsion Collection, Cleveland, OH.
52. Joseph Dietrich, Memorandum to Acting Executive Engineer, “Conference at AERL on August 7, 1945, To Discuss Nuclear Power for Aircraft Propulsion,” 8 August 1945, NASA Glenn History Collection, Nuclear Propulsion Collection, Cleveland, OH.
53. Joseph Dietrich Memorandum to the Executive Engineer, “Atomic-Power Aircraft Engines,” 7 August 1945, NASA Glenn History Collection, Nuclear Propulsion Collection, Cleveland, OH.
54. Joseph Dietrich Memorandum for the Chairman, Atomic Energy Commission, “Heated Hydrogen as a Rocket Propellant,” 21 February 1946, NASA Glenn History Collection, Nuclear Propulsion Collection, Cleveland, OH.
55. Raymond Sharp to George Lewis, “NACA Work on Nuclear Energy Power Plants for Aircraft,” 29 October 1946, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
56. John Kenton, “Who’s Who in the Aircraft Nuclear Program,” *Nucleonics* (August 1956).
57. “Cyclotron Data Tabulation,” 1961, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
58. Ray Williamson and John Logsdon, editor, “Access to Space: Steps to the Saturn V,” *Exploring the Unknown Selected Documents in the History of the U.S. Civil Space Program, Volume 4* (Washington, DC: NASA SP-4407, 1999), <http://ntrs.nasa.gov>
59. John Sloop, Air Force Special Chronology, 1974, NASA Glenn History Collection, Sloop Collection, Cleveland, OH.
60. John Sloop, “Problems Faced by Early Space Transportation Planners,” Fifteenth Space Congress, 26–28 April 1978, NASA Glenn History Collection, Sloop Collection, Cleveland, OH.
61. Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959*.
62. Kenton, “Who’s Who in the Aircraft Nuclear Program.”



Image 19: A Lewis photographer films the test of a liquid-hydrogen/liquid-oxygen engine in Cell 22 of the Rocket Lab during January 1955. Researchers used the film footage to analyze the combustion (GRC-1955-C-37427).

◆ Chapter 2 ◆

Lewis Takes Up the Hydrogen Mantle

Although Lewis continued to focus the majority of its engine research on turbojets and ramjets in the 1950s, newly appointed Chief of Research Abe Silverstein expanded nonaeronautical research efforts such as high-energy propellants, rocket engines, and nuclear propulsion. Significantly, Lewis rocket researchers turned their attention to liquid hydrogen now that other institutions had ceased their hydrogen efforts. Silverstein took a personal interest in hydrogen and expanded the lab's rocket research staff and test capabilities.

Meanwhile, the Cold War reached unprecedented heights in the early 1950s with the eruption of hostilities in Korea, the introduction of thermonuclear weapons, and the Soviet Union's acquisition of nuclear weapons. As a result the military renewed its interest in rocket-powered missiles, liquid-hydrogen fuels, and nuclear propulsion. These efforts, which dovetailed with the emerging Lewis work, led to the creation of the Rocket Systems Area at Plum Brook Station and paved the way for the use of liquid hydrogen in the U.S. space program.

Acknowledgment

In August 1949 Lewis Director Raymond Sharp selected Silverstein to serve as the laboratory's Chief of Research. By the end of the year, Silverstein reorganized the research divisions. This included the cleaving of the Fuels and Thermodynamics Division and the establishment of a new Fuels and Combustion Division under Walter Olson.⁶³ Olson's group continued to study variations of traditional turbojet and ramjet fuels, but also analyzed fundamental combustion problems involving a range of fuels, including high-energy propellants.⁶⁴

Their initial research revealed that only hydrogen, beryllium, and boron derivations (pentaborane and diborane) possessed higher combustion temperatures than traditional hydrocarbon fuels. Hydrogen and diborane required special handling procedures, whereas beryllium and pentaborane produced serious toxicity. Hydrogen, with its high specific impulse and nontoxic exhaust, appeared to be the most promising.⁶⁵ Lewis differentiated itself from the hydrogen studies at Ohio State, Aerojet, and the Jet Propulsion Laboratory (JPL) by using larger engines that more realistically reflected flight-type rockets.⁶⁶

In January 1950, 200 military, industry, and university guests attended a two-day propulsion conference at Lewis to discuss fuel alternatives for various types of engines.⁶⁷ John Sloop presented the paper on fuels for missiles. He stated that liquid hydrogen with either oxygen or fluorine would provide the best performance, but if the low-density hydrogen caused too many design problems, hydrazine or ammonia were the best options. It was the lab's first strong stance on liquid hydrogen.⁶⁸ Two months later Lewis briefed U.S. Air Force representatives on their fuels research. These events led to informal requests for specific rocket investigations and the formation of an NACA Subcommittee on Rocket Engines in October 1950.⁶⁹ The subcommittee, which included Sloop, Olson, and representatives from several rocket manufacturers, the military, and universities, focused on the use of rocket engines for missile or jet-assist applications.



Image 20: Silverstein in 1948 (GRC-1948-C-21800).

Silverstein began his career as a mechanical engineer at the NACA Langley Memorial Aeronautical Laboratory before transferring to Lewis in 1943 to manage the lab's largest wind tunnel. After the war he was named head of the Wind Tunnels and Flight Division and soon became the laboratory's driving force. As a member of the NACA's Special Committee on Self-Propelled Guided Missiles, Silverstein witnessed the postwar missile development taking place on the West Coast firsthand.⁷⁰ Silverstein had the ability to quickly grasp the essence of a problem and appoint capable people to resolve the issue; and he was not afraid to make tough decisions. Silverstein would go on to be a key organizer of NASA in the late 1950s and serve as Lewis's Center Director throughout the 1960s.

The Lewis rocket group sought to expand their high-energy propellant work by increasing the size of the engines being tested, but it was difficult to obtain sufficient amounts of liquid hydrogen.⁷¹ Ohio State and Aerojet had built modest hydrogen liquefaction machines to support their research, but it was impractical at this time for the NACA to transport the fluid from either of these facilities.⁷² In the spring of 1950 President Harry Truman initiated the development of a thermonuclear weapon—referred to as the hydrogen bomb.¹ The lack of plants capable of producing the large quantities of liquid hydrogen needed to support this program spurred the creation of the National Bureau of Standards's Cryogenic Engineering Laboratory in Colorado and the development of hydrogen transportation and storage equipment.⁷³ In the meantime, Lewis convinced NACA management to seek funding for a liquefaction device of its own. It was the NACA's first budget request specifically to support rocket research. Congress approved the funding in 1951, and system began generating liquid hydrogen in the next year or so.⁷⁴

The advent of the hydrogen bomb also led to a resurgence in military interest in rocket-powered missiles. The new bomb's light weight and greater destructive capabilities reduced missile payload and accuracy requirements, making the use of rocket engines more reasonable than previously anticipated. In addition, the Rand Corporation issued an air-force-sponsored report supporting the feasibility and usefulness of satellites.⁷⁵ In September 1951 the air force asked Aerojet/Convair to begin designing what would become the Atlas missile. Atlas used new technology that Aerojet had introduced for the V-2 missiles, including lightweight pressurized tanks, uninsulated oxygen tanks, and swiveling engines.⁷⁶

¹In simple terms, thermonuclear weapons use the atomic bomb's fission of heavy elements to fuse or compress atoms from hydrogen isotopes. This fusion releases a tremendous amount of energy.

Pursuance

With growing pressure from the military, the NACA began shifting its policy of supporting only rocket engines for cruise missiles and jet-assisted takeoff (JATO) engines. In a January 1952 the Executive Committee agreed to examine issues related to flight in the upper atmosphere to support proposed military vehicles and satellites.⁷⁷ On 20 March 1952 the NACA resolved to increase its overall propulsion work, particularly in regards to high-energy fuels and rockets.⁷⁸ Two days later, *Colliers Magazine* published the first of a series of articles by Wernher von Braun that accurately forecasted space travel in the coming years. In January 1953 the National Research Council initiated plans to launch a scientific satellite into space during a 1957–58 period referred to as the International Geophysical Year.⁷⁹

Despite lingering opposition at headquarters, the NACA resolved to expand both its rocket efforts and introduce spaceflight to its portfolio during the summer of 1952.⁸⁰ The Subcommittee on Rocket Engines recommended that the NACA pursue “a broader and more advanced approach to the solution of rocket propulsion problems.”⁸¹

With this new mandate Lewis pushed ahead with its plans to build a new facility that could fire 20,000-pound-thrust rocket engines with a variety of propellants for up to 3 minutes. Researchers would use this Rocket Engine Test Facility (RETF) to study injector and combustion chamber performance.⁸² Congress approved the \$2.5 million project in 1954, and construction began the following year in a ravine along the western edge of the campus. The NACA also allocated funds to improve the Rocket’s Lab’s Cell 22 by adding higher thrust capacity, an exhaust scrubber, and a hydrogen liquefier. Cell 22 was Lewis’s premier rocket tool until the RETF came online in late 1957.

In December 1952 Silverstein expanded the rocket group further by increasing staffing and elevating the section to a branch level. The Rocket Branch, led by John Sloop, now had three sections of its own—Combustion, Propellants, and Thermodynamics.⁸³ Silverstein also authorized the addition of a control room and four larger test cells to the Rocket Lab.



Image 21: A technician on the RETF engine stand shortly after the facility’s completion in 1957 (GRC-1957-C-45870).

Lewis Stakes a Claim

The intensification of the Cold War in the early 1950s spurred the military's renewed interest in new weapons systems involving guided missiles, liquid hydrogen, and nuclear aircraft. In 1951 the U.S. Air Force and the Atomic Energy Commission (AEC) resumed their atomic aircraft efforts with the Aircraft Nuclear Propulsion (ANP) program. The AEC hired General Electric and Pratt & Whitney to develop nuclear propulsion systems for the vehicle. Lewis researchers, who were involved from the start, used the cyclotron to study the effects of radiation on different types of materials for the aircraft. The cyclotron, however, could only generate modest levels of radiation. It was clear that a larger reactor would be needed to support the program.

In February 1952 Lewis leaders requested permission to build a 60-megawatt test reactor. The AEC, which licensed all reactors, approved the NACA's request in October 1954.⁸⁴ The reactor would be too large for Lewis Field so a site selection team was created to evaluate alternative locations. The team examined 18 Midwestern sites, including the Plum Brook Ordnance Works (PBOW), and rated them based on waste disposal options, available acreage, remoteness, emergency services, and utilities.⁸⁵

The PBOW had shut down immediately after the close of World War II and remained relatively vacant and devoid of activity for the next 10 years.⁸⁶ Between 1946 and 1949, a private firm oversaw the property for the government, and the government sold roughly 3,000 acres of perimeter area to the public with the caveat that it could repurchase the land in 20 years. In 1949 the General Services Administration began managing the Plum Brook property. They took measures to preserve the manufacturing facilities by verifying utility systems, cleaning machinery, and painting the structures.⁸⁷ The Ravenna Arsenal assumed control in 1954 as the NACA began searching for a site to construct a nuclear test reactor.⁸⁸ By March 1955 the selection team decided on 500 acres of the 6,000-acre PBOW just south of Sandusky. Construction of the \$5 million Plum Brook Reactor Facility began in September 1956.⁸⁹



Image 22: Construction of the reactor's containment vessel c1958. The reactor took five years to complete. By that time, most of the Rocket Systems Area sites were operational (GRC-2016-C-05109).

NERVA Roots

While research was under way on nuclear aircraft, there was a resurgence in interest in nuclear-powered rocket systems. The military investigated the concept after World War II until the number of technical hurdles became apparent. In 1953, however, Oak Ridge National Laboratory researcher Robert Bussard determined that the earlier feasibility studies were too conservative. Bussard's analysis indicated that nuclear propulsion was superior to chemical rockets for all but the very lightest space missions.⁹⁰



Image 23: NACA Executive Secretary John Victory addresses local officials, NACA leaders, and the press at a luncheon following the groundbreaking ceremony for the reactor. "Plum Brook offered the best combination of advantages in all the [prerequisite] factors," Victory explained. "But, it offered two extra dividends as well. These are, a progressive thinking community and convenient access to the NACA Lewis Laboratory in Cleveland."⁹¹ (GRC-1955-C-43042).

Meanwhile Lewis researchers were working on their own reactor designs for nuclear rockets. In June 1955, they presented the Air Research & Development Command with a research proposal to investigate nuclear aircraft engine designs and to compare the performance of chemical and nuclear missile systems.⁹² The renewed Oak Ridge and NACA interest spurred the air force and AEC to initiate the Project Rover effort in November 1955 to develop reactors to power upper stages for missile systems.⁹³ The first phase, referred to as Kiwi, sought to test basic nuclear principles in a nonflying reactor. This would be followed by the creation of a flyable reactor (Nuclear Rocket for Rocket Vehicle Application (NERVA)) and then construction of complete nuclear stage that would be launched on a Saturn rocket (Reactor-In-Flight-Test). In 1956 the air force hired the Rand Corporation to compare the performance of chemical and nuclear rockets for a range of missions.⁹⁴



After considering ammonia, the AEC and Rocketdyne decided in 1956 to use liquid hydrogen as the nuclear rocket propellant.⁹⁵ Like chemical rockets, nuclear systems require regenerative cooling, low-pressure tanks, and self-starting turbopumps. The primary difference is that the nuclear engine uses radiation to heat the hydrogen, whereas the chemical rocket combusts the fuel with an oxidizer. AEC scientist Roderick Spence later wrote, "The compelling thing about nuclear rockets is not just their ability to pack the power of the Hoover Dam into a package the size of an oil drum (that's arresting, even spectacular, but not particularly compelling), but their ability to use hydrogen as a propellant."⁹⁶

It was reported at the time that the nuclear rocket had the potential to produce a specific impulse that was twice that of liquid-hydrogen/liquid-oxygen engines and nearly three times as much as typical chemical rockets.⁹⁷ The development of liquid-hydrogen engines for chemical and nuclear rockets was conducted concurrently in the 1950s and 1960s. The basic issues were the same in both circumstances: storage, pumping, and the expansion of the heated gas to produce thrust. Nuclear engines also required the analysis of the interaction of the cryogenic hydrogen with the high-temperature radiation. It was not known what the effect of this combination would have on engine materials or heat transfer systems.⁹⁸

Meanwhile, the AEC was investigating different reactor designs for the engines. The Soviet Union also studied the feasibility of nuclear rockets in the mid-1950s. Soviet designers proposed nuclear upper stages for the N-1, their largest launch vehicle, but support faded once leaders discovered the length of the required development period. They would reconsider the concept in the mid-1960s.⁹⁹

Chief Advocate

Abe Silverstein's interest in liquid hydrogen was critical to its ultimate acceptance, but the genesis of that interest is uncertain. Silverstein claimed that he broached the liquid-hydrogen/liquid-oxygen combination during a briefing by John Sloop on a chlorine and ammonia propellant. Silverstein recalled asking one of the staff members what Robert Goddard had calculated for the specific impulse of a hydrogen and oxygen propellant. Although hydrogen-oxygen was not as powerful as the chlorine-ammonia mixture, it was much easier to handle and burned more smoothly.¹⁰²

Sloop, himself, recalled Silverstein witnessing the firing of a Lewis-built regeneratively cooled engine. "When Silverstein witnessed a hydrogen-oxygen rocket engine operation, the sweetness of the hydrogen-oxygen combination came through to him, and to us, loud and clear."¹⁰³ Historian Virginia Dawson suggests that Silverstein became interested in hydrogen because of a Johns Hopkins University recommendation that it would be the optimal propellant for a nuclear rocket.¹⁰⁴

Whatever the origin of Silverstein's attention, the breakthrough arrived on two fronts in late 1954. On the night of 23 November 1954 Edward Rothenberg fired a 5000-pound-thrust rocket engine in Cell 22. It was the first successful liquid-hydrogen/liquid-oxygen run at Lewis. The engine was also more powerful than any of those previously run at Ohio State, Aerojet, or JPL. The researchers repeated the tests several more times over the next six weeks.¹⁰⁵

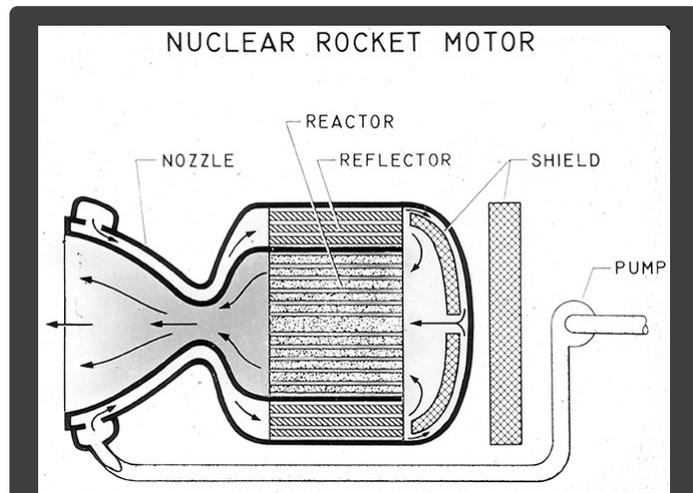


Image 24: Diagram of nuclear rocket engine (NACA CS-15514A).

The reactor releases hydrogen steam into the pump's turbine. Then the turbine converts the heat into energy that rotates the drive shaft and powers the turbopump. The pump drives the liquid hydrogen from the tank and through the cooling passages in the regeneratively cooled nozzle. The liquid expands into gaseous form as it passes through holes in the reactor.¹⁰⁰ The expanding hydrogen is accelerated in the contracting portion of the nozzle. The hot hydrogen gas then enters the expanding section of the nozzle where it pushes against the nozzle walls and forces the rocket forward.¹⁰¹



Image 25: Firing of a 5,000-pound-thrust liquid-hydrogen/liquid-oxygen engine from Cell 22 of the Rocket Lab in early January 1955. It was part of Lewis's first series of hydrogen-oxygen engine tests, which were suspended to redesign the injector and engine controls (GRC-1955-C-37428).

In the fall of 1954, Lewis researchers were also exploring high-energy propellants for potential use in aircraft engines. During a test of a turbojet combustor with gaseous hydrogen, the hydrogen yielded more than 90 percent of its theoretical efficiency despite poor mixing of the fuel and air.¹⁰⁶ Silverstein saw the potential of hydrogen for both aircraft and rocket applications. He enlisted Eldon Hall to work out optimal mixture ratios and then refine the calculations. Silverstein and Hall coauthored a seminal report which predicted that the performance of a liquid-hydrogen-powered aircraft would far exceed those using traditional aircraft fuels.¹⁰⁷ Silverstein presented the findings to the U.S. Air Force in the spring of 1955 and expanded hydrogen-related research at Lewis.¹⁰⁸



Lewis researchers, Sloop in particular, remained intrigued by liquid fluorine as an oxidizer. During this period, they developed tools to mitigate many of fluorine's handling and toxicity issues. Initially they analyzed different materials that were impervious to fluorine's causticity and developed proper techniques for handling the chemical.¹⁰⁹ They found that they could minimize fluorine's reaction with metal components by coating the metal with a small amount of fluorine prior to engine ignition (passivation). They perfected procedures for reducing contamination in the system and developed a method using a water shower to decontaminate the engine exhaust at test stands.¹¹⁰

The Lewis rocket team successfully operated their fluorine rockets with JP-4, ammonia, hydrazine, and diborane in the early 1950s, but they were unable to run them with liquid hydrogen. Rothenberg made several attempts to operate a low-thrust hydrogen-fluorine engine in Cell 22, but he struggled to cool the combustion chamber. “The wickedness of fluorine was catching up with him,” recalled Howard Douglass.¹¹¹ Lewis’s first successful hydrogen-fluorine run occurred in March 1955. Although the firing lasted only 4 seconds, it yielded the highest propellant performance yet of any Lewis test.¹¹²



Two months later Walter Olson, head of the Fuels and Combustion Division, created a plan to expand NACA rocket research. He advocated increasing the size of experimental engines up to a million pounds of thrust. He also called for a new rocket research laboratory with test stands, turbopumps facilities, and other equipment. “Looking about ten or twelve years ahead it is possible to see the nation’s first efforts toward intercontinental flight by rocket propulsion nearing fruition,” Olson predicted. “Satellite flight, which still seems visionary to many minds now, may well be receiving man’s first serious efforts. These are logical extensions of the frontier of flight. NACA should participate.”¹¹³

If anything, Olson’s forecasts were too conservative. The NACA management, however, avoided satellite research and did not yet have the will or funding to create the new rocket propulsion research laboratory. That would have to wait until the Soviets forced the issue two years later. Meanwhile Lewis was prepared to make immediate contributions with liquid hydrogen and nuclear propulsion.



Image 26: Walter “Ted” Olson. Olson joined the laboratory as a chemist in 1942. In 1945 he was named head of the Combustion Branch, which included the Rocket Section. In 1950 Olson became Chief of the Fuels and Combustion Research Division (GRC-2016-C-05781).

Milestones

After nearly a decade of tremendous growth, aircraft engine development seemed to plateau in the 1950s. This deceleration came as the U.S. Air Force was exploring options for a new reconnaissance aircraft with significantly greater range and altitude.¹¹⁴ The use of alternative fuels was one method of dramatically increasing engine performance without drastic new designs. The report by Silverstein and Hall, issued in April 1955, had shown that hydrogen was the most compelling nonnuclear option.¹¹⁵

Within six months of the report, the air force initiated a top secret three-pronged effort to introduce hydrogen-fueled aircraft. There were two schools of thought—modify existing aircraft to fly on liquid hydrogen or design a new, larger aircraft to fully take advantage of liquid hydrogen’s power. Under codename Project Suntan, the air force contracted Pratt & Whitney to pursue the use of hydrogen in existing engines, and Lockheed and Garrett to design a new aircraft and engine, respectively. Meanwhile, in December 1955, Lewis agreed to undertake a fast-paced effort to modify a Martin B-57B Canberra to fly on liquid hydrogen. Neither Lewis nor the industry participants were aware of one another’s efforts.¹¹⁶



Paul Ordin was responsible for coordinating the Lewis program, referred to as Project Bee, but Silverstein kept a very close eye on the activities. He not only hand-picked a crack research team from a variety of disciplines but stationed them in offices directly below his own in the Administration Building.¹¹⁷ For the first time since World War II Lewis's various research groups integrated their talents on a single project. For example, up until then, the pump researchers did not necessarily interact with the fuels people even though their fields were closely related.¹¹⁸ Nonetheless only a handful of the participants were aware of the entire scope of the clandestine program. To obscure the nature of the work, management assigned liquid hydrogen the code name "X-35" and later referred to it as "SF-1."¹¹⁹

The Bee team worked throughout 1956 to integrate the hydrogen system into the B-57B, test the engines in the lab's altitude facilities, and create special 500-gallon wingtip fuel tanks.¹²⁰ In 1956 a new chemical production plant located 45 miles to the east of the lab began providing Lewis with all of its liquid hydrogen.¹²¹ The lab built a new structure, appropriately named the Bee Building, near the hangar to test pumping and storage systems on a mock-up B-57B wing. Engineers later expanded upon several of the Bee Building rigs when designing the Rocket Systems Area.¹²²

The B-57B test flights commenced in December 1956. The bomber took off using jet fuel, then switched to liquid hydrogen over Lake Erie. Once the hydrogen supply was depleted, the pilot switched back to jet fuel for the return to the hangar.¹²³ During the initial flights, the aircraft did not attain the desired cruising speeds so the pilots did not make the switch to hydrogen. The first successful flight took place on 13 February 1957. The aircraft operated on liquid hydrogen for 20 minutes at an altitude of 49,000 feet. The feat was repeated several times in the coming months.¹²⁴ The Lewis demonstrations were the world's only liquid-hydrogen-fueled aircraft flights for decades.



Image 27: Martin B-57B Canberra used for Project Bee. The aircraft was powered by two Wright J65 engines—the one on the right was modified to operate on either jet fuel or liquid hydrogen. Lewis installed the two wingtip tanks. The one on the right stored the hydrogen and the one on the left contained the helium used to pressurize the flow system (GRC-2016-C-07419).



Meanwhile, work was progressing on the larger hydrogen aircraft effort: Project Suntan. Pratt & Whitney, which was designing the new hydrogen engines, was acquainted with Lewis's basic hydrogen work and a unique hydrogen turboprop concept by Johns Hopkins University's innovator Randy Rae. Pratt & Whitney first modified their successful J57 turbojet to operate on liquid hydrogen. They tested the customized engine throughout 1956 and felt confident that standard jet engines could run on liquid hydrogen.

The Pratt & Whitney researchers concluded, however, that the best performance would come from an engine designed specifically to run on hydrogen. They began planning a new liquid-hydrogen engine, referred to as the 304.¹²⁵ The turbopump was the critical component of the 304. Its unique turboexpander cycle diverted a small quantity of gaseous hydrogen back into the system in order to operate the turbine, which powered the pump.¹²⁶

Project Suntan began fading in mid-1957 as concerns arose about the required hydrogen infrastructure, the aircraft's capabilities, and the program's political ramifications. The U.S. Air Force officially canceled the program in 1959.¹²⁷

Nonetheless, Projects Suntan and Bee were a critical bridge to the development of flight-ready liquid-hydrogen engines. The operation of hydrogen in existing jet engines at Lewis and Pratt & Whitney demonstrated that full-scale propulsion systems were possible. In addition, the military funded three new large-scale liquefaction plants and new tanker trucks to produce and transport liquid hydrogen for the programs.¹²⁸ Perhaps most importantly, Pratt & Whitney quickly began applying the technology and equipment developed for the 304 engine to a new liquid-hydrogen/liquid-oxygen rocket engine.¹²⁹

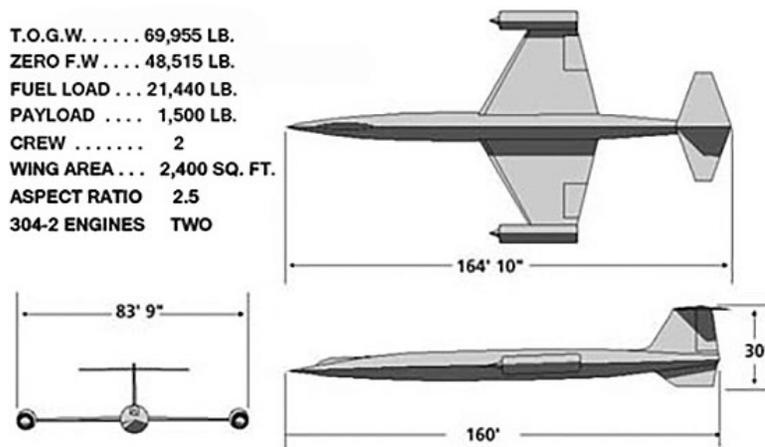


Image 28: Specifications for the CL-400 Project Suntan aircraft. The engines were located on the wings to compensate for the large hydrogen fuel tanks in the fuselage (NASA SP-4404, Fig. 34).



In the mid-1950s liquid hydrogen finally broke into the national consciousness. The hydrogen bomb effort increased hydrogen technology and infrastructure, the urgent need for advanced spy plane capabilities led to the military's renewed interest in hydrogen, and the new nuclear rocket program relied on hydrogen as its working fluid. Concurrently Lewis was making advances in the use of fluorine as an oxidizer, regenerative cooling, and basic nuclear fundamentals. Although not the first to test liquid-hydrogen engines, Lewis was able to expand on those initial experiments and transition liquid hydrogen from its theoretical promise to an actual flight-tested fuel. Lewis work with liquid hydrogen would dramatically affect the space program and set the stage for the activities at Plum Brook in the 1960s.

References

63. Abe Silverstein Memorandum, “Reorganization of Research Divisions,” 21 December 1949, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
64. “Fuels Research Program at the Lewis Laboratory of the NACA,” 28 December 1949, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
65. Walter Olson, editor, *Current Trends in Research and Development for Aircraft Powerplants* (Cleveland, OH: Lewis Flight Propulsion Laboratory, 4 September 1958).
66. John Sloop, “High-Energy Rocket Propellant Research at the NACA/NASA Lewis Research Center, 1945–60,” Seventh International History of Astronautics Symposium Proceedings, 8 October 1973, NASA Glenn History Collection, Sloop Collection, Cleveland, OH.
67. “Laboratory Holds Engine Meeting,” *Wing Tips* (14 January 1950).
68. Sloop, “High-Energy Rocket Propellant Research.”
69. R. M. Hazen to the NACA, “Proposed Subcommittee on Rocket Engines,” 19 October 1950, NASA Glenn History Collection, NACA Collection, Cleveland, OH.
70. Abe Silverstein interview, Cleveland, OH, by John Sloop, 29 May 1974, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
71. Sloop, “High-Energy Rocket Propellant Research.”
72. Roger Bilstein, *Stages to Saturn: A Technological History of the Apollo/Saturn Launch Vehicles* (Washington, DC: NASA SP-4206, 1996), <http://ntrs.nasa.gov>
73. M. E. DeWeese, M. A. Luebs, and H. L. McCullough, editors, “Significant Papers From the First 50 Years of the Boulder Labs” (Boulder, CO: National Institute of Standards and Technology, 2004).
74. John Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959* (Washington, DC: NASA SP-4404, 1977), <http://ntrs.nasa.gov>
75. Constance McLaughlin Green and Milton Lomask, *Vanguard: A History* (Washington, DC: NASA SP-4202, 1970), <http://ntrs.nasa.gov>
76. John Sloop, “Problems Faced by Early Space Transportation Planners,” Fifteenth Space Congress, 26–28 April 1978, NASA Glenn History Collection, Sloop Collection, Cleveland, OH.
77. NACA Executive Committee, Meeting Minutes, 14 July 1952, NASA Glenn History Collection, NACA Collection, Cleveland, OH.
78. “Report of Committee on Powerplants for Aircraft,” January–June 1952, NASA Glenn History Collection, NACA Collection, Cleveland, OH.
79. Homer Newell, *Beyond the Atmosphere: Early Years of Space Science* (Washington, DC: NASA SP-4211, 1980), <http://ntrs.nasa.gov>
80. M. B Ames to Langley, “Research on Space Flight and Associated Problems,” 10 July 1952, NASA Glenn History Collection, Sloop Collection, Cleveland, OH.
81. B. E. Gammon, Memorandum for the Record, “Resolution Passed at the June 26–27 Meeting of the Special Subcommittee on Rocket Engines,” 30 June 1952, NASA Glenn History Collection, NACA Collection, Cleveland, OH.
82. Virginia Dawson, *Ideas Into Hardware: A History of the Rocket Engine Test Facility at the NASA Glenn Research Center* (Washington, DC: NASA, 2004).
83. Abe Silverstein Memorandum, “Personnel Appointments in Fuels and Combustion Research Division,” 12 December 1952, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
84. Lewis Strauss to Jerome Hunsaker, 27 October 1954, NASA Glenn History Office, Nuclear Propulsion Collection, Cleveland, OH.
85. Nuclear Development Corporation of America, “Site Survey for NACA Research Reactor,” 13 September 1955, NASA Glenn History Office, Plum Brook Ordnance Works Collection, Cleveland, OH.
86. Roelif Loveland, “Plum Brook Ordnance Works is Now Silent and Desolate,” *Cleveland Plain Dealer* (13 March 1946).
87. David Vormelker, “Plum Brook Being Polished to Join Mothball Reserve,” *Cleveland Plain Dealer* (11 June 1949).

88. Anonymous to John Weeks, "Plum Brook Historical Items," 10 March 1965, NASA Glenn History Office, Plum Brook Ordnance Works Collection, Cleveland, OH.
89. Mark Bowles, *Science in Flux: NASA's Nuclear Program at Plum Brook Station 1955–2005* (Washington, DC: NASA SP–2006–4317, 2006), <http://ntrs.nasa.gov>
90. Robert Bussard, "Nuclear Rocketry—The First Bright Hopes," *Astronautics* (December 1962).
91. "Developments in Nuclear Power Set for Erie-Co," *Sandusky Register* (26 September 1956).
92. Eugene Emme, *Aeronautics and Astronautics: An American Chronology of Science and Technology in the Exploration of Space, 1915–1960* (Washington, DC: NASA, 1961), pp. 77–88, <http://ntrs.nasa.gov>
93. William Corliss and Francis Schwenk, *Nuclear Propulsion for Space* (Oak Ridge, TN: Atomic Energy Commission, 1971).
94. James Dewar, "Project Rover: A Study of the Nuclear Rocket Development Program, 1953–1963" (Doctoral thesis, Kansas State University, 1974).
95. Stanley Gunn and Ernest Robinson, "Application of Proven Rover/NERVA Nuclear Thermal Rocket Technology for Near-Future Manned Planetary Missions," *Aerospace America*, http://www.aerospaceamerica.org/Documents/Augustine%20Commission%20Reports/Rover_NERVA.pdf (accessed 17 May 2016).
96. Roderick W. Spence, "Nuclear Rockets," *International Science and Technology* (July 1965).
97. W. H. Easelman, "The NERVA Nuclear Rocket Reactor Program," *Westinghouse ENGINEER* 24, no. 3 (May 1965).
98. Dewar, "Project Rover," doctoral thesis.
99. Asif Siddiqi, *Challenge to Apollo: The Soviet Union and the Space Race, 1945–74* (Washington, DC: NASA/SP—2000-4408, 2000), <http://ntrs.nasa.gov>
100. Melvin Hartmann, Donald Connolley, Sidney Huntley, et al. *Propellant Flow System Components* (Washington, DC: NASA X66–51408, 1966), <http://ntrs.nasa.gov>
101. Corliss, *Nuclear Propulsion for Space*.
102. Silverstein interview by John Sloop.
103. John Sloop, "NACA High Energy Rocket Propellant Research in the Fifties" 28 October 1971, NASA Glenn History Collection, Dawson Collection, Cleveland, OH.
104. Virginia Dawson, *Engines and Innovation: Lewis Laboratory and American Propulsion Technology* (Washington, DC: NASA SP–4306, 1991), <http://ntrs.nasa.gov>
105. Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959*.
106. V. F. Hlavin, E. R. Jonash, and A. L. Smith, *Low Pressure Performance of a Cylindrical Combustor With Gaseous Hydrogen* (Washington, DC: NACA RM–E54L30A, 1955), <http://ntrs.nasa.gov>
107. Abe Silverstein and Eldon Hall, *Liquid Hydrogen as a Jet Fuel for High-Altitude Aircraft* (Washington, DC: NACA RM–E55C28a, 1955), <http://ntrs.nasa.gov>
108. Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959*.
109. William Tomazic, Harold Schmidt, and Adelbert Tischler, *Analysis of Fluorine Addition to the Vanguard First Stage* (Washington, DC: NACA RM E56K28, 1957), <http://ntrs.nasa.gov>
110. Walter T. Olson, "Problems of High Energy Propellants for Rockets," 7 December 1959, NASA Glenn History Collection, Cleveland, OH.
111. Howard Douglass interview, Cleveland, OH, by John Sloop, 28 May 1975, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
112. Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959*.
113. Walter T. Olson, "A Suggested Policy and Course of Action for NACA With Regard to Rocket Engine Propulsion," 6 May 1955, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
114. Robert Miedel, "Statements by Mr. Robert Miedel of Directorate of Procurement GQ ARDC, and Mr. William Miller and Lt. Richard Doll of the Sun Tan Procurement Office," December 1958, NASA Glenn History Collection, John Sloop Collection, Cleveland, OH.
115. Norman Appold, "A Statement by Colonel Norman C. Appold of the Sun Tan Project Office," December 1958, NASA Glenn History Collection, Sloop Collection, Cleveland, OH.
116. Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959*.

117. Paul Ordin interview, Cleveland, OH, by John Sloop, 30 May 1974, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
118. Walter T. Olson interview, Cleveland, OH, by John Sloop, 11 July 1974, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
119. Paul Ordin to Howard Childs, Minutes of Meeting December 22, 1955, 22 December 1955, NASA Glenn History Collection, Project Bee Collection, Cleveland, OH.
120. Abe Silverstein to NACA Headquarters, “Progress Report No. 1 on Applied X-35 Project,” 14 March 1956, NASA Glenn History Collection, Cleveland, OH.
121. Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959*.
122. Abe Silverstein to NACA Headquarters, “Progress Report No. 3 on Air Force Project No. 3099,” 28 June 1956, NASA Glenn History Collection, Cleveland, OH.
123. R. Mulholland, Joe Algranti, and Ed Gough, Jr., *Hydrogen for Turbojet and Ramjet Powered Flight* (Washington, DC: NACA RM–E57D23, 1957), <http://ntrs.nasa.gov>
124. Paul Ordin, “Progress Report on Project Bee” 1957, NASA Glenn History Collection, Cleveland, OH.
125. Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959*.
126. Virginia P. Dawson and Mark D. Bowles, *Taming Liquid Hydrogen: The Centaur Upper Stage Rocket* (Washington, DC: NASA/SP—2004-4230, 2004), <http://ntrs.nasa.gov>
127. Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959*.
128. John Sloop, Air Force Special Chronology, 1974, NASA Glenn History Collection, Sloop Collection, Cleveland, OH.
129. Sloop, “High-Energy Rocket Propellant Research.”

LEWIS RESEARCH CENTER
FISCAL YEAR 1964 ESTIMATES

NASA PLUM BROOK STATION

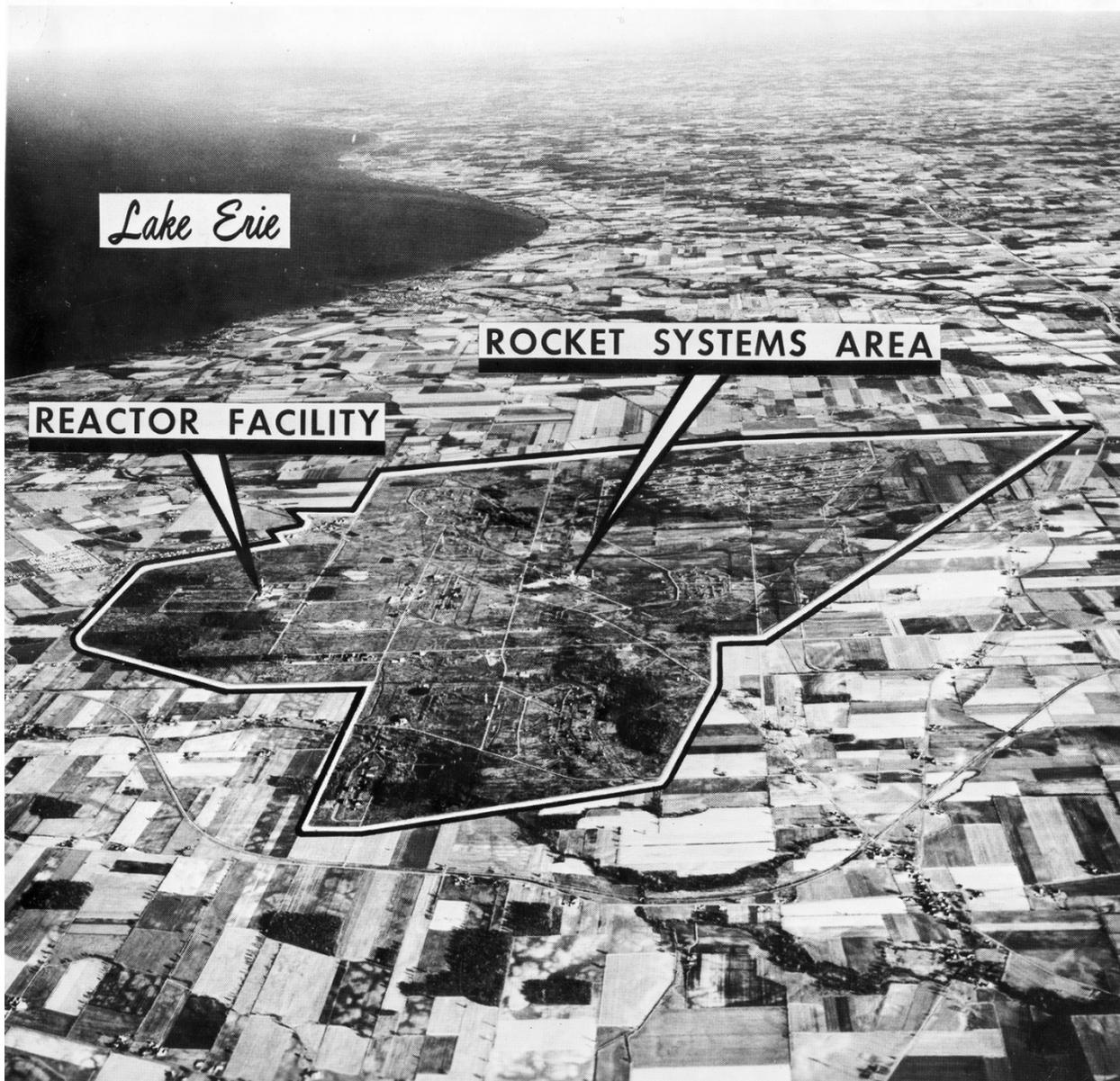


Image 29: View eastward of Plum Brook and the Sandusky area in 1964. In 1958 NASA was leasing all of the property except the 2,800 acres in the upper right corner (GRC-1964-P-65682).

◆ Chapter 3 ◆

Big Boost for Rockets

Despite the hydrogen and fluorine successes, the Lewis rocket propulsion research did not increase as rapidly in the mid-1950s as its staff intended. Associate Director Abe Silverstein took steps to rectify the situation in 1957 by diminishing the lab's traditional air-breathing engine work and adding new test facilities. By the end of the year, Congress approved funding for the Rocket Systems Area at Plum Brook Station. In addition, Lewis continued with the Project Bee aircraft flights, proposed a hydrogen-fluorine demonstration missile, and fired the lab's first regeneratively cooled hydrogen-fluorine rocket engine. The laboratory planned two conferences for the fall to share these accomplishments with the aerospace community.

Interest in rocket propulsion was on the rise elsewhere, as well. General Dynamics conducted initial flight tests of the Atlas missile, Pratt & Whitney began designing a liquid-hydrogen/liquid-oxygen rocket engine, and the military prepared to send a small experimental satellite into space. These activities, however, were quickly overshadowed by the Soviet Union's launch of *Sputnik* in October. *Sputnik* led directly to the creation of NASA in 1958 and a unified U.S. space program. Silverstein played a critical role in defining NASA's new space activities and the Agency's decision to use liquid hydrogen to fuel its upper-stage space vehicles.

Inception

Between 1946 and 1958 Lewis concentrated 60 percent of its research on turbojet and ramjet technology and only 20 percent on all other forms of propulsion, including rocket engines.¹³⁰ By the 1950s, however, the military was increasingly emphasizing the use of rockets to propel missiles. In 1949 the government moved Wernher von Braun and his Peenemunde colleagues from White Sands, New Mexico, to Huntsville, Alabama where they created the V-2-inspired Redstone and Jupiter missiles. The military also accelerated General Dynamics's work on the Atlas and hired Glenn Martin Company to develop the Titan two-stage missile. The military canceled its most significant air-breathing missile project, the Navaho, in 1957 after several years of poor performance from its ramjet engines.¹³¹

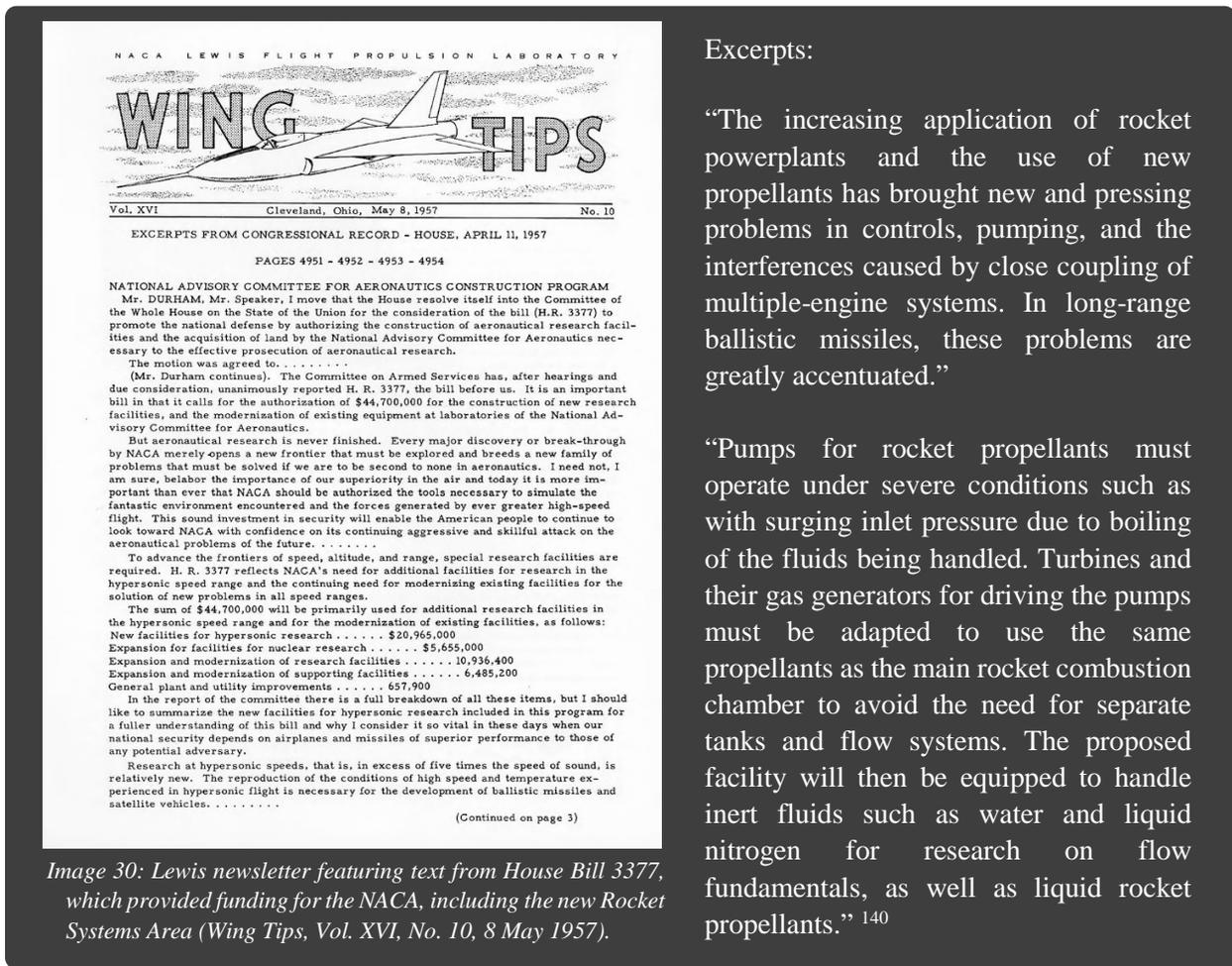
In March 1957 Silverstein established a Research Planning Council to outline the lab's future research goals and determine the resources and facilities required to carry them out. The group, composed of six senior managers, decided to scale back the lab's turbojet research and significantly increase the rocket work.¹³² As a result, Silverstein disbanded the seminal Compressor and Turbine Division and reassigned the staff to the new Nuclear Reactor and the Fluid Systems Components divisions.¹³³ The former managed the activities at the Plum Brook Reactor Facility, and the latter focused on issues regarding the pumping of fluids, particularly cryogenic liquids. The new council and divisions would play significant roles in guiding the research conducted at the Rocket Systems Area in the 1960s.

In mid-April Lewis management began preparing to host an NACA Inspection event in October.¹³⁴ Each year the NACA invited representatives from the military, aeronautical industry, universities, and the press to one of its three research laboratories for well-rehearsed briefings on the NACA's latest research and a tour of the test facilities. Silverstein also announced that Lewis would be holding a conference in November focusing specifically on propulsion. For the next six months there was a surge in rocket-related activity at Lewis and a push to complete the new Rocket Engine Test Facility (RETF) facility in time for the twin events.¹³⁵



As the RETF neared operational status in 1957, Lewis engineers began taking steps to expand upon or possibly replace Cell 22 at the Rocket Lab. The new facility, soon to be referred to as the Rocket Systems Area, was actually a cluster of small sites that would not only test midsized rocket engines but study turbopumps, propellant tanks, seals, and the structural dynamics of missiles. Researchers would be able to analyze similarly sized engine components individually and then assemble them to test the entire systems.¹³⁶

On 11 April 1957 the House of Representatives approved a \$17.5 million expenditure for the Lewis laboratory that included \$5.48 million to construct the Rocket Systems Area.¹³⁷ President Dwight Eisenhower signed the bill on 3 September 1957.¹³⁸ The bill’s language made it clear that the funding was intended to improve missile performance. It stated, “The rate at which NACA is able to attack and solve fundamental scientific problems limits the rate of progress in the development of aircraft and missiles in the United States. A strong NACA is essential to our national security.” There was no mention of spaceflight.¹³⁹ Spaceflight, however, would become a priority just 31 days after the President’s concurrence.



Excerpts:

“The increasing application of rocket powerplants and the use of new propellants has brought new and pressing problems in controls, pumping, and the interferences caused by close coupling of multiple-engine systems. In long-range ballistic missiles, these problems are greatly accentuated.”

“Pumps for rocket propellants must operate under severe conditions such as with surging inlet pressure due to boiling of the fluids being handled. Turbines and their gas generators for driving the pumps must be adapted to use the same propellants as the main rocket combustion chamber to avoid the need for separate tanks and flow systems. The proposed facility will then be equipped to handle inert fluids such as water and liquid nitrogen for research on flow fundamentals, as well as liquid rocket propellants.”¹⁴⁰

Image 30: Lewis newsletter featuring text from House Bill 3377, which provided funding for the NACA, including the new Rocket Systems Area (Wing Tips, Vol. XVI, No. 10, 8 May 1957).

Invitation

Although there was no mention of space in the new funding bill, emerging missile systems were capable of reaching space. In Huntsville, Wernher von Braun was covertly considering launching satellites with the Redstone and Jupiter while the navy struggled to get its Vanguard rocket off the pad to orbit a satellite for the International Geophysical Year effort. Just days after the President signed the NACA appropriations bill, the Lewis's Research Planning Council recommended that the organization build an entire new laboratory dedicated specifically to spaceflight.¹⁴¹

Several key figures at NACA Headquarters remained dismissive, however, and often derided those who saw missiles as a means to access space. The NACA, which was still smarting from the rigorous Congressional audits of the early 1950s, did not want to appear to be performing duplicative or nonmandated work—especially during the high-profile 7 to 10 October Inspection. The week before the event, NACA Executive Secretary John Victory traveled to Cleveland to witness the final dress rehearsal. The agenda included talks on hypersonic flight, nuclear propulsion, ion engines, and high-energy fuels. Upset at what he heard, Victory ordered the speakers to remove of any mention of space from their presentations.¹⁴²

On Friday night, 4 October 1957, the Soviet Union launched *Sputnik*, the first artificial satellite. The satellite, which passed over North America every 95 minutes, instilled the perception that the Soviets, which had acquired the hydrogen bomb in 1953, had not only caught up but had surpassed the United States technologically.¹⁴³ Victory quickly instructed the Lewis researchers to reinstall sections referring to space applications into their talks before the event opened on Monday.¹⁴⁴

A speaker at the RETF explained that the current solid rockets and kerosene-fueled missiles did not produce sufficient power to conduct complex space missions. “There are other higher energy propellant combinations that we can consider for future rocket vehicles beyond Vanguard, but considerable research is needed to put them into practical use,” he explained. “We are interested in these propellants because they can put higher speeds into a payload, thus giving longer range, or can give the same range with less propellant.”¹⁴⁵



Image 31: Display at the RETF stop during the NACA's 1957 Inspection. The panel compares the performance of several rocket propellants, including hydrogen-oxygen, hydrogen-fluorine, kerosene, hydrazine, and solid fuels (GRC-1957-C-46150).



Image 32: A Lewis-designed hydrogen-oxygen demonstration missile (GRC-1959-C-51418).

In 1957 Lewis rocket researchers considered building a simple, low-cost liquid-hydrogen/liquid-fluorine rocket, nicknamed “Rainmaker,” to be launched on a Thor booster from Wallops Island.¹⁴⁶ Silverstein approved the project, but assigned it to a new diverse special projects team similar to that created for Project Bee.

Silverstein also insisted on the substitution of liquid oxygen for liquid fluorine.¹⁴⁷ The design group built experimental propellant tanks and the gas generators for the turbopumps, but soon encountered difficulties designing the hydrogen system for the small-sized rocket.¹⁴⁸ Bruce Lundin referred to the issues as, “a wilderness of technical difficulties.”¹⁴⁹ The project that was intended to showcase Lewis’s hydrogen work faded away over the next couple years. By the time work on Rainmaker ceased, General Dynamics was designing a new full-scale space vehicle that would truly demonstrate Lewis’s liquid-hydrogen development work.

Substantiation

Sputnik was still in orbit when Abe Silverstein proposed adding a new 1-million-pound-thrust test stand to the recently approved Rocket Systems Area. The NACA, whose operating budget could not support the expense, shelved the proposal.¹⁵⁰ Meanwhile, members of the Rocket Research Branch began formulating a more modest test facility. At the time, the NACA only had rights to use 500 acres at Plum Brook for its test reactor. The Lewis engineers conceived a portable rocket stand that could be built on a flatbed trailer and placed near the reactor area. Since this would not constitute new construction, Congressional approval was not required. Former researcher Howard Douglass later explained, “We’d go out there and build our equipment into the trailers and put them within earthen mounds and so forth; and it was not to be a permanent facility. No brick and mortar, just put together what you can.” He also admitted, “[It] was not portable. It was temporary.”¹⁵¹ This would eventually become the J-2 test stand.

On 3 November 1957 the Soviet Union further demonstrated its technological prowess by orbiting the 1120-pound *Sputnik II*. The next day, Lewis’s Research Planning Council suggested that the NACA request

a \$6 to 7 million appropriation the following year—to be followed by subsequent requests in ensuing years—for new and more complex test facilities and related infrastructure.¹⁵² Congress would continue to approve the funding requests as the space race accelerated over the coming years. Larry Ross, a former center director explained, “The things that were going on were more in line with the broad vision of a very ambitious space program, including nuclear propulsion. [Silverstein’s] vision, and his commitment to that broader ambitious program he saw the nation undertaking, led to the development of the facilities.”¹⁵³

The form of that national space program was not yet to be determined. President Dwight Eisenhower was slow to react to the public’s anxiety, but by mid-November 1957, he appointed a new science advisor and broached the possibility of a new space agency.¹⁵⁴

Up Against the Wall

Meanwhile Lewis was preparing to host the Flight Propulsion Conference on 21–22 November 1957 to discuss a variety of propulsion options for different military weapons systems. The classified conference featured talks on both air-breathing and rocket engine options for aircraft and missiles, and on different propellants, fluid pumping, and missions for rocket engines. One of the more dramatic moments came Friday morning when Douglass presented the results of a regeneratively cooled liquid-hydrogen/liquid-fluorine rocket engine test conducted just hours before.¹⁵⁵

Douglass and colleagues Glen Hennings, Edward Baehr, and Harold Price sought to replicate a hydrogen-fluorine engine firing that had occurred in March 1955, but with the addition of a regenerative cooling system. The team spent months in Cell 22 preparing for the test.¹⁵⁶ As they initiated a run on the evening of 5 November 1957, a lookout across the street frantically indicated that the roof was on fire. There were some tense moments inside the control room as the Lewis fire department arrived on the scene. Hosing down of the fluorine tank would cause the vacuum jacket to malfunction and allow the cryogenic fluorine to evaporate rapidly. Douglass later explained, “[The firemen] came in and squirted water all over every place, but by that time, although we didn’t know it, the fluorine had already all been discharged, and that’s what had fired the roof up.”¹⁵⁷ Hennings recalled, “I was reaching for the toggle switch to fire the engine when it blew.”¹⁵⁸

Silverstein demanded that the test be run before the conference since the researchers had yet to conduct a practical test of hydrogen’s cooling capability. The staff hurriedly repaired the test cell and resumed preparations just days before the event.¹⁵⁹ The men worked determinedly around the clock to resolve a series of continuing technical issues. At 6 a.m. on Friday the 5,000-pound-thrust hydrogen-fluorine rocket came to life and performed at 96 percent of the propellant’s theoretical efficiency. Price crunched the data throughout the morning while Douglass went home to change clothes before his presentation.¹⁶⁰

Robert “Bucky” Walter was instructed to remove the engine from Cell 22 and bring it into the conference. The security guards, however, prevented Walter, who was fresh out of university, from entering the classified event.

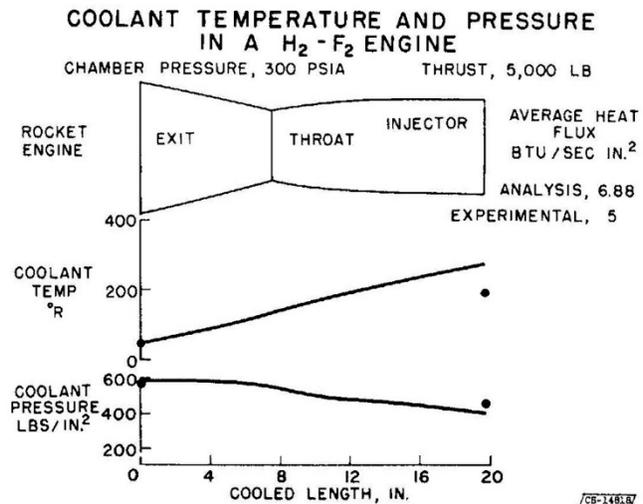


Image 33: Chart from Propulsion Conference showing the cooling characteristics of a regeneratively cooled hydrogen-fluorine engine (NASA TM X-67368, Fig. 22).

Eventually Walter recognized one of those cleared for the meeting and had them take the fluorine engine inside.¹⁶¹ Meanwhile Douglass began his presentation on high-energy propellants. As he reached the section on the engine's cooling performance, Price rushed into the conference with the data from that morning's test.¹⁶² Douglass indicated that the Lewis test "gave high performance and ample cooling." He concluded, "A small engine has been regeneratively cooled successfully; bigger engines should prove easier."¹⁶³

Rockets in Motion

In February 1956 Henry Pfanner and Paul Mandrik designed and built a 2-foot-tall rocket for a junior class assignment at St. Mary's High School. Despite the faculty's displeasure with the potentially dangerous work, the students' "Rockets in Motion" project proved to be a success and made the local newspaper. Pfanner and Mandrik received "superior" merit ratings for the effort and participated at the National Science Teachers Association's 1957 convention in downtown Cleveland. NACA officials James Braig and Ed Kaltenstein heard about the project and invited the two students to tour the Rocket Lab at Lewis Field in Cleveland.¹⁶⁴

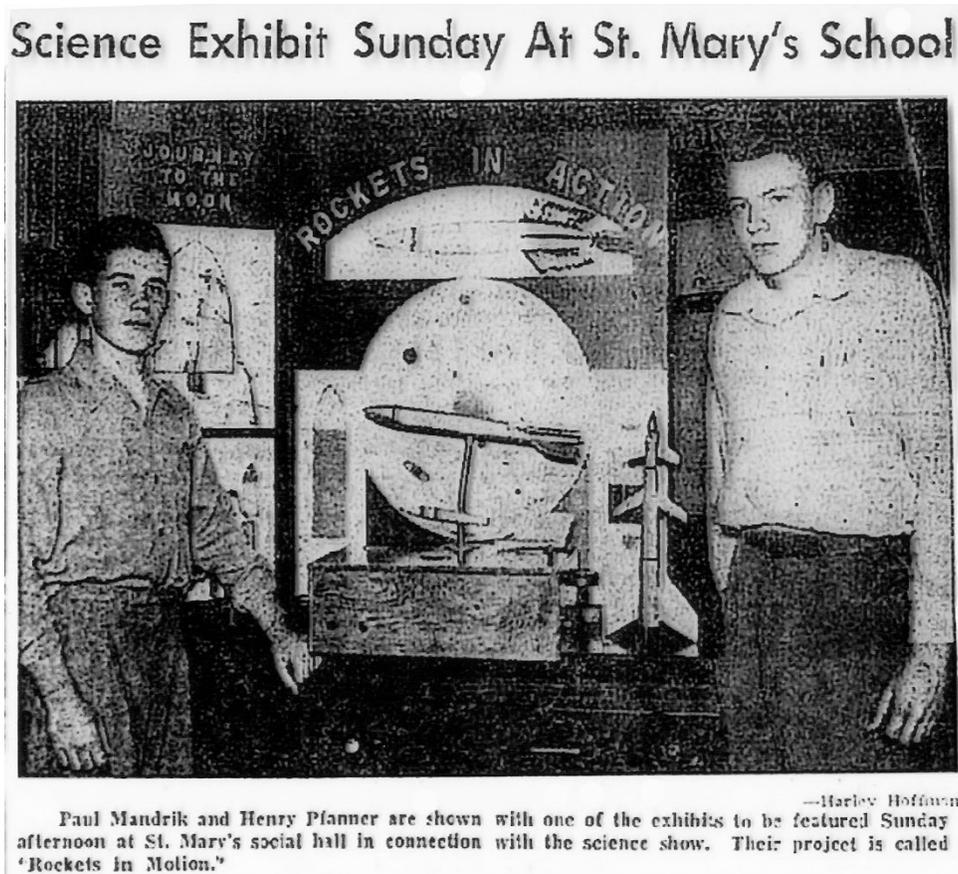


Image 34: Mandrik and Pfanner with their "Rockets in Action" exhibit (Courtesy of Henry Pfanner).

After graduation Pfanner and Mandrik entered the General Motors Institute in Flint, Michigan. The launch of *Sputnik* in the fall of 1957 piqued their colleague's interest in the pair's rocket experiment. They urged the two to construct another rocket with the assistance of the college's machine shop. On 3 February 1959 Pfanner and Mandrik demonstrated their alcohol-gaseous oxygen rocket for a local television station and participated in a panel discussion.¹⁶⁵ In the summer of 1963 Pfanner took a temporary position at Plum Brook while earning

his master's degree at night. This led to a long successful career with NASA. Pfanner later recalled, "I build a rocket in the basement, so what do I end up doing, testing rockets [at Plum Brook]."166

Birth of NASA

On 22 November the same day as Douglass's presentation, Senator Lyndon Johnson outlined the agenda for upcoming Senate hearings on the status of U.S. missile and space technology. After the ensuing six weeks of hearings, the subcommittee concluded that space missions were imperative to the nation's survival. Congress considered success in space not as a matter of national prestige, but one of controlling the world.¹⁶⁷ Despite President Eisenhower's reluctance, the Space Race was born.

The Lewis laboratory had been a vocal proponent of the NACA's involvement in space for several years. Lewis researchers at the recent propulsion conference analyzed propulsion options for a variety of space missions including satellites, interplanetary probes, and human spaceflight.¹⁶⁸ During Johnson's hearings, Bruce Lundin, Chief of the Propulsion Systems Division, updated Walter Olson's 1955 document that advocated for a strong NACA effort in space. Lundin stated that the NACA should not just support, but lead the new space agency.¹⁶⁹ Abe Silverstein refined Lundin's proposal and presented it to NACA Director Hugh Dryden on 18 December 1957. In February 1958 the NACA passed a resolution, based on Lundin's ideas, to expand its space-related research and facilities.¹⁷⁰ The document outlined the future space program, including the use of high-energy chemical and nuclear rockets.¹⁷¹

After considering several options, Eisenhower decided to create a civilian space agency built around the existing NACA laboratories but also incorporating the Jet Propulsion Laboratory (JPL), the Army Ballistic Missile Agency (ABMA), and other existing groups. Congress approved the proposal in April 1958. NASA officially came in to being on 1 October 1958, and the NACA's Lewis Flight Propulsion Laboratory became the NASA Lewis Research Center. Lewis would expand dramatically in the coming years. One of the first steps was building the Rocket Systems Area.

Place Out There

Lewis intended to place the new Rocket Systems Area in a ravine at the far edge of its Lewis Field campus in Cleveland near the Rocket Lab and RETF. By the late 1950s Lewis's 400-acre plot, hemmed in by the Cleveland Municipal Airport on one side and a deep valley along the other, was densely populated. The laboratory's high-energy fuels testing was causing an increasing number of fires, explosions, and releases of toxic pollutants at the Rocket Lab. One incident in the summer of 1957 caused a Camp Fire Girls group to permanently abandon a large cabin that they had built years before in the adjacent park.¹⁷² The proposed Rocket Systems Area would be even larger and would be dealing with even larger quantities of propellant. Explosions were inevitable. Although engineers could mitigate dangers from flying objects at the Lewis site, it was impossible to prevent damage to the surrounding community from the resulting pressure waves.

The hazards also forced facility engineers and researchers to schedule test runs in the evenings or on weekends after most employees departed. In addition to preparing the facility and equipment on test days, the researchers had to get personal approval from Silverstein and Director Ray Sharp to go forward with the run and make arrangements for the guards to clear out any remaining personnel from the surrounding buildings in the early evening.¹⁷³ Cancellation of a run at the last minute required removal of the cryogenic propellants from the tanks and purging of the system. This was as difficult to perform as an actual run. "So we tried awfully hard to get our runs on a weekend," Glen Hennings recalled, "because when we were missing a day we were missing a week."¹⁷⁴



Image 35: Damage to the RETF in December 1958. The RETF's first six months of operation were so eventful that Silverstein terminated fluorine testing at the site (GRC-1958-C-49372).¹⁷⁵



Image 36: Aerial view of the Rocket Systems Area in 1960. This image shows the distance between facilities and remoteness from the community (GRC-1960-C-05419).

To reduce the hazards and alleviate the scheduling issues, Silverstein decided in January 1958 to build the Rocket Systems Area at Plum Brook. The NACA leased an additional 2,712 acres at Plum Brook for the new facilities. Hennings recalled, “Because of the hazards we started looking at the quantities of hydrogen and all that kind of thing. The reactor had already moved up [there] and had got the site. It was decided then that the right place to build this thing was here at Plum Brook.”¹⁷⁶

The traits that made Plum Brook appealing for the reactor also applied to the rocket sites. Plum Brook is 55 miles to the west of Lewis Field, accessible by several modes of transportation, had an existing infrastructure, and offered plenty of space. The military had built roadways, railroad spurs, security tools, and utilities systems in the 1940s. “The increasing application of rocket powerplants for missile and spaceflight, and the use of new propellants have brought new and pressing problems,” stated Sharp during this period. “Use of the new facilities at Plum Brook will hasten their solution.”¹⁷⁷

Plum Brook’s large unused tracts of land were perfect for the potentially dangerous propellants work. The vastness gave the civil engineers more flexibility in their designs and allowed future expansion. Researchers would not be limited in the size of their tests. The open spaces negated the need for the large exhaust scrubbers employed at the Rocket Lab and RETF. Any harmful contaminants would dissipate before contacting any people or structures. The acreage also provided ample room to protect the staff and safeguard the local community during the testing. Former Plum Brook manager Robert Kozar explained, “If it did blow up, the engineers were in the block house a half a mile away. No one was injured, nobody’s property was damaged, and we could go on and learn from that. With that kind of an attitude, that kind of an empowerment, we made tremendous strides in a very short period of time.”¹⁷⁸



For almost a year Rocket Lab veterans Paul Ordin, Bob Kohl, and George Kinney worked on the Rocket Systems Area designs.¹⁷⁹ Douglass and Hennings took the concepts and followed up with the civil engineers.¹⁸⁰ The original plans included a Liquid Hydrogen Pump Facility (A Site), the High Energy Rocket Engine Research Facility (B-1 Stand), the Turbopump Facility (C Site), the Controls and Turbine Test Facility (D Site), the Dynamics Stand (E Stand), the Fluorine Pump Facility (I Site), and the Rocket Systems Test Site (J Site). Most of these sites were tied to a remotely located Control and Data Building (H Control Building). In addition, Lewis engineers decided to use excess Plum Brook Ordnance Works (PBOW) equipment to quickly erect another rocket-related facility, referred to as the Pilot Plant (G Site). Larger, more sophisticated test facilities were later added.

The new Rocket Systems Area facilities, many of which were housed in prefabricated “Butler”^j buildings, were purposely designed to be disposable. Former facility engineer Dick Heath explained, “You know those sheet metal and riveted structures would take about half a PSI [air pressure], and it will blow all the rivets off and just fly around a bit, and they don’t hurt a soul. Whereas if you put a concrete wall up, you would have concrete to pick up half a mile away. It was actually a smart thing to do and a big savings in construction cost.”¹⁸¹ Construction began in mid-1958 and proceeded concurrently with the reactor facility.¹⁸²

Dealing with the Ruins

Lewis, which was now leasing nearly half of Plum Brook, had to deal with the PBOW’s residual equipment, structures, and contamination. Starr Truscott, of the Lewis property control group, was among those sent to inventory the equipment and buildings in early 1958. He later recalled, “We were all wandering around empty buildings, and it’s cold and very, very bitter at times. Looking, going through each and every

^jButler buildings are prefabricated ready-to-assemble structures originally manufactured by the Butler Manufacturing Company. “Butler building” has become a generic term for a variety of premade structures.

building to see what was there that could be of value to the NACA.... We didn't know what we were going to see, and we saw many, many interesting things and a great deal of ruins."¹⁸³ The PBOW property was so expansive that the men lost their way back to the entrance at one point. Engineers took advantage of former PBOW equipment when designing several of the Rocket Systems Area sites, most notably the Pilot Plant, J Site, and the Cryogenic Propellant Tank Facility (K Site).



Image 37: James "Ross" Braig (left) and Truscott in the Administration Building in June 1960 (GRC-1960-C-53827).

Braig transferred to Lewis from the NACA Langley Memorial Aeronautical Laboratory in 1941, making him one of the lab's first employees. In February 1956 the lab assigned him to Plum Brook to supervise the disposition of the PBOW materials and oversee the construction contracts for the reactor and, later, the Rocket Systems Area. The cigar-smoking Braig was a skilled negotiator with local contractors and unions. He became Plum Brook's Deputy Manager in 1962.¹⁸⁴

In August 1958, after the PBOW inventory was complete, Braig requested that Truscott return to Plum Brook permanently to serve as Administrative Officer. Truscott supervised the guards and maintenance staff and served as the initial Plum Brook photographer. He went on to head Plum Brook's personnel office (GRC-1960-C-53827).

The manufacturing of munitions during World War II required a number of hazardous materials and chemicals. Although the military performed some cleanup after the war, many buildings, underground lines, and ponds were still contaminated in the mid-1950s. The NACA and the Ordnance Ammunition Command, which held the title to the property at the time, hired personnel from the nearby Ravenna Arsenal to burn the buildings and remove debris from the reactor site during the summer of 1956.¹⁸⁵ The NACA obtained cost estimates for decontamination of nearby areas for possible future use, but decided to forgo the work at the time.¹⁸⁶ Lewis negotiated for nearly five years before finally authorizing the work. In the meantime the staff erected fences to prevent access to the main PBOW structures.



Image 38: NACA officials examine equipment and supplies at the PBO in the spring of 1958 (GRC-1958-C-47284).

Centaur and Saturn

In the spring of 1958 Abe Silverstein transferred to NACA Headquarters in Washington, DC, to assist Hugh Dryden with the transformation of the NACA into NASA. As Director of Space Flight Systems, Silverstein was extremely influential in the planning of the early satellites and space probe, as well as the Mercury and Apollo missions.¹⁸⁷ His most important contribution to the nation's space program, however, may have been his dogged drive to use liquid hydrogen to fuel upper-stage rockets. Silverstein was unique in that he was both well-versed on liquid-hydrogen technology and in a position to guide NASA's work. There were two programs in the works that would be impacted by liquid hydrogen—Saturn and Centaur.

Wernher von Braun and his colleagues had been working on kerosene and oxygen-fueled Redstone and Jupiter missiles in Huntsville since 1949. In 1955, the army created the ABMA at the site to expand the effort. Von Braun first proposed the concept of clustering rocket engines to increase thrust in December 1957, but the military did not approve the effort for another eight months. In October 1958 the military asked von Braun to expand his design and incorporate upper stages. Concurrently the military contracted with Rocketdyne to upgrade the kerosene engines used to power the Jupiter, resulting in what would become the F-1. In February 1959 the new ABMA rocket project became officially known as Saturn.¹⁸⁸

The military also rejected a General Dynamics December 1957 proposal to create a new high-energy upper stage to launch satellites from its new Atlas missile. The Atlas incorporated unique design characteristics such as the balloonlike propellant tanks and rotating engines. Engineer Krafft Ehrlicke proposed adding an upper stage that employed many of these same design elements. The proposed stage would be the first to use a liquid-hydrogen and liquid-oxygen propellant.¹⁸⁹

Meanwhile, Pratt & Whitney was putting their hydrogen-fueled 304 aircraft engines through their initial runs in late 1957 despite the disintegration of Project Suntan. Their engineers, who began visiting the Lewis Rocket Lab regularly in 1957, decided to use the 304 experience to develop a liquid-hydrogen rocket engine. Neither General Dynamic nor Pratt & Whitney were aware of one another's interest in liquid hydrogen.¹⁹⁰

In 1958 Silverstein led a committee that analyzed the requirements for NASA's proposed upper-stage vehicles. Over a series of meetings in August 1958 the committee concluded that high-energy propellants, namely liquid hydrogen with either fluorine or oxygen, were required if NASA was to achieve its desired missions. On 29 August 1958, the day after a significant committee meeting, the military approved a plan that would merge the Pratt & Whitney hydrogen engine work with the hydrogen-oxygen stage proposed by General Dynamics. This was the official genesis of the Centaur rocket.¹⁹¹

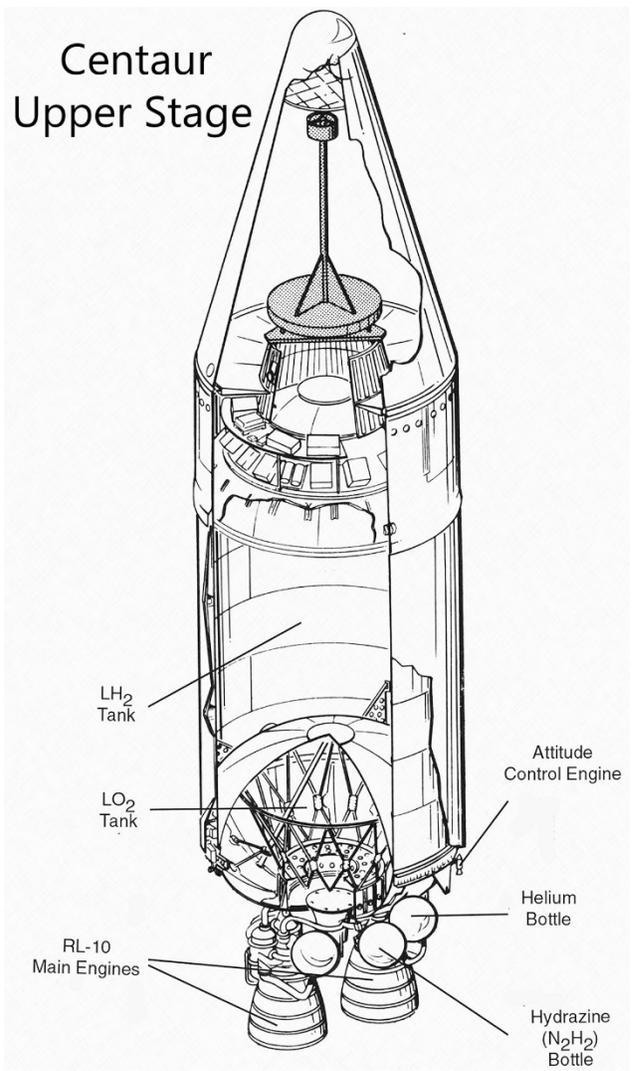


Image 39: Diagram of the Centaur stage (GRC-1998-C-02814).

Nuclear Pumping Systems

Nuclear rocket engines not only require a compact, structurally sound, and powerful reactor but also a liquid-hydrogen system that quickly supplies large quantities of fuel, cools the nozzle, and provides reliable startup capability. During Project Rover's first three years, Atomic Energy Commission (AEC) researchers studied a variety of basic reactor designs while the U.S. Air Force sought to resolve the hydrogen pumping and storage issues. At the time, liquid hydrogen had yet to be utilized in such a demanding environment.¹⁹²

Turbopumps were a major concern. There were no high-capacity hydrogen pumps available at the time. The pump would not only have to send nearly 3 tons of high-pressure liquid hydrogen to the reactor each minute, but it would have to do it with hydrogen heated to a near-boiling state by the reactor.¹⁹³ Designers would also have to minimize the pump's weight and the amount of propellant required to drive the turbine.¹⁹⁴

Rocketdyne and Aerojet were contracted to explore turbopump designs specifically for nuclear rocket engines.¹⁹⁵ Rocketdyne proposed an axial-flow pump, whereas Aerojet recommended a centrifugal design. The former increased the flow pressure gradually, whereas the latter powerfully pushed the fluid through, increasing the amount of gas in the fluid. In June 1958 the air force accepted the Rocketdyne proposal. The six-stage Mark IX was the first axial-flow pump to be developed for a U.S. rocket engine.¹⁹⁶

In 1958 the air force transferred its Project Rover responsibilities to NASA. NASA management was not confident that Rocketdyne could create a pump that would meet the nuclear rocket's challenging requirements and maintain the program's schedule. They instead recommended the use of a pressure-fed flow system that omitted the pump altogether until Lewis researchers could design a new pumping system. The pressure method used a stable high-pressure gas to push the fluid out of the tank. In the end, Rocketdyne was allowed to continue their turbopump development, but only as a backup to the pressurized system.¹⁹⁷

When Lewis announced its plans for the Rocket Systems Area in May 1958, they included the B-1 Stand, a tall test stand designed to study the hydrogen propellant feed system for the nuclear rocket in simulated altitude conditions.¹⁹⁸ The Rover Program, however, would change significantly before the B-1 Stand became operational in 1964.

The AEC unveiled a prototype of the first Rover reactor, Kiwi-A, in early October 1958 to study instrumentation, control, fuel element design, and structural design.¹⁹⁹ The researchers first tested the Kiwi-A 300-megawatt, gaseous-hydrogen-fueled reactor at the AEC's Nevada Test Site in July 1959 and operated it twice more the following year. The tests were useful to the engineers but revealed severe structural problems within the graphite reactor core and with the hydrogen flow.²⁰⁰ During this period, the AEC was also developing the 1,000-megawatt Kiwi-B reactor. The high-power Kiwi-B introduced a host of severe technological issues to be resolved.²⁰¹

In August 1960 NASA and the AEC jointly created the Space Nuclear Propulsion Office (SNPO), managed by former Lewis compressor researcher, Harold Finger, to coordinate the nuclear rocket efforts. The SNPO was responsible for the technical and administrative direction of Rover, management of industry activities, and design of propulsion facilities for the Nevada site.²⁰²

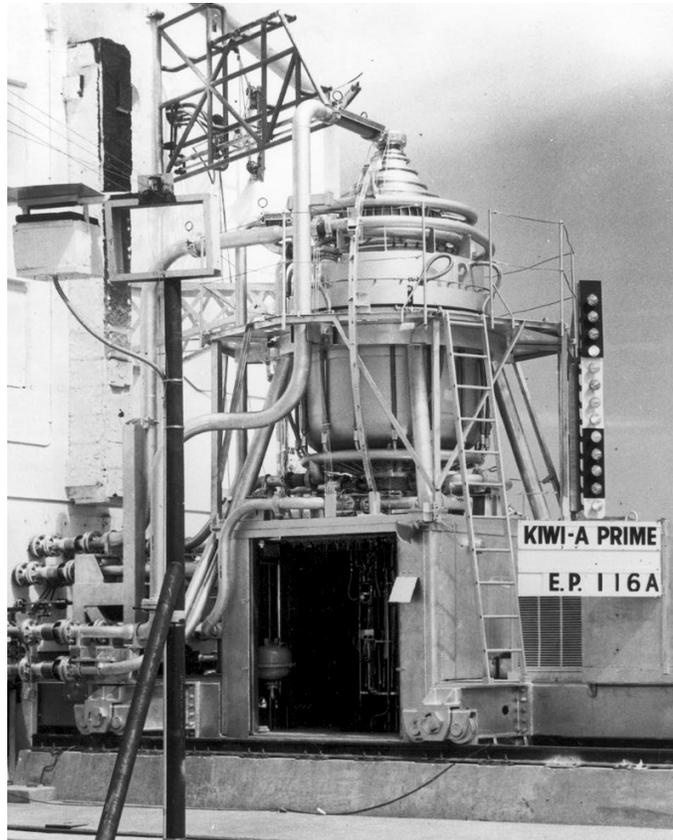


Image 40: Kiwi-A reactor preparations for test at Los Alamos (NASA CC-214).

The Hydrogen Decision

NASA's new Marshall Space Flight Center [formerly the ABMA] was responsible for both Saturn and Centaur.²⁰³ In 1959 von Braun explored upper-stage options for the Atlas, Titan, and Jupiter missiles, as well as the Saturn. At NASA Headquarters Abe Silverstein led another team responsible for selecting the upper stages for the Saturn booster. This group, referred to as the "Silverstein Committee," again stated that only vehicles using high-energy propellants would be practical. Wernher von Braun was an expert in liquid-fueled rockets, but he was wary of the handling concerns associated with liquid hydrogen. After a week of discussions, during which Silverstein reminded the group that Lewis had flown a hydrogen-fueled aircraft two years before, von Braun reluctantly agreed to the recommendations. NASA Administrator T. Keith Glennan approved the plan on 31 December 1959.²⁰⁴ Silverstein later referred to this as "the significant technical decision that enabled the U.S. to achieve the first manned lunar landing."²⁰⁵

NASA and the military were excited about the possibilities of Pratt & Whitney's RL-10, but also sought a larger hydrogen-oxygen engine. In the fall of 1959 NASA sponsored design studies for a 150,000-pound-thrust engine. The Silverstein Committee increased the power requirement to 200,000 pounds and suggested the development of a series of increasingly powerful Saturn models (what would become Saturn I, IB, and V).²⁰⁶ In May 1960 NASA contracted with Rocketdyne to proceed with the 200,000-pound-thrust liquid-hydrogen/liquid-oxygen engine, the J-2. The J-2 employed a more powerful version of the Mark IX turbopump that Rocketdyne had developed for Rover.²⁰⁷

Saturn included two hydrogen-fueled upper stages—the S-II and S-IVB. The S-II, the world's most powerful hydrogen rocket for decades, was powered by five J-2 engines. It also employed a unique external spray foam insulation. S-IVB played a top-stage role similar to that of Centaur. It was powered by a single J-2 and was insulated internally with foam blocks. Selecting the correct type of insulation system was critical. Internally mounted insulation was easier to implement but added extra weight. External insulation provided extra strength but was difficult to secure to the vehicle.²⁰⁸



Image 41: Silverstein in 1955 (GRC-1955-C-40501).

Charting the Course

As the 1950s came to a close, the government finally committed to liquid hydrogen and spaceflight after over a decade of dragging its feet. The former NACA, now NASA, led the way in space exploration, satellites, nuclear propulsion, and high-energy propellants. NASA Lewis embarked on a myriad of tasks necessary to make liquid hydrogen use practical for spaceflight.

On 9 May 1959 Assistant Director Bruce Lundin sent Silverstein a 10-page memorandum analyzing NASA's proposed upper-stage vehicles and recommending an expansion of Lewis's work on high-energy propulsion systems. Lundin outlined much of the center's propulsion research to be conducted during the early 1960s at Lewis Field and the new Rocket Systems Area at Plum Brook. This included analysis of the RL-10 engine at Lewis and comprehensive investigations of the loading, pumping, and storing of cryogenic propellants, particularly fluorine, at the Rocket Systems Area. Lundin explained, "After a year's experience on these problems at Plum Brook, the space group should be in a good position to contribute importantly to handling and launching of Centaur; they will be the only group with any real experience."²⁰⁹

In 1959, however, construction of the Rocket Systems Area sites was still in its early stages. The work, and more importantly the facilities' systems checkouts, would take two more years to complete. During this period, the space program continued to intensify, the center designed additional rocket sites for Plum Brook, and an entire division of personnel was created for the Rocket Systems Area.

References

130. Bruce Lundin, *The NASA and Propulsion Research* (Washington, DC, NASA TM X-50508, 1958).
131. John Sloop, "Problems Faced by Early Space Transportation Planners," Fifteenth Space Congress, 26–28 April 1978, NASA Glenn History Collection, Sloop Collection, Cleveland, OH.
132. John Evvard, Minutes of Research Planning Council, 6 September 1957, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
133. "NASA Lewis Research Divisions and Branches," 1 September 1959, NASA Glenn History Collection, Directors, Collection, Cleveland, OH.
134. Mary Lou Gosney to Raymond Sharp, "Plans for 1957 Inspection at Lewis in October," 15 April 1957, NASA Glenn History Collection, Inspections Collection, Cleveland, OH.
135. John Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959* (Washington, DC: NASA SP-4404, 1977), <http://ntrs.nasa.gov>
136. John Gibb, Glen Hennings, Harold Christianson, and Dave Fenn interview, Cleveland, OH, by John Sloop, May 1974, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
137. "OK's 17 Million for Air Lab Here," *Cleveland Plain Dealer* (12 April 1957).
138. "Missile Lab Here Getting 2 Buildings," *Cleveland Plain Dealer* (4 September 1957).
139. Carl Durham, "National Advisory Committee for Aeronautics Construction Program," Report No. 209 to accompany HR 3377, 19 March 1957.
140. Durham, "National Advisory Committee for Aeronautics Construction Program."
141. Evvard, Minutes of Research Planning Council.
142. Virginia Dawson, *Engines and Innovation: Lewis Laboratory and American Propulsion Technology* (Washington, DC: NASA SP-4306, 1991), <http://ntrs.nasa.gov>
143. William Jorden, "Soviet Fires Earth Satellite Into Space," *New York Times* (5 October 1957).
144. Virginia Dawson, *Ideas Into Hardware: A History of the Rocket Engine Test Facility at the NASA Glenn Research Center* (Washington, DC: NASA, 2004).
145. "Triennial Inspection, Lewis Laboratory, High Energy Rocket Propellants," October 1957, NASA Glenn History Office, Inspections Collection, Cleveland, OH.
146. Howard Douglass interview, Cleveland, OH, by John Sloop, 28 May 1975, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.

147. Gibb, Hennings, Christianson, and Fenn interview by Sloop.
148. Douglass interview by Sloop.
149. Bruce Lundin interview, Cleveland, OH, by John Sloop, 30 May 1974, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
150. Irving Pinkel, Minutes of Meeting of Research Planning Council, November 4, 1957, 6 November 1957, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
151. Douglass interview by Sloop.
152. Pinkel, Minutes of Meeting of Research Planning Council.
153. Larry Ross interview, Cleveland, OH, by Robert Arrighi, 1 March 2007, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
154. David Portree, *NASA's Origins and the Dawn of the Space Age* (Washington, DC: NASA, 1998).
155. *NACA 1957 Flight Propulsion Conference* (Washington, DC: NASA TM-X-67368, 1957), <http://ntrs.nasa.gov>
156. Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959*.
157. Douglass interview by Sloop.
158. Gibb, Hennings, Christianson, and Fenn interview by Sloop.
159. Douglass interview by Sloop.
160. Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959*.
161. Robert Walter email to Robert Arrighi, 17 November 2013, NASA Glenn History Collection, Cleveland, OH.
162. John Sloop, “NACA High Energy Rocket Propellant Research in the Fifties” 28 October 1971, NASA Glenn History Collection, Dawson Collection, Cleveland, OH.
163. *NACA 1957 Flight Propulsion Conference*.
164. Henry Pfanner interview, Cleveland, OH, by Robert Arrighi, 6 September 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
165. “Two Sandusky Men To Tell About Rockets On TV,” *Sandusky Register* (2 February 1959).
166. Pfanner interview by Arrighi.
167. Alan Wasser, “LBJ’s Space Race: What We Didn’t Know Then,” *The Space Review* (26 June 2005), <http://www.space-settlement-institute.org/Articles/LBJSpaceRaceHistory.pdf> (accessed 19 April 2016).
168. *NACA 1957 Flight Propulsion Conference*.
169. Bruce Lundin, “Lewis Laboratory Opinion of a Future Policy and Course of Action for the NACA,” 1957, NASA Glenn History Collection, Lundin Collection, Cleveland, OH.
170. “A Program for Expansion of NACA Research in Space Flight Technology With Estimates of the Staff and Facilities Required” (10 February 1958) <http://history.nasa.gov/SP-4103/app-h4.htm#45> (accessed 28 May 2014).
171. Dawson, *Engines and Innovation*.
172. Alexander Ginn to William Minshall, 9 May 1958, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
173. Douglass interview by Sloop.
174. Gibb, Glen, Harold, and Fenn interview by Sloop.
175. Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959*.
176. Gibb, Glen, Harold, and Fenn interview by Sloop.
177. “Rocket Test Site for Plum Brook,” *Sandusky Register* (9 May 1958).
178. Robert Kozar interview, Cleveland, OH, by Virginia Dawson, 30 March 2000, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
179. Paul Ordin interview, Cleveland, OH, by John Sloop, 30 May 1974, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
180. Robert Walter interview, Cleveland, OH, by Robert Arrighi, 5 November 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
181. Richard Heath interview, Cleveland, OH, by Robert Arrighi, 15 August 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
182. “Additional Facilities to be Built at Plum Brook,” *Wing Tips* (13 May 1958).

183. Starr Truscott interview, Cleveland, OH, by Virginia Dawson and Jim Polaczynski, 22 August 2001, NASA Glenn History Office, Oral History Collection, Cleveland, OH.
184. “Plum Brook Deputy J.R. Braig Retires,” *Lewis News*, 8 May 1970.
185. J. C. Duer to Commanding Officer at Ravenna Arsenal, “Decontamination of Pentolite Area—Plum Brook Ordnance Works,” 23 January 1956, NASA Glenn History Office, Plum Brook Ordnance Works Collection, Cleveland, OH.
186. James Braig, “Decontamination of Areas A, B, and C,” 18 July 1956, NASA Glenn History Office, Plum Brook Ordnance Works Collection, Cleveland, OH.
187. Arnold S. Levine, *Managing NASA in the Apollo Era* (Washington, DC: NASA SP-4102, 1982) chap. 2, <http://ntrs.nasa.gov>
188. David Akens, *Saturn Illustrated Chronology* (Huntsville, AL: NASA MHR-5, 1971).
189. Erasmus Kloman, “Centaur,” May 1971, NASA Glenn History Collection, Centaur Collection, Cleveland, OH.
190. Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959*.
191. A. O. Tischler interview, Cleveland, OH, by John Sloop, 25 January 1974, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
192. James Dewar, “Project Rover: A Study of the Nuclear Rocket Development Program, 1953–1963” (Doctoral thesis, Kansas State University, 1974).
193. “A Program for Expansion of NACA Research in Space Flight Technology,” 16 January 1958, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
194. Harold Rohlik and James Crouse, *Analytical Investigation of the Effect of Turbopump Design on Gross-Weight Characteristics of a Hydrogen-Propelled Nuclear Rocket* (Washington, DC: NASA Memorandum 5-12-59E, 1959).
195. Dewar, “Project Rover,” doctoral thesis.
196. James Dewar, *To the End of the Solar System: The Story of the Nuclear Rocket* (Lexington, KY: University Press of Kentucky, 2004).
197. Dewar, *To the End of the Solar System*.
198. *Report to the Congress From the President of the United States, United States Aeronautics and Space Activities, 1964* (Washington, DC: NASA-TM-85587, 1965), <http://ntrs.nasa.gov>
199. Ray Williamson and John Logsdon, editors, *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program, Volume 4* (Washington, DC: NASA SP-4407, 1999), chap. 1, <http://ntrs.nasa.gov>
200. W. H. Easelman, “The NERVA Nuclear Rocket Reactor Program,” *Westinghouse ENGINEER*, 24, no. 3 (May 1965).
201. Dewar, “Project Rover,” doctoral thesis.
202. Dewar, “Project Rover,” doctoral thesis.
203. Andrew Dunar and Stephen P. Waring, *Power to Explore: A History of Marshall Space Flight Center, 1960–1990* (Washington, DC: NASA, 1999).
204. Akens, *Saturn Illustrated Chronology*.
205. Abe Silverstein, “How It All Began,” Speech at Kennedy Space Center, 1 September 1977, NASA Glenn History Collection, Silverstein Collection, Cleveland, OH.
206. Akens, *Saturn Illustrated Chronology*.
207. M. C. Huppert and K. Rothe, “Axial Flow Pumps for Propulsion Systems,” *Fluid Mechanics, Acoustics, and Design of Turbomachinery, Part I* (Washington, DC: NASA SP-304, 1974), <http://ntrs.nasa.gov>
208. Mike Jetzer, “S-II Insulation,” *The Apollo Flight Journal* (22 August 2010), <http://history.nasa.gov/afj/s-ii/s-ii-insulation.html> (accessed 28 May 2014).
209. Bruce Lundin Memorandum for Associate Director, “Proposal for Expanded and Intensified Research on High Energy Upper Stage Propulsion Systems,” 12 May 1959, NASA Glenn History Collection, Directors Collection, Cleveland, OH.



Image 42: An operator inside the control room for the Pilot Plant. The control room was built inside a 9- by 36-foot tubular PBOW tank (GRC-2016-C-05167).

◆ Chapter 4 ◆

Establishing the Sites

The Lewis Research Center's mission changed dramatically as the Rocket Systems Area was being constructed in the late 1950s and early 1960s. Lewis reorganized its staff and shifted almost all of its resources to space, particularly propulsion and power systems. Walter Olson later described the transformation. "Rockets had been one little branch in the division under my direction, suddenly we had rockets scattered clear across the spectrum in the laboratory, from cooling, to materials, pumping, electronics, and we also took on space missions."²¹⁰ Liquid hydrogen was the central element of much of this activity.

Construction of the Rocket Systems Area at Plum Brook Station progressed during this period, and Lewis managers outlined the initial research programs for the sites. Just as these sites began coming online in 1961, President John F. Kennedy instructed NASA to send humans to the Moon and initiate plans to visit other planets. Congress infused the Agency with funds to quickly acquire the extra staffing and facilities needed to accomplish the goal. The center immediately began expanding its footprint at both its Lewis Field campus in Cleveland and Plum Brook in Sandusky. The Rocket Systems Area activities required the integrated skills of several different groups of people. Recruiters brought new employees from across the country to Sandusky to carry out this work.

Now's The Time

After deciding in early 1958 to build the Rocket Systems Area at Plum Brook Station, Abe Silverstein was anxious to begin construction, but governmental approvals were required before any contracts could be issued or equipment purchased. In March Silverstein instructed James "Ross" Braig to use Lewis staff to grade and drain the site for the Pilot Plant.²¹¹ Braig managed NASA's activities at Plum Brook from a small office in a former Plum Brook Ordnance Works (PBOW) building, and he reported directly to the head of Lewis's Technical Services divisions, Oscar Schey.

Construction of the Pilot Plant (G Site), which included a Pump Building, a Turbine Building, and an underground control room, began early in the summer of 1958. Engineers incorporated equipment from the PBOW into the design to expedite the construction. This included a compressor to supply airflow to the rigs and two cylindrical tanks that were transformed into the control and instrumentation room. The tanks were placed end-to-end on concrete slabs 350 feet from the rigs and joined. Crews covered them with earthen mounds for protection from possible explosions. The staff could view the two test cells through a periscope.²¹²

Once the bureaucratic hurdles had been cleared, Braig hired contractors to build the other sites. In September 1958, just as the NACA was transitioning into NASA, construction crews began grading the land near the center of the Plum Brook property and laying foundations for the Rocket Systems Area sites. Construction of the reactor complex was progressing just north of the area. NASA contractors refurbished the roads, railroad equipment, and utility systems, but many of the PBOW structures still remained. The entire property seemed to be entangled in utility poles and overhead cables.²¹³



Image 43: Grading and early construction work in the fall of 1958 at the Liquid Hydrogen Pump Facility (A Site). The facility's structures were in place in the spring of 1959. A Site began operations in 1961 (GRC-2016-C-05092).



Image 44: View to the west with the Hydraulics Laboratory (F Site) in the foreground. The background includes farm fields to the left and PBO structures to the right (GRC-2016-C-05110).

About a dozen Lewis civil engineers and technicians took a NASA bus out to Plum Brook every morning to inspect the work, make deliveries, or identify equipment that could be repurposed.²¹⁴ Offices were available in the PBOW buildings near the main gate. Bucky Walter regularly transported equipment from Lewis Field to the new pump sites. When making deliveries at night, he had to ring the buzzer at the gate and wait for the guards to return from their rounds of the 6,000 acre site. Eventually security gave Walter a key.²¹⁵ Starr Truscott recalled that Plum Brook had a very fluid feel during this period. In addition to the NASA construction work and the empty PBOW structures, there were agricultural activities. Farmers, who had existing land leases from the government, worked corn and tomato fields along the perimeter and even grazed cattle on empty fields inside the fence.²¹⁶

Pilot Plant and Rocket Systems Test Site (J Site)

In December 1958 the Pilot Plant became Plum Brook’s first operational test site. Former facility engineer John Gibb recalled that the two rigs “were just kind of thrown together quickly to get some input into the design of the rest of the [sites].”²¹⁷ Although built to study pumps and turbines, researchers from Lewis’s Fluid System Components Division initially used the Pilot Plant to test small gas generators used to power turbines. Turbines rotate turbopump drive shafts at specific speeds and torques. The turbine consists of an inlet, several stages with wheels and nozzles, and the drive shaft.²¹⁸ Turbine effectiveness is critical to the engine’s overall fuel efficiency.²¹⁹



Image 45: Technician adjusting the setup of a gaseous-hydrogen turbine at the Pilot Plant in August 1960 (GRC-2016-C-05133).

The design of Pratt & Whitney's new RL-10 engine included a unique turboexpander^k that converted a portion of the liquid hydrogen into a gas in order to power the turbopump's turbine. Pratt & Whitney had employed the device on its 304 aircraft engine in 1957, but their engineers were uncertain if the technology would transfer smoothly into rocket engines. Lewis sought to apply its wealth of aircraft turbine experience to the effort. Robert Wong and David Darmstadt of Lewis's Turbopump Component Branch felt that if it was determined that the aircraft turbine designs could be applied to hydrogen pumps then the existing fundamental aeropropulsion data could be utilized for rocket engine design. They were particularly interested in the use of heated hydrogen to drive the pump's turbine.²²⁰

The Wong and Darmstadt tested two single-stage turbines powered by gaseous hydrogen and gaseous nitrogen over a range of speeds and inlet pressure levels at the Pilot Plant. They found that the performance was in line with the theoretical predictions and that there was little operational difference between the two gases.²²¹ Both Pratt & Whitney and Lewis would continue their turbine research, and ultimately, the use of the propellant to power the turbine proved to be a significant advance in the development of both chemical and nuclear rocket systems.

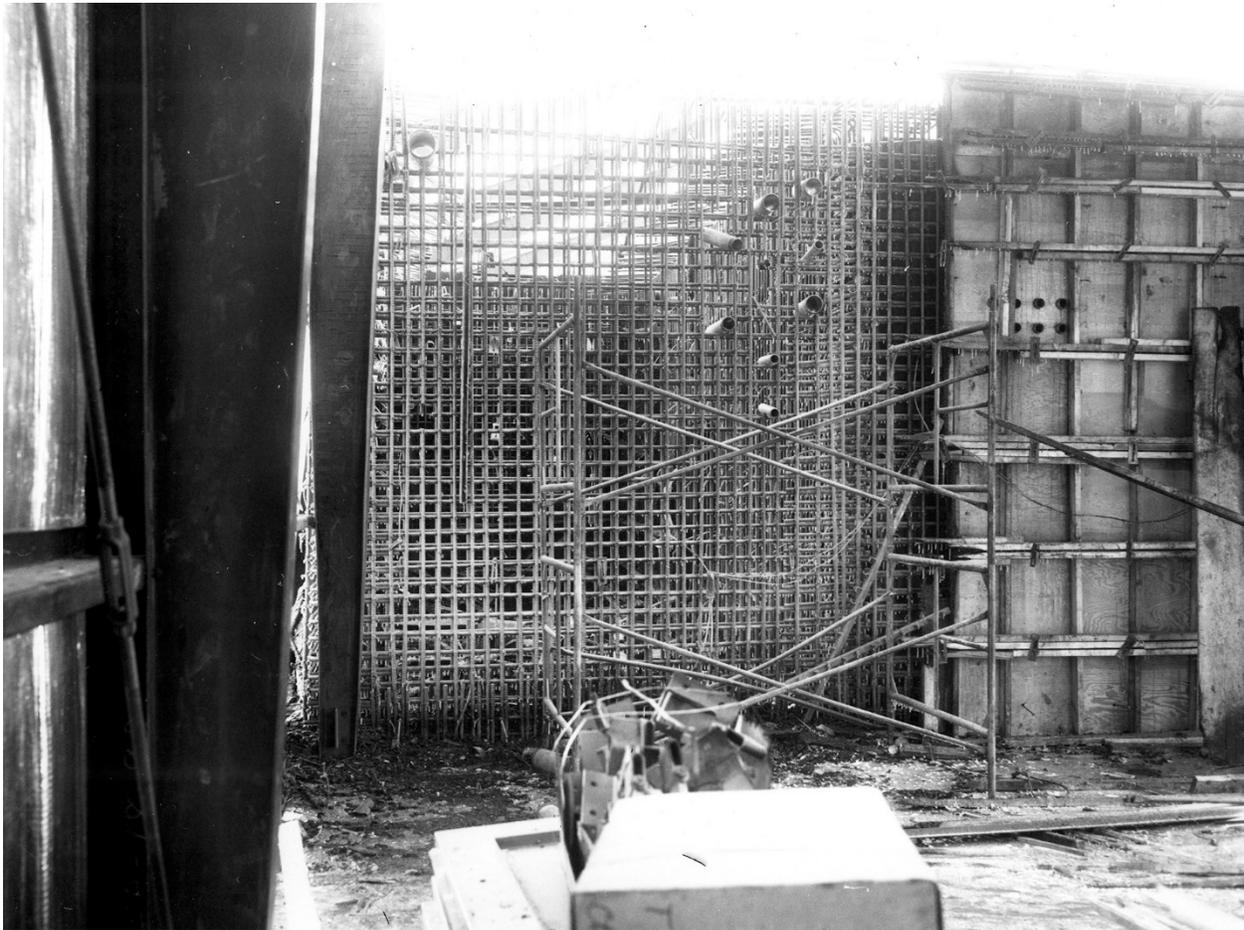


Image 46: Construction of F Site in December 1958. Electrical and hydraulic flow problems delayed testing until July 1963 (GRC-2016-C-07418).

^kThe liquid propellant is heated, and the resulting gas enters the turbine inlet. The gas expands through the turbine nozzles and then the wheels, creating the energy to rotate the drive shaft. The more the gas expands, the less propellant flow is required to rotate the shaft.



Between the fall of 1958 and spring of 1959 all five of the J Site structures were in place, and the horizontal J-1 stand was operating by the fall of 1959.²²² The winds roaring across Plum Brook's fields gave the J Site engineers problems at first. Because the facility was considered a portable site, no permanent structures were supposed to be built. Bucky Walter suggested using dirt mounds as a windbreak. Similar embankments had been employed at Lewis's Rocket Lab in Cleveland and could be considered temporary. The idea was quickly approved and implemented. J Site was thus frequently referred to as the Barricade Area. It was not long before engineers constructed corrugated walls around the mounds.²²³

By the end of 1959 most of the Rocket Systems Area facilities were close to completion. Then came the even more laborious task of putting the facilities through countless systems checks and dry runs. The technicians were confronted with a myriad of issues that would have to be resolved before each facility could begin its research runs. The installation of the test hardware could also be difficult. In some instances the original test plans for a site were modified during the construction, and new setups or systems had to be incorporated and checked out. The facility checkout process required months or even years in some instances. In almost every case, this process took longer than expected.



Image 47: Plum Brook staff gathers at J-2 to mark the first liquid-hydrogen/liquid-fluorine engine test at Plum Brook on 13 August 1960. Standing top: Ralph Jacko, John Gibb, Lively Bryant, Al Percival, and Bucky Walter. Crouched top: Bob Crowl, Ron Roskilly, Gordon Mackay, Emil Napholz, Don Burton, and Jim Gervis; Standing ground: Luke Eschels, Jack Glaze, Randy Burton, Harold White, Aaron Aule, Glen Hennings, unknown, Jack Langhals, and unknown. Crouched ground: Jim Brichacek, Joe Busa, Leo Theobald, and Bill Thompson (GRC-2015-C-06550).

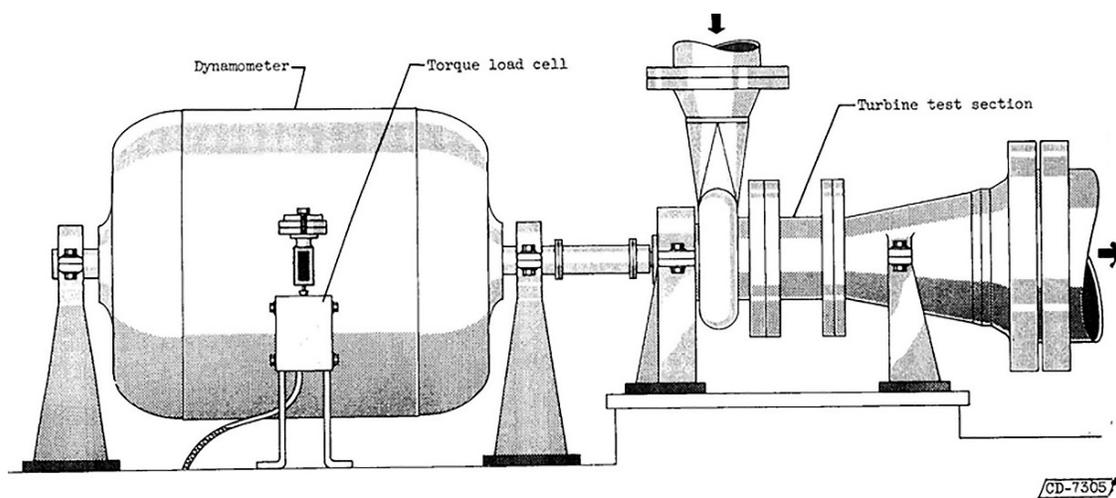
In August 1960 J-2 became the second NASA site to begin operation at Plum Brook. J-2 was a vertical test stand used to test throttling and combustion instability with regeneratively cooled liquid-hydrogen/liquid-fluorine and liquid-hydrogen/liquid-oxygen engines. The first program was the analysis of a 20,000-pound-thrust liquid-hydrogen/liquid-fluorine engine. The testing was similar to that conducted at Lewis Field's Rocket Lab, but the vertical stand allowed more realistic engine configurations.

During the initial years, the test engineers conducted the runs on Saturdays. Personnel from the Lewis Field Rocket Lab drove out to Sandusky in the morning to begin preparations for the run. NASA permitted the migrant farmers in and around Plum Brook to work in the fields until noon on Saturdays. The security force and some of the rocket engineers would drive around to ensure that the area was vacant before the test was run.²²⁴

Turbines for Nuclear Engines

Rocketdyne's development of the Mark IX axial-flow turbopump, which was driven by an Aerojet Mark III turbine, proceeded rapidly in the late 1950s.²²⁵ The Mark IX was designed to pump 10,000 gallons of fuel per minute.²²⁶ At the time, Harold Rohlik and Milton Kofskey of Lewis's Fluid Systems Division's Turbopump Components Branch were in the midst of an extensive analysis of turbopump and multistage turbine designs for nuclear rockets. After a 1959 review of the Mark IX design, Rohlik concluded that the selection of stages and flow area was based on "irrelevant parameters and unnecessary calculations" and suggested that the pump's slow speed and poor blade geometry would produce performance inefficiencies.²²⁷

Rohlik's early turbine analysis led him to conclude that at least eight stages were required to minimize the hydrogen flow rate to the turbine and the overall weight of the pump.²²⁸ He installed an eight-stage turbine with a 100-pound-per-second pump in the Pilot Plant's Turbine Building to verify that the spacing between the rows of blades provided optimal performance and prevented choking in the later stages. Rohlik analyzed three turbine configurations over a variety of speeds and pressures and found that the first two stages performed somewhat better than predicted.²²⁹ He then operated the same turbine with four-, six-, and eight-stage assemblies. Rohlik concluded that the first stage should have higher efficiency than the others, the aspect ratio should be lowered, and blades should be constructed more solidly.²³⁰



(a) Overall view.

Figure 2. - Turbine test rig.

Image 48: Diagram of the Pilot Plant's turbine test rig (NASA TM X-481, Fig. 2).

Aerojet manufactured a prototype nuclear rocket turbine and allowed Lewis researchers to include it in their turbopump research program. Rohlik and Kofskey installed the 11-inch-diameter turbine in the Pilot Plant using one-, two-, and three-stage configurations to determine the loading limits and reliability with various fluids. They then compared the Aerojet turbine with NASA's three- and eight-stage turbines. Rohlik and Kofskey found that additional stages, blade redesigns, and increased inlet temperatures would significantly increase the performance of the Aerojet turbine.²³¹

B-1 Stand Sets an Example

The High Energy Rocket Engine Research Facility (B-1 Stand) provides a good example of the extended construction and checkout process required for the Rocket System Area sites. NASA engineers completed the initial design work during 1959. The excavations and work on the infrastructure were probably well under way by the time that the first set of drawings was created in March 1960. The erection of the B-1 Stand and its water tower began in the fall of 1960. By May 1961 the test stand was in place and most of the infrastructure complete. The massive 140-ton steam accumulators, which were part of the altitude simulation system, arrived the following month. There were several unforeseen issues that caused delays, however, including the discovery of a buried PBO explosives line within 100 yards of the stand and NASA's decision to alter the B-1 design to test turbopumps for nuclear rockets.²³²

On 18 December 1963 operators scrapped the first attempted run at the B-1 Stand due to problems with the instrumentation and monitoring equipment. The latter was quickly rectified but the former required weeks of investigation.²³³ The first test run finally took place on 17 January 1964. A second hydrogen run attempt failed on 28 January because of problems with the instrumentation channels, the failure of a hydraulic pumping unit, and a discharge valve leak.²³⁴ Over the next seven months Plum Brook engineers and technicians struggled with a variety of problems as the facility testing continued. The final practice test took place on 12 August 1964.²³⁵ The B-1 Stand was the last of the original Rocket Systems Area sites to begin operation.



Image 49: Construction of the B-1 Stand in 1962 (GRC-1962-P-01858).



Image 50: Construction of the B Control Building in June 1963. During this period, controls specialists Henry Pfanner and Bob Smalley were exiled to the then uninhabited B Control. Pfanner explained, "We'd go over the ideas we had at Cochran's over 15-cent beer the night before. We were relatively successful [at B Control], and we would be in and out of there." The pair's expediency with their assignments left them with extra time on their hands. They decided to hang a hoop up behind the building. "[We] were playing basketball," recalled Pfanner, "until Glen Hennings came down one day, and that was the end of our basketball hoop." (GRC-1963-P-01480).²³⁶

The Dynamics Stand (E Stand), Turbopump Facility (C Site), Vacuum Environment Facility (J-3), and Materials Compatibility Laboratory (J-5) became operational in the summer of 1961. The Fluorine Pump Facility (I Site), A Site, and Tank Test Facility (J-4) went online in the spring of 1962. These sites went through similar trials during the postconstruction checkout period. These struggles to get everything functioning properly at the right time were an unavoidable aspect of research at any large test facility. The steps would be repeated for each new test program and sometimes between runs. Regardless, over just a couple of years Plum Brook was transformed from an industrial ghost town into a thriving new test complex.

Time to Take Longer Strides

After assuming office in early 1961, newly elected President John Kennedy confronted a succession of consequential Cold War events and a series of deflating space setbacks. The Soviet Union launched and safely retrieved two satellites containing animals, Centaur missed its first launch date, Yuri Gagarin became the first human to enter space and the first to orbit Earth, and a *Mercury*-Atlas rocket exploded on the launch pad. Alan Shepard's suborbital *Mercury* flight on 5 May finally provided the new president some respite.

It was in this atmosphere that Kennedy stood before Congress on 25 May 1961 and called for an enhanced space program that famously included sending a man to the Moon by the end of the decade. He also advocated an increased effort to develop nuclear rockets "for even more exciting and ambitious exploration of space, perhaps beyond the Moon, perhaps to the very end of the solar system itself."²³⁷



Image 51: Left to right: Vice President Lyndon Johnson, Arthur M. Schlesinger, Admiral Arleigh Burke, President Kennedy, and Mrs. Kennedy watch Alan Shepard become the first American in space. At Plum Brook, Ross Braig expressed the growing nationalism when stating, "The whole world knows we really did it...The Russians just made a propaganda flight—a body was there."²³⁸ (John F. Kennedy Presidential Library and Museum).

It is worth noting that the Sandusky progressiveness cited by John Victory five years prior was now being called into question. Local congressman and staunch NASA advocate, Charles Mosher, conducted a poll in the summer of 1961 that revealed that the community opposed Kennedy's goal of landing a man on the Moon. In an op-ed written just days before the Soviets segregated Berlin with a wall, the *Sandusky Register* editors rebuked this view. "Conservatism is one thing, but sticking one's head in the sand so one

will not have to look at the rest of the world is something else again.” The piece concluded, “Those who do not believe that Moon shots, space exploration and weapon development are absolutely essential, had better take another look at the world about them. They can be making a fatal mistake.”²³⁹

Reaching Forth

Administrator James Webb emphasized from the start that NASA sought to develop a wide array of technology and missions, not just the singular goal of landing a man on the Moon. Congress supported NASA’s new mission by significantly increasing the Agency’s budget to hire additional staff, build new test facilities, and establish new complexes. The latter included the large NASA Johnson and Kennedy space centers, but also smaller auxiliary test areas such as the Michoud Assembly Facility, Stennis Space Center, Santa Susana Field Laboratory, and White Sands Missile Range. Like Plum Brook, these were associated with a main NASA center and were located on military property.²⁴⁰

Lewis began converting existing aeronautical facilities to space applications and constructing new sites. The center also acquired 115 acres adjacent to its main campus in Cleveland and began taking steps that would lead to the center’s acquisition of Plum Brook in 1963. In December 1959 the Defense Department had announced that it no longer needed the PBOW.²⁴¹ Although NASA did not immediately exercise its option at Plum Brook immediately, it did develop an ambitious plan to create an environment for a broad range of space-related research. As the reactor and Rocket Systems Area came online in 1961, Lewis proposed a new wave of space facilities for Plum Brook. Some would be running within a few years; others would take nearly a decade to complete.



Image 52: Sign at the main gate for Lewis’s Plum Brook facilities in the early 1960s. Lewis renamed the site Plum Brook Station in 1962 (GRC–2003–C–00850).



After three years at NASA Headquarters, Abe Silverstein returned to Lewis as Center Director in October 1961. He immediately held a press conference to announce the center’s new recruiting drive to hire over 600 new employees in positions ranging from scientist to mechanic. Lewis dispatched recruiters to universities, aerospace corporations, and job fairs across the country.²⁴² The staff nearly doubled between 1961 and 1964, including 500 employees at Plum Brook.²⁴³ By the late 1960s, there would be 630 civil servants and 132 support service contractors at Plum Brook.²⁴⁴

NASA’s expansion in the early 1960s brought an influx of new, mostly young people into the Sandusky area in north central Ohio. Dick Heath, a former facility engineer, joked that housing prices shot up by 20 percent once the residents heard about the impending arrival of the new federal employees.²⁴⁵ Sandusky,

which was founded on a Lake Erie harbor in the early 1800s, was in the midst of postwar growth, regardless of the new NASA personnel. In 1957 the area witnessed the construction of a slew of new homes, the opening of the Sandusky High School, and completion of a major causeway.²⁴⁶

Some of the new staff for the Rocket Systems Area transferred from Lewis Field, others heard of the openings from friends or family members, and others were from the local area. Most, however, appear to have been hired through NASA's recruiting efforts. Tom Brink was working on the Atlas missile in San Diego when he saw a newspaper ad. Even though the deadline had passed, Plum Brook managers hired him over the telephone.²⁴⁷ A Lewis recruiter convinced Don Perdue to quit his position designing Minuteman missile stages in Utah and join NASA.²⁴⁸ Jim Cairelli, an engineer at a steel plant, learned of the openings at a job fair in Chicago.²⁴⁹



Image 53: A pickup game of football at the Plum Brook picnic grounds. Many of the new employees were young and new to the Sandusky area. The group quickly became close-knit, and enduring friendships were formed (GRC-2016-C-05785).

Dick Heath had just completed a project installing Atlas missiles in silos in Nebraska, when a colleague left to join the staff at Plum Brook. Reluctant to return to General Dynamics's plant in San Diego, Heath and his wife decided to take a chance on Sandusky. "This sounded like a nice little bucolic farm area," he recalled. Some of the new hires had trouble integrating into the area, but the Heaths were befriended by neighbors who "had been Sanduskians since the Stone Age" and quickly acclimated.²⁵⁰ Henry Pfanner, who grew up in the area, played down talk of any negative reaction to the newcomers and emphasized that the arrivals were actually dispersed over several communities.²⁵¹

Organizing the Staff

Upon returning to Lewis in the fall of 1961, Abe Silverstein quickly reorganized the entire center and created four new divisions to be located at Plum Brook. Bucky Walter was sitting at his desk in the Rocket Operations Building at Lewis Field when his section head stopped in to inform Walter that he was being reassigned to the Rocket Systems Area at Plum Brook. Before he had the chance to ask more than a question or two, the manager instructed Walter to get ready to leave. "Everything went fast," Walter later recalled. "They didn't fool around. They said, 'We're going to do this.' Bingo."²⁵² Like most of the Lewis Field transfers, Walter commuted from Cleveland for several years before relocating to the Sandusky area.

The Plum Brook staff was initially segregated into the Facilities Service, Reactor, Engineering, and Rocket Systems divisions. The Engineering Division handled Plum Brook's utilities, infrastructure, and property. The Reactor Division was responsible for all activities at the nuclear reactor. The Facilities Service and Rocket Systems divisions performed most of the day-to-day work at the Rocket Systems Area. The former supplied the technical staff—mechanics, electricians, cryogenic handling technicians, and shop people—for the test sites. The latter provided the professional staff that set up the research equipment, managed the controls and instrumentation, and operated the facilities.

The Rocket Systems Division emerged from Lewis's Propulsion Systems Division and was augmented by new recruits. Its Propulsion Systems Branch, led by James Gay, handled testing related to nuclear and chemical rockets; the Propulsion Components Branch under Robert Siewert specialized in turbopumps and system dynamics; and Robert Zimmer's Instrument and Control Branch managed the remote controls and data recording.²⁵³



Lewis veteran Glen Hennings was named head of the Rocket Systems Division and managed all of Plum Brook's hydrogen work. Although educated as an agricultural engineer, Hennings became an expert on liquid hydrogen during the 1950s at Lewis. He had started with the NACA during World War II as an aircraft icing researcher. By the early 1950s he was involved with the laboratory's burgeoning hydrogen and fluorine test programs. Colleague Howard Douglass recalled that Hennings educated himself on liquid hydrogen and "learned how to handle it very effectively, very early."²⁵⁴ Hennings explained, "I never thought of it being a lot tougher than a lot of other things. I rather enjoyed working with hydrogen and always liked the hydrogen-fluorine combination."²⁵⁵

Hennings managed the activities at the Rocket Systems Area sites and made sure that the researchers' needs were met. He was not afraid to push the center's management to provide support for Plum Brook when necessary. He could be brusque at times but made an effort to be present for the test runs and had the respect of his staff. Former employees referred to him "as a good one," "an ideal boss," and "a wealth of knowledge that he showered on me."²⁵⁶ Pfanner explained his philosophy, "He came in [and] he said, 'I can go down the street to the bar and get a bunch of people to tell me they don't know how to do it or can't do it.... What I need is somebody that will do it.'"²⁵⁷

In February 1962 NASA signaled its growing presence in Sandusky by officially naming the site Plum Brook Station. Reactor manager Alan "Hap" Johnson was named Director of all of Plum Brook with Ross Braig as his Deputy Director. Both men had started at the Cleveland lab during World War II. Braig had been managing the Plum Brook construction since 1956. Johnson came out later to get the reactor up and running. As such, Johnson remained closer to the reactor over the years than the rocket areas. In fact, when later asked about the rocket sites, Johnson replied, "I'm not too familiar with them."²⁵⁸ Hennings's strong presence minimized the need for close oversight by Johnson.



Image 54: Alan "Hap" Johnson, left, and Glen Hennings in 1963 (GRC-1963-P-01673).



Image 55: Hennings managed the rocket systems work from behind a desk piled high with papers and reports. Despite the apparent mess, he knew exactly where each document could be found and what was going on out in the field.²⁵⁹ "Glen would rather have been out at the sites, but he couldn't," remembered Heath (GRC-1962-P-01222).



Image 56: The Plum Brook staff was initially housed in PBOW structures near the gate, including the Administration Building, seen here. NASA permitted Perkins Township to use this building for their Sesquicentennial Celebration in June 1959 (GRC-2016-C-05141).

Initiation of Test Programs

Now that construction was completed and staff hired, the Rocket Systems Area was ready to contribute to the nation's rapidly accelerating space program. There was still much to master regarding one of the program's critical elements—liquid hydrogen. The Rocket Systems Area required a cohesive, multifaceted team to perform this research. It included Lewis Field researchers and Plum Brook engineers, technicians, electricians, mechanics, and test operators.

The Rocket Systems Area test programs emanated from a number of Lewis divisions. Lewis Field researchers devised test programs for the Rocket Systems Area based on discussions with mission planners, participation in professional meetings, and general awareness of the nation's aerospace activities.²⁶⁰ Occasionally, outside groups such as Pratt & Whitney requested specific tests. These could be general investigations of design concepts such as impellers for turbopumps, tests of mission-specific hardware like the Centaur structural dynamics, or analysis of technology for future missions such as insulation systems for long-term propellant storage.

Once they determined the test objectives, the Lewis researchers contacted representatives from the Rocket Systems Division to arrange for the installation of the experimental equipment in an appropriate test site. The Plum Brook staff met with the research engineers in the fall to plan the test programs for the upcoming fiscal year. The Rocket Systems Division scheduled enough time to prepare the site, install the test hardware, and acquire the propellants, gases, and any specific hardware for the tests.²⁶¹

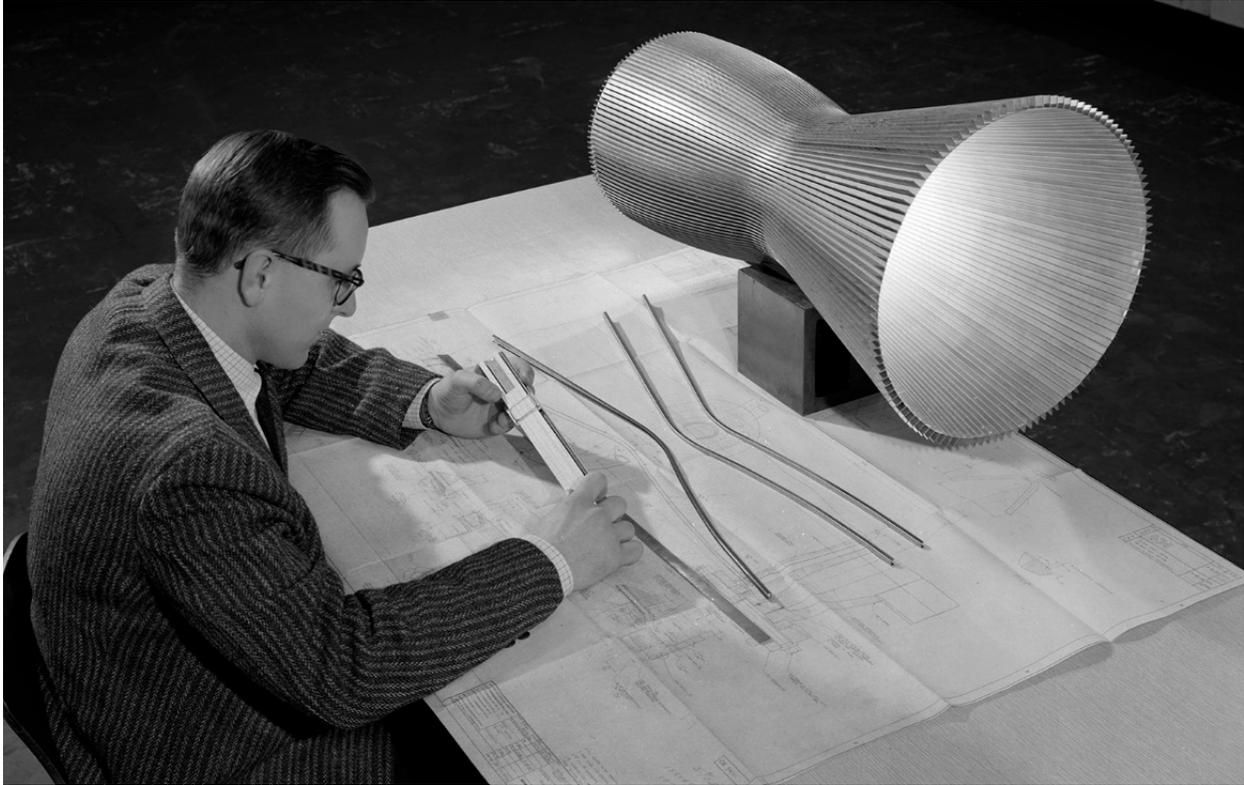


Image 57: A Lewis engineer examines a drawing showing the assembly and details of a 20,000-pound-thrust regeneratively cooled rocket engine (GRC-1958-C-49377).

Safety Permits

The center established hazard areas around the test sites according to existing military regulations. As a precaution NASA also created exclusion areas around the hazard areas; these were based on the types of propellants used and the nature of the tests. All of the test facilities at Lewis Field and Plum Brook were under the jurisdiction of a particular Area Safety Committee. Area Safety Committees were responsible for issuing safety permits and for vetting the safety procedures of all tests being conducted in their zone. The committees were composed of engineers familiar with the type of work. The Lewis Safety Officer was responsible for ensuring that all of the committees were staffed and operating.²⁶²

The Lewis Safety Officer required the facility engineers to obtain a safety permit from their Area Safety Committee before a test program could be run. The committee members met with the project engineers to discuss what steps were being taken to mitigate potential hazards to both personnel and the environment. If they were satisfied, they issued a renewable one-year safety permit. If not, they ordered modifications to the procedures or equipment. An Executive Safety Board, which was composed of high-level Lewis managers, resolved any disputes between the test engineers and the safety committees. Ultimately, the center director was the final arbiter.²⁶³

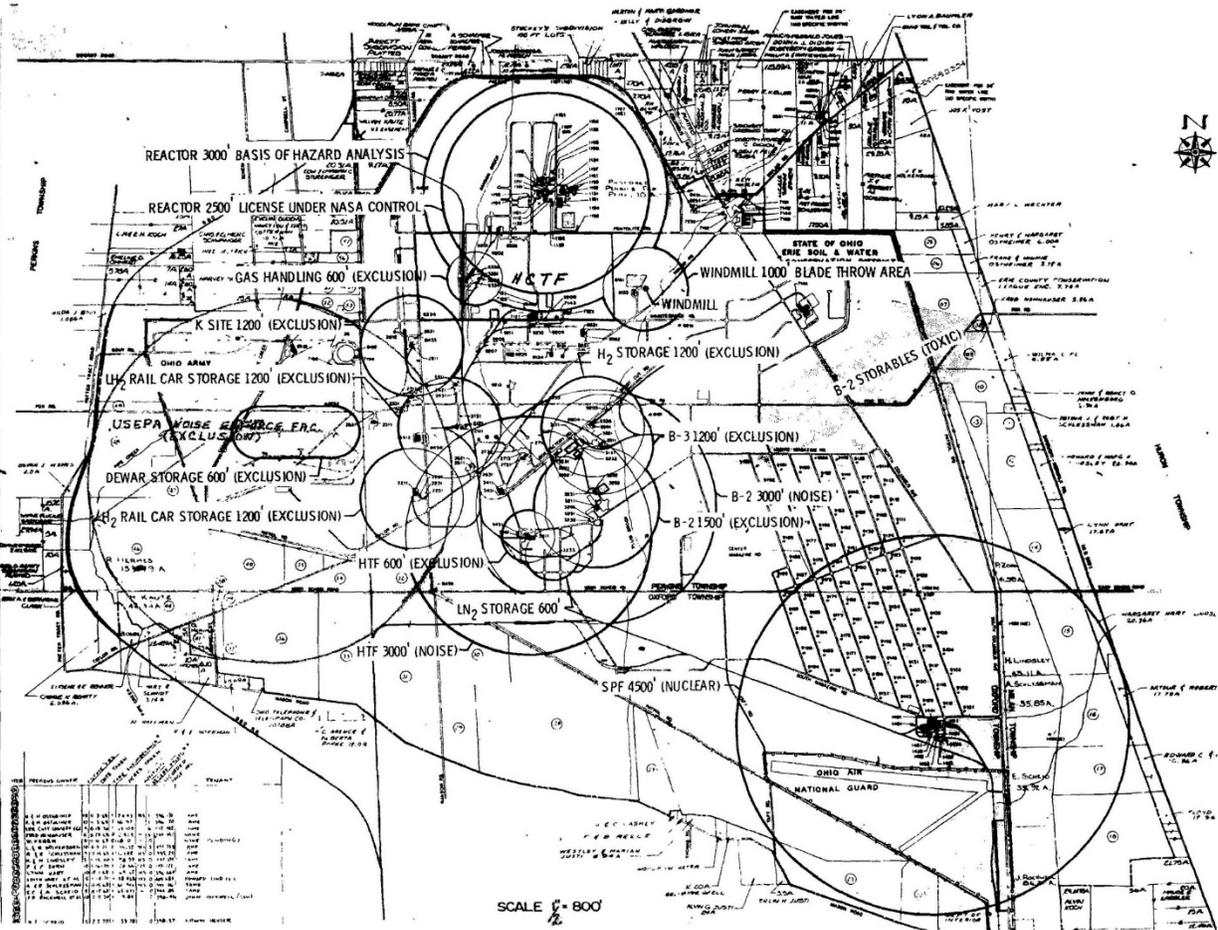


Image 58: Plum Brook map. The hazards exclusion areas are the test sites (NASA).

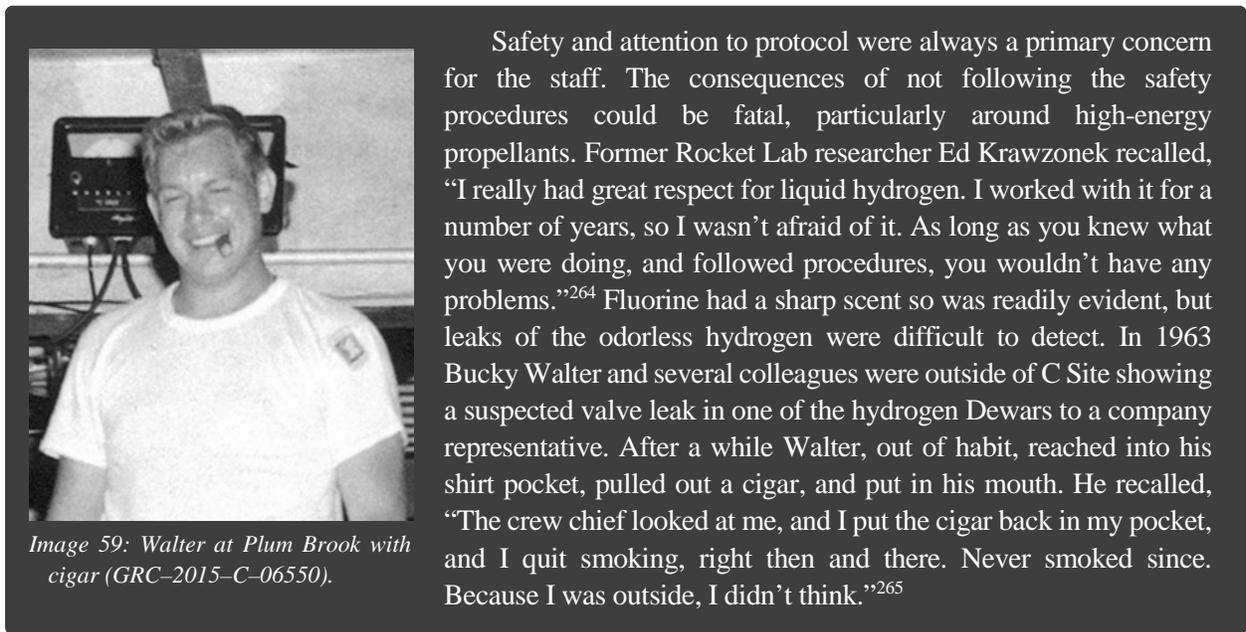


Image 59: Walter at Plum Brook with cigar (GRC-2015-C-06550).

Safety and attention to protocol were always a primary concern for the staff. The consequences of not following the safety procedures could be fatal, particularly around high-energy propellants. Former Rocket Lab researcher Ed Krawzonek recalled, “I really had great respect for liquid hydrogen. I worked with it for a number of years, so I wasn’t afraid of it. As long as you knew what you were doing, and followed procedures, you wouldn’t have any problems.”²⁶⁴ Fluorine had a sharp scent so was readily evident, but leaks of the odorless hydrogen were difficult to detect. In 1963 Bucky Walter and several colleagues were outside of C Site showing a suspected valve leak in one of the hydrogen Dewars to a company representative. After a while Walter, out of habit, reached into his shirt pocket, pulled out a cigar, and put in his mouth. He recalled, “The crew chief looked at me, and I put the cigar back in my pocket, and I quit smoking, right then and there. Never smoked since. Because I was outside, I didn’t think.”²⁶⁵

The Implementers

After establishing the parameters of the test program and acquiring the safety permit, the researchers worked with the Rocket Systems Division, who Henry Pfanner referred to as “the implementers,” to schedule the runs, integrate the hardware into a site, and conduct the test.²⁶⁶ Some researchers were very hands-on during this process, but Dick Heath said others “didn’t get into the nuts and bolts of it. They just said, ‘We would like to run this engine at 350 degrees, 350 psi [pounds per square inch], for the duration of two minutes.’ That’s what we would set up for.”²⁶⁷

Each site had a facility engineer, two electricians, and a mechanic to implement the researcher’s test.²⁶⁸ The facility engineers managed the installation of the experimental equipment into the facility and the operation of the site. Most would check in at the office in the morning, but spend most of the day out at their test site. “There were times when you weren’t sure what you were doing,” remembered Jim Cairelli. “You were just kind of feeling your way along. That’s the way a lot of that was. Nobody had done it before. You didn’t know what you were doing. You made your best estimate of how to do it, and either you made it work, it didn’t work, or almost work [laughs].”²⁶⁹

The facility, instrumentation, and electrical engineers created checklists of steps that needed to be taken just prior to a test. These were generally similar for all the runs in a given program with slight variations in the operating conditions to examine different parameters. A computer in the Administration Building converted the lists into machine-readable punch cards. The cards were sorted in the proper order, then run through a reader machine that would print out the checklists on continuous-form computer paper.

Lewis’s long tradition of cooperation between the researchers and technical staff continued at Plum Brook. Ned Hannum stated, “Let me just say that absolutely nothing of value could have ever happened without the operations people being able to perform their tricks...to simulate environments and make things happen in a cost-effective, quick way.”²⁷⁰ Researcher Bob Hendricks concurred. “We had excellent support people, eager to assist, highly talented and going all out to get the task accomplished.”²⁷¹

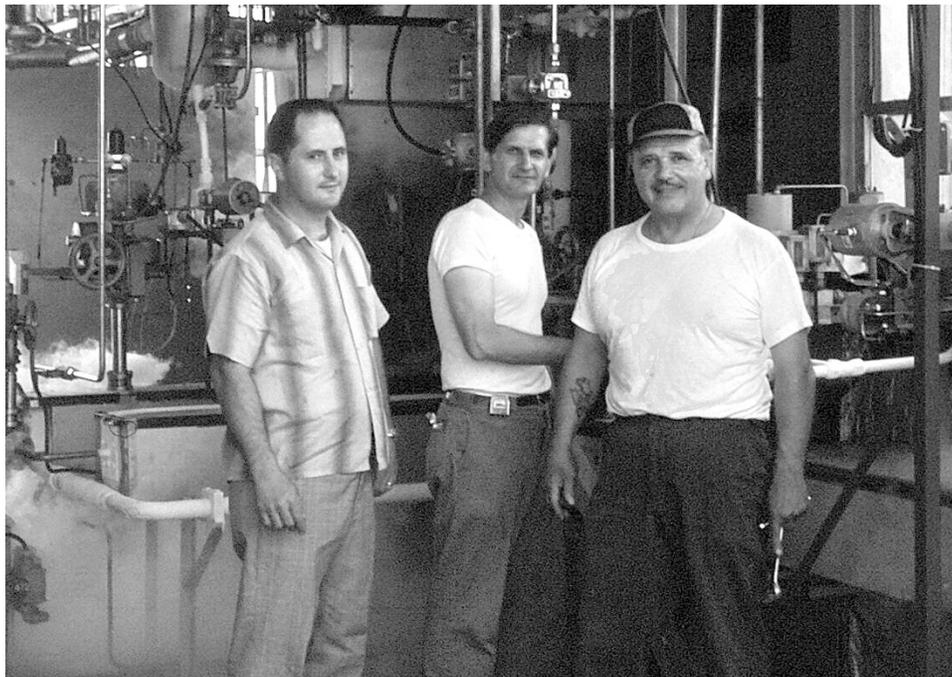


Image 60: The Facilities Service Division’s Metro Marchak, Carl Baker, and Richard Gawryszewski work on a pump in May 1967. Marchak and Baker were mechanics and Gawryszewski an electrician (GRC-2016-C-05789).

Members of Plum Brook's Propulsion Systems Branch or Propulsion Components Branch readied the facility for the test. This often required the installation of new pumping systems and specialized hardware; the calibration of controls and instrumentation systems; and the scheduled delivery of gases and propellants for the runs. The engineers also obtained test articles or components from industry or other centers to. Preparation for a run could require anywhere from a day to months depending on the complexity of the test and the condition of the facility.

The mechanics and technicians from the Facilities Service Division supported the facility engineers and performed much of the actual work at the sites. The electricians set up the physical controls used to actually run the test and sensors to relay data to the control room. Gordon MacKay was a young facility engineer in the early 1960s. He explained, "You learn to respect your mechanics and don't tell them how to do the job. You learn a lot from them. You build a rapport with them. Get their advice, their help, especially if they've had a lot of experience."²⁷²

Lewis mechanics have a long history of contributing to the facility operations and test programs. Many received modest cash bonuses for developing new and more efficient processes and often created tricks of the trade. One Plum Brook mechanic developed an impromptu fix to a low-pressure hydrogen leak during a propellant transfer operation at J Site. He wrapped a couple of wet rags around the pipe. The rags immediately froze on the pipe's cryogenic surface and formed a seal sturdy enough to complete the hydrogen transfer. The process was used occasionally afterward for similar low-pressure leaks.²⁷³

PLUM BROOK ROCKET SYSTEMS DIVISION STATUS REPORT				CONTINUED
SITE	LABORATORY	RESEARCH INSTALLATION (FOR)	DESCRIPTION	
J	ROCKET SYSTEMS	J-2 Liquid Hydrogen Liquid Oxygen <u>Throttling Tests</u> (I.A. Johnsen)	Throttling and combustion instability tests of a liquid oxygen-liquid hydrogen pressure fed rocket system.	
	STATUS:	J-2	On April 10th one research data run was made of 25 seconds duration. During the 25 second period, both the engine and injector suffered burn out failures. Leaks in the engine had been repaired prior to this run with silver solder. This was the first firing after the engine had been repaired. It is believed that engine failure occurred first which resulted in the injector burn out. This was the last regenerative engine of its size available for test firing. A new engine of shorter length is being fabricated and is expected at Plum Brook for installation during the week of May 13th. Cell modifications now in progress include larger hydrogen and oxygen flow lines and valves, instrument changes, and engine exhaust system changes to accept the new engine. Test firings are planned for the last week of May.	
		<u>M-1 Hydrogen-Oxygen Gas Generator</u> (I.A. Johnsen)	Investigation of the gas generator for the Aerojet M-1 rocket engine program.	
	STATUS:		The ordering of vendor supplied hardware is 90% complete. Drawings for plumbing of flow lines and for locations of equipment and dewars are 50% complete. Tentative date for system check out should be late July.	

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Image 61: Rocket Systems Division Test Operations Report for J-2. Plum Brook's research divisions were required to file monthly Test Operations Reports detailing the activities at each test site. The facility engineers submitted their input to Glen Hennings's office, where the administrative staff compiled all the notes into a cohesive report that covered all the activities at Plum Brook. These status reports, which survive in Plum Brook's records room today, provide a detailed description of day-to-day life at Plum Brook's test sites during the 1960s and early 1970s²⁷⁴ (NASA).

Gas Handling

Plum Brook used large quantities of gaseous and liquid chemicals in the 1960s, even more than the Lewis Field campus. The Gas Handling Area just north of the Rocket Systems Area provided facilities to store, process, and transfer these chemicals—particularly nitrogen, helium, oxygen, and hydrogen. The liquids or gases were placed in pressurized tanker trailers, taken to the test sites, and hooked up.²⁷⁵

The Gas Handling Unit was also responsible for purchasing liquid hydrogen from industrial plants. The head of the unit received requests from the test site engineers and worked through the procurement staff at Lewis Field to place the orders.²⁷⁶ Lewis owned four railcar Dewars that were regularly sent south to industrial plants on the Gulf of Mexico. These vacuum-sealed railcars could make the entire journey without allowing any of the cryogenic hydrogen to boil off.

The most remarkable component of Plum Brook’s gas-handling infrastructure was a 200,000-gallon liquid-hydrogen Dewar built in 1963 near the High Energy Rocket Engine Research Facility (B–1 Stand), referred to as “the ball.”²⁷⁷ The 38-foot-diameter tank was designed to allow only one-half percent of the hydrogen evaporate each day.²⁷⁸ Glen Hennings explained in 1974, “I’m guessing at one time it was the world’s best storage vessel, and probably still is.”²⁷⁹ Later, Los Alamos added two 500,000-gallon Dewars and Cape Canaveral built an 800,000-gallon Dewar.



Image 62: Gas Handling Area with both a railcar Dewar and roadable Dewars. The site was located just north of E Stand (GRC–2016–C–05788).



Image 63: The 200,000-gallon liquid-hydrogen Dewar at B Complex. The container consisted of a thick steel shell that was protected by a 9-inch-thick multilayer foil-and-glass-wool insulation and was encapsulated by a thin outer shell (GRC–1965–P–02580).

At one point the outer shell developed a vacuum leak that could have caused the liquid hydrogen to boil and dissipate through the vents. Herb Junod noticed the leak and quickly ordered the railcar tanks to the site so that the large Dewar could be emptied. Bucky Walter drove to the Engineering Building to inform Hennings. Hennings’s secretary would not allow Walter to disrupt a meeting that was in progress. Walter scribbled, “The ball is leaking!” on a slip of paper and asked her to pass it along. Walter recalls, “He comes running out and says, ‘Well, get those railcars over there.’”²⁸⁰



Image 64: Lewis’s railcar Dewars parked beside the Locomotive Shop at Plum Brook. The four railcars were later transferred to Cape Kennedy for the space shuttle program (GRC-2016-C-05187).

On Friday 19 August 1966 a hydrogen railcar on route to Plum Brook began releasing a plume of hydrogen gas into the sky. Local authorities halted the train near Nashville. Law enforcement officers, concerned residents, and even the governor converged on the site as the white tanker, with the NASA logo and “DANGER—KEEP FIRE AWAY” painted on it, spewed its mysterious contents into the night air. Railroad officials contacted someone at Lewis Field, who then frantically attempted to reach someone at Plum Brook.

It was a Friday evening, and Bucky Walter and Don Perdue had been flying a model airplane near I Site. Walter went out afterward and returned home later to discover that the telephone had been ringing all night.²⁸¹ In the meantime Lewis officials reached Perdue at home. Arrangements were quickly made for Perdue and mechanics Bob Baker and Herb Junod to drive into Cleveland to catch a NASA flight to the site. They arrived in Tennessee at 1:15 a.m.

Upon arrival they made their way through the news media, flashing lights, and barricades. Despite the fact that hydrogen is odorless, one resident complained that the stench was permeating the neighborhood. Perdue and his colleagues ascertained the problem almost immediately—the brass vent valve was stuck open. Perdue instructed one of the mechanics to rap it with a wrench. “It went shut,” Perdue recalled. “So we climbed back on the airplane and came home.”²⁸² The men did not arrive at their homes until 9 a.m. Saturday morning. For their 11-hour overnight efforts, Perdue and his colleagues each received \$4 in per diem.²⁸³

SCHEDULE OF EXPENSES AND AMOUNTS CLAIMED						
PREVIOUS TEMPORARY DUTY (Complete these blocks only if on travel status immediately prior to period covered by this voucher and if administratively required.)						
DEPARTURE FROM OFFICIAL STATION (DATE)		TEMPORARY DUTY STATION LAST DAY OF PRECEDING VOUCHER PERIOD (DATE)		TEMPORARY DUTY STATION LAST DAY OF PRECEDING VOUCHER PERIOD (DATE OF ARRIVAL)		
DATE	NATURE OF EXPENSE	AUTHORIZED MILEAGE RATE		AMOUNT CLAIMED		
		SPERMETER RANGES	No. of MILES	MILEAGE	SUBSISTENCE	OTHER
8-19	Dep Plum Brook Station, Sandusky, Ohio, via government auto at 8:50 PM EST					
8-19	Arr Lewis Research Center, Cleveland, Ohio, via government auto at 10:00 PM EST					
8-19	Dep Lewis Research Center, Cleveland, Ohio, via government auto at 10:30 PM EST					
8-20	Arr Nashville, Tennessee, via government air at 1:15 AM EST					
8-20	Was taken to the NLAX 202 dewar by Louisville & Nashville Rail Road personnel and returned to the Nashville, Tennessee airport.					
8-20	Dep Nashville, Tennessee, via government air at 5:50 AM EST					
8-20	Dep Sandusky, Ohio, via private auto at 8:45 AM EST					
8-20	Arr Huron, Ohio, via private auto at 9:00 AM EST					
	11 hours of per diem at \$0.00 for 12 hours					4.00
Grand total to face of voucher (Subtotals to be carried forward if necessary)				\$0.00		4.00

Image 65: Expense report for Perdue’s overnight trip to Tennessee (NASA).

Controls and Data

Although the Pilot Plant, J Site, and the Cryogenic Propellant Tank Facility (K Site) had their own ad hoc control areas, the Rocket Systems Area's two primary control and data buildings were the H Control and B Control buildings. The two reinforced-concrete structures were located a quarter to a half mile away from their respective test sites. H Control contained the analog and digital data acquisition equipment for all of the Rocket System facilities and the control panels for A Site, C Site, the Controls and Turbine Test Facility (D Site), E Stand, F Site, and I Site. B Control contained the control rooms for the B-1 Stand and the Nuclear Rocket Dynamics and Control Facility (B-3 Stand), the Hydrogen Heat Transfer Facility (HHTF), and later the Spacecraft Propulsion Research Facility (B-2).

More than 13,500 wires, equaling 14.3 miles of cable, tied H Control to the various test sites.²⁸⁴ The Controls Section was responsible for the lines used to operate the site, and the Instrumentation Section handled the lines that recorded the data. The set up included valve systems, servo feedback controls, heaters, safety equipment, and other specialty items. Each thermocouple or control device at the test rig had to be connected to the remote control room, and it could take up to 10 wires for each device.²⁸⁵ The wires were connected to patchboards in the control room that were similar to old telephone operator switchboards.²⁸⁶

The collection and recording of the data was critical to all tests. Test runs were useless if the data were not preserved. Installing and setting up the data acquisition systems could be even more difficult than setting up the controls. There were hundreds of instrument channels to be recorded on any particular test, and problems frequently arose. It could take days just to get one data channel functioning properly. There were many problems getting the system up and running. These had to be verified by inspections of the servos and the valves set up at the facility. Problems with the recording equipment caused months of delays in some situations. After a test run, the operator had to go through the tedious process of verifying that the data-recording equipment had worked properly.



Image 66: Control and Data Building (H Control Building), as seen in 1960, with its myriad of wires running out to the test sites. Universal Marine Construction Company was responsible for laying the 600 control cables, 500 pairs of instrumentation cables, and eight television lines emanating from these facilities in 1959.²⁸⁷ The number of cables soon increased (GRC-1960-C-54934).

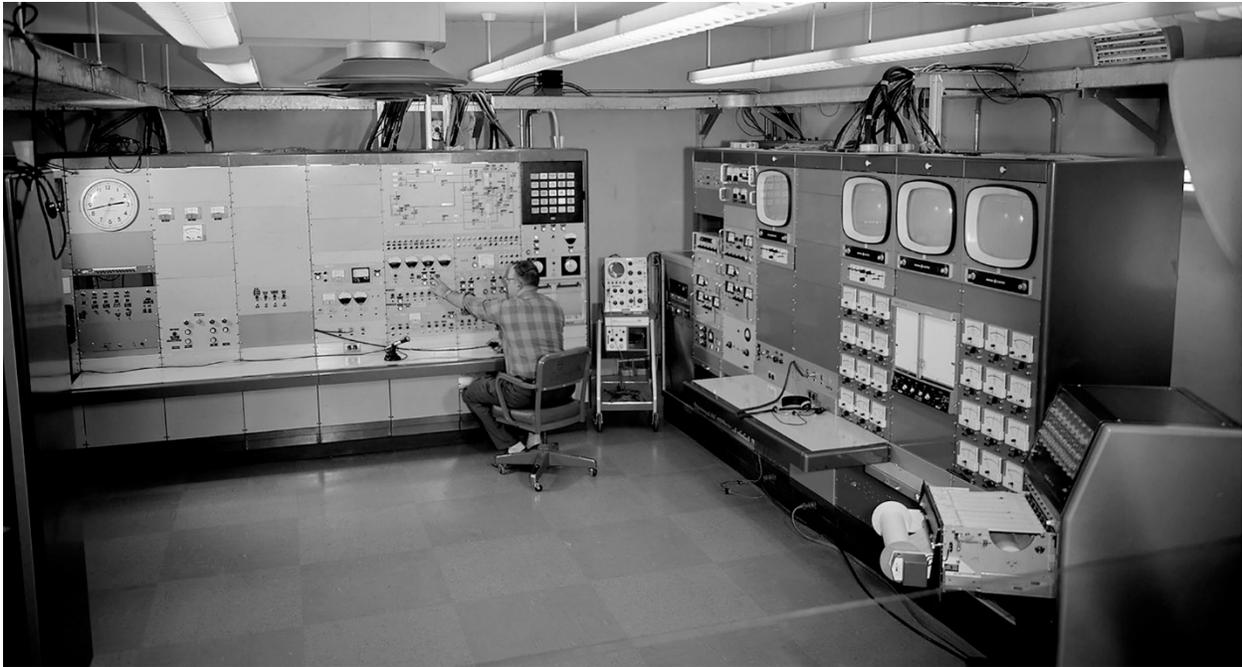


Image 67: Stations inside B Control (GRC-1965-P-2147).

Test Day

On the test day, the operations engineer ensured that the check sheets for the test run were up to date and that the proper computer cards had been punched. The safety officer put up road blocks, activated warning lights, and ensured that all nonessential personnel exited the area before a test was begun.²⁸⁸ The operator and mechanics made a final check of the test setup and facility, then retreated to the control room. The building was usually crowded on run days with technicians, engineers, researchers, and frequently Glen Hennings.

At B Control two operators ran the test from the main facility panels, which controlled the liquid-hydrogen tank feed, the ejector system, and the purge system. Others monitored a television console and other displays that issued warnings regarding leaks or other safety issues. Two technicians monitored the carbon dioxide and hydrogen detection systems, and the facility systems. Others watched the pumps, control system, amplifiers, servoprogrammer, and overspeed indicators.²⁸⁹

The engineers then went through the check sheets. Dick Heath dispelled any drama or effort regarding the operator's role in running the test. "One man stood there and said, 'Ok, everything's ready.' Beep, hit the button."²⁹⁰ These runs were typically very short, some shorter than others. "Sometimes you'd just push a button, and you'd blow up," John Gibb recalled.²⁹¹

The staff then returned the propellants to the storage Dewars and purged any residual hydrogen in the systems with gaseous nitrogen or helium. After checking the sensor equipment for any lingering hydrogen, the staff returned to the site to inspect the test article.²⁹²

The test data were recorded onto magnetic tape in H Control then taken to Lewis Field for analysis by the Computing Section and researchers. The reams of data had a downside for the researchers, however. Early rocket research at Lewis often yielded a single piece of paper that described the performance. The newer data acquisition systems produced stacks of paper that had to be analyzed.²⁹³



Image 68: Engineers in H Control monitor a test run. Notice the television consoles on the right (GRC-1962-C-59449).



Image 69: IBM data processing equipment in B Control (GRC-1967-C-00722).



Image 70: A technician works on a cryogenic supply system at the J-1 facility (GRC-1961-C-57678).



The scope of the U.S. space program broadened significantly during the construction of the Rocket Systems Area. NASA was now responsible for sending humans to the Moon and developing space vehicles that would someday lead to human exploration of other planets. Although the United States had decided that it would use liquid hydrogen to fuel its upper-stage vehicles, Pratt & Whitney's struggles with its RL-10 engines impacted both the Saturn and Centaur schedules. NASA launched its first Saturn I in October 1961 but intentionally did not fire the hydrogen-fueled upper stages. Clearly there was still much to be determined before hydrogen rockets became a reality.

NASA expanded both its staff and facilities at Lewis Field and Plum Brook. Lewis transformed Plum Brook into a major research facility during the early 1960s. The land itself underwent its third major alteration in the past 150 years—first from wilderness to farmland, then to munitions plant, and lastly to a rocket testing site. Now that the first wave of facilities was operational and the staff was in place, the Rocket Systems Area was ready to tackle an array of hydrogen-related research topics for NASA.

References

210. Walter Olson interview, Cleveland, OH, by Virginia Dawson, 16 July 1984, NASA Glenn History Office, Oral History Collection, Cleveland, OH.
211. John Weeks, “Plum Brook Pilot Plant and Rocket Stand Site Preparation Work,” 25 March 1958, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
212. “Plum Brook Today,” *Lewis News* (25 September 1959).
213. Starr Truscott interview, Cleveland, OH, by Virginia Dawson and Jim Polaczynski, 22 August 2001, NASA Glenn History Office, Oral History Collection, Cleveland, OH.
214. Gordon MacKay interview, Cleveland, OH, by Robert Arrighi, 14 January 2014, NASA Glenn History Office, Oral History Collection, Cleveland, OH.
215. Robert Walter interview, Cleveland, OH, by Robert Arrighi, 5 November 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
216. Truscott interview by Dawson and Polaczynski.
217. John Gibb, Glen Hennings, Harold Christianson, and Dave Fenn interview, Cleveland, OH, by John Sloop, May 1974, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
218. George Sutton and Oscar Biblarz, *Rocket Propulsion Elements* (New York, NY: John Wiley & Sons, Inc., 2001).
219. John Sloop, “Hydrogen-Oxygen for Rocket Propulsion,” 16 October 1963, NASA Glenn History Collection, Dawson Collection, Cleveland, OH.
220. R. Y. Wong and D. L. Darmstadt, *Comparison of Experimentally Obtained Performance of Two Single-Stage Turbines With Design Ratios of Blade to Jet Speed of 0.191 and 0.262 Operated in Hydrogen and in Nitrogen* (Washington, DC: NASA TM X-415, 1961), <http://ntrs.nasa.gov>
221. Wong and Darmstadt, *Comparison of Experimentally Obtained Performance of Two Single-Stage Turbines*.
222. “Plum Brook Today.”
223. Walter interview by Arrighi.
224. Walter interview by Arrighi.
225. James Dewar, *To the End of the Solar System: The Story of the Nuclear Rocket* (Lexington, KY: University Press of Kentucky, 2004).
226. Robert Kraemer, *Rocketdyne: Power Humans Into Space* (Reston, VA: American Institute of Aeronautics and Astronautics, 2006).
227. Eugene Manganiello to Harold Finger, “Review of report entitled ‘Preliminary Design Study of the Mark 9 Turbine by S. Hozaki and A. B. Neale of Rocketdyne, WADC TN 58-298 R-1123,’” 9 April 1959, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
228. Harold Rohlik and James Crouse, *Analytical Investigation of the Effect of Turbopump Design on Gross-Weight Characteristics of a Hydrogen-Propelled Nuclear Rocket* (Washington, DC: NASA Memorandum 5-12-59E, 1959).
229. Harold Rohlik, *Investigation of Eight-Stage Bleed-Type Turbine for Hydrogen-Propelled Nuclear Rocket Applications, I—Design of Turbine and Experimental Performance of First Two Stages* (Washington, DC: NASA TM X-475, 1961), <http://ntrs.nasa.gov>
230. Harold Rohlik, *Investigation of Eight-Stage Bleed-Type Turbine for Hydrogen-Propelled Nuclear Rocket Applications, II—Experimental Overall and Stage Group Performance Determined in Cold Nitrogen* (Washington, DC: NASA TM X-481, 1962), <http://ntrs.nasa.gov>
231. Harold Rohlik and Milton Kofskey, *Performance Evaluation of Three-Stage Prototype NERVA Turbine Designed for Blade-Jet Speed Ratio of 0.107* (Washington, DC: NASA TM X-719, 1963), <http://ntrs.nasa.gov>
232. R. M. Griffin to James Braig, “Proposed S.O.P. for Removal of Explosive Contaminated Flume Line— TNT Area B,” NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
233. Rocket Systems Division Test Operations Report, High Energy Rocket Engine Research Facility, December 1963, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
234. Rocket Systems Division Test Operations Report, High Energy Rocket Engine Research Facility, 1964, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.

235. Rocket Systems Division Test Operations Report, December 1964.
236. Henry Pfanner interview, Cleveland, OH, by Robert Arrighi, 6 September 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
237. John F. Kennedy, "Special Message to the Congress on Urgent National Needs," 25 May 1961.
238. "Joy at Plum Brook," *Sandusky Register* (6 May 1961).
239. "Fatal Error," *Sandusky Register* (10 August 1961).
240. Roger Bilstein, *Orders of Magnitude: A History of the NACA and NASA, 1915–1990* (Washington, DC: NASA SP-4406, 1989), <http://ntrs.nasa.gov>
241. "Plum Brook Gets Ordnance Area," *Sandusky Register* (17 December 1959).
242. Karl Abraham, "Lewis Lab Plans for Big Expansion," *Cleveland Plain Dealer* (4 November 1961).
243. "Lewis Growth Great in Last Two Years," *Lewis News* (28 February 1964).
244. "Additional Facilities to be Built at Plum Brook," *Wing Tips* (13 May 1958).
245. Richard Heath interview, Cleveland, OH, by Robert Arrighi, 15 August 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
246. "Sandusky Keeps Pace," *Cleveland Plain Dealer* (3 January 1958).
247. Thorvald Brink interview, Cleveland, OH, by Robert Arrighi, 29 November 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
248. Donald Perdue interview, Cleveland, OH, by Robert Arrighi, 12 November 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
249. James Cairelli interview, Cleveland, OH, by Robert Arrighi, 19 November 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
250. Heath interview by Arrighi.
251. Pfanner interview by Arrighi.
252. Walter interview by Arrighi.
253. "Lewis Research Center Research and Development Activities," May 1964, NASA Glenn History Office, Organizations Collection, Cleveland, OH.
254. Howard Douglass interview, Cleveland, OH, by John Sloop, 28 May 1975, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
255. Gibb, Hennings, Christianson, and Fenn interview by Sloop.
256. Heath interview by Arrighi.
257. Pfanner interview by Arrighi.
258. Alan Johnson interview, Cleveland, OH, by Mark Bowles, 20 March 2002, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
259. Perdue interview by Arrighi.
260. Ned Hannum interview, Cleveland, OH, by Virginia Dawson, 22 January 2003, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
261. Perdue interview by Arrighi.
262. William Brown interview, Cleveland, OH, by Robert Arrighi, 17 December 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
263. Brown interview by Arrighi.
264. Edward Krawczonek interview, Cleveland, OH, by Virginia Dawson, 23 January 2003, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
265. Walter interview by Arrighi.
266. Pfanner interview by Arrighi.
267. Heath interview by Arrighi.
268. Perdue interview by Arrighi.
269. Cairelli interview by Arrighi.
270. Hannum interview by Dawson.
271. "Plum Brook Station Senior Science Student Tour," 6 October 1965, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
272. MacKay interview by Arrighi.

273. Heath interview by Arrighi.
274. Pfanner interview by Arrighi.
275. “Plum Brook Station Review,” 30 December 1976, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
276. Heath interview by Arrighi.
277. “The Year at Plum Brook,” *Lewis News* (22 January 1965).
278. “High Energy Rocket Engine Research Facility and Nuclear Rocket and Dynamics Control Facility,” 1 March 1967, NASA Glenn History Collection, Rocket Systems Area Collection, Cleveland, OH.
279. Gibb, Hennings, Christianson, and Fenn interview by Sloop.
280. Walter interview by Arrighi.
281. Walter interview by Arrighi.
282. Perdue interview by Arrighi.
283. Donald Perdue, Travel Voucher TAC-684, 22 August 1966.
284. “Plum Brook Today,” *Orbit* (22 January 1960).
285. Henry Pfanner email to Robert Arrighi, 3 January 2014, NASA Glenn History Collection, Cleveland, OH.
286. Pfanner email to Arrighi.
287. A. I. McCall, “Two Test Facilities Completed at NASA; Experiments Started,” *Sandusky Register* (16 September 1959).
288. Brown interview by Arrighi.
289. John Esterly, *Nuclear Rocket Simulator Tests, Facility and Research Apparatus Description* (Washington, DC: NASA TM X-52043, 1964), <http://ntrs.nasa.gov>
290. Heath interview by Arrighi.
291. Gibb, Hennings, Christianson, and Fenn interview by Sloop.
292. Walter Osborne, *Noncavitating and Cavitating Performance of a Liquid-Fluorine Pump Designed by Stream-Filament Method* (Washington, DC: NASA TM X-722, 1963), <http://ntrs.nasa.gov>
293. Walter interview by Arrighi.



Image 71: The Dynamics Stand as it nears completion in July 1959. The 144-foot-tall tower had a 14-foot-diameter well that ran the length of the structure to accommodate missiles (GRC-1959-C-51298).

◆ Chapter 5 ◆

The Chase Is On

“Making a ‘race’ out of this is probably a good thing,” stated John Weeks, of the Plum Brook Station administrative office. “We work off our energies and competitive spirit without fighting.”²⁹⁴ The Cold War and the Space Race, both unofficial, quickly accelerated in the early 1960s. The Soviet Union sent the first female into space, orbited two two-person spaceships simultaneously, and set an in-space endurance record, while the United States sent three *Mercury* capsules into orbit and launched key early communications satellites. Despite this peaceful competition, events such as the construction of the Berlin Wall and the Cuban Missile Crisis brought the United States and Soviet Union closer to war than ever.

As NASA rolled out its plans for space in the early 1960s, it became apparent that new rocket systems were required—particularly the Saturn, Atlas/Centaur, and Nuclear Engine for Rocket Vehicle Application (NERVA). Lewis researchers utilized the Rocket Systems Area for a range investigations using liquid hydrogen, which was a key element of all three vehicles. Glen Hennings explained, “Almost anything we do with hydrogen is applicable to both [chemical and nuclear rockets].”²⁹⁵ In the early 1960s the Rocket Systems Area supported nozzle cooling studies for the nuclear engines, tests of Centaur’s structural dynamics and insulation, and the evaluation of liquid-fluorine turbopumps.

Straight Ahead

As the first wave of new space-related facilities began operation in the early 1960s at Lewis Field and at Plum Brook Station in Sandusky, the Lewis Research Center began planning larger, more advanced facilities. The new Plum Brook sites included the Nuclear Rocket Dynamics and Control Facility (B–3), Hydrogen Heat Transfer Facility (HHTF), and Cryogenic Propellant Tank Facility (K Site) at the Rocket Systems Area; the massive Space Power Facility (SPF); and what was then referred to as the Apollo Propulsion Facility (B–2).¹ These sites were primarily geared toward issues relating to future long-duration nuclear rocket missions.

The continual addition of new test sites, first proposed in November 1957, supported Abe Silverstein’s philosophy that all space hardware should be tested in conditions that would simulate the environment in which the hardware would operate. Engineers should test components first, then systems, and when possible, full-scale articles. Former Plum Brook manager Robert Kozar explained that this progressive analysis gave engineers the confidence “to make it any size we want, and we know that it will work.”²⁹⁶

Lewis submitted proposals for the B–3, HHTF, SPF, and B–2 with NASA’s fiscal year 1963 budget. Local Congressman and member of the House Committee on Science and Astronautics, Charles Mosher, was serving on the House Committee on Science and Astronautics at the time. He claimed that the requests were, “so vital they certainly must be authorized.”²⁹⁷ In May 1962, Congress approved \$40 million for new facilities at Plum Brook. The funds also covered modifications to the High Energy Rocket Engine Research Facility (B–1) and the Dynamics Stand (E Stand).²⁹⁸

¹The Space Propulsion Research Facility (B–2) and SPF are outside the scope of this project and are not discussed in detail.

NUCLEAR ROCKET DYNAMICS AND CONTROLS FACILITY

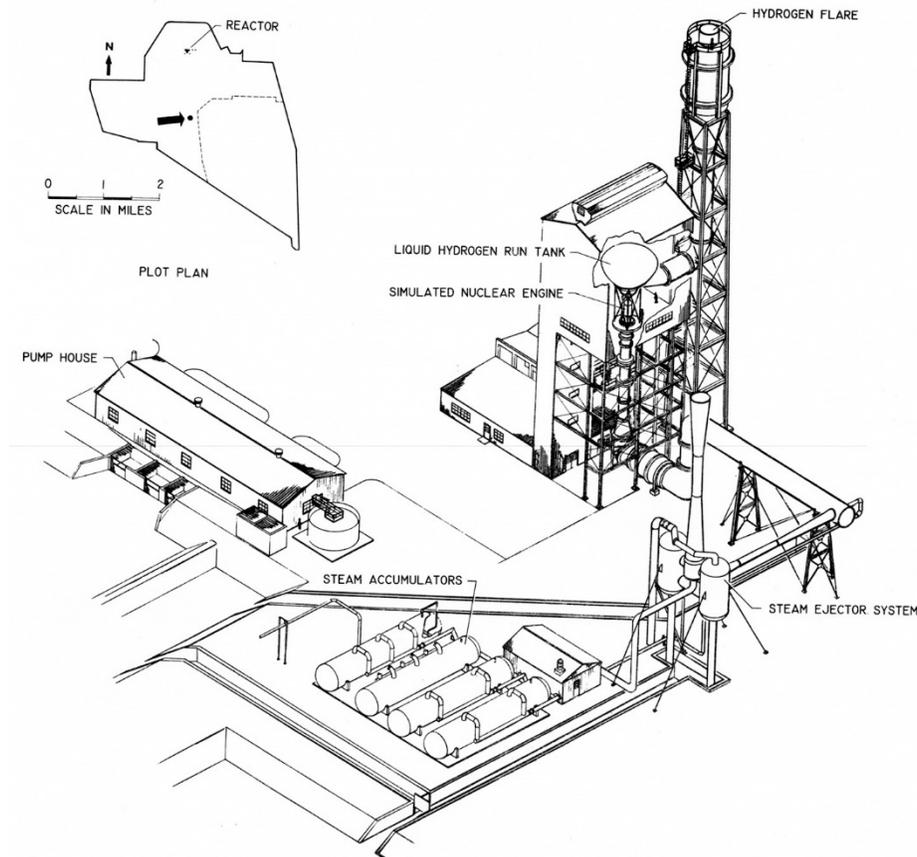


Image 72: Early conception of the B-3 Stand included in Lewis's fiscal year 1963 budget request (NASA).

Emergence of NERVA

In March 1961 President John F. Kennedy canceled the Aircraft Nuclear Propulsion program after years of disappointing results. The President, however, proposed an escalation of Project Rover's nuclear rocket development. In the 1940s Lewis researchers considered nuclear propulsion to be more applicable to rockets than aircraft since theoretically rockets possess unlimited speed and range. In addition, nuclear rockets were inherently safer than aircraft since the reactor would not be activated until the upper stage exited the atmosphere.²⁹⁹

The Atomic Energy Commission's (AEC's) work on Rover's first generation Kiwi-A reactors produced mixed results in 1959 and 1960. Nonetheless, on 7 June 1961 the Space Nuclear Propulsion Office (SNPO) selected Aerojet General to develop a flyable engine and Westinghouse Astronuclear to create the accompanying reactor. This was the official start of Project Rover's Nuclear Engine for Rocket Vehicle Application (NERVA).³⁰⁰ Aerojet began work on the NERVA engine, referred to as NRX, which employed a regeneratively cooled nozzle and a Rocketdyne Mark IV turbopump.³⁰¹ Both Los Alamos and Lewis expanded their test capabilities during this period to address this new phase of the nuclear rocket effort.

As work on the NERVA engine commenced, AEC researchers tested a series of nonflyable Kiwi-B reactors at the Nevada Test Site. The Kiwi B reactors were roughly 10 times as powerful as the Kiwi-A's and used liquid rather than gaseous hydrogen.³⁰² The first Kiwi B test with liquid hydrogen took place in September 1962. Although the hydrogen system performed well during this and a subsequent run in late November 1962, the reactor core suffered severe vibrational damage. President John F. Kennedy, who visited the Nevada facility just a week after the second failure, suspended the planned flight test of the engine on a Saturn rocket.³⁰³ The SNPO decided to put full-system testing of the Kiwi-B on hold until the source of the problems could be identified.³⁰⁴

The Copper Cannon

Nuclear rockets perform optimally when operating at the highest possible temperature without increasing the vehicle's weight. Cooling was a primary concern during operation at these temperatures, which could be twice that found in chemical rockets. The engine would literally melt within seconds without a sufficient cooling system.³⁰⁵ Nuclear engines employed a nozzle with a converging-diverging shape that was sharply pinched.

The pinched nozzle presented engineers with a unique set of cooling problems. The regenerative cooling system flowed cold hydrogen through tubes around the nozzle wall to absorb heat, but the designers needed reliable methods for calculating the rate of this heat transfer, particularly at the nozzle contraction, to optimize the design. Lewis researchers had studied this phenomenon previously in chemical rockets but were hesitant to assume that the data would apply to the pinched nozzles of nuclear rockets.³⁰⁶

Lewis undertook a wide-ranging program in the early 1960s to establish these predictive tools, including a heat transfer study at Plum Brook's Rocket Systems Test Site (J Site). There researchers from the Rocket Heat Transfer Branch analyzed the transfer of heat from the hot exhaust gases to the nozzle wall and from the nozzle wall to the coolant in an experimental 26,000-pound-thrust engine that simulated the shape of the NERVA engine.³⁰⁷ The engine, nicknamed the "copper cannon," included a thick copper thrust chamber and nozzle that naturally dissipated heat and withstood high temperatures.³⁰⁸

The first phase of the investigation began in 1962 at the J-1 horizontal test stand. Over the next two years the researchers repeatedly studied the engine's cooling characteristics with various gaseous-hydrogen and liquid-oxygen mixtures and pressure levels.³⁰⁹ The test operators briefly fired the engine—the longest run was 9 seconds—then allowed the nozzle to return to ambient temperature. The researchers calculated the heat absorption by comparing the temperature readings during the run to copper's standard properties.³¹⁰ They used the data from these early runs to devise an equation to correlate the heat transfer properties from exhaust gas to any location on the nozzle wall.³¹¹

Although the firings lasted only seconds, the engine produced a loud thunder that frequently damaged the instrumentation and shook the surrounding community. Dick Heath, the facility engineer for the tests, remembered, "Every time we fired it we blew the thermocouples out and had to get it fixed." One employee's parents, who lived up the road from Plum Brook, telephoned their son after some of these runs to make sure that the explosion was not caused by something serious. Technicians eventually resolved the rough combustion issue by adding a minute dose of fluorine to the hydrogen line.³¹²

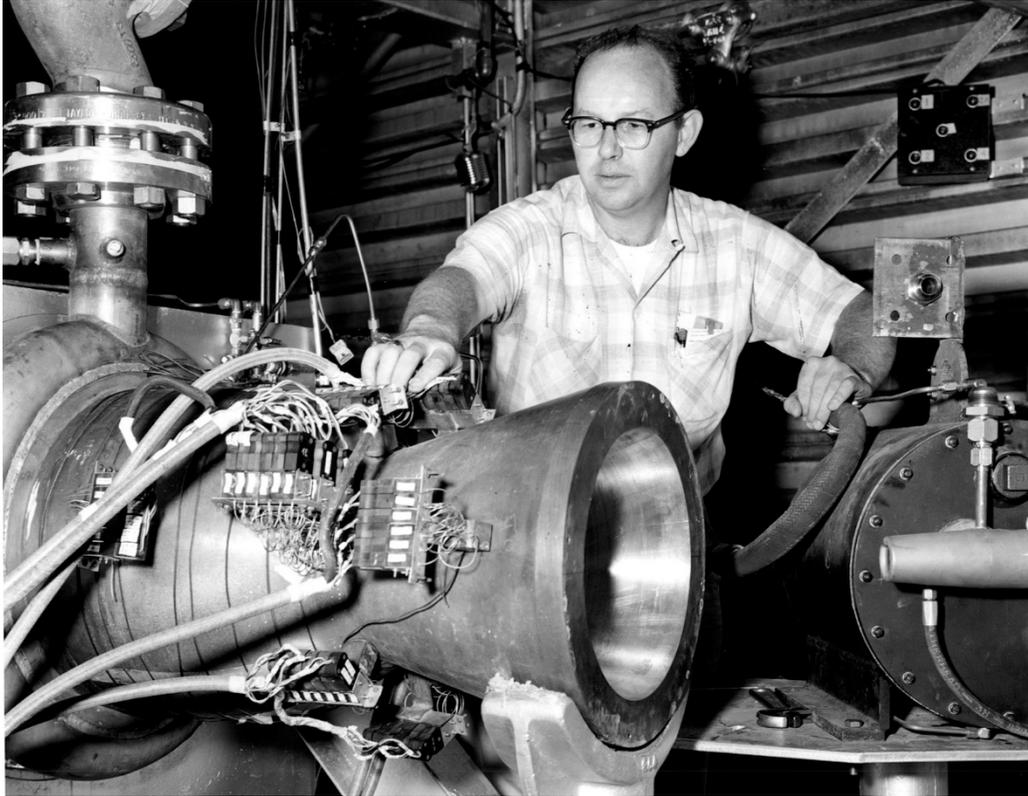


Image 73: James Coates inspects the 28,000-pound-thrust copper engine used for the nozzle heat transfer testing at J-1 in June 1962. The nozzle had a 5-inch-diameter throat that expanded to 11 inches and a coaxial injector to maintain stable operation and even mass flux and temperature (GRC-1962-P-01213).



Image 74: Firing of the copper nozzle rocket with gaseous hydrogen and liquid oxygen at J-1 in 1962 (GRC-2016-C-05089).

Engine manufacturers requested more detailed data on this heat transfer process, particularly in the nozzle's contraction. There were also questions regarding the effect of different fuel mixtures and injector designs on the heat transfer. By this point, the AEC had already operated its Kiwi-B engines in Nevada, but these systems were not instrumented to measure the nozzle's heat transfer data. In August 1963 Lewis researchers resumed their testing at J-1 using three different types of injectors with various hydrogen-oxygen mixture ratios. They concluded that the design of injectors should be based on the geometry of the nozzle and recommended that all new nuclear engine designs undergo similar testing during the design phase.³¹³ These copper cannon tests at J-1 would continue for several more years.

Missile Dynamics

On 23 October 1958, U.S. Army officials watched their Jupiter C vehicle roar into the night skies above Cape Canaveral carrying an inflatable satellite. The ground crew lost contact with the vehicle 2 minutes into the launch, just as the second stage was about to fire.³¹⁴ It was just one of NASA's 25 failures in its first 37 launch attempts in 1958 and 1959.³¹⁵ The officials suspected that vibrations from the launch caused the Jupiter C's payload to literally fall off the rocket, but they conceded, "it's like trying to reconstruct an accident when you have no witnesses."³¹⁶ The Jupiter C was not the first missile lost because of oscillations referred to as "POGO."^m POGO is a cyclical phenomenon in which engine thrust vibrations lead to a longitudinal bending or distress, which is perpetuated by overcompensation of the vehicle's steering system. This not only weakens the vehicle's structure but affects the thrust performance, damages wiring and circuitry, and increases pressure on the propellant tanks.³¹⁷

These types of losses were frustratingly difficult to troubleshoot, so Lewis engineers designed the E Stand to subject full-scale missiles to vibrations similar to those that would occur during an actual launch. Researchers could determine if the shaking damaged hardware or electronics, adjust the rocket's steering system to minimize the vehicle's bending, and study the effect of combustion chamber pressure levels on propellant flow.³¹⁸ "When there is a mission failure in flight, it's pretty hard to pinpoint the cause," explained Assistant Director Bruce Lundin. "A failure on the ground is not really a failure because you can find the cause and correct it."³¹⁹

Researchers had conducted some basic vibrational studies using small shaker rigs at Lewis Field, but the 30-square-foot by 117-foot-tall E Stand was large enough to accommodate a 55-foot-long Atlas missile.³²⁰ The missile was suspended by a steel cable from a spring box, hydraulic cylinder, and load cell near the top of the stand. This suspension system allowed the vehicle to remain free from restraints. A 15,000-pound-force exciter located at the base of the stand could shake the vehicle up and down, while a 200-pound exciter on the side provided lateral vibrations.³²¹ Engineers used a large amplifier in an adjacent blockhouse to adjust the amount of force for a particular run. This large amplifier was generally operated just below the broadcast band, so it emitted a low hum. Henry Pfanner recalled that an engineer had created a speaker cone and placed it on top of the amplifier to play a Little Richard record.³²²

In 1961 researchers began using the E Stand for smaller-sized tests that did not take advantage of the facility's height. These included shake tests of a trial hydrogen tank, the Space Electric Rocket Test (SERT), and the Mercury Evaporation & Condensing Analysis (MECA) experiment.³²³ The legacy of the E Stand, however, is firmly tied to the Atlas/Centaur launch vehicle.

^mPOGO is a cyclical phenomenon in which engine thrust vibrations lead to a longitudinal bending or distress.

Centaur's Inauspicious Start

Centaur was critical to NASA's near-term space missions. The vehicle's manufacturer, General Dynamics, boasted, "No other space vehicle in the free world is capable of such a wide range of missions."³²⁴ As the first space vehicle to operate on liquid hydrogen and liquid oxygen, Centaur's development was imperative not only for its own missions but for the technology for the Saturn rocket. Lewis engineer Edward Otto explained in April 1962, "Centaur points up all the problems we expect to encounter in future vehicles, and its performance will point up necessary changes in design that can be incorporated in future vehicles."³²⁵ In addition, NASA committed to using the Atlas/Centaur to deliver a series of *Surveyor* spacecraft to the lunar surface in preparation for the *Apollo* landings. Under the management of the NASA Marshall Space Flight Center, however, Centaur had already missed its targeted first launch date in January 1961.³²⁶

So on Wednesday afternoon 9 May 1962 there were many anxious eyes watching the Atlas/Centaur lift off from Cape Canaveral on its maiden flight. Fifty-four seconds later, the vehicle burst into flames and plummeted into the Atlantic.³²⁷ Although it was just the first of eight developmental test flights designed to work out any problems with the vehicle, the failure had significant implications across NASA. Congress held hearings on the situation, and NASA grappled with its options during the summer of 1962. Although key figures such as Wernher von Braun advocated for the program's cancellation, it became apparent that Centaur was the only vehicle capable of hauling *Surveyor*.³²⁸

In September 1962 NASA decided to transfer the Centaur Program from Marshall to Lewis. NASA Administrator James Webb said at the time, "Lewis engineers started the study of liquid-hydrogen propulsion in 1950 and began a series of test firings of a 5000-pound-thrust hydrogen engine in 1953. Combining hydrogen propulsion development programs, such as Centaur and the M-1ⁿ at Lewis with their on-going liquid-hydrogen technology program should benefit both efforts."³²⁹

Under the close watch of Director Abe Silverstein, Lewis embarked on a crash effort to remedy Centaur's problems and keep the developmental launches on schedule. This included examination of an alternative insulation system at J Site and the structural dynamics testing in E Stand.



Image 75: A Centaur stage is lifted into E Stand just before dawn in January 1964. Centaur was powered by two Pratt & Whitney RL-10 engines, which ran on liquid hydrogen and liquid oxygen (GRC-1964-P-01084).

³²⁴The Agena second-stage rocket and the M-1 rocket programs were also transferred to Lewis in October 1962. At 1.2-million pounds of thrust, the M-1 was the largest liquid hydrogen rocket ever attempted.

Reconsidering Centaur's Insulation

The maintenance of a cryogenic fluid's low temperatures is one of the most critical design issues for space vehicles that run on high-energy fuels. Liquid-oxygen tanks frost over creating a natural thermal protection. Moisture on liquid hydrogen tanks, however, turns into liquid-air condensation which causes a temperature increase in the tank.³³⁰

Because liquid hydrogen is kept in a near-boiling state, even a slight increase in temperature can cause the propellant to evaporate. Heat sources include atmospheric conditions at the launch pad, aerodynamic heating during the launch, solar radiation, and heat from the rocket engines and electronics during spaceflight. The resulting hydrogen vapor is vented out of the tank, robbing the spacecraft of fuel critical to the completion of the mission.³³¹ Lewis researchers expended more effort studying thermal retention systems than any other aspect of tank design during the 1960s. Much of the work was conducted at the Rocket Systems Area.

James Dewar's eponymous double-walled storage vessels were widely used for ground storage, but their weight made them impractical for spaceflight. So tank developers, dating back to Robert Goddard, turned toward methods of applying either interior or exterior insulation to standard single-walled tanks. There was only a minute amount of available data on lightweight cryogenic tank insulation in the 1950s. Lewis researchers compared the thermal properties of materials such as cork, balsa, glass laminate, and foam. Initial studies demonstrated the good performance of heavy corkboard and the benefits of using a thin external seal over the insulation.³³² Subsequent investigations showed that low-density foam provided an adequate thermal barrier for short-term missions, but questions remained regarding its form, application, and sealing.³³³

General Dynamics designed Centaur with four fiberglass insulation panels that were jettisoned during separation of the stages. Lewis engineers had been concerned with General Dynamics's inattention to development of the insulation system for some time.³³⁴ During the unsuccessful first launch attempt, the failure of the panels caused the tank to overheat which sparked the explosion.³³⁵ A Marshall postfailure report stated that the "Centaur tank insulation material is not optimal, and the method of construction and mounting is poor."³³⁶



Porter Perkins and his colleagues from Lewis's Materials and Structures Division began investigating different approaches to insulating Centaur's tank, using three of the most effective methods from Lewis's previous experiments—corkboard affixed to the tank, foam panels wrapped against the tank, and foam panels with a liquid-nitrogen film applied to the exterior.³³⁷

Perkins began by studying the heat transfer rates of the three systems on a small aluminum tank at the Rocket Systems Area's Tank Test Facility (J-4). The staff filled the pressurized tank with cryogenic fluid then measured how long it took to evaporate. This could take hours or even days. Although all three of the insulation methods performed relatively well, the researchers decided to pursue the constrictively wrapped foam panels, which weighed the least. Unlike Centaur's current insulation panels, the wrapped insulation would not be jettisoned during flight.³³⁸



Image 76: Perkins in 1958 (GRC-1958-C-47794).

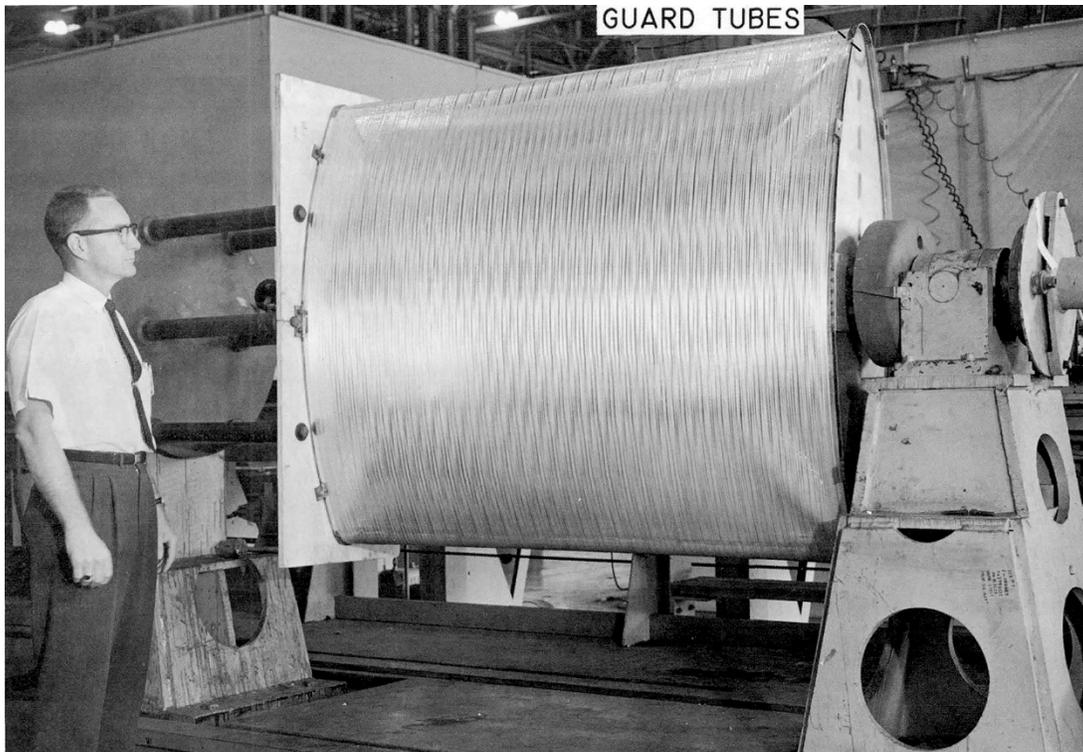


Image 77: A subscale insulated tank having a full-scale Centaur tank radius with a constrictive nylon wrap. NASA contracted Goodyear to fabricate four of the tanks and wrap three of them with a 160-strand-per-inch nylon constrictive wrap, and the fourth with a 64-strand-per-inch fiberglass binding³³⁹ (NASA TM X-52004, Fig. 5).

In the fall of 1963 Lewis obtained four specially designed 5-foot-long flask-shaped tanks that simulated the curvature of the Centaur tank. Goodyear Aerospace Corporation applied the rigid polyurethane foam panels to the tanks and sealed them with a Mylar- (DuPont Teijin Films) encapsulated aluminum laminate. They then used a large winding machine to wrap the tanks with a nylon constrictive wrap.³⁴⁰

The Lewis researchers measured the boiloff rates for these tanks in ground hold conditions at the J-4 vertical stand. They then repeated the tests in the Vacuum Environment Facility (J-3), which could simulate postliftoff conditions by lowering the chamber pressure and using infrared lamps to replicate aerodynamic heating. Perkins and his colleagues were pleased to find that, despite some minor leaks, the constrictively wrapped foam insulation performed well in both standby and launch phases. Alternative winding patterns did not impact the results.³⁴¹



The researchers used their findings to compare the wrapped insulation to Centaur's jettisonable panels. They found that their new system did not provide the same amount of thermal protection as the current system and that it would require unwrapping the tank for defueling on the ground. Nonetheless, the constrictive wrap system would simplify the launch procedures, remove the need for a helium purge system, and eliminate the danger of a jettisoned panel striking the vehicle. Lewis felt that this made the comparison of the two systems competitive.³⁴²

General Dynamics continued to use the jettisonable fiberglass panels for nearly 30 years. The company resurrected the foam insulation concept in the 1980s and formally instituted it in 1992. Virginia Dawson and Mark Bowles noted, “The switch to foam insulation, not only increased performance and reliability but also reduced cost. As a result of successful implementation, the new philosophy of continuous improvement permeated the company.”³⁴³



Image 78: Constrictively wrapped full-scale Centaur tank in the J-4 test stand. Twenty foam panels were affixed to the tank, covered with the Mylar and aluminum laminate, an aerodynamic shield, and the constrictive wrap (NASA TM X-52004, Fig. 10).

Lifting the Flight Restraint

Both Atlas and Centaur had a unique thin outer skin that relied on internal pressurization to maintain its shape. Marshall had had serious reservations about this balloonlike design and indicated that winds of less than 2 knots could require launch restrictions.³⁴⁴ With the acquisition of the Centaur Program in the fall of 1962, Lewis wanted to test the Atlas/Centaur’s structural integrity in their new E Stand.

Lewis engineers designed E Stand to accommodate full-scale missiles, but it was not large enough to hold a missile and an upper stage. NASA provided \$875,000 from the Centaur transfer budget to modify E Stand. The alterations included extending the height of the stand by 27 feet, adding a 110-foot-tall rolling door (then the nation’s largest), strengthening the support structure and weather protection, installing a new hydraulic shaker, and improving the data acquisition and fluid pumping systems.³⁴⁵

There was intense pressure to complete the modifications, which began in May 1963, in time to test the Atlas/Centaur before the launch scheduled for November 1963. The delayed shipment of new equipment strained the Rocket Systems Division’s resources and schedule. After working 14-hour days throughout the summer, the crew completed the work on time in August.³⁴⁶



The Centaur Program Office first needed to verify that the Atlas booster could handle a heavy stage like Centaur. “The Centaur weighs about 39,000 pounds loaded,” explained Bruce Lundin. “Under six G’s this will mean a quarter of a million pounds pushing down on the Atlas booster. This is nearly twice as much load as Atlas ever carried before. We don’t want to learn in flight that it is not strong enough to carry the load.”³⁴⁷

On 31 July 1963 a General Dynamics trailer and police escort delivered an Atlas to Plum Brook.³⁴⁸ Plum Brook technicians replaced the Atlas engines with mass models and hoisted the booster into E Stand in August 1963.³⁴⁹ On 11 October 1963 the Atlas structure withstood 248,000 pounds of pressure, the maximum force that would be experienced in flight. The test was successfully repeated with the addition of heating elements to simulate aerodynamic heating during launch. The engineers then subjected the Atlas to a maximum-bending test without any issue. The Rocket Systems Area Test Operations Report noted, “During the month of October, several important test milestones were passed, all of which culminated in lifting of the flight restraint for AC-2 [Atlas/Centaur 2].”³⁵⁰



Image 79: Atlas missile is delivered to Plum Brook in July 1963. The vehicle had to avoid tight turns, most bridges and underpasses, and large urban areas during its 2,500-mile trek from the General Dynamics plant in San Diego to Sandusky. (GRC-1963-C-65589).



Image 80: General Dynamics designed a unique 64-foot-long cradlelike trailer to transport the missile. It was so large that additional drivers were placed at the rear of the trailer to guide it around turns (GRC-1963-P-01708).³⁵¹

Meanwhile, the Rocket Systems Division staff rushed to reconfigure the E Stand setup for the next series of tests, which would include both the Atlas and Centaur. An actual Centaur was not available in time for these runs, so the researchers used a model with simulated propellants in the tanks.³⁵² In mid-November the Atlas/Centaur successfully withstood a series of longitudinal vibration tests.³⁵³

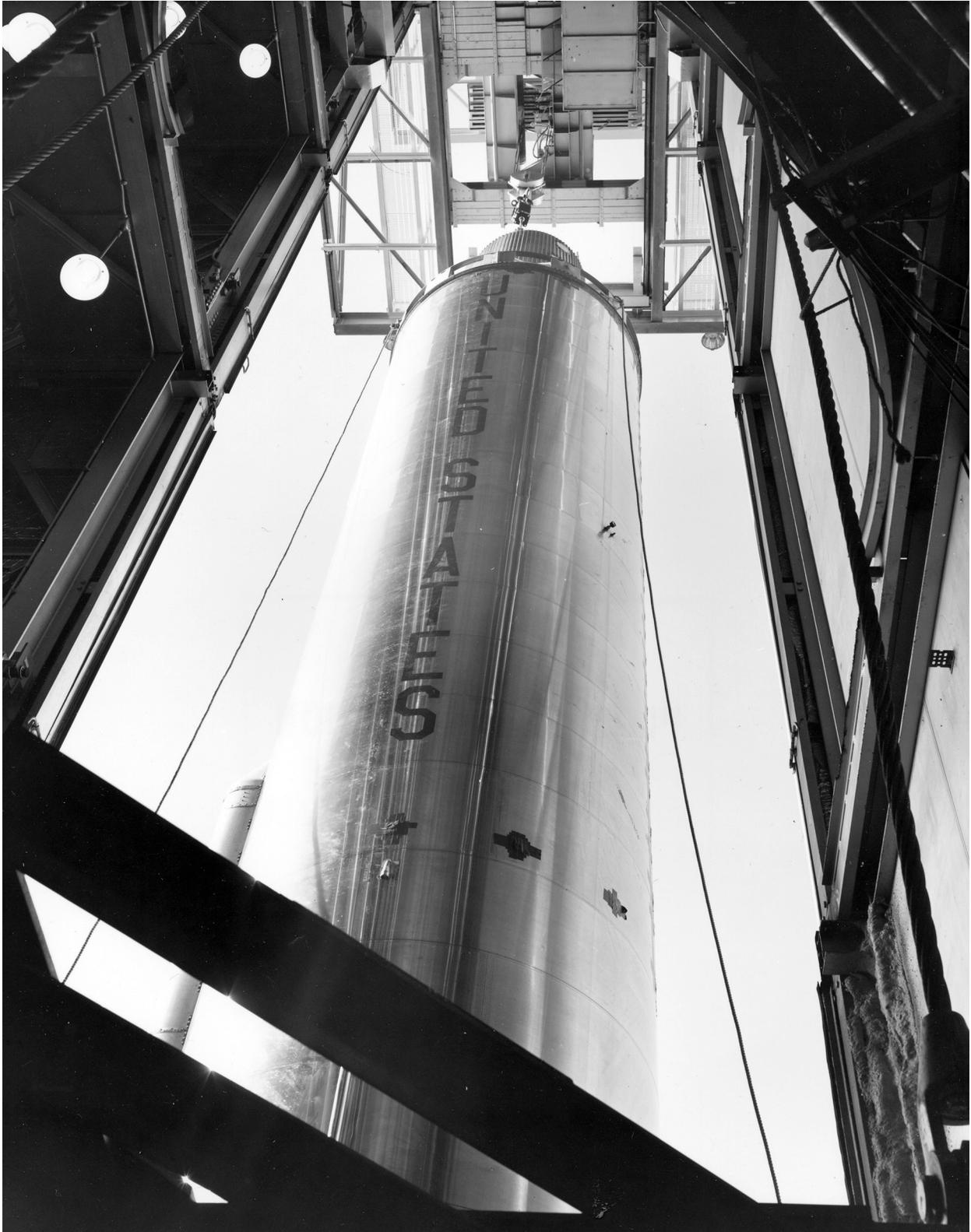


Image 81: Installation of Atlas stage into E Stand in August 1963. The vehicle had to be pressurized during the process to avoid damage to the aluminum shell (GRC-1963-P-01716).



On 27 November 1963 Silverstein joined more than two dozen Lewis engineers at Cape Canaveral for Lewis's first attempt at launching a Centaur (AC-2). Ninety other Centaur staffers monitored the proceedings from the hangar in Cleveland. The Centaur Program Office had spent the previous 13 months preparing for the launch, which had been delayed by the assassination of President John F. Kennedy the previous week.³⁵⁴

A scrub appeared eminent as cloud cover forced the suspension of the countdown in the morning. The skies cleared around noon, however, and the countdown resumed. At 2:03 p.m. the 109-foot-long Atlas/Centaur roared into the sky. Four minutes and twenty seconds later the Centaur upper stage separated from the booster and raced into orbit, where it remains in 2016. The Lewis personnel burst into cheers, and NASA managers breathed a sigh of relief.³⁵⁵ Centaur was back on track, and Lewis proved it could manage a large rocket program. The AC-2 launch was most significant, however, as the first full-scale demonstration that liquid hydrogen could be used as a propellant.



Image 82: AC-2 launch on 27 November 1963. It was Lewis's first launch attempt and the first successful launch of a liquid hydrogen-fueled rocket (NASA).



Image 83: Centaur E Stand Project staff receives Lewis's first ever Agency-wide Group Achievement Award on 23 June 1964. The 12-person group was cited for "significant contributions resulting in the successful completion of research testing of the Atlas 116 D booster under simulated loading and environmental conditions and providing data vital to the first flight of the Centaur vehicle." Front row, left to right: George Thomas, Alvin Schultz, Abe Silverstein, Alan Johnson, and William Thompson. Back row: Glen Hennings, Russell Koger, Joseph Gillete, Norman Schroeder, Darrell Baldwin, Lawrence Gentile, Donald Cooksey, and Robert Siewert (GRC-1964-P-01398).

NASA Takes Over Plum Brook

On 15 March 1963 NASA Lewis finally exercised its option to utilize the remaining 2,800 acres at Plum Brook. NASA and the army signed an agreement in which Lewis would no longer lease the Plum Brook property, but assume full control. NASA was now in possession of the reactor's 500 acres, the Rocket Systems Area's 2,725 acres, and the remaining 2,800 acres at the southeast end, which would be the site for the Space Power Facility.³⁵⁶

After leasing the additional land for the Rocket Systems Area in 1958, Lewis had been anxious to clear out the Plum Brook Ordnance Works (PBOW) structures and decontaminate the area, which included three trinitrotoluene (TNT) manufacturing complexes and three acid-producing facilities.³⁵⁷ Negotiations with contractors, however, delayed the work. In 1962 Lewis began clearing the TNT Area No. 2 where B-1, B-2, and B-3 would be built.³⁵⁸ With the formal acquisition of the land in 1963, NASA sought to expand the decontamination work to the TNT areas to the west of the Rocket Systems Area and at the future Engineering Building site and to the two former acid producing sites.³⁵⁹

The acid area structures could be merely washed down with water and disassembled.³⁶⁰ The TNT buildings were more difficult because the crews could not use cutting torches in such potentially explosive areas. These structures were often just burned to the ground. The removal of the underground flumes, pipes, and remnants of TNT was dangerous and painstaking. A local reporter noted, "The [underground] carry-off pipes were a bit like rattlesnakes...where there was one, there usually was at least one more in the immediate vicinity."³⁶¹ Once located, the demolition team loaded the offending structures with straw and ignited them. Small explosions were frequently heard across Plum Brook that summer.³⁶² After burning the structures out, the demolition companies salvaged the steel infrastructure. The burning took place over several days in mid-August 1963, but the removal of debris and required several months.³⁶³

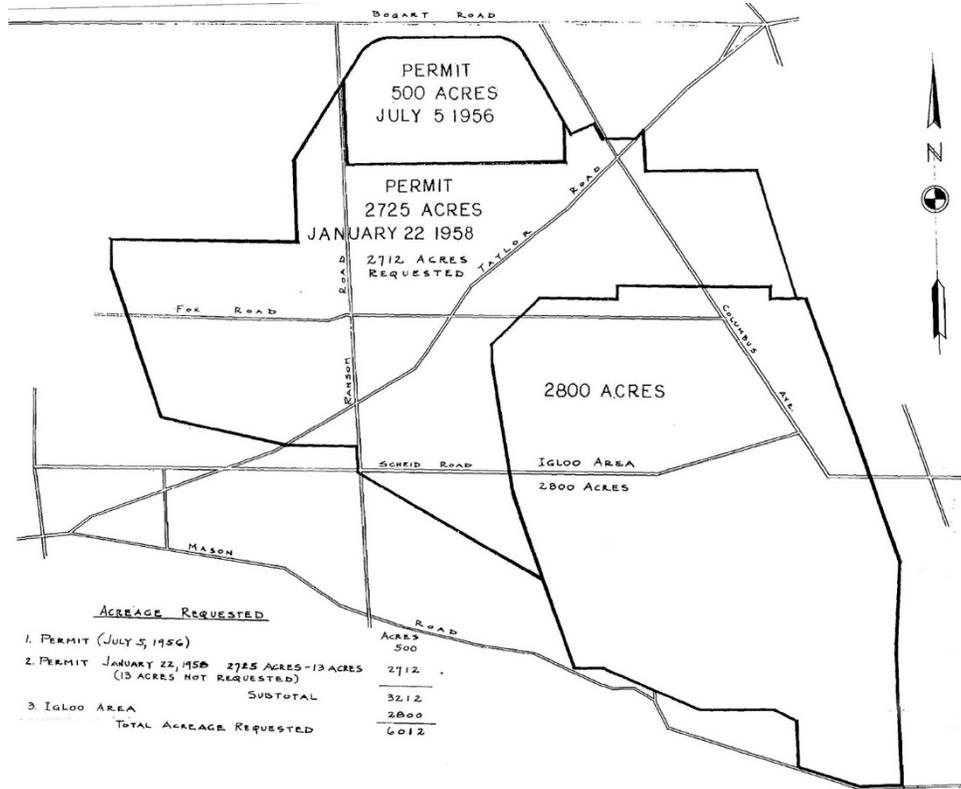


Image 84: Diagram of Plum Brook showing Lewis's three primary land acquisitions (NASA).



Image 85: Destruction of unneeded PBOW structures in the summer of 1963 (GRC-2016-C-05582).



Image 86: Destruction of unneeded PBOW structures in the summer of 1963 (GRC-2016-C-05176).

Fallout Shelter

Nuclear war was a tangible possibility in the early 1960s. On 25 July 1961 President Kennedy informed the nation that the United States was prepared to use force if necessary to prevent the Soviet Union from carrying out its plan to block the United States from West Berlin. That day Lewis management issued a memorandum summarizing the steps to be taken during an attack on the center.³⁶⁴

After the Soviet Union tested its first atomic weapon in 1949 a web of local and state civil defense organizations emerged to deal with the effects of a nuclear attack, and President Harry Truman created the Federal Civil Defense Administration to educate citizens on survival practices. In 1952 the NACA instructed its laboratories to develop plans to shield personnel from an attack, recover damaged buildings and equipment, and continue operations from remote locations. Lewis, which coordinated with the county's civil defense group, established teams responsible for issues such as rescue, communications, and fuels control;³⁶⁵ installed military warning sirens and whistles;³⁶⁶ and conducted periodic full-scale drills.³⁶⁷

During the Cuban Missile Crisis of October 1962, the Office of Supply Management informed NASA that it should stock 30 days of food and supplies at relocation sites.³⁶⁸ Lewis considered a direct strike on Sandusky unlikely, so it initiated plans to operate the center remotely from Plum Brook in the event of an attack. Plum Brook Manager Hap Johnson outlined a formal plan to evacuate key Lewis personnel and their families to a command center at Plum Brook. The plan described scenarios in which there was no damage, minor damage, and extensive damage, with the number of evacuees increasing in each instance. The Cleveland personnel would use existing Plum Brook offices and in some cases stay in the homes of Plum Brook employees.³⁶⁹

Johnson and Ross Braig also examined the conversion of the concrete PBOW bunkers into fallout shelters. The bunkers, built during World War II to store TNT, were designed to contain massive explosions. In 1965, they identified 66 available bunkers, each capable of sheltering 33 people. They concluded that the long-term relocation of Lewis's key personnel and families would require the installation of electric and water lines and the construction of a concrete barrier wall inside.³⁷⁰ By this time, however, tensions between the United States and Soviets had abated, and management never pursued the bunker modifications.

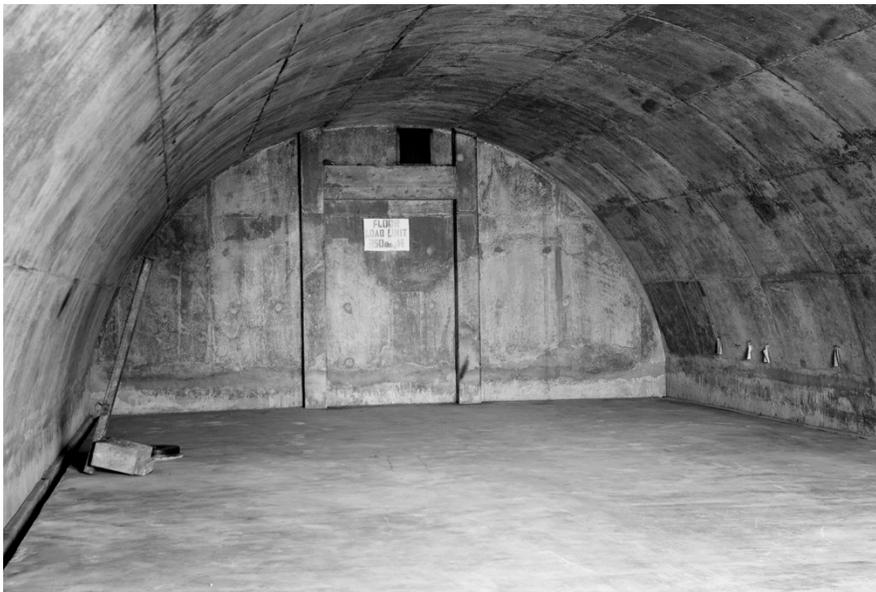


Image 87: Interior of PBOW bunker. In the mid-1960s NASA considered using them as fallout shelters during a nuclear attack. Each was estimated to hold 33 people (GRC-2009-C-01188).

Mars Missions

“Men to Mars Possible in 60’s, Experts Say,” announced a sanguine *Science News* headline in January 1960.³⁷¹ In the early 1960s scientists and engineers predicted a myriad of ambitious future space missions, including human journeys to Mars, human flybys of Venus, and an elaborate colonization of the Moon. Lewis studied a number of technologies to support these ambitious schemes.

Human exploration of Mars has long been the subject of both science fiction and scientists. In the 1940s and 1950s Soviet rocket engineer Sergei Korolev and Werhner von Braun openly discussed sending humans to Mars, but Mars travel was generally still seen as fantasy until the space age. Lewis researchers identified nuclear and electric propulsion requirements for a Mars mission in 1957. In 1960 they obtained funding to develop a comprehensive mission analysis for the effort. They devised a theoretical 420-day round trip journey with a nuclear rocket to be launched in May 1971. The plan was to launch the spacecraft into Earth orbit, perform any required assembly, then journey to Mars. The spacecraft would enter Mars orbit and send a smaller vehicle to the Mars surface. The procedure would be reversed for the return journey.³⁷²

The Lewis researchers presented the findings, NASA’s first human Mars mission analysis, at a professional conference in January 1961. Five months later President Kennedy announced that the United States would be sending humans to the Moon, and the Mars effort was relegated to a subordinate role. In addition, NASA’s decision to forgo its direct ascent to lunar orbit for Apollo led to a deprioritization of more powerful launch vehicles such as NERVA and Saturn’s successor, Nova. It also became apparent that much more information on radiation levels in space was required before humans could be sent to Mars.³⁷³

Marshall, which was seeking post-Apollo uses for the Saturn rocket, sponsored a series of studies in the early 1960s regarding the logistics of sending humans on a flyby mission of Mars to obtain some of the information required before a landing could be attempted. One plan used a two-stage nuclear rocket, another used the Saturn C-5, and a third proposed a series of modular nuclear-powered ships. The target date for implementation of these plans was the mid-1970s.³⁷⁴

Thermal Protection

The Saturn and NERVA rockets were essential to these advanced missions. With either chemical or nuclear rockets, high-energy cryogenic propellants were a critical element. These extended missions would require the storage of the cryogenic propellants both on the spacecraft as it traveled across the solar system and in fuel depots in space.³⁷⁵ The refueling of the spacecraft during the mission would be essential, but it had never been attempted in a space environment. Traditional liquid fuels such as kerosene were relatively easy to store in space, but their performance was limited. High-energy cryogenic fuels performed much better but required a great deal of research and development before they could become a reality. Thermal



Image 88: Lewis researchers examine a model of a nuclear rocket concept in November 1960 (GRC-1960-C-54776).

protection was the most pressing concern. Even a slight temperature rise could cause the cryogenic fluids to evaporate.

Taking into account different trajectory considerations, Lewis researchers devised a variety of methods to defend the tank against both internal and external heat sources. By the mid-1960s a consensus emerged that the use of multilayer foil insulation for the near-Earth phase of the mission, in conjunction with the proper orientation of the spacecraft behind shadowshields for the long-duration portion of the flight, could adequately prevent heating without imposing undue weight.³⁷⁶ The multilayer insulation systems consist of alternate layers of reflective foil and Mylar (DuPont Teijin Films) surfaces separated by a vacuum. These multilayer designs, however, were difficult to affix to the tank and were subject to failure if the vacuum was compromised. Shadowshields were externally mounted guards deployed to block solar radiation once the vehicle was in space.

Throughout the 1960s Lewis's Cryogenic Fluids Management Division worked with tank manufacturers including Arthur D. Little (ADL), Lockheed, and Air Products to develop lasting thermal protection systems. The tank test sites at the Rocket Systems Area provided key research data on several types of insulation in the early 1960s and continued to advance multilayer insulation development until the mid-1970s.



Carl von Linde, who developed the first industrial liquefaction of hydrogen in Germany during the 19th century, created a U.S. company, Air Products, in 1907. Air Products established plants throughout the country, including a facility about 60 miles east of Lewis in Painesville, Ohio.³⁷⁷ Air Products not only supplied bottled gases and liquids but also manufactured the containers to store them in, including propellant tanks for space vehicles.

In the early 1960s NASA contracted with Linde's company to develop a thermal protection system referred to as "superinsulation." Although superinsulation became a generic term to describe multilayer systems, this early 1-inch-thick version consisted of 70 alternating aluminum and fiberglass layers sealed with an evacuated jacket that was fastened with glue to the tank. The baglike jacket was composed of a thin layer of aluminum between two layers of Mylar. A diffusion pump removed the air from it. Engineers considered superinsulation particularly useful for ground-based applications.³⁷⁸

During April and May 1963 Porter Perkins and Mario Colaluca tested the superinsulation system on a 150-gallon Linde tank in the J-3 vacuum chamber. They sought to determine the effect of typical atmospheric pressure on the flexible jacket. The Rocket Systems Division staff suspended the tank by its neck in the J-3 vacuum chamber and subjected it to a variety of pressures in both atmospheric and simulated space conditions. They also filled the tank with hydrogen and let it evaporate for 12- to 24-hour periods.

Linde's vacuum jacket functioned as designed. The researchers found that the heat transfer increased during the ground hold, but Perkins and Colaluca surmised that it was due to the imperfect nature of the



Image 89: Linde superinsulated tank at the J-3 facility in May 1963. The 150-gallon stainless steel tank was designed to be suspended by its neck, so it was not a true space tank (GRC-1963-P-01446).

first test. They felt confident enough with the results to proceed with the program.³⁷⁹ It was Lewis's very first test of a multilayer insulation system. In June 1963 the staff moved the Linde tank to the J-4 test stand where the researchers subjected it to 30- and 48-hour boiloff tests in atmospheric conditions.³⁸⁰



NASA Lewis also contracted with ADL to develop an aluminum and Mylar multilayer insulation system and worked with the firm to improve it. In the summer of 1963 Rocket Systems Division engineers modified the J-3 test cell to test the system on an experimental ADL tank. The J-3 alterations included the extension of the cylindrical vacuum chamber, the addition of a second floor, and installation of a monorail crane. The test runs in December 1963 revealed that the insulation allowed much greater heat transfer than ADL had predicted. In June 1964 the staff tested a different ADL tank equipped with urethane foam insulation at the J-4 atmospheric stand. This was followed by a J-3 vacuum test of a polyurethane- and laminate-insulated tank, which once again had greater thermal losses than the ADL engineers had projected.³⁸¹



Image 90: Insulated ADL calorimeter installation in the 5-foot-diameter J-3 test chamber (GRC-1963-P-01653).

Lewis extended the ADL contract so that the company could improve the performance of insulation materials and develop a new calorimeter^o to test the system.³⁸² In early 1967 NASA technicians wrapped five layers of ADL's gold, Mylar, and foil insulation around the calorimeter in J-3. This time the tests confirmed the positive findings ADL had found at their facility.³⁸³ The engineers, however, struggled to secure the insulation around the tank's various supports, piping, and electrical work. The J-3 tests improved the understanding of application methods, but further research was required before the insulation could be considered practical.³⁸⁴

During the 1960s Lewis and ADL partnered to test over a dozen insulation systems in simulated space conditions. ADL engineers considered the J Site tests important to their development of multilayer insulation systems and techniques for applying them to tanks.³⁸⁵ These early thermal protection investigations spurred Lewis to design a larger tank facility at the Rocket Systems Area. There, Lewis researchers would conduct more elaborate insulation tests in the mid- and late 1960s.

Lewis's Pumping Experts

In 1961 Abe Silverstein stated, "Of greatest importance to the development of the liquid-hydrogen engine is the establishment of sound design methods for the pumps."³⁸⁶ Turbopumps drive the propellant from the storage tank to the engine at high rates of speed and pressure. The pump's rotor rotates tens of

^oA calorimeter is a tool designed to measure the production and transfer of heat and energy. Calorimeters are basically insulated tanks with temperature measurement devices inside.

thousands of times each minute in order to move hundreds of gallons of propellant at the correct speed and pressure level. The turbopumps must perform this task reliably thousands of times per mission, often for mere seconds at a time.³⁸⁷

Rocket designers select a tank pressure level that will provide the lowest pressure at which the turbopump can operate efficiently. The lower the pressure, the thinner the tank walls can be and the lighter the vehicle. If the tank pressure is not sufficient, the temperature of the liquid rises as it travels to the pump, causing the formation and bursting of bubbles. The phenomenon, known as cavitation, limits the turbopump's performance and can cause physical degradation of the pump.³⁸⁸

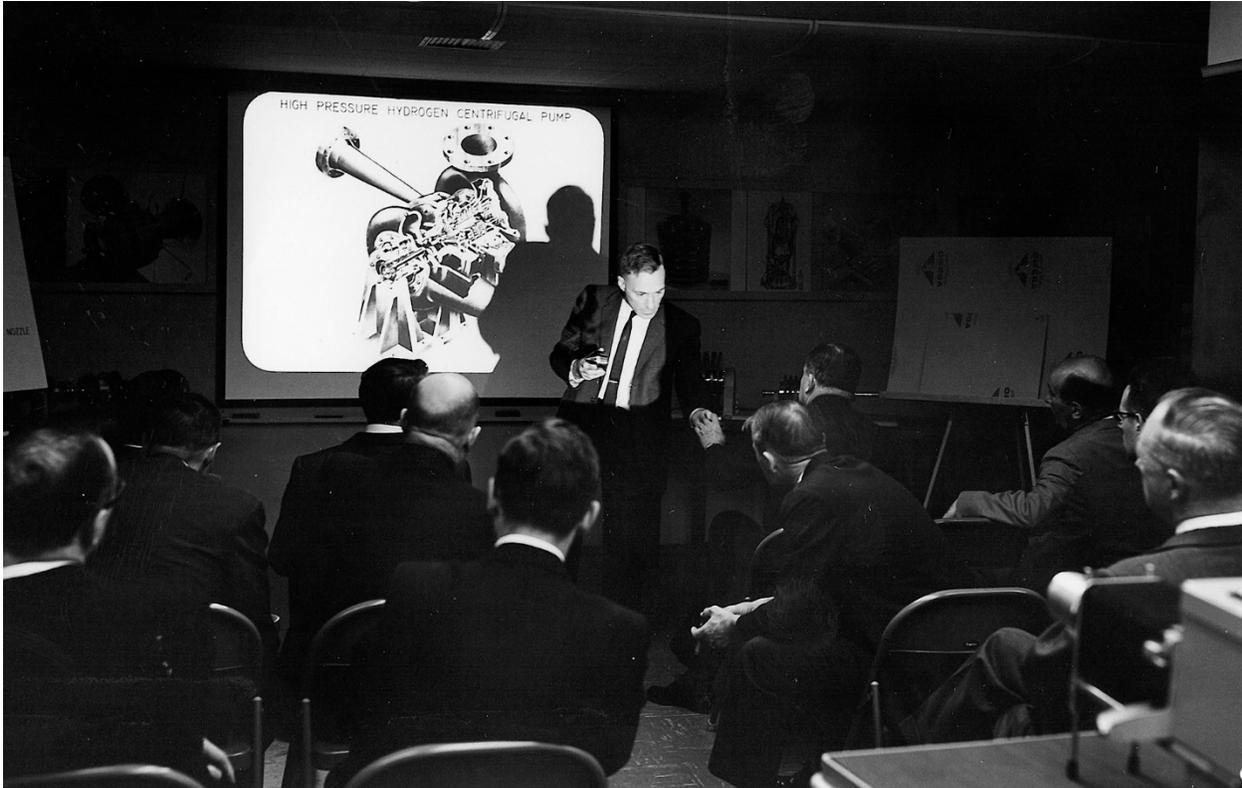


Image 91: Irving Pinkel, Chief of the Fluids Components Division, briefs Administrator James Webb and other NASA officials on hydrogen turbopump research during a December 1961 tour of Plum Brook (GRC-1961-C-58720).

Rocket engine manufacturers sought basic information on flow rates and pressure increases to improve their turbopump designs.³⁸⁹ To address this issue, Silverstein assigned many of the former Compressor and Turbine Division's engineers to the new Fluid Systems Components Division in July 1957.³⁹⁰ These engineers used their experience with aircraft engines to tackle cavitation and a myriad of issues surrounding turbopumps for rocket engines.³⁹¹ The Flow Systems Branch, which cut their teeth on the hydrogen fuel-handling problems for Project Bee in the mid-1950s, went on to study fuel tanks, flow lines, boiling hydrogen, and other issues with cryogenic propellants.³⁹² Much of this work would be conducted at the Rocket Systems Area.



The center had three water facilities to study turbopumps at Lewis Field, including the Water Tunnel in the Engine Research Building. The use of water was not only cost-effective but it also permitted longer test runs and better flow visualization. Pumping data from water, however, did not always translate well to

cryogenic liquids. The researchers had to verify the data from their water runs with expensive and potentially dangerous tests using hydrogen, fluorine, or other cryogenics.³⁹³ Testing high-speed turbopumps with these fluids posed a hazard at Lewis Field. Robert Kozar explained, “You can’t do this kind of work at in Cleveland, because it’s very dangerous. If the turbopump decides to blow itself apart, you know the shrapnel from it is going to be a big deal, and it’s going to injure people and stuff like that.”³⁹⁴

The open expanses of Plum Brook alleviated those concerns, and turbopump test facilities were an integral component of the Rocket Systems Area. The Liquid Hydrogen Pump Facility (A Site) and the Turbopump Facility (C Site) were designed to test inlets and inducers for hydrogen and oxygen pumping systems. C Site was also capable of analyzing pumps in boiling hydrogen. The Controls and Turbine Test Facility (D Site) was dedicated to testing pump turbines; the Pilot Plant (G Site) studied small-scale models of turbines, bearings, and pumps; and the Fluorine Pump Facility (I Site) was specifically designed for liquid-fluorine pumps.

Taking Pumps to the Next Level

In the early 1960s Lewis was working with Rocketdyne and Aerojet to improve turbopump performance by identifying optimal rotor blade, turbine, seal, and other component designs.³⁹⁵ The center was concurrently studying these concepts at its own facilities. Rotor blade design was essential to improving axial-flow pump performance. Engineers sought to maximize the amount of pressure each blade could provide in order to reduce the number of stages, and thus lower the pump’s weight, without decreasing the flow rate. They had to determine the load levels that could be achieved without causing fatigue that could damage the pump.³⁹⁶

In the summer of 1961 researchers from the Fluid System Components Division began using the Pilot Plant’s Pump Building to determine the best blade loading for multistage turbopumps. The Pilot Plant runs during 1961 and 1962 confirmed that data from tests in the Water Tunnel could be applied to hydrogen pumps.³⁹⁷

Preparations for follow-up runs using a different blade design dragged out for nearly two years because of delays in acquiring the experimental pump and problems with the facility systems. The charm of the Pilot Plant’s design was its use of existing hardware to minimize expenses and accelerate construction. By the mid-1960s that old equipment became a detriment, however, particularly the data recording equipment. The facility engineer noted in August 1964, “The equipment is undergoing intensive maintenance with the hope of getting ‘just one more job done.’”³⁹⁸

As the engineers and technicians initiated a test of the pump on 14 September 1964, a tremendous blast rocked the entire area. Facility engineer Jim Cairelli was in the control room observing the site through a periscope. “We looked out at it, and there was nothing to look at,” he recalled. “It disappeared. It was kind of scary, but everything had shut down. It was alright except that it had blown the building apart.”³⁹⁹ The blast rattled the Control and Data Building (H Control Building), blew out windows at the Compressor Building, and sent debris flying all the way to E Stand. Even though electrician Roger Hershiser was outside the exclusion zone he remembered feeling his trousers blowing backward.⁴⁰⁰

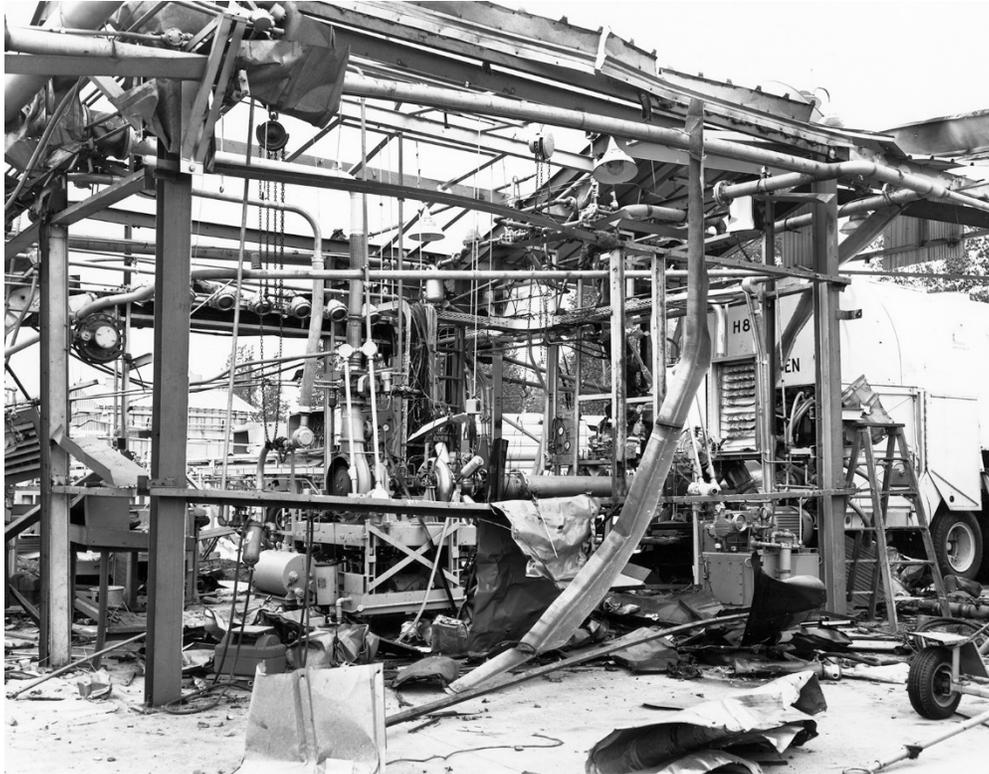


Image 92: Damage to the Pilot Plant's Pump Building following a hydrogen explosion in September 1964. The test rig is visible near the center of the structure, and a liquid-hydrogen trailer is to the right (GRC-1964-P-01562).



Image 93: Damage at the Pilot Plant following a liquid-hydrogen explosion on 14 September 1964. The blast convinced engineers to install a protective concrete wall inside the H Control entrance (GRC-1964-P-1559).

The ensuing investigation determined that liquid hydrogen had escaped from a transfer pipe, vaporized, and exploded when a thermostat sparked.⁴⁰¹ Dick Heath explained, “They got some heavy hydrogen vapor and spark together, and that took care of G Site.”⁴⁰² The building’s sheet metal walls and ceiling were blown away, and there was significant damage to the test hardware, pumping system, and liquid-hydrogen Dewars.⁴⁰³ Replacement of the hardware would have taken some time but would have been relatively inexpensive. Nonetheless, in October 1964 management decided against rebuilding the Pilot Lab. The multistage turbopump program was transferred to A Site.⁴⁰⁴

Fluorine Dreams

By 1961 NASA had selected the liquid-hydrogen/liquid-oxygen combination as the propellant for the Centaur and Saturn upper stages, but Lewis researchers continued their pursuit of liquid-fluorine technology. As the Soviet Union continued adding to its legacy of space firsts, U.S. engineers sought ways to expedite the space program by improving the performance of its existing engine systems. The substitution of fluorine for oxygen was one such possibility. By this time Lewis had tested fluorine with several fuels, including hydrogen, in regeneratively cooled engines with 1,000 to 20,000 pounds of thrust.⁴⁰⁵

On 9 March 1961 Lewis researchers presented a conference paper expressing their confidence that Lewis had developed sufficient technology to demonstrate full-scale, regeneratively cooled hydrogen-fluorine engines and had established proper ground-handling techniques. They argued that the performance of a pressure-fed hydrogen-fluorine system would compete with, if not surpass, that of a pumped hydrogen-oxygen vehicle. They also stated that the fluid’s hypergolicity,^p its stable and efficient combustion, and the reduction of required engine components made fluorine more reliable than oxygen. Fluorine also offered superior engine throttling and a reduction in oxidizer tank size.⁴⁰⁶

Fluorine pumping was one of the issues that gave some engineers pause. Adelbert Tischler, a former Lewis researcher who transferred to headquarters in 1957, later recalled the comparisons between the hydrogen-oxygen system and hydrogen-fluorine systems. He explained, “I felt that pumping was not a serious problem with hydrogen-oxygen systems so long as we were using relatively safe propellants.... What was worrying me was pumping fluorine. I didn’t know whether we could safely build the pumps.”⁴⁰⁷

Lewis researchers, however, felt that fluorine pumps were similar to oxygen pumps except that fluorine required special materials for its seals and bearings.⁴⁰⁸ Plum Brook possessed two sites dedicated to fluorine research—I Site and the Materials Compatibility Laboratory (J-5). Researchers employed these facilities in the early 1960s to analyze fluorine pumping, its effect on gasket materials, and its reactivity with different launch site materials.

^pA hypergolic material is one that has the ability to spontaneously ignite when in contact with another fuel or oxidizer.

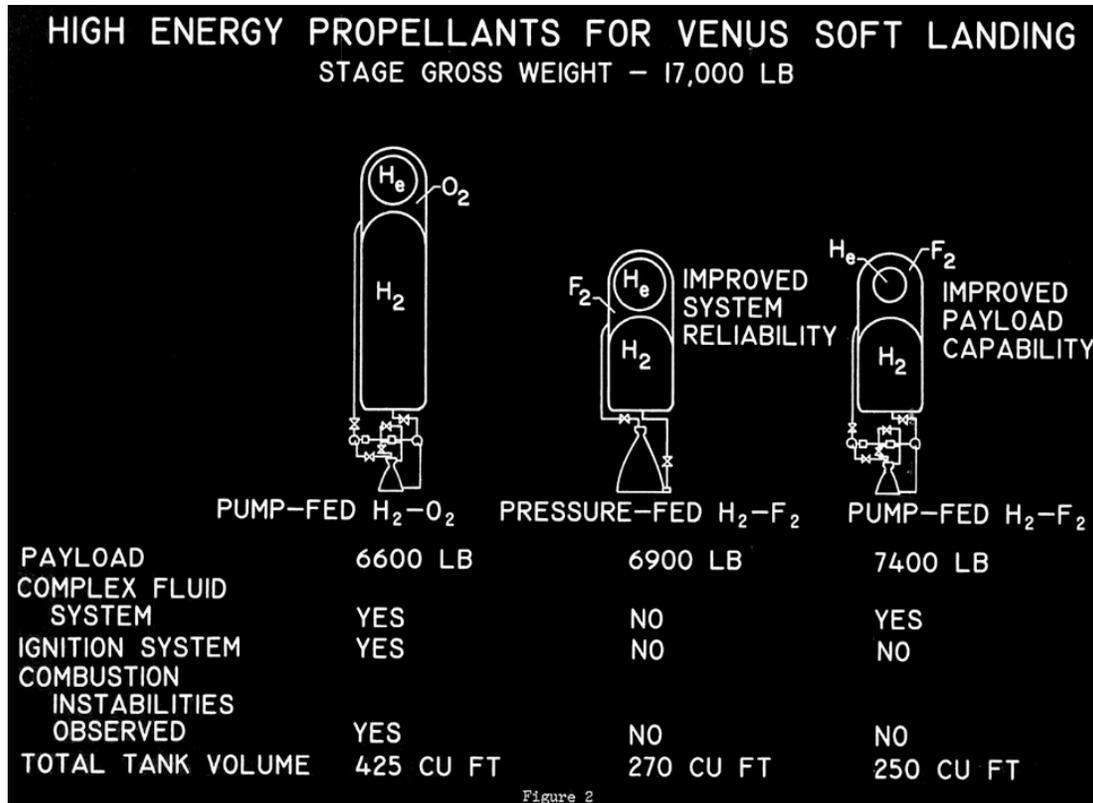


Image 94: Chart from 1962 demonstrating the superior performance of hydrogen-fluorine space vehicles. Fluorine increased payload weights and reduced the size of the tanks (NASA TM X-69544, Fig. 2).

NASA-Designed Fluorine Pumps

Walter Osborne of the Pump and Compressor Branch devised a study to determine the performance of a Lewis-designed fluorine pump in cavitating conditions and the effect of cavitation on the pump's protective passivation coating and the rotating shaft seal. The investigation was conducted on a rotating basis with a series of Pratt & Whitney turbopump tests at I Site, which was designed specifically to test fluorine turbopumps operating at speeds up to 20,000 revolutions per minute (rpm). The experimental pump, which was enclosed in a massive steel containment vessel, circulated liquid fluorine to and from a storage Dewar. The facility could safely discharge fluorine into the atmosphere without significant concentrations downwind.⁴⁰⁹ This was important because ingestion of the pungent chemical could cause serious health problems. "We got some bad whiffs," Don Perdue recalled, "but nothing to go to the hospital for."⁴¹⁰

After months of preparation, Osborne began testing his pump in March 1962. The pump performed well during the first three runs, but the potential hazards of fluorine soon manifest themselves.⁴¹¹ On April 7 a fluorine leak sparked an intense explosion that destroyed the entire test facility. Glen Hennings, who was safe with the staff in H Control, later recalled, "We did not have anything to do except stand around and watch it burn down."⁴¹²



Image 95: View from H Control as smoke pours from I Site after a fluorine explosion in April 1962 (GRC-1962-P-01131).

Lamenting I Site's poor layout, Bucky Walter recalled, "[The explosion] was the best thing that could have happened to it." Engineers redesigned I Site so that the test pump was out in the open, and the staff could use cameras to remotely check for fluorine leaks.⁴¹³ It took the Rocket Systems Division staff over nine months to restore the facility. Although the staff installed a new pump in May 1963, component failures and the lack of replacement parts delayed the program for months.⁴¹⁴

Osborne added an inducer to the turbopump to increase its suction speed. For the upcoming tests, Osborne was particularly interested in the performance of the Kentanium K-162B⁹ seals that went around the rotating drive shaft. The seals had to withstand fluorine's toxicity and perform their primary function without absorbing frictional heat.⁴¹⁵

The pump underwent three runs in February 1964 without damaging the K-162B seals or other components.⁴¹⁶ Osborne then incorporated a larger inducer and redesigned the impeller to determine the effect of even higher pump speeds on the components. A series of runs in July 1964 revealed that wear occurred only in areas where the component had been repaired, reinforcing the idea that fluorine pumps must remain free of contamination. The I Site test program led Osborne to conclude that "it is probable that cavitation damage will not be a problem in liquid-fluorine pumps for rocket applications."⁴¹⁷

⁹The K-162B titanium carbide-nickel composite was used with aluminum oxide.

Pratt & Whitney Fluorine Pumps

Pratt & Whitney also was interested in hydrogen-fluorine rocket engines in the 1960s. They undertook an extensive program to determine the feasibility of substituting fluorine for oxygen in a slightly modified RL-10A engine. The RL-10 was the first commercial liquid-hydrogen rocket engine. Pratt & Whitney conducted full-scale engine testing with fluorine at their facilities in Florida, but relied on I Site to test the RL-10's single-stage centrifugal turbopump throughout 1963 and 1964. They were primarily interested in examining different materials for the seals between the gearbox and the pump. The short-term solution was the use of the Kentanium K-162B, but their engineers were seeking a long-term substitute.⁴¹⁸

During preparations in October 1963, a problem arose with the I Site rig's speed control. Bucky Walter and one of the Controls engineers discovered a loose wire and quickly fixed the problem. The two returned to H Control and started the run.⁴¹⁹ Sixteen minutes later an explosion ripped through the facility. The abort system shut down the pump quickly enough to prevent massive damage to the pump or facility. An investigation determined that pressure changes in the system caused a carbon seal to break down and react with the fluorine.⁴²⁰ Even though the seal was normally impervious to fluorine, Walter explained, "if you move it, you're going to start getting little pieces of carbon off, and you have ignition."⁴²¹

The Rocket Systems Division soon restored I Site, but Pratt & Whitney decided to suspend the fluorine pump investigations until better seal materials were identified. These intensive studies, which included friction tests at Lewis Field, demonstrated that the Kentanium K-162B and alumina combination was the most viable option.⁴²² Pratt & Whitney resumed their fluorine turbopump tests at I Site in March 1964. After a 32-minute run with the new K-162B seals in April, the Rocket Systems Division report noted, "The success of this test has proved that the Pratt & Whitney L-208S33 liquid-fluorine pump is now an operational flight-weight pump for use on the Pratt & Whitney hydrogen-fluorine rocket engine."⁴²³ The I Site runs were the first time that the seal materials had been tested in a full-scale pump under normal operating conditions. The program, which concluded shortly after Walter Osborne's, confirmed that the K-162B/aluminum combination was the best available seal material for fluorine.⁴²⁴

Eating Them Alive

One of fluorine's principal drawbacks is that it reacts easily with other materials. This was a particular problem with engine gaskets, seals, and other components. As early as 1954 Lewis researchers had studied fluorine's corrosion of different metals.⁴²⁵ Harold Schmidt, who became Lewis's resident expert on fluorine, studied the effects of material types, rates of propellant flow, pressure levels, sharp edges in the piping, and contamination during high-speed fluorine flow. Schmidt concluded that the rapid flow, high

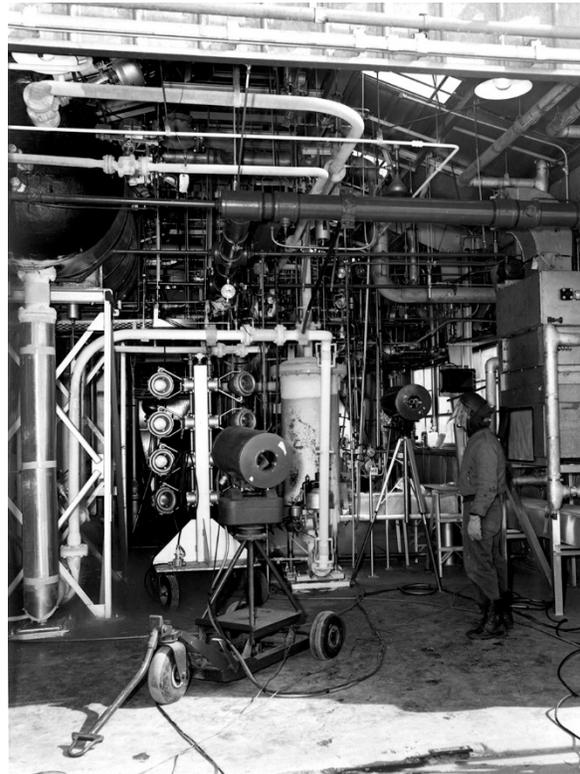


Image 96: Fluorine pump rig inside I Site. Two cameras are set up to film the test (GRC-1962-C-59411).

pressure, and sharp corners were not issues with fluorine, but passivation^r of the system with trace amounts of fluorine and the avoidance of contamination, particularly water, were essential to operating fluorine. He noted that the selection of appropriate materials, proper cleaning of the system, and attention to procedures would lead to successful fluorine behavior.⁴²⁶

During concurrent hydrogen-fluorine engine tests in Rocket Lab, Howard Douglass and Harold Price found that even something as simple as screw threads required special materials.⁴²⁷ Ensuing tests of fluorine's reaction with various liquids, greases, and solids produced varied results which offered no unifying theory. Some samples reacted with gaseous fluorine but not liquid and vice versa.⁴²⁸

In 1961 Lewis continued its fluorine materials compatibility study with an investigation at the new J-5 facility—the 38-foot-diameter hortonsphere^s at J Site.⁴²⁹

Engineers transported the repurposed PBOW tank to J Site in September 1958 and installed a concrete floor and a high-pressure fluorine flow system inside the tank. The control room for J-5 was a cylindrical PBOW tank that was buried under an earthen mound away from the test site. Cameras provided views inside the tank, and a periscope allowed examination the chamber's exterior.

Louis Russell, Harold Schmidt, and Larry Gordon first exposed various solid and grease materials to different mixtures of gaseous and liquid fluorine/oxygen (FLOX) in static, atmospheric conditions. From the control room, the staff lowered the samples into a glass cylinder containing the FLOX^t for 15 seconds then agitated for another 45. They found some materials had no reaction, others smoldered, and some exploded.⁴³⁰



Image 97: J-5 hortonsphere on the J Site complex (GRC-1960-C-54671).



In 1963 Schmidt and his colleagues from the Centaur Program Office decided to expand their materials compatibility effort by subjecting six variations of Teflon (Chemours) to high-speed fluorine and FLOX flow. They were particularly interested in the effect of pressure on the reaction. J-5, which had been idle for over a year, would have to be reactivated and updated for the effort.⁴³¹

Tom Brink joined NASA Lewis in May 1963 after several years of working out West on the Atlas and Mace missile programs. His hiring coincided with the decision to restart the J-5 facility for the fluorine tests. Rocket Systems Division Chief Glen Hennings tasked Brink with the design of a tank to encapsulate the fluorine rig's test section.

^rPassivation was the floating of unpressurized fluorine into the system and allowing it to build up a layer along the interior of the piping. This coating provided some protection against the general corrosiveness of the high-pressure liquid hydrogen.

^sHortonspheres are large, strong spherical pressurized tanks used to store liquids or gases without vaporization.

^tFLOX is short for a fluorine-liquid oxygen combination used as an oxidizer.

As a new engineer for NASA, Brink spent a good deal of time on the project and made sure his calculations were correct. When he presented the plans to Hennings, however, his boss asked, “How do you know this? How do you know that?” Brink went off and redesigned that tank using standard issue piping. Hennings was pleased. “He didn’t have to trust my capability,” Brink explained good naturedly. “He didn’t really want to sit down and understand every detail of your calculation because your slide rule might be off.”⁴³²

The J-5 test rig consisted of a supply and receiver tank with two test sections in between. Two flanges held the experimental materials in the test section. Beginning in October 1963 the researchers analyzed several Teflon samples each day. Unlike the previous investigations, the materials were in the shape of actual seals and tested dynamically in high-speed FLOX flows. The staff increased the flow rate incrementally for each fluorine or FLOX run. The samples were exposed to the flow for up to 5 minutes at each rate or until a reaction was achieved.⁴³³ Few were able to withstand the high-pressure flow, however. Brink recalled, “We managed to eat them all alive.”⁴³⁴

On 16 January 1964 Brink and his crew were in the midst of their 26th run on when an explosion ripped through J-5. A Teflon sample combusted as it was being exposed to the highest velocity FLOX flow of the day. The force blew the test rig out of its protective enclosure and severely damaged the facility. Afterward Brink and mechanic Ralph Jacko decided to investigate the J-5 chamber. It was nearly a grave mistake. Upon entering the hortonosphere they discovered that one of the shutoff valves was still open, and fluorine had spilled throughout the chamber. They could feel the fluorine fumes on their faces. The two quickly retreated and headed to the nurse’s station to shower repeatedly. Brink recalled having to throw out the clothes he had been wearing, but things could have turned out much worse.⁴³⁵ It took three months to repair J-5, but the investigators were able to complete the first stage of the FLOX compatibility program in the spring of 1964.

After some delays due to additional damage to facility, the staff initiated the second phase of the program using gaseous FLOX.⁴³⁶ The researchers found that FLOX was more reactive in its liquid form than its gaseous form. The reactions of the former were energetic, smooth-burning, and explosive, whereas those of the latter were smoldering and nonexplosive. They determined that the flow rate was a key factor to the reactivity of all the materials and recommended that seals not be directly exposed to the fluorine flow to prevent degradation. Slight amounts of contamination and marginal increases in flow rate can cause seals to breakdown in high-flow systems.⁴³⁷

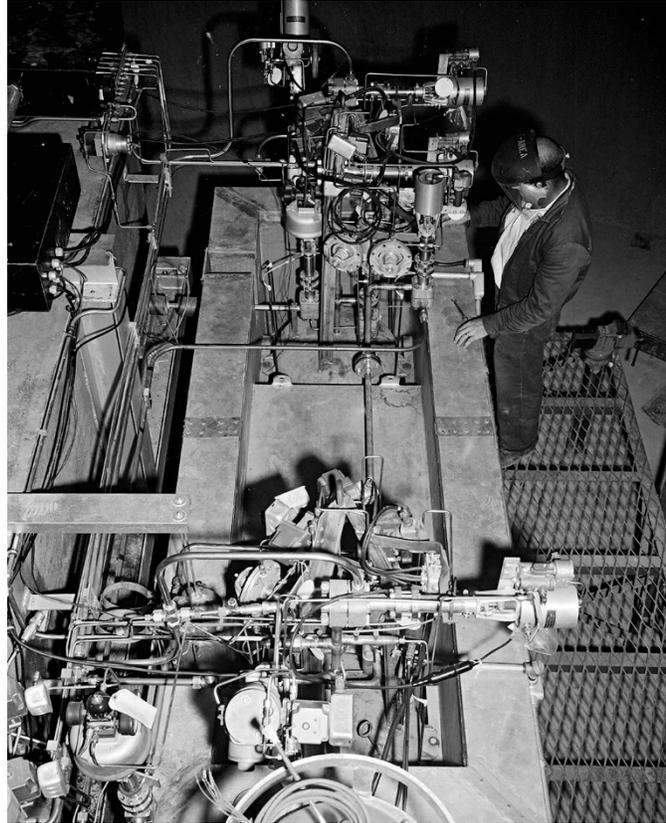


Image 98: Fluorine flow rig inside J-5 in June 1961 (GRC-1961-C-57138).

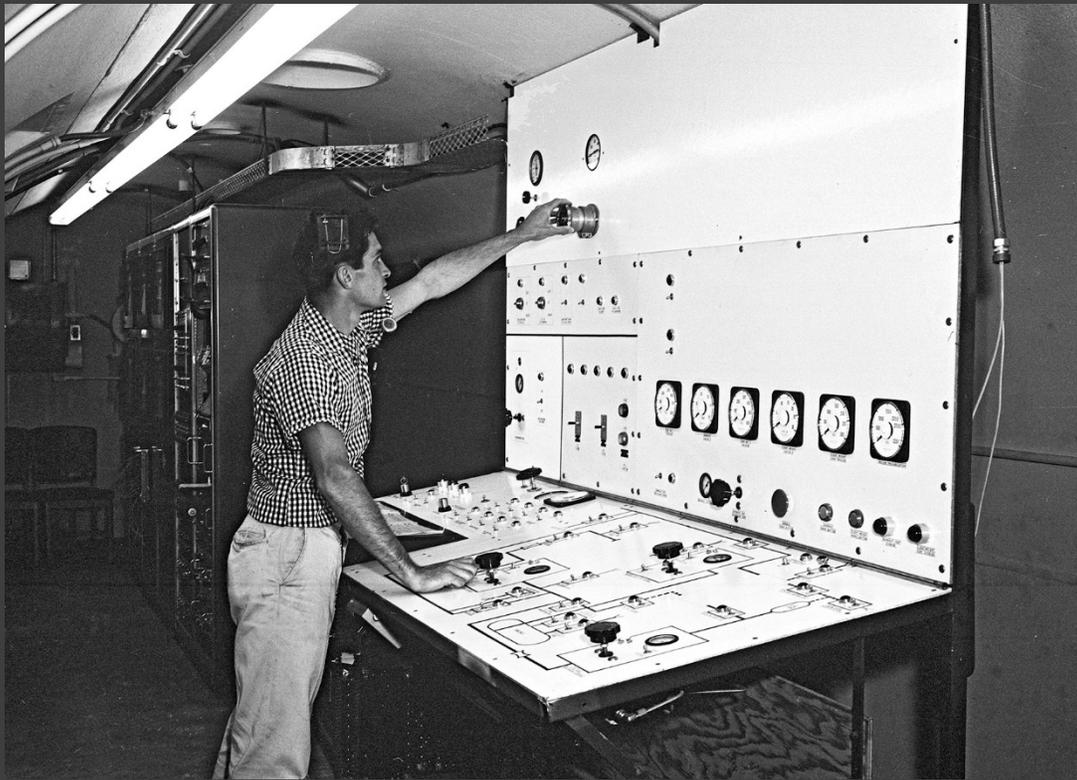


Image 99: Interior of the submerged J-5 control room (GRC-1961-C-57136).

On 22 November 1963 Brink and his crew of mechanics were hunkered down in the room preparing for a test run when the news of President John F. Kennedy's assassination arrived. The FLOX tank was full, and the men were marooned in the control room. "My decision was we just have to struggle on," recalled Brink, "because we're not in a position that we're going to shut it off and go home." Emptying of the fluorine tanks would require hours, so they proceeded with the test. After several hours the runs were complete and the excess FLOX was burned off. The men were finally free to open the bunker door and go home to their families.⁴³⁸



By 1964 the new space agency and Plum Brook were up and running smoothly. The assassination of President Kennedy could have deflated the U.S. space efforts. Instead, as exemplified by the renaming of Cape Canaveral as Cape Kennedy, it spurred them on. Gordon Cooper's 22-orbit *Mercury* flight in May 1963 brought the first phase of NASA's human space program to an end. The U.S. liquid-hydrogen work was showing some promise with the first successful Atlas/Centaur launch, the first extended firing of Rocketdyne's J-2 engine, and the first test of Saturn's S-IVB upper stage with its J-2.⁴³⁹ NASA continued exploring advanced space missions even though the NERVA program was temporarily suspended while AEC redesigned the reactor.

The Rocket Systems Area provided cooling data on nuclear rocket nozzles, verified the structural strength of the Atlas/Centaur, confirmed that fluorine could be safely pumped, and analyzed fluorine's reaction to different materials. The staff was becoming settled and more comfortable operating the facilities. NASA had formally taken over Plum Brook and made plans to add several large new facilities. Everything was in place for a successful future.

References

294. “Why Yuri Got There First,” *Sandusky Register* (22 April 1961).
295. Rita Tessmann, “Hydrogen Rules Rocket Division,” *Sandusky Register* (21 August 1965).
296. Robert Kozar interview, Cleveland, OH, by Virginia Dawson, 30 March 2000, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
297. “House Whittles Space Budget,” *Elyria Chronicle-Telegram* (11 May 1962).
298. “Plum Brook Project Given Green Light,” *Sandusky Register* (4 May 1962).
299. Joseph Dietrich Memorandum for the Chairman, Atomic Energy Commission, “Heated Hydrogen as a Rocket Propellant,” 21 February 1946, NASA Glenn History Collection, Nuclear Propulsion Collection, Cleveland, OH.
300. “NERVA,” *Flight International* (9 August 1962).
301. *Liquid Rocket Engine Axial-Flow Turbopumps* (Washington, DC: NASA SP-8125, 1978), <http://ntrs.nasa.gov>
302. James Dewar, “Project Rover: A Study of the Nuclear Rocket Development Program, 1953–1963” (Doctoral thesis, Kansas State University, 1974).
303. Papers of John F. Kennedy, 12 December 1962, Presidential Papers, President’s Office Files, Press Conferences.
304. William Corliss and Francis Schwenk, *Nuclear Propulsion for Space* (Oak Ridge, TN: Atomic Energy Commission, 1971).
305. John Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959* (Washington, DC: NASA SP-4404, 1977), <http://ntrs.nasa.gov>
306. Ralph Stacht, Richard Quentmeyer, and William Jones, *Hot-Gas-Side Heat Transfer With and Without Film Cooling on a Simulated Nuclear Rocket Thrust Chamber Using H₂-O₂* (Washington, DC: NASA TN D-6638, 1972), <http://ntrs.nasa.gov>
307. Richard Quentmeyer interview, Cleveland, OH, by Virginia Dawson, 22 January 2003, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
308. Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959*.
309. Ralph Schacht, Richard Quentmeyer, and William Jones, *Experimental Investigation of Hot-Gas Side Heat-Transfer Rates for a Hydrogen-Oxygen Rocket* (Washington, DC: NASA TN D-2832, 1965), <http://ntrs.nasa.gov>
310. Stacht, Quentmeyer, and Jones, *Hot-Gas-Side Heat Transfer*.
311. Schacht, Quentmeyer, and Jones, *Experimental Investigation of Hot-Gas Side Heat-Transfer Rates*.
312. Richard Heath interview, Cleveland, OH, by Robert Arrighi, 15 August 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
313. Ralph Stacht and Richard Quentmeyer, *Axial and Circumferential Variations of Hot-Gas-Side Heat Transfer Rates in a Hydrogen-Oxygen Rocket* (Washington, DC: NASA TN D-6396, 1971), <http://ntrs.nasa.gov>
314. John Finney, “Balloon Rocket Lost Soon After Firing,” *New York Times* (23 October 1958).
315. Roger Bilstein, *Orders of Magnitude: A History of the NACA and NASA, 1915–1990* (Washington, DC: NASA SP-4406, 1989), <http://ntrs.nasa.gov>
316. “Orbit Failure of Satellite Baffles Army,” *Lodi News-Sentinel* (24 October 1958).
317. Curtis Larsen, *NASA Experience With Pogo in Human Spaceflight Vehicles* (Washington, DC: NASA RTO-MP-AVT-152, 2008).
318. “The Plum Brook Story—A Progress Report,” *Orbit* (31 July 1959).
319. Robert Shafter, “Rugged Tests of Centaur Rocket Are Planned for Research Center in Ohio,” *Portsmouth Times* (1 August 1963).
320. Eugene Manganiello Memorandum to Headquarters, “Information on Environmental Test Facilities at Lewis Research Center,” 20 November 1959, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
321. Theodore Gerus, John Housely, and George Kusic, *Atlas-Centaur-Surveyor Longitudinal Dynamics Tests* (Washington, DC: NASA TM X-1459, 1967), <http://ntrs.nasa.gov>
322. Henry Pfanner interview, Cleveland, OH, by Robert Arrighi, 6 September 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.

323. Rocket Systems Division Reports, Dynamics Laboratory, 1 July 1961 to 1 July 1962, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
324. Convair Division, General Dynamics Corporation, "The Centaur Program" (San Diego, CA: General Dynamics, 1961).
325. Karl Abraham, "Lewis, Pesco Have Stake in Centaur Test," *Cleveland Plain Dealer* (3 April 1962).
326. Virginia P. Dawson and Mark D. Bowles, *Taming Liquid Hydrogen: The Centaur Upper Stage Rocket* (Washington, DC: NASA/SP—2004-4230, 2004), <http://ntrs.nasa.gov>
327. George C. Marshall Space Flight Center, *Test Results Centaur F-1 Vehicle*, (Huntsville, AL: NASA MTP-LOD-62-2.3, 1962).
328. Brian Sparks to Homer Newell, 21 September 1962, NASA Glenn History Collection, Centaur Collection, Cleveland, OH.
329. "Liquid Hydrogen Program Stepped Up," NASA press release 62-209, 30 September 1962, NASA Glenn History Collection, Press Release Collection, Cleveland, OH.
330. Roger Bilstein, *Stages to Saturn: A Technological History of the Apollo/Saturn Launch Vehicles* (Washington, DC: NASA SP-4206, 1996), <http://ntrs.nasa.gov>
331. Richard Priem, *Liquid Rocket Technology for the Chemical Engineer* (Washington, DC: NASA TM X-52695, 1969), <http://ntrs.nasa.gov>
332. Vernon Gray, Thomas Gelder, R. P. Cochran, and J. H. Goodykoontz, *Bonded and Sealed External Insulations for Liquid-Hydrogen-Fueled Rocket Tanks During Atmospheric Flight* (Washington, DC: NASA TN D-476, 1960), <http://ntrs.nasa.gov>
333. Porter J. Perkins and Jack B. Esgar. 1964. *A Lightweight Insulation System for Liquid Hydrogen Tanks of Boost Vehicles* (New York, NY: AIAA Conference Publication CP-8) pp. 361-371.
334. Dawson, *Taming Liquid Hydrogen*.
335. George C. Marshall Space Flight Center, *Test Results Centaur F-1 Vehicle*.
336. George C. Marshall Space Flight Center, *Centaur Evaluation Team Report of Propulsion and Vehicle Engineering Ad Hoc Group* (Huntsville, AL: NASA IN-P&VE-V-62-4, 1962).
337. Porter Perkins, *Experimental Study Under Ground-Hold Conditions of Several Insulation Systems for Liquid-Hydrogen Fuel Tanks for Launch Vehicles* (Washington, DC: NASA TN D-2679, 1965), <http://ntrs.nasa.gov>
338. Perkins, *Experimental Study Under Ground-Hold Conditions*.
339. Porter Perkins, Mario Calaluca, Frank Behning, and Francis Devos, *Fabrication and Tests of Insulated Subscale Tanks* (Washington, DC: NASA ND D-2685, 1965).
340. Perkins, *Fabrication and Tests of Insulated Subscale Tanks*.
341. Perkins, *Fabrication and Tests of Insulated Subscale Tanks*.
342. Porter Perkins and Jack Esgar, *A Lightweight Insulation System for Liquid Hydrogen Tanks of Boost Vehicles* (Washington, DC: NASA TM X-52004, 1964), <http://ntrs.nasa.gov>
343. Dawson, *Taming Liquid Hydrogen*.
344. George C. Marshall Space Flight Center, *Centaur Evaluation Team Report*.
345. Joy Owens, "NASA Asks \$12 Million for Plum Brook Expansion," *Elyria Chronicle-Telegram* (26 May 1963).
346. Ted Gerus interview, Cleveland, OH, by Bonita Smith, 2 August 2002, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
347. Robert Shafter, "Rugged Tests of Centaur Rocket are Planned for Research Center in Ohio," *Portsmouth Times* (1 August 1963).
348. "First Rocket Arrives at Plum Brook," *Sandusky Register* (2 August 1963).
349. Rocket Systems Division Reports, Dynamics Laboratory, September 1963, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
350. Rocket Systems Division Reports, Dynamics Laboratory, October 1963, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
351. Cliff Lethbridge, "Atlas Program Background" (2012), <http://www.spaceline.org/rocketsum/atlas-program-background.html> (accessed August 10, 2016).
352. Gerus, *Atlas-Centaur-Surveyor Longitudinal Dynamics Tests*.

353. Rocket Systems Division Reports, Dynamics Laboratory, November 1963, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
354. "Mourning to Delay One Space Launching," *Cleveland Plain Dealer* (24 November 1963).
355. William Treon, "Lewis Lab Workers Proud of Their Centaur," *Cleveland Plain Dealer* (28 November 1963).
356. Department of the Army to the National Aeronautics and Space Administration, "Transfer and Acceptance of Military Real Property," 15 March 1963, NASA Glenn History Office, Plum Brook Ordnance Works Collection, Cleveland, OH.
357. Minutes on the Plum Brook Facilities Meeting Held in the Ad Building Foyer on March 24, 1958 at 1:30 p.m., 25 March 1958, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
358. "Proposed Decontamination of TNT Area B NASA Plum Brook Station," 26 September 1962, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
359. James Braig Memorandum, 26 March 1963, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
360. Alan Johnson to Thrift Hanks, 24 October 1966, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
361. Joy Owens, "TNT Buildings Yield to Space-Age 'Boom'," *Elyria Chronicle-Telegram* (18 August 1963).
362. Heath interview by Arrighi.
363. Owens, "TNT Buildings Yield to Space-Age 'Boom'."
364. Charles Herrmann Memorandum for Staff, 25 July 1961, NASA Glenn History Collection, Directors Collection, Cleveland, Ohio.
365. Mike Sajna, "War Emergency Plan is Key to Lewis Defense," *Wing Tips* (19 September 1952).
366. "Lab Signals Ready for War Emergency," *Wing Tips* (6 February 1953).
367. "Civil Defense Test Exercise," *Wing Tips* (23 July 1954).
368. L. L. Leeper to Albert Siepert, 6 November 1962, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
369. Alan Johnson Memorandum for the Record, 8 November 1962, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
370. John Everett to Abe Silverstein, "Status of Lewis Civil Defense Emergency Plans and Readiness Conditions," 25 March 1965, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
371. "Men to Mars Possible in 60's, Experts Say," *Science News* (16 January 1960), Vol. 77, No. 3.
372. David Portree, *Humans to Mars: Fifty Years of Mission Planning, 1950–2000* (Washington, DC: NASA/SP—2001-4521, 2001), <http://ntrs.nasa.gov>
373. Portree, *Humans to Mars*.
374. Portree, *Humans to Mars*.
375. George Smolak and Richard Knoll, *Cryogenic Propellant Storage for Round Trips to Mars and Venus* (Washington, DC: NASA 68–85018, 1960).
376. Smolak, *Cryogenic Propellant Storage*.
377. John Sloop, "NACA High Energy Rocket Propellant Research in the Fifties," 28 October 1971, NASA Glenn History Collection, Dawson Collection, Cleveland, OH.
378. Porter Perkins, L. S. Smith, M. A. Colaluca, *Preliminary Test Results on a Compressed Multi-Layer Insulation System for a Liquid Hydrogen Fueled Rocket* (Washington, DC: NASA N65–88890, 1963).
379. Perkins, *Preliminary Test Results on a Compressed Multi-Layer Insulation System*.
380. Rocket Systems Division Test Operations Report, Vacuum Environment Tank, 1963, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
381. Rocket Systems Division Test Operations Report, Vacuum Environment Tank, 1964, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
382. Arthur D. Little, *Advanced Studies on Multi-Layer Insulation Systems* (Washington, DC: NASA CR–54929, 1966), <http://ntrs.nasa.gov>
383. Rocket Systems Division Test Operations Report, Vacuum Environment Tank, 1967, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
384. Little, *Advanced Studies on Multi-Layer Insulation Systems*.

385. Little, *Advanced Studies on Multi-Layer Insulation Systems*.
386. Abe Silverstein, "Space Research in the USA," *Flight* (21 September 1961).
387. *Turbopump Systems for Liquid Rocket Engines* (Washington, DC: NASA SP-8107, 1974), <http://ntrs.nasa.gov>
388. Robert Ruggeri and Thomas Gelder, *Cavitation and Effective Liquid Tension of Nitrogen in a Hydrodynamic Cryogenic Tunnel* (Washington, DC: NASA TM-X-50517, 1965), <http://ntrs.nasa.gov>
389. Karl Abraham, "Moon-Landing Rocket Is in Our Back Yard," *Cleveland Plain Dealer* (5 March 1962).
390. "NASA Lewis Research Divisions and Branches," 1 September 1959, NASA Glenn History Collection, Directors, Collection, Cleveland, OH.
391. *Turbopump Systems for Liquid Rocket Engines*.
392. Fluid Systems Division Data Tabulation, 1961, NASA Glenn History Collection, Directors Collection, Cleveland, Ohio.
393. Lewis Research Center, *Facilities and Techniques Employed at Lewis Research Center in Experimental Investigations of Cavitation in Pump* (Cleveland, OH: NASA TP 19-63, 1964), <http://ntrs.nasa.gov>
394. Kozar interview by Dawson.
395. Melvin Hartmann Memorandum for Eugene Manganiello, "Proposed Contract Study, 'Preliminary Design of Turbopump for Advanced Nuclear Rockets'," 6 December 1962, NASA Glenn History Collection, Nuclear Propulsion Collection, Cleveland, OH.
396. Max Miller and Donald Sandercock, *Blade Element Performance of Axial-Flow Pump Rotor With Blade Tip Diffusion Factor of 0.66* (Washington, DC: NASA TN D-3602, 1966), <http://ntrs.nasa.gov>
397. Rocket Systems Division Report, Pump and Turbine Laboratory, 5 July 1962, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, Ohio.
398. Rocket Systems Division Report, Pump and Turbine Laboratory, August 1964, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, Ohio.
399. James Cairelli interview, Cleveland, OH, by Robert Arrighi, 19 November 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
400. Roger Hershiser interview, Cleveland, OH, by Robert Arrighi, 17 December 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
401. Cairelli interview by Arrighi.
402. Heath interview by Arrighi.
403. "No Injuries in Blast at NASA Site," *Sandusky Register* (15 September 1964).
404. Rocket Systems Division Report, Pump and Turbine Laboratory, October 1964, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, Ohio.
405. Harold Schmidt and Jack Harper, *Handling and Use of Fluorine and Fluorine-Oxygen Mixtures in Rocket Systems* (Washington, DC: NASA SP-3037, 1967), <http://ntrs.nasa.gov>
406. Howard Douglas, William Tomazic, and Reino Salmi, *Hydrogen-Fluorine and Hydrogen-Oxygen Rocket Research at NASA's Lewis Research Center* (Washington, DC: NASA TM X-69544, 1961), <http://ntrs.nasa.gov>
407. Adelbert Tischler interview, Cleveland, OH, by John Sloop, 25 January 1974, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
408. Walter T. Olson, "Problems of High Energy Propellants for Rockets," 7 December 1959, NASA Glenn History Collection, Cleveland, OH.
409. Walter Osborne, *Noncavitating and Cavitating Performance of a Liquid-Fluorine Pump Designed by Stream-Filament Method* (Washington, DC: NASA TM X-722, 1963), <http://ntrs.nasa.gov>
410. Donald Perdue interview, Cleveland, OH, by Robert Arrighi, 12 November 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
411. Osborne, *Noncavitating and Cavitating Performance*.
412. John Gibb, Glen Hennings, Harold Christianson, and Dave Fenn interview, Cleveland, OH, by John Sloop, May 1974, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
413. Robert Walter interview, Cleveland, OH, by Robert Arrighi, 5 November 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.

414. Rocket Systems Division Reports, Fluorine Pump Site, 1963, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
415. Pratt & Whitney, *Research on a Hydrogen-Fluorine Propulsion System Final Report* (Washington, DC: NASA CR-72074, 1966), <http://ntrs.nasa.gov>
416. Walter M. Osborn, *Investigation of a Liquid-Fluorine Inducer and Main-Stage Pump Combination Designed for a Suction Specific Speed of 20,000* (Washington, DC: NASA TM X-1070, 1965), <http://ntrs.nasa.gov>
417. Walter Osborn, *Operation of a Liquid Fluorine Pump in Cavitating Flow at an Inducer Tip Speed of 188 Feet per Second* (Washington, DC: NASA TM X-1573, 1968), <http://ntrs.nasa.gov>
418. T. E. Bailey, *Research on a Hydrogen-Fluorine Propulsion System, Final Report* (West Palm Beach, FL: PWA FR-1585, 1966).
419. Donald Perdue interview, Cleveland, OH, by Robert Arrighi, 12 November 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
420. Pratt & Whitney, *Research on a Hydrogen-Fluorine Propulsion System*.
421. Walter interview by Arrighi.
422. Pratt & Whitney, *Research on a Hydrogen-Fluorine Propulsion System*.
423. Rocket Systems Division Reports, Fluorine Pump Site, April 1964, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
424. Schmidt, *Handling and Use of Fluorine and Fluorine-Oxygen Mixtures*.
425. Richard Gundzik and Charles Feiler, *Corrosion of Metals of Construction by Alternate Exposure to Liquid and Gaseous Fluorine* (Washington, DC: NACA TN 3333, 1954), <http://ntrs.nasa.gov>
426. Harold Schmidt, *Compatibility of Metals With Liquid Fluorine at High Pressures and Flow Velocities* (Washington, DC: NACA RM E58D11, 1958), <http://ntrs.nasa.gov>
427. Harold Price and Howard Douglass, *Material Compatibility With Gaseous Fluorine* (Washington, DC: NACA RM E56K21, 1957), <http://ntrs.nasa.gov>
428. Harold Price and Howard Douglass, *Non-Metallic Material Compatibility With Liquid Fluorine* (Washington, DC: NASA RM E57G18, 1957), <http://ntrs.nasa.gov>
429. Rocket Systems Division Reports, Hydraulics Laboratory, July 1, 1961–July 1, 1962, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
430. Louis Russell, Harold Schmidt, and Larry Gordon, *Compatibility of Polymeric Materials With Fluorine and Fluorine-Oxygen Mixtures* (Washington, DC: NASA TN D-3392, 1966), <http://ntrs.nasa.gov>
431. Russell, *Compatibility of Polymeric Materials*.
432. Thorvald Brink interview, Cleveland, OH, by Robert Arrighi, 29 November 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
433. Russell, *Compatibility of Polymeric Materials*.
434. Brink interview by Arrighi.
435. Brink interview by Arrighi.
436. Rocket Systems Division Reports, Hydraulics Laboratory, 1964–1965, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
437. Russell, *Compatibility of Polymeric Materials*.
438. Brink interview by Arrighi.
439. David Akens, *Saturn Illustrated Chronology* (Huntsville, AL: NASA MHR-5, 1971).



Image 100: Researchers analyze a Kiwi B-1 engine before installation in the Nuclear Rocket Dynamics and Control Facility (B-3 Stand) in May 1967 (GRC-1967-P-01290).

◆ Chapter 6 ◆

Hitting Its Stride

High levels of public and Congressional support led to a surge in NASA's space efforts in the mid-1960s. NASA continued the development of the hydrogen-fueled Saturn, proceeded with the Nuclear Engine Rocket Vehicle Application (NERVA) and Centaur vehicles, launched a succession of ambitious *Gemini* spacecraft, and began robotically exploring the Moon with *Ranger*, the Lunar Orbiter, and *Surveyor* spacecraft. With the Apollo missions in sight, NASA planners strove to formulate new programs for the 1970s and 1980s.

Staffing levels at Lewis Field and at Plum Brook Station in Sandusky reached their peaks in the mid-1960s, and several new test facilities were added at both locations. Four new Rocket Systems Area facilities began operation in the mid-1960s—the High Energy Rocket Engine Research Facility (B-1 Stand), the Nuclear Rocket Dynamics and Control Facility (B-3 Stand), the Cryogenic Propellant Tank Facility (K Site), and the Hydrogen Heat Transfer Facility (HHTF). The new facilities were larger and more sophisticated than the earlier Rocket Systems Area sites. The sites could test actual size propellant flow systems (the B-1 and B-3 stands), nozzles (HHTF), and tanks (K Site) in the conditions in which they would operate. Researchers used the Rocket Systems Area to support the Centaur and NERVA programs, continue turbopump and fluorine compatibility studies, and investigate insulation and pressurization systems for cryogenic propellant tanks. It was a busy period for the Rocket Systems Area—contributing to both NASA's current missions and developing the technology required for future endeavors.

The Second Wave

Lewis had performed some modest tank studies at Lewis Field and at the Rocket Systems Area's Materials Compatibility Laboratory (J Site) in the early 1960s, but sought a new facility to study full-scale propellant tanks in simulated space conditions. It was just one of several expensive new facilities that Lewis sought, and Congress decided not to fund the project. Lewis Director Abe Silverstein considered the tank research critical to future space missions and was willing to pay for it out of Lewis general operating funds. The catch was that the operating funds could only be used to modify or repair existing structures. New facilities required the congressionally approved construction funding.

Plum Brook management instructed facility engineer Dick Heath to scour the station for existing structures to convert into the new K Site and its control room. Heath identified an old brick boiler house left over from the Plum Brook Ordnance Works (PBOW) that could house the test equipment. Finding a building for the control room was more challenging. The only thing in the vicinity was a 4-foot-high curved concrete wall about 500 feet away. "Now, we're supposed to find buildings," he recalled. "It had to have a building. There was a 120 degree arc with no building remaining. A wall about this high of concrete wrapped around. [It was] absolutely no use to anything, just some spalled up concrete. There was something there in 1940, but it was long gone. That's K Site today."⁴⁰ NASA engineers incorporated the wall into the circular control room.



Image 101: K Site vacuum chamber inside a former PBOW power plant (GRC-1966-C-04023).



Image 102: K Site control room as it appeared in 2006. The original wall is apparent (GRC-2006-C-01731).

Despite the use of existing PBOW equipment, construction of K Site proceeded slowly. Workers had to remove the massive boiler equipment from inside the main building and modify the roof to prevent the formation of pockets of hydrogen gas during the tests.⁴⁴¹ The delays were exacerbated by inadequate design work, reservations regarding the facility’s safety and operation, and poor contracting.

Bob Siewert, head of the Propulsion Components Branch, commented in October 1964, “Conservatively speaking, it can be said that contracting for the various segments of the total job was done in such a manner to maximize confusion and complication. This, of course, was partly the result of funding difficulties, but there may have been errors in judgment and procedure as well. As a result, there exists a hodge-podge of interlocking contracts that cause delay and require excessive amounts of NASA Administration effort.”⁴⁴² The staff persevered, and K Site, which began testing in January 1966, soon became the Rocket Systems Area’s most active facility.



The B Complex, which included the B-1 and B-3 stands, and later, the Spacecraft Propulsion Research Facility (B-2),^u was the most ambitious portion of the Rocket Systems Area. Researchers could test full-scale rocket stages and realistic propellant flow configurations in simulated space conditions. The B-1 Stand was designed to test engine systems with up to 30,000 pounds of thrust, although researchers never did fire engines at the site. The stand included a vacuum capsule for testing entire engines in a vacuum and a steel test carriage for propellant flow tests.⁴⁴³ The 210-foot-tall B-3 Stand was designed to investigate tanking and flow systems for nuclear rocket systems. Researchers were able to study the effects of combustion chamber pressure on propellant flow without firing the engines.⁴⁴⁴ The steam ejectors evacuated the exhaust ducts at both stands to simulate altitude conditions in the rocket nozzle, and a massive 200,000-gallon Dewar supplied the complex with liquid hydrogen. The test operators ran the B sites from the Control and Data Building located roughly 2,500 feet away.

^uB-2, which could fire an entire rocket stage in altitude conditions, was added to the site in 1969. B-2 is outside the scope of this manuscript.



Image 103: Construction of the B-3 Stand began in the spring of 1963.⁴⁴⁵ Construction crews assembled the steel framework during the summer and added the siding and platforms in October. The basic structure was complete by mid-November 1963. The next year and a half were spent installing the other infrastructure and support systems, including the connection to the B-1 altitude exhaust system (GRC-1963-P-01751).



Image 104: The B Complex included the Pump and Shop Building, a substation, two boiler buildings, a Valve House, and the steam ejector apparatus. The B Control Building is visible in the upper right corner (GRC-1964-C-72620).

Nuclear Bootstrapping

The ability for the engine to vary its speed and restart itself without any external power is critical for liquid-fueled upper stages. Contemporary batteries were too heavy to use in early space vehicles, so engineers developed a method of self-starting referred to as “bootstrapping.” Bootstrapping was accomplished by allowing a small amount of liquid hydrogen to flow into a gas generator (in chemical rockets) or the reactor (in nuclear rockets) where it vaporized. The resulting gas started the turbine, which drove the turbopump. The turbopump then impelled additional liquid hydrogen to the engine, where it was converted into thrust.⁴⁴⁶ The concept was first conceived by Randall Rae in the mid-1950s, then applied by Pratt & Whitney to their 304 engine for Project Suntan.⁴⁴⁷ Bootstrapping has become an essential element of all liquid rockets.

The engine’s performance during the bootstrap sequence was extremely difficult to analyze compared with normal operation. Engine designers needed to know the loss of pressure in the propellant flow to properly design the turbopump, the reactor core’s temperature and pressure to calculate the engine’s thrust, and the temperatures of the structure to predict deterioration and stress in the reactor core.⁴⁴⁸

In the early 1960s researchers from Lewis's Advanced Development and Evaluation Division sought to create a safe programmable startup system for nuclear engines. They first needed to determine the limitations of the control system and the engine's heat transfer rates for different operating conditions. Lewis used analog computer programs to construct the programmed startup. The researchers found that their predictive computer code agreed with the test data during normal performance but had to be adjusted for dynamic operations such as startup. This information could only be obtained with a test of an actual engine.⁴⁴⁹

In February 1962 Lewis management introduced plans to evaluate the operation of a full-scale, but non-nuclear, Kiwi B-1B reactor system at the B Complex. The first phase, to be conducted at the B-1 Stand, would study the engine's startup using a six-stage Rocketdyne Mark IX axial-flow turbopump. The second phase, ultimately run at B-3, would analyze the engine's startup and operation with a two-stage Aerojet Mark III centrifugal turbopump.⁴⁵¹ The Rocket Systems

Division immediately began modifying B-1 to accommodate the Kiwi reactor and arranging for delivery of the test equipment. Repeated manufacturer delays pushed back the installation until the spring of 1963. The staff then worked for nearly a year to install the Kiwi system in the stand.⁴⁵²

Nuclear Heat Exchanger

Nuclear rocket engines require a moderator of some type to control the fission inside the reactor core. NERVA engines relied on graphite moderators, but other nuclear system designs used water to maintain the efficient fission. A heat exchanger transferred the heat from the water to the cryogenic liquid-hydrogen propellant. The exchanger was basically a tube within a tube. The hot moderator water flowed through the inner tube and the cold hydrogen through the outer tube.



Image 105: A Lewis engineer examines the cooling passages on a converging-diverging nozzle for a nuclear engine. The nozzle had a unique 12 to 20 contraction ratio and 45-degree contraction half-angles⁴⁵⁰ (GRC-1963-C-66545).

The formation of ice on the heat exchanger's surface posed a potential problem, particularly when the propellant supply was running low. The ice could degrade the exchanger's performance and potentially block the flow passages. Lewis researchers undertook a multiyear effort to measure the moderator's ice buildup and analyze the conditions that created the ice. After some initial basic studies which included the testing hydrogen in a single heat exchanger tube, they expanded the investigation. They designed a triangular 19-tube heat exchanger to determine performance and ice level variations on the different tubes during both startup and normal operating conditions.⁴⁵³

The experimental heat exchanger was installed at the Rocket Systems Area's Hydraulics Laboratory (F Site), which had a series of cryogenic fluid tanks that were linked to one another. The test hardware, such as the heat exchanger, was installed between the supply and catch vessels. High-pressure nitrogen propelled water through the test section and into the receiving tank. The hydrogen flowed through the heat exchanger in the opposite direction of the water and into an empty Dewar.⁴⁵⁴

After several months of delays, the heat exchanger tests began in August 1963. A series of issues during the early runs caused damage to both the facility and the exchanger. The staff was able to correct the problems and conduct over 50 successful runs between in the spring of 1964.⁴⁵⁵ That fall the researchers began running the tests with both the hydrogen and water flowing in the same direction. They determined that their calculations were usually correct when predicting that no ice would form but that their ice accumulation estimates were significantly lower than the actual buildup.⁴⁵⁶

Kiwi's Propellant Flow

During 1963 Atomic Energy Commission (AEC) engineers in Nevada addressed the vibrational problems that had plagued the Kiwi-B reactors during the previous year. Despite opposition from the Space Nuclear Propulsion Office (SNPO), NASA and the AEC advocated for reinstatement of the suspended flight test of the NERVA vehicle in the fiscal year 1965 budget. At the urging of the Budget Office, which foresaw the flight test as the first step to an eventual exorbitant human mission to Mars, President Lyndon Johnson canceled the effort in December 1963.⁴⁵⁷

Nonetheless, funding for NERVA ground-based studies spiked in 1964 and remained relatively even throughout the mid-1960s.⁴⁵⁸ During this period the AEC continued testing its NERVA and Kiwi engines and introduced the larger 1,500-MW Phoebus reactors.⁴⁵⁹ In May 1964 the AEC briefly operated the improved Kiwi B reactor with liquid hydrogen at its full 1,000 MW of power before the nozzle cracked. In July 1964, the AEC finally ran the Kiwi-B reactor successfully at full power for 8 minutes.⁴⁶⁰ It was a major milestone for Project Rover. The engine was not instrumented to capture data during the bootstrap phase, however, so the planned cold flow tests at the B-1 Stand were still required.^v

The cold-flow nuclear rocket simulation test program at the B-1 Stand simulated different types of nuclear rocket cycles in an unfueled Kiwi B-1B reactor, its Mark IX turbopump, Rocketdyne RN-2 nozzle, and 2,000-gallon liquid-hydrogen tank.⁴⁶² The propellant was pumped through the rocket system as during a normal startup, but the engine was not fired. The first phase of the B-1 tests, which commenced in March 1964, sought to obtain data on the engine controls, fluid instabilities, and heat transfer during the initiation of propellant flow and immediately afterward.⁴⁶³ The tests progressed from flow rates congruous with the NERVA engines to the levels in the larger Phoebus engine.⁴⁶⁴

^v“Cold flow” refers to a test in which the propellant is pumped through the system but the engine is not fired.



Image 106: Arrival of the Kiwi B-1B engine at Plum Brook in April 1963. The engine was first shipped to Lewis Field for assembly and instrumentation, then trucked to Plum Brook. The staff placed a rubber foam pad underneath the reactor on a truck bed, inserted Teflon (Chemours) shims inside the reactor to keep components from moving, and used accelerometers to monitor vibrations to prevent damage during the 50-mile trek west to Sandusky. They also instructed the driver to lower the pressure of the truck's tires and keep the speed below 30 miles per hour⁴⁶¹ (GRC-1963-P-01350).

The B-1 runs demonstrated that the pump accelerated as needed, the pressure fluctuations in the reflector and nozzle were not as severe as in other tests, and the separation of flow from the nozzle surface caused significant vibrations.⁴⁶⁵ The researchers used the data to calculate the effect of disturbance in the propellant flow on the pump's ability to accelerate.⁴⁶⁶

The second phase of the B-1 Kiwi-B tests sought to confirm that nuclear engines could bootstrap themselves. Chemical rocket systems had successfully started up independently for some time, but there was no guarantee that this would translate to nuclear engines, which require a longer startup period, consume all of the propellant, and have an intricate propellant flow path.⁴⁶⁷

Each of the approximately 1-minute test runs required two days of preparation—primarily to calibrate the electronics and purge the propellant system with helium. The test engineers then filled the liquid-hydrogen tank, chilled the turbopump, and flowed steam through the ejectors to purge the exhaust system. When the exhaust system reached its predetermined pressure level, the controls automatically initiated the desired test conditions. At that point, the operator opened a valve below the turbopump to release the liquid hydrogen to the engine and initiate the test. First gaseous then liquid hydrogen flowed through the feed line and into the nozzle's cooling passages. Within 4 seconds the hydrogen had flowed throughout the system and cooled the entire engine. The B-1 test runs concluded when the propellant entered the reactor core.⁴⁶⁸



Image 107: A Kiwi-B engine is hoisted into the B-1 Stand on 11 April 1963. After undergoing initial checkout runs, the engine was lowered for analysis of the reactor and its fuel elements. Issues with the new facility delayed the reinstallation and checkout work into January 1964 (GRC-1963-P-01355).

Lewis researchers conducted their first bootstrap test of a Kiwi 1-B1 at the B-1 Stand on 21 September 1964. Three days later, the AEC completed its first successful full-scale test of the NERVA NRX-A2 engine in Nevada. Aerojet, the engine's manufacturer, took out a full-page ad in the *Wall Street Journal* to tout this major accomplishment.⁴⁶⁹ A follow-up run at the B-1 Stand on September 30 demonstrated that the turbine could be bootstrapped at even higher acceleration rates than previously achieved.⁴⁷⁰ The AEC bootstrapped its NRX-A2 just weeks later at Los Alamos. NERVA historian James Dewar wrote, "Unglamorous compared to a roaring full-power run [of the nuclear engine], this was actually a major milestone: [NRX-A2] ran stably under all conditions, clarified questions about hydrogen's reactivity, pointed to its ability to control the engine, and gave confidence in computer simulations."⁴⁷¹

Lewis successfully continued the startup runs throughout the fall of 1964 using newly installed flight-type propellant feed lines.⁴⁷² Once the tests were complete, members of the Nuclear Propulsion Branch analyzed the B-1 data to determine the effect of the different fuel line and insulation designs on the engine's chilldown.⁴⁷³ They also found that the turbine could be started using the latent energy from the engine components.⁴⁷⁴ After examining data from five of the later test runs, the researchers confirmed that their computer code accurately predicted nearly all of the reactor's performance values during the startup phase.⁴⁷⁵

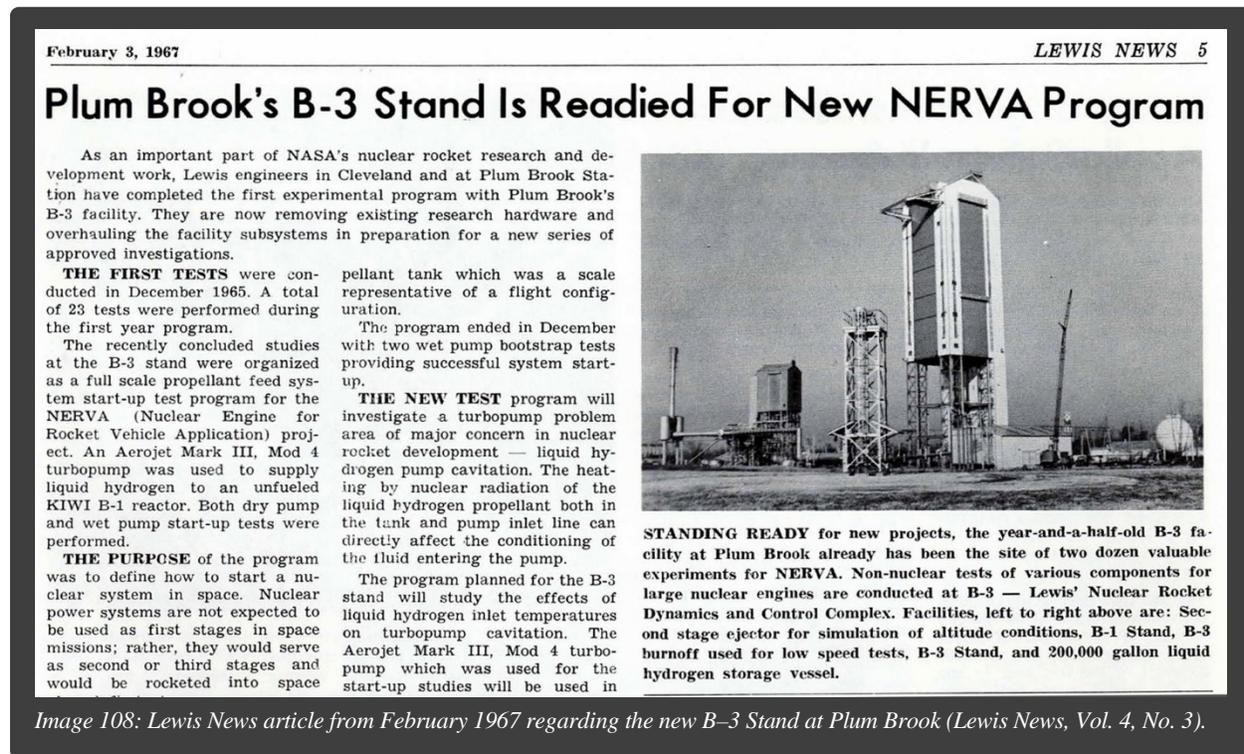
Booting the Can Down the Road

As the Rocketdyne Mark IX turbopump tests at the B-1 Stand wound down in the spring of 1964, the Rocket Systems Division was making arrangements to modify the facility for the follow-up tests of the Aerojet Mark III pump.⁴⁷⁶ In April 1964, however, Lewis management decided to transfer the Mark III investigations to B-1's new sister stand, B-3.⁴⁷⁷

The B-1 bootstrap tests had verified the analytical methods for calculating the startup characteristics of an axial-flow pump, but it was not demonstrated that these methods could be applied to centrifugal pumps.⁴⁷⁸ Although Aerojet had tested the pump extensively at its normal operating speed, there were no data for the low-speed realm. Certain issues only manifest themselves at lower velocities. The B-3 bootstrap tests of the Kiwi B-1B reactor and Mark III pump were designed to provide this information.⁴⁷⁹

The transfer of the test hardware from one stand to the other proceeded quickly, but it took another six months to work out the bugs of the new B-3 Stand. During this period the Rocket Systems Division installed a reheat system that returned the test hardware and its components to ambient temperatures immediately after the cryogenic test runs. This shortened the program by allowing two tests to be run in a single day.⁴⁸⁰

Meanwhile at the Nevada Test Site, a major test of the NERVA NRX engine took place in February 1966. It was the first time that all the NERVA engine components were integrated, albeit in a nonflightworthy arrangement. The test demonstrated that the engine could be bootstrapped and automatically controlled. It also proved that the reactor, turbopump, and other components could operate reliably in a range of conditions. SNPO Chief Harry Finger referred to it as, "the culmination of a long line of Rover research and development tasks."⁴⁸¹



The B-3 tests, which ran from March to December 1966, provided data on the Mark III pump's operation at low speeds, its bootstrapping capability, and the system's reaction to cryogenic temperatures. The researchers found that the normal pump efficiency equations did not apply at low startup speeds, but the propellant flow characteristics did.⁴⁸² The program was a success in another way, as well. Plum Brook engineers estimated that the \$3,000 reheater shortened the estimated length of the program by three months and saved \$50,000 worth of propellants.⁴⁸³

The Plum Brook staff overhauled the B-3 Stand to test the Kiwi B turbopumps in cavitating propellant conditions. As they were completing the final checkout runs in June 1966, Lewis management canceled the program.⁴⁸⁴ It is unclear why the effort was canceled, but it was likely due to lack of funding of the overall NERVA program.

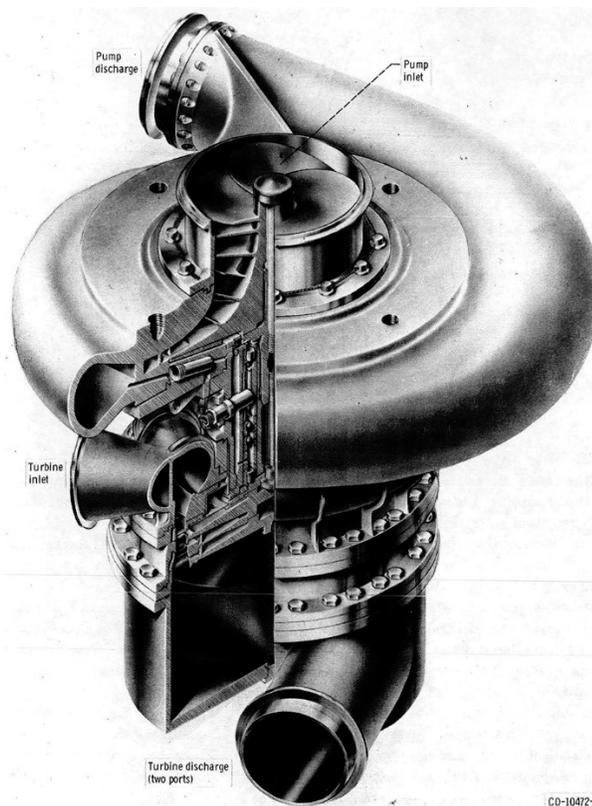


Image 109: Aerojet Mark III Turbopump. Several early missile systems used the Mark III, including the Navaho, Thor, Jupiter, Saturn I, and Saturn IB (NASA CD-10472-15).

Portent

In August 1964 Congress passed the Gulf of Tonkin resolution regarding Vietnam and the first of several pieces of War on Poverty legislation. The resulting Vietnam War and Great Society programs consumed large portions of the federal budget over the coming years. The introduction of these new expenses took place just as the new President, Lyndon Johnson, was asking NASA to identify postlunar landing roles for humans in space.

In response NASA began studying the feasibility of using Saturn and Apollo equipment to conduct a series of near-Earth missions that included proto-space stations, conversion of an *Apollo* capsule into a lunar base, and long-duration orbiting of the Earth and Moon. The proposal dimmed the prospects of human planetary exploration and the need for nuclear rockets. The budgets for both were cut in fiscal year 1965.⁴⁸⁵

In February 1965 NASA Marshall Space Flight Center researchers released a plan that would use several Saturn vehicles to launch a spaceship with humans on a flyby of Mars. That same month, however, the United States began bombing North Vietnam and preparing hundreds of thousands of troops for war. In addition, the *Mariner 5* spacecraft sent the very first images of the Martian landscape back to Earth in July 1965. Not only was Mars barren but the spacecraft was exposed to greater levels of radiation than scientists had predicted. NASA's fiscal year 1966 budget contained the Agency's first decrease in funding ever. Although not traumatic, the cuts came primarily from the post-Apollo missions, while funding for the lunar landing remained steady.⁴⁸⁶

Despite the cuts, NASA elevated its post-Apollo planning as funding for the Saturn rockets was coming to an end. The Agency created an Apollo Applications program office to study concepts for the future use of the Saturn, including an orbiting space laboratory that would become Skylab.⁴⁸⁷ In addition, the space science community gathered in the summer of 1965 to generate ideas for future space exploration, yielding 150 proposals for experiments that could be launched with Saturns.⁴⁸⁸

In 1966 NASA introduced an integrated post-Apollo plan that would use Saturn and Apollo hardware to create a space station over the next seven years and send robotic spacecraft on flybys of Mars and Venus in the early 1970s. This would be followed by human flybys in the late 1970s and the placement of humans on Mars in the 1980s. The Mars portions were referred to as Voyager.⁴⁸⁹ Despite these efforts, NASA's fiscal year 1967 budget contained the Agency's first major reduction. Again the post-Apollo missions, including Project Rover, bore the brunt of the reductions. The Vietnam War was escalating and civil unrest emerged in many U.S. cities.

Hot Hydrogen

The Kiwi and NERVA reactors flowed hydrogen through the nozzle and other components to keep them cool. This raised the temperature of the hydrogen before it entered the reactor. The AEC had opted to use graphite fuel elements, which were corroded by the hot steam hydrogen. Lewis constructed the \$2.4-million HHTF at Plum Brook to study the effects of superheated hydrogen.

A pebble bed heater supplied the facility with the hot hydrogen gas needed to simulate the high-temperature exhaust of nuclear rockets. The heater, located 50 feet below ground, was a cylindrical brick structure with baseball-size carbon pebbles at the bottom. The pebbles were electrically heated over a period of several days. This required an enormous amount of electricity and coordination with the local power company. The hydrogen gas flowed through the pebbles and upward into the test section, supplying the experimental nozzle in the test section with 57,500 cubic feet of 4,200°R hydrogen gas per second. The gas was then expelled through the 88-foot-tall stack on top of the facility.⁴⁹⁰

In July 1963 NASA contracted the T.J. Hume Company to build the HHTF.⁴⁹¹ The construction suffered many setbacks, particularly electrical shorts caused by hot spots in the heater. Hume personnel disassembled the entire heater in the spring of 1966 in an effort to resolve the problem, but NASA decided to release the company from its contract and took over the reassembly of the heater. The Rocket Systems Division's Dick Heath worked with the Lewis design engineers to resolve the problem, and Tom Brink managed the reconstruction of the pebble bed. The engineers decided to replace the balls with stacks of graphite rings.⁴⁹²

By this time, however, Lewis was already looking beyond the nuclear nozzle tests. In 1966 Abe Silverstein reorganized the center to increase aeronautics research. Researchers were seeking a facility to test air-breathing ramjet engines at speeds between Mach 5 and 7. As NASA's budgets began leveling in the mid-1960s, Lewis was forced to modify an existing facility to "to do a job [the center] hadn't planned on."⁴⁹³ In March 1966 a Congressional subcommittee approved \$2 million to convert the unused HHTF into the Hypersonic Tunnel Facility (HTF).^w Thus began a massive six-year effort to bring the hypersonic tunnel online.

^wHTF is outside of the scope of this project and is not discussed in detail.



Image 110: HHTF shortly after construction (GRC-1966-C-01676). Image 111: HHTF test section (GRC-1966-C-01879).

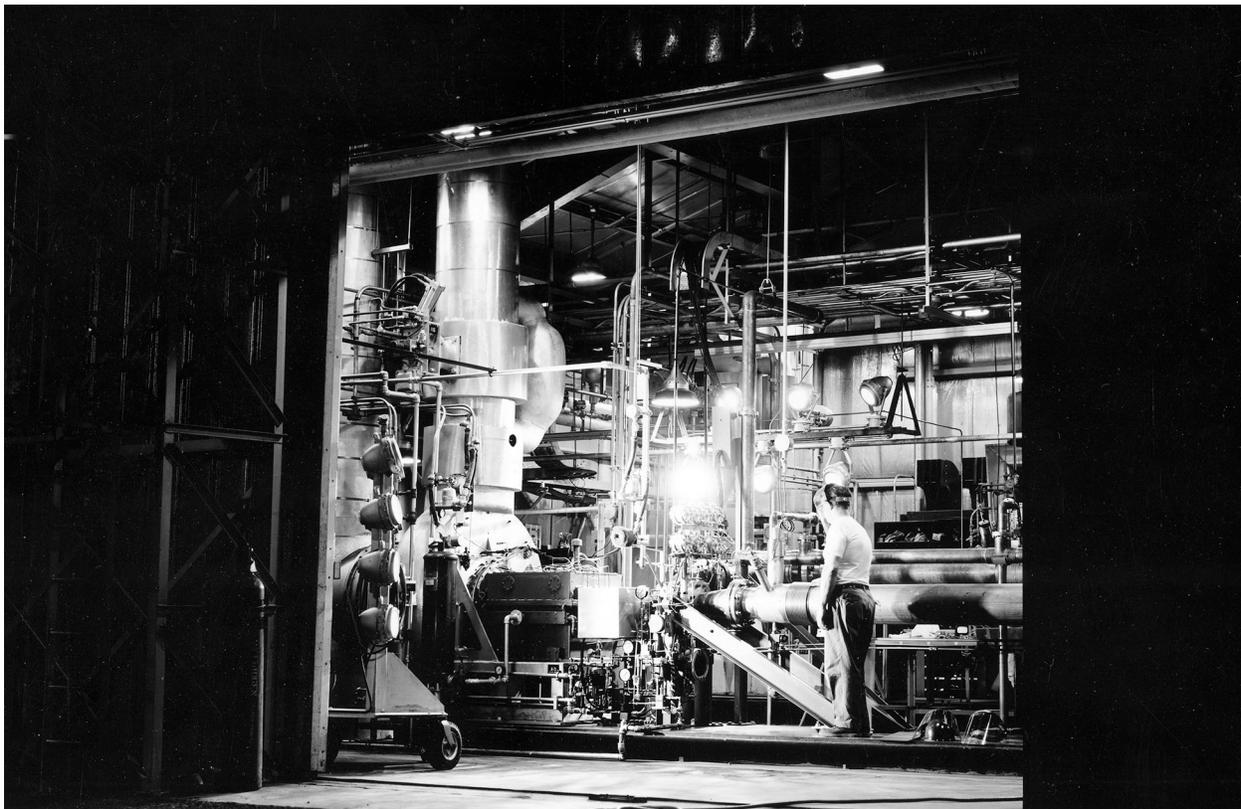


Image 112: View into the Liquid Hydrogen Pump Facility (A Site). Lewis researchers used the hydrogen loop extensively in the 1960s to study centrifugal and multistage axial-flow pump configurations (GRC-1963-P-01196).

Pumping Hydrogen

Lewis researchers continued to use the Rocket Systems Area for basic turbopump research throughout the 1960s. They were particularly interested in the improvement of impeller and inducer designs. The impeller is the powerful rotor that pushes the liquid into the pump's internal stages. Typically impellers have a shroud to prevent recirculation of the fluid and dynamic forces from affecting the pump. Researchers in the mid-1960s investigated impellers without shrouds in an effort to accelerate the pump speed and reduce its weight. Pratt & Whitney's RL-10 was the most significant implementation of turbopump with unshrouded impellers.⁴⁹⁴

A Site contained two test loops—one for hydrogen and one for oxygen—to study the performance of turbopumps in conditions similar to what would be experienced in a liquid-chemical rocket engine.⁴⁹⁵ Each loop consisted of a test section for the turbopump located between two 6,000-gallon tanks. The experimental pump transferred the fluid from one tank to another. Researchers used A Site's liquid-hydrogen loop in 1963 to study several shrouded and unshrouded impeller designs on a centrifugal turbopump. They ran the centrifugal pump at 22,500 rotations per minute using both shrouded and unshrouded impellers well over 100 times throughout the year.⁴⁹⁶

Researchers then began testing inducer designs at A Site. In the 1940s and 1950s engineers introduced the spiral-shaped inducers as the first stage for some pumps to improve performance in low pressure and cavitating conditions.⁴⁹⁷ The inducer reduced the amount of pressurization required in the tank and improved pump efficiency. Turbopumps on the Jupiter missiles, the follow-up to the Redstone missiles, included a rudimentary inducer that allowed the pump to rotate faster. This resulted in improved performance and smaller pump diameter.⁴⁹⁸

Lewis researchers believed that increasing the inducer blade angle would reduce instability at low pump speeds. If the blade loading was too great, however, the pump might suffer pressure losses or produce unsteady flow conditions. In the fall of 1965 Don Urasek of Lewis's Rocket Pump Branch used A Site's hydrogen loop to analyze the performance of three titanium inducers with different blade angles. For each run, the operator ran the centrifugal pump at three different speeds while decreasing the liquid-hydrogen flow from its maximum level to the point where the pump stopped. Over the next several months Urasek found that the experimental inducers significantly increased the impeller's flow rate, but the increased flow did little to improve the overall instability.⁴⁹⁹

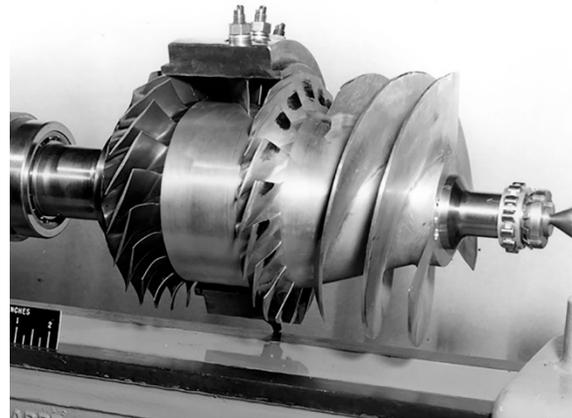


Image 113: A three-stage pump. The spiral-shaped inducer is to the right, the impeller to its left, and the single rotor stage is near the center of the photograph (GRC-1964-P-01638).

Working with Boiling Hydrogen

As engineers began creating turbopumps for liquid hydrogen, they learned that hydrogen, which has a low-density, requires significantly lower pressure levels to pump than other fluids. This meant that the pumps performed well with the fluid in a near-boiling state. This trait reduced the amount of required pressurant gas in the tank, which in turn permitted the use of tanks with thinner, lighter weight walls. The use of fluids near their boiling point, however, increases the instances of cavitation.⁵⁰⁰

The Fluid Systems Components Division undertook a series of studies in the 1960s to investigate the performance of 5-inch-diameter inducers with different blade angles in varying temperatures and flow rates. Preliminary investigations in Lewis's Water Tunnel found that a minimal blade angle performed best during cavitation and produced the best flow rates.⁵⁰¹ The researchers then expanded the tests using liquid hydrogen in the Turbopump Facility's (C Site's) Boiling Fluids Rig.

The Boiling Fluids Rig was one of the most active sites at the Rocket Systems Area. It was designed to test pumps operating with liquid hydrogen that was near or at its boiling temperature and where the pressure levels of the pump and propellant were nearly the same. The Boiling Fluids Rig consisted of an experimental turbopump submerged at the bottom of a 2,500-gallon tank that recirculated the hydrogen out from the bottom of the tank and back into the top of the tank. An adjustable heater near the pump inlet simulated heating that would occur in nuclear rockets. The pump was encased in Lucite and that tank had portals that facilitated filming of the tests.⁵⁰²

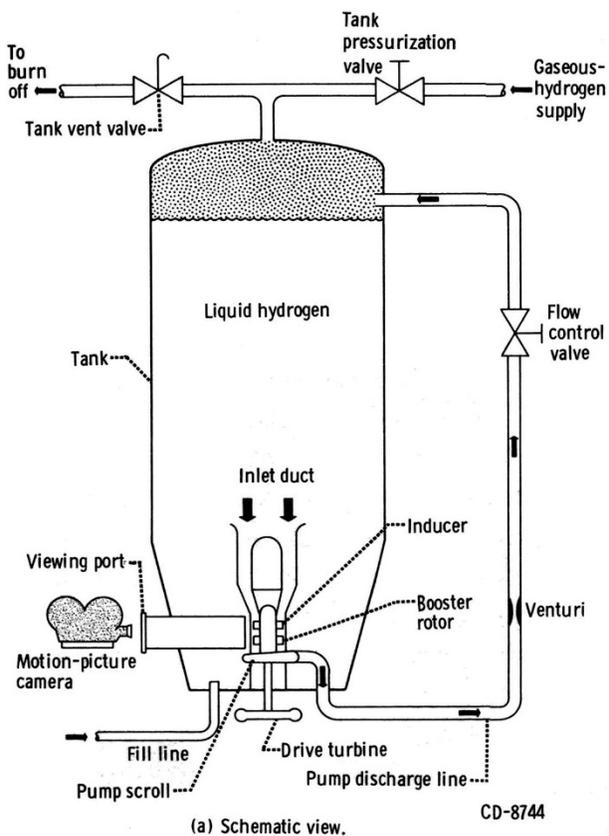


Image 114: Boiling Fluids Rig schematic drawing (NASA TM X-1360, Fig 2).



Image 115: Boiling Fluids Rig inside of C Site (GRC-1961-C-57350).



Researchers developed methods to predict the general pumping tendencies of small pumps with relatively slow speeds in cavitation, but these formulas could not be used to calculate the performance with a specific fluid or pump. The turbopumps used on contemporary rockets, particularly liquid-hydrogen-fueled rockets, were significantly larger and faster than those used for the predictive models. Calvin Ball, Phillip Meng, and Lonnie Reid arranged to test a 20,000-rpm pump and inducer with an 84-degree blade

angle in the Boiling Fluids Rig. The researchers measured the flow rate and net positive suction head (NPSH)^x as the pump was run several times for up to 15 minutes over varying temperatures. They identified the optimal blade angle and found that the inducer successfully pumped the boiling hydrogen at low flow rates. The inducer's performance decreased as the propellant's flow rate and temperature increased.⁵⁰³

The test program continued focusing on the effect of radiation on the hydrogen temperature in nuclear engines. Increases in the temperature of the hydrogen could affect the inducer performance and the tank pressurization requirements. Researchers were able to predict the cavitation rate at the inducer when the hydrogen heating was uniform, but there was no method of predicting it with uneven heating. In June 1963 Meng and Robert Connelly began testing in the Boiling Fluids Rig with an experimental pump that included heating elements to simulate thermal radiation. The heat caused vapor buildup that hindered the inducer's performance. When the researchers adjusted the propellant flow to compensate for the increased vapor, the inducer performed well. Meng and Connelly felt confident that modifications to a nuclear rocket's tank pressure could compensate for the effects of the radiation.⁵⁰⁴

Decreased propellant flow also caused cavitation in nuclear rockets. The flow rate is directly related to the amount of pressure in the line. Meng and Connelly continued their turbopump studies in the Boiling Fluids Rig without the heating elements. Instead they lowered the propellant pressure until the liquid vaporized. The tests demonstrated that the inducer's performance in cavitation is dependent on the amount of vapor in the line.⁵⁰⁵

In 1964 Meng studied the opposite conditions—inducer performance with lower-temperature propellants. Some engineers predicted that the size of propellant tanks could be reduced if the liquid hydrogen was stored at a lower temperature as a slush. Typical hydrogen turbopumps, however, were designed to operate in near-boiling conditions. The facility engineers at C Site were able to pull a vacuum on the Boiling Fluids Rig, which caused the liquid hydrogen to become a slush.⁵⁰⁶ Meng operated a pump in slush conditions and found that the lower temperatures decreased cavitation at the inducer. This increased the amount of NPSH needed to maintain performance.⁵⁰⁷

In the mid-1960s Lewis researchers sought to determine the minimal tank pressure required to maintain enough pressure in the feed line for sufficient pump performance. An equation was developed to predict the fluid's loss of pressure as it traveled between the tank and turbopump. The formula was verified using a water and methyl-alcohol mixture in the Boiling Fluids Rig. It was then tested with several other fluids, including liquid hydrogen. Researchers concluded that “the general utility of the method is regarded with confidence.”⁵⁰⁸

^xNPSH is the difference between the pump's inlet pressure and the pressure at which the propellant will vaporize. Each turbopump is designed with a minimum NPSH number for operation, referred to as Required NPSH. The difference between the liquid's pressure level and the pressure at which it will vaporize is called Available NPSH. Available NPSH must be greater than the amount of pressure the pump technically requires to operate, or Required NPSH.



Image 116: C Site at night with a hydrogen burnoff line to the left in 1962 (GRC-2016-C-05178).

Disappointment at D Site

The Rocket Systems Area's Controls and Turbine Test Facility (D Site) was equipped with two rigs to test turbines that powered multistage axial-flow pumps. D Site's turbine rigs were designed to be powered by atmospheric air, but the researchers wanted to test the turbines with hot gas to simulate nuclear rocket systems. In 1961 facility engineers built a hydrogen-oxygen rocket engine to supply the rigs with hot gas.⁵⁰⁹ The first run with hot gas took place in February 1962, but the system was plagued with problems that delayed testing for a year.⁵¹⁰

Lewis researchers were particularly interested in studying turbines used with three-stage pumps for chemical rockets and with eight-stage turbopumps for nuclear rockets. The staff began testing at D Site in early 1963 with the eight-stage turbine, but the turbine casing cracked in March. They then installed the three-stage turbine in the facility's second rig. The turbine runs throughout the summer and fall of 1963 were beset by a host of facility issues and manpower shortages. The staff reinstalled the repaired eight-stage turbine during the summer of 1963, but struggled to incorporate an oxygen flow system for the rig.⁵¹¹

After over a year of work, attempts to run the nuclear rocket turbine resumed in May 1964. "The first time they tried to run it," Bucky Walter recalled, "it threw the shaft right out on the road."⁵¹² The torque shaft broke leaving the turbine stages to accelerate uncontrollably. This damaged the drive shaft, bearings, and rotor blades. The following month, Rocket Systems Division engineers determined that the equipment was too damaged to continue and canceled the eight-stage turbine program before it produced any data.⁵¹³

The researchers, however, were able to complete several successful checkout runs with the three-stage turbine in the summer of 1964. During a hot gas checkout run in September, however, the rig's stator housing became warped. The resulting damage required a complete overhaul of the facility and multimonth delay.⁵¹⁴ The staff replaced the turbine shaft and restored the facility during the winter. Checkout tests with the three-stage turbine resumed in March 1965, but the problems persisted. On 19 April they ran the three-stage turbine with hot gas for 57 seconds before a ball bearing in the turbine failed. The staff concluded that "the turbine was damaged beyond reasonable repair."⁵¹⁵

In May 1965 Lewis canceled the three-stage turbine program and terminated all research projects for D Site.⁵¹⁶ Walter recalled one of the engineers saying, "Well, [D Site] wasn't designed for hot gas. We just wanted to see what it would do."⁵¹⁷ After four years of steady effort, Plum Brook walked away from the troublesome facility without any research data. It was the final turbine research at the Rocket Systems Area.

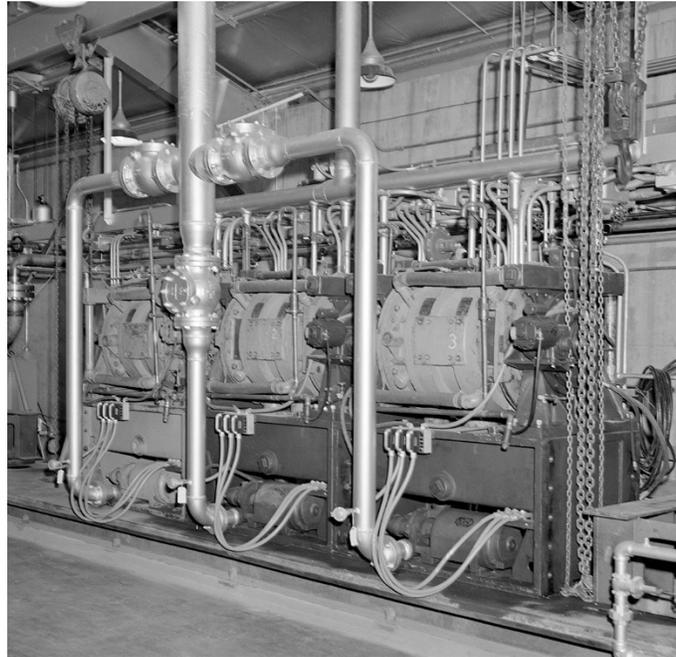


Image 117: Hot gas generator inside D Site. The equipment was used to supply gaseous hydrogen to experimental turbines to simulate the first stage in nuclear engine startups (GRC-1961-C-55372).

Fluorine Spills

The ability to use fluorine in an engine on a test stand was one thing, but the logistics of its use during an actual launch were another. Thousands of gallons of the toxic fluid would have to be stored and loaded onto the vehicle at the launch pad, and there was little known regarding the consequences of a large spill or other accident. Fluorine's reaction with other materials was not only a hazard to engine components but also to the materials found at a launch site or storage area. Fluorine could combust when it came into contact with most substances including water. "If you put a drop [of fluorine] on blacktop," explained Tom Brink, "the hydrocarbons in the blacktop would just burn instantly."⁵¹⁸ It was important to determine the reaction of fluorine with the surrounding area and the behavior of its toxic fumes in the atmosphere.

In June 1964 Harold Schmidt and his colleagues performed a preliminary investigation of these situations at J-5. They sought to determine the interaction of spilled fluorine, fluorine/oxygen (FLOX), and oxygen with sand, stones, asphalt, jet fuel, water, and other materials found at a launch pad. They were also interested in determining the type of combustion that occurred, the behavior of the resulting gas clouds, and the ability to mitigate the toxic releases with charcoal.⁵¹⁹

Glen Hennings gave Thorvald Brink responsibility for building the test setup at J-5 for the spill program. The spill rig was set up a short distance away from J-5's large containment vessel. The rig consisted of a 3.5-gallon stainless steel tank atop a test stand with a pipe below leading to a spill pan containing the sample material. When the valve was opened, 5 to 10 pounds of liquid fluorine would flow down the drain pipe and splash into the open pan on the ground.⁵²⁰



Image 118: Top: Fireball from FLOX spill onto JP-4 fuel. Bottom: Resulting fire 2.5 seconds later on 6 October 1965 (GRC-1965-C-02830).

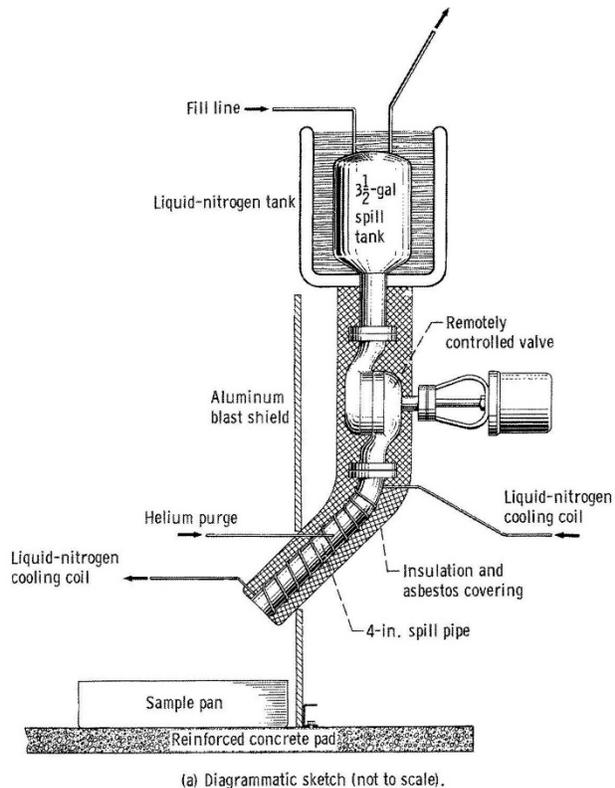


Image 119: Diagram of the spill test setup near J-5. The fluorine tank was at the top with a 4-inch pipe descending from the tank to approximately 2 feet above a 1-foot-deep and 3-foot-diameter pan that held the sample material. (NASA TM X-3118, Fig. 1).



Image 120: Photo of the spill test setup near J-5. A vertical aluminum shield was placed between the pan and the stand to protect the latter from damage⁵²¹ (GRC-1964-P-91511).

Brink explained, “It didn’t take us more than a month to design the rig and build it. In another month we kind of blew the stand backward.”⁵²² Nonetheless, the researchers performed 26 spills over the course of six run days in the fall of 1964. Schmidt and his colleagues studied the reaction of fluorine, FLOX, and liquid oxygen with the various test materials. These test materials were segregated into three classes: tarmac materials such as asphalt, sand, and pavement; water; and JP-4 rocket fuel. The two liquids were tested in puddles, streams, and soaked over some of the tarmac materials.⁵²³

The researchers found that fluorine combusted with all of the sample materials except concrete, but the combustion was relatively smooth. The FLOX mixture did not combust with water or several of the tarmac materials, but the reactions with JP-4 and oil soaked materials were much more violent than that experienced with straight fluorine. The interaction of both fluorine and FLOX with water was quite noxious and acidified the water.⁵²⁴

The more fiery or explosive reactions tended to create fireballs that resulted in a rapidly rising gas cloud that quickly dispersed. The toxic fumes lingered along the ground when there was low-energy fire or no combustion. The researchers felt that addition of charcoal to a spill area showed promise as a possible method for reducing the amount of toxicity entering the atmosphere. The researchers found that fluorine and FLOX both combusted with charcoal and burned smoothly. The fluorine-charcoal interaction produced an inert and nontoxic byproduct.⁵²⁵



Image 121: A 90-percent FLOX spill onto charcoal as seen from 50 yards (GRC-1965-C-02831).

The team used liquid oxygen for the final phase of the program. The liquid oxygen did not naturally combust with any of the materials, including the rocket fuel. Brink remembers thinking, “[I] wonder what would happen if there’s an ignition source.’ So we put a sparkplug out there, and it blew up.” The explosion was so powerful that pieces of the test pan sailed passed a photographer located behind a barrier 1,000 feet away. “We didn’t think anything would blow that far, and if it did it would just spread the pan out, but it broke the pan.” Although Brink advocated the rebuilding the heavily damaged test stand, management decided to terminate the program. “We did repairs,” he recalled, “but we kind of got shut down by somebody that knew better.”⁵²⁶

Lewis contracted General Dynamics to conduct a larger-scale version of the spill tests at their facilities in San Diego in the summer of 1965. The tests included the use of a water fog to suppress the toxicity. The results were mixed, but they confirmed the effectiveness of charcoal. There was no damage to tanks, transfer lines, and other launch area equipment placed at the site.⁵²⁷

It All Just Disappeared

Lewis researchers were able to determine that most fluorine engine failures were caused by contamination in the system, not—as previously thought—by fluorine’s reaction to the system materials. They also standardized fluorine’s handling and cleaning procedures, carefully selected component materials, and perfected the passivation technique of coating the exposed surfaces with a fluorine gas before introducing the liquid fluorine.⁵²⁸ They concluded that fluorine’s inherent difficulties could be overcome with precise systems engineering, maintenance, sanitation, and procedures. Lewis technicians and researchers repeatedly demonstrated that this perfection could be attained without excessive encumbrance.

This success gave Lewis the confidence that fluorine could be used as an oxidizer in contemporary rocket systems.⁵²⁹

Nonetheless, the use of liquid fluorine and FLOX as a rocket propellant has largely been forsaken. Lewis test engineer John Kobak recalled, “We were very confident we could figure out all the problems. We could handle it safely....All of a sudden nobody was interested in fluorine any more. It all just disappeared.”⁵³⁰ Glen Hennings believed that fluorine’s destiny was sealed in 1957 when Abe Silverstein approved the switch of the Rainmaker demonstration rocket from hydrogen-fluorine to hydrogen-oxygen. “Had we gone ahead on the H-F vehicle, then I think H-F would have been developed, if it had been successful.”⁵³¹

Many felt that the toxicity of fluorine itself, as well as the hydrogen-fluorine exhaust products, was too threatening to justify the enhanced performance. Charcoal worked as a toxicity suppressant but it required large quantities and handling equipment. There remained questions regarding the expansion of the Lewis safety procedures from a test facility to a large-scale rocket program with hundreds of people involved.⁵³² In addition, the need for fluorine diminished as the Centaur and Saturn upper stages began proving themselves, and the U.S. space program began catching up with the Soviets. “Pratt & Whitney had an oxygen pump that was working really well for the Atlas-Centaur,” explained Perdue. “So we just didn’t have any more research to do on fluorine, nor demand.”⁵³³



Image 122: The Engineering Building, which opened in February 1966, was Plum Brook’s primary office building. It included four conference rooms, a library, and an auditorium/cafeteria (seen to the right). The Engineering Division was downstairs and many of the Rocket Systems Division engineers were on the second floor. Plum Brook management occupied offices at the far left of the ground floor (GRC-1971-C-03062).

Plum Brook Opens Its Doors

Outreach has always been one of NASA's core tenets. The Space Act of 1958, which established NASA, called for "the widest practicable and appropriate dissemination of information concerning its activities." In the early 1960s Lewis began engaging the public for the first time and established an educational program. At the time, public interest in the space program was high. Lewis sponsored several wildly popular science fairs in downtown Cleveland and began dispatching employees to community groups and schools to discuss their activities.

In 1962 Hap Johnson began hosting student tours of the Plum Brook facilities. Groups of local high school science students were invited to view the test sites and hear about the research activities being conducted at Plum Brook.⁵³⁴ For example, in an effort to explain the effect of extremely low temperatures on some materials, the staff put students in protective gear and asked them to dip an apple in a bucket of cryogenic liquid nitrogen. After removing the deep frozen apple from the vat, they were instructed to throw it against a wall where it shattered like glass.⁵³⁵



Image 124: Students participate in a cryopumping demonstration (GRC-1962-P-01739).

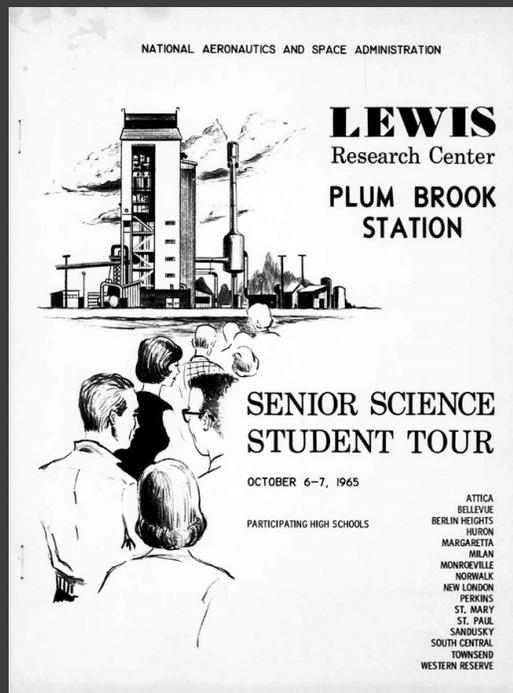


Image 123: Tour Brochure (NASA).

In 1965 Johnson instated annual driving tours of Plum Brook. Over three Sundays each October the public could use their own vehicle to drive by the B test stands, K Site, pump sites, reactor, and PBOW's bunkers.⁵³⁶ The visitors could enjoy the fall colors and view wildlife while driving the 12 miles through Plum Brook's forests and meadows. They were provided with a brochure that included a map and brief site descriptions and could tune in a local radio station to hear a prerecorded audio tour.⁵³⁷ In later years the stops shifted from the Rocket Systems Area to the new Space Power Facility (SPF) and B-2. The staff also set up exhibits in the Engineering Building with models of items such as the Centaur rocket and RL-10 engine.⁵³⁸

All Shook Down

The successful Atlas/Centaur launch in November 1963 breathed new life into the Centaur Program, but there remained hurdles to overcome and additional developmental flights before the vehicle would be ready to carry a *Surveyor* spacecraft to the Moon. Lewis's Centaur Program Office took measures to test the shroud jettison system, restart the engines and verify the performance of the electronics in a space environment, and ensure that the vehicle could withstand the vibrations associated with a launch. The Rocket Systems Area's Dynamics Stand (E Stand) played the critical role resolving this last issue.

As launch vehicles push their way through the atmosphere on the way to space, they must withstand the forces from atmospheric air and winds. The force of the engines against these pressures can result in compression or bending of the slender vehicle, which may cause the steering miscalculations. This was a particular concern for the unique pressurized Atlas/Centaur.⁵³⁹

General Dynamics created the pressurized steel propellant tanks for its Atlas missile in the 1950s. The thin-walled design reduced the vehicle's weight, but the lack of framework initially caused anxiety regarding the vehicle's structural integrity.⁵⁴⁰ General Dynamics's application of the same technology to the Centaur second stage raised new concern that the aerodynamic and inertial loads during launch would cause significant bending in the Atlas/Centaur. The designers needed to understand this bending phenomenon in order to take advantage of the vehicle's strength.

Researchers had previously conducted investigations of pressurized membranes using small Mylar (DuPont Teijin Films) cylinders. The Centaur staff did not feel that the findings could be applied to the much larger metal structure that had protuberances and other anomalies.⁵⁴¹ In addition, tests of an Atlas/Centaur model in Lewis's 8- by 6-Foot Supersonic Wind Tunnel revealed that the bending forces from the Centaur were far greater than the Atlas had ever experienced.⁵⁴² General Dynamics calculated that steadiness could be maintained through a large amount of stabilization, or damping. Lewis's Centaur Program Office set up a full-scale test program at E Stand to verify the General Dynamics calculations and confirm that the Atlas was robust enough to carry the large Centaur stage.⁵⁴³



The Rocket Systems Division began preparing to add a Centaur to the Atlas test setup in E Stand almost immediately after the Atlas/Centaur 2 (AC-2) launch. On 18 December 1963, in the midst of a massive blizzard, an U.S. Air Force C-133 Globemaster arrived at Lewis's Lewis Field campus in Cleveland with a Centaur from General Dynamics. The rocket was mounted on a massive dolly and trucked the following day to Plum Brook in Sandusky.⁵⁴⁴ The Plum Brook staff worked with General Dynamics technicians throughout the winter to prepare for the next series of tests. General Dynamics had a stretcher apparatus to maintain the vehicle's rigidity when the tanks were not pressurized. The stretcher, however, did not fit into E Stand. This meant that technicians had to keep the vehicle pressurized at all times to prevent it from collapsing on itself between runs. A mock-up *Surveyor* spacecraft was added to the vehicle in March 1964. This was the first time that the Atlas/Centaur/*Surveyor* combination had ever been assembled.⁵⁴⁵

The Atlas/Centaur was suspended by a steel cable from a spring box near the top of the stand. This suspension system allowed the vehicle to remain free floating while in contact with the shaker at the bottom of the stand. The Centaur Program Office decided that cryogenic propellants were not necessary for these runs so the staff filled the propellant tanks with varying amounts of deionized water to represent different stages of the flight.⁵⁴⁶



Image 125: Unloading of the Centaur from the Globemaster at the Lewis hanger on 18 December 1963 (GRC-1963-C-67580).



Image 126: Truck delivering the Centaur from Lewis Field in Cleveland to Plum Brook in Sandusky in December 1963 (GRC-1963-C-67582).

The first test analyzed the Atlas/Centaur/*Surveyor* vehicle's ability to withstand the vertical POGO vibrations that had affected early missiles. Between March and July 1964 the staff subjected the Atlas/Centaur/*Surveyor* vehicle to five 2½-minute tests in which the vehicle was vertically shaken by up to 5,000 pounds of pressure.⁵⁴⁷ These runs produced the first measurements of the longitudinal dynamics of a full-scale rocket in the United States.⁵⁴⁸

The researchers concluded that the oscillations found during previous E Stand tests of a mock-up Centaur differed significantly from those of the actual vehicle. The longitudinal studies also revealed that the Atlas/Centaur had four to five times as much damping, or energy absorption characteristics, as predicted. This meant that it could withstand greater bending levels than earlier believed.⁵⁴⁹ The Centaur Program Office felt confident enough after just the first test run to remove the flight restraint on the upcoming AC-3 launch on 30 June 1964.⁵⁵⁰ Although the launch attempt failed when Centaur's engines prematurely shut off, the vehicle performed well structurally.

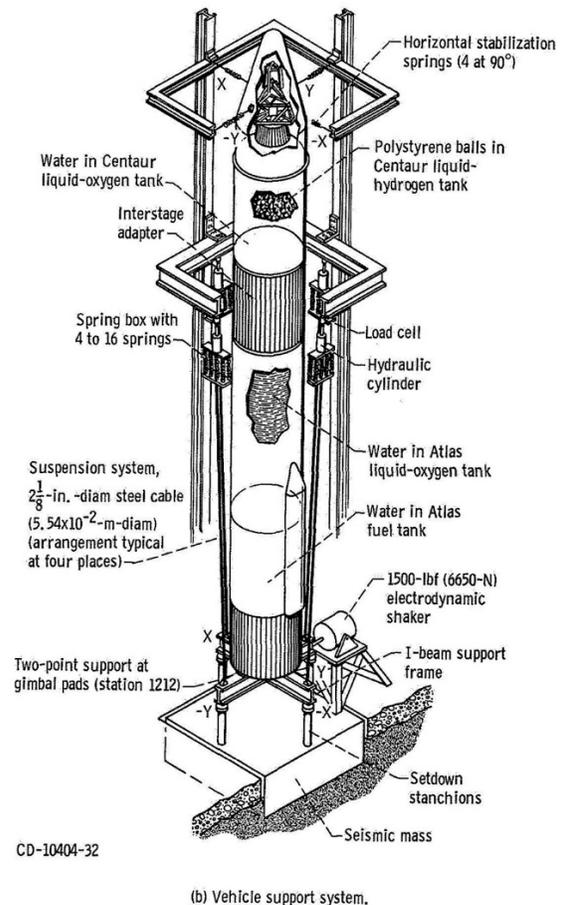


Image 127: E Stand test setup configuration (NASA TM X-1837, Fig. 2).



During this period, researchers were also testing the Atlas/Centaur's response to lateral vibrations. The Atlas/Centaur's flight control system acted in conjunction with the vehicle's lateral bending behavior, so bending or structural abnormalities could cause the vehicle's attitude sensors to make improper flight adjustments. It was important to analyze the vehicle's bending and stabilization processes at various points in the simulated launch to improve the control system's analysis of stability, loads, and clearance.⁵⁵¹

The test setup for the Atlas/Centaur/*Surveyor* model vehicle was virtually the same as for the longitudinal tests except that an exciter alongside the vehicle was used to apply force. A profiler device ran up and down the vehicle during the runs to measure changes to its shape. The 10 runs in the spring of 1964 were conducted with varying propellant levels to simulate different times during the flight. The researchers found that tank pressure only affected the vehicle's natural bending slightly and that the bending was the same for longitudinal and lateral surfaces.⁵⁵²

For the next series of tests, the researchers wanted to verify the integrity of the thin wall that separated Centaur's hydrogen and oxygen tanks. To minimize weight, General Dynamics designed the tanks to share a common bulkhead. The company altered the mass of the bulkhead specifically for the upcoming Atlas/Centaur (AC-4) launch, which was the first attempt to restart Centaur's engines in space. Lewis wanted to verify Centaur's structural integrity during the restart period. The Rocket Systems Division installed a new floor at E Stand's 80-foot level so that the shaker could be mounted next to Centaur. The

researchers performed the runs with the AC-4 configuration satisfactorily in the fall of 1964.⁵⁵³ The launch of the vehicle on 11 December 1964 was successful, but Centaur failed to restart its engines as planned.



Despite the unusual pressurized structure of both the Atlas and Centaur, General Dynamics engineer David Peery predicted that the vehicle could withstand even greater amounts of force than it was designed for. Peery recommended testing the rocket to the point of failure to determine its buckling point.⁵⁵⁴ Lewis researcher Robert Miller and the Rocket Systems Division worked to install the necessary equipment in E Stand throughout 1965.

The first test was run in February 1966. A lateral force was applied to the adapter that joined the Atlas and the Centaur. The staff adjusted the level of force to simulate the point during flight with maximum load pressures. These forces were often sufficient enough to cause the vehicle's thin metal skin to temporarily wrinkle. Miller then analyzed the impact on the vehicle's flexibility and propellant tanks. The operator increased the force during the follow-up test in May 1966 until it damaged the Atlas's oxidizer tank. Despite lingering bulges in the metal skin, the vehicle's internal pressure was not compromised.⁵⁵⁵

For the final test in August 1966, the researchers sought to bend the entire vehicle, not just the adapter section. Roger Hershiser remembers that the test operator halted the run before the final push. "The engineers put a barbeque on to kind of celebrate the end of the thing," he recalled. "They said, 'Ok, when we go back we're going to bust it. We're going to crack it.' They gave that hydraulic system all they could give it, and it just bent. It wouldn't break. They couldn't break it."⁵⁵⁶

Miller found that the overall bending strength of the vehicle was similar to that around the oxidizer tank, and that wrinkling of the external skin did not damage the tanks. The Atlas possessed enough bending strength to endure 150-percent of the force that caused wrinkling.⁵⁵⁷ General Dynamics was able to use the new data from E Stand to redesign the rocket to withstand even greater buckling.⁵⁵⁸

Centaur's Validation

E Stand was an essential component of Lewis's intense four-year effort to prepare Centaur for the Surveyor missions. The E Stand tests proved that the Atlas was not only robust enough to support the Centaur vehicle but could withstand greater loads than it was designed for. That meant that the vehicle could be launched into stronger winds. In addition E Stand's dynamics data provided the groundwork for the Automatic Determination and Dissemination of Just Updated Steering Terms (ADDJUST) in the early 1970s. ADDJUST is a computerized control system designed to guide the launch vehicle through winds without increasing loads.⁵⁵⁹

After the initial elation over the AC-2 launch in November 1963, came a series of failures. The third launch attempt failed to reach orbit in June 1964, the fourth in December 1964 reached orbit but could not restart its engines, and the fifth launch in March 1965 rose only a few feet off of the pad. There was intense pressure to make Centaur a reliable vehicle. Finally on 11 August 1965 Lewis successfully completed another launch of the Atlas/Centaur (AC-6). The follow-up in April 1966 (AC-8) was an even bigger success. It was the first time that Centaur had been able to restart its engines in orbit.

Next up was the program's most significant test yet—the first attempt to launch an actual *Surveyor* spacecraft. Cape Kennedy was particularly windy on 30 May 1966, and the launch would probably have been scrubbed if it were not for the structural testing at E Stand.⁵⁶⁰ At 9:41 a.m. the Atlas/Centaur lifted off from the cape and sent the *Surveyor* spacecraft on its way. Three days later *Surveyor* began transmitting images back to Earth from the surface of the Moon. It was the first U.S. spacecraft to soft-land on another planetary body.

On 7 October 1966, NASA awarded 123 members of the Lewis Centaur Program staff a Group Achievement Award. The Lewis and General Dynamics team drew praise from NASA management, Congress, and the media. Over the next two years, NASA used Atlas/Centaurs to send six more *Surveyors* to the Moon, which provided vital information on the composition of the lunar surface and helped to identify landing sites for the *Apollo* spacecraft. The *Surveyor* landing was a significant milestone for both NASA and the center.

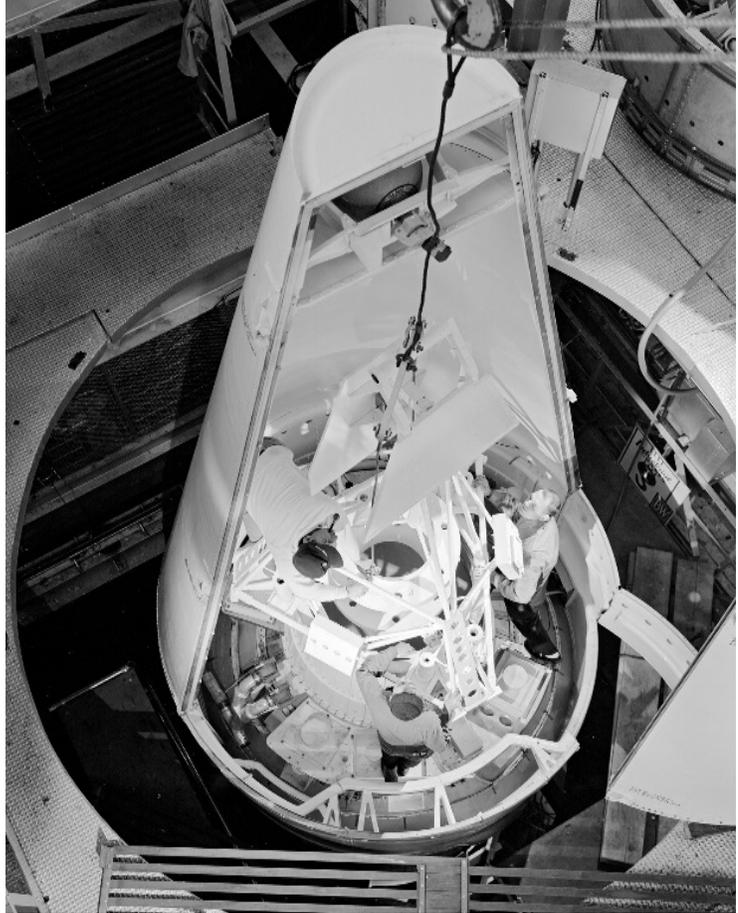


Image 128: Technicians install a mock-up *Surveyor* spacecraft atop the Atlas/Centaur in the E Stand (GRC-1964-P-01239).



The mid-1960s were the tipping point for the Space Race. NASA had more employees, facilities, and funding than ever before. The rapid succession of Gemini missions kept the Apollo effort in the public eye, and the Saturn 1 completed 10 launches, including 6 with the hydrogen-fueled S-II stage. NASA human-rated the Saturn 1B over the course of several launches in 1966, including one with an *Apollo Command Module*.⁵⁶¹ In addition, the Atlas/Centaur sent the first of seven *Surveyor* spacecraft to the Moon, and the AEC successfully fired the Kiwi B and NERVA NRX nuclear engines. Nonetheless, fissures began appearing in the nation's unwavering support for the space program.

Lewis, the former NACA laboratory, established itself as a key contributor to the space program. Its work with liquid hydrogen was now paying off with NASA's largest rockets, and the management of Centaur brought the center acclaim. The Rocket Systems Area, which now included additional sites, provided key testing for the Kiwi and Centaur programs and continued perfecting the pumping of cryogenic fluids. With newer and even more complex facilities on the way, the future was promising.

References

440. Richard Heath interview, Cleveland, OH, by Robert Arrighi, 15 August 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
441. Heath interview by Arrighi.
442. Robert Seiwert to Robert Godman, “Cryogenic Propellant Tank Laboratory Review,” 22 October 1964, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
443. “High Energy Rocket Engine Research Facility B–1, Nuclear Rocket and Dynamics Control Facility B–3,” 1 March 1967, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
444. “High Energy Rocket Engine Research Facility B–1.”
445. “NASA Lets Contracts for Plum Brook Projects,” *Sandusky Register* (8 May 1963).
446. Herbert Heppler, Benjamin Colmery, James Watt, and Vernon Gebben, *Startup Dynamics and Control* (Washington, DC: NASA X66–51410, 1966), <http://ntrs.nasa.gov>
447. John Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959* (Washington, DC: NASA SP–4404, 1977), <http://ntrs.nasa.gov>
448. John Clark, *Analytical and Experimental Study of Startup Characteristics of a Full-Scale Unfueled Nuclear Rocket Core Assembly* (Washington, DC: NASA TM X–1231, 1966), <http://ntrs.nasa.gov>
449. Clark, *Analytical and Experimental Study of Startup Characteristics*.
450. Ralph Stacht, Richard Quentmeyer, and William Jones, *Hot-Gas-Side Heat Transfer With and Without Film Cooling on a Simulated Nuclear Rocket Thrust Chamber Using H₂-O₂* (Washington, DC: NASA TN D–6638, 1972), <http://ntrs.nasa.gov>
451. Bruce Lundin to Herman Gerstein, “Turbopump and Nuclear Rocket Systems Evaluations To Be Made in the NASA Lewis B–1 Facility” 16 February 1962, NASA Glenn History Collection, Directors Collection.
452. Rocket Systems Division Reports, High Energy Rocket Engine Research Facility, 1962–1964, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
453. Walter Weiland and Donald Adams, *Heat Transfer Characteristics of a Water-to-Cryogenic-Hydrogen Heat Exchanger* (Washington, DC: NASA TN D–5429, 1969), <http://ntrs.nasa.gov>
454. Weiland, *Heat Transfer Characteristics*.
455. Rocket Systems Division Reports, F Site, 1964, NASA Glenn History Collection, Plum Brook Collection, Cleveland, OH.
456. Weiland, *Heat Transfer Characteristics*.
457. David Portree, *Humans to Mars: Fifty Years of Mission Planning, 1950–2000* (Washington, DC: NASA/SP—2001-4521, 2001), <http://ntrs.nasa.gov>
458. Jane Van Nimmen, Leonard Bruno, and Robert Rosholt, *NASA Historical Databook Volume I, NASA Resources 1958–1968* (Washington, DC: NASA SP–4012, 1976), <http://ntrs.nasa.gov>
459. Stanley Gunn, “Nuclear Propulsion—A Historical Perspective,” *Space Policy* 17 (2001).
460. James Dewar, “Project Rover: A Study of the Nuclear Rocket Development Program, 1953–1963” (Doctoral thesis, Kansas State University, 1974).
461. John Esterly, David Straight, John Pierce, et al., *Nuclear Rocket Simulator Tests, Facility and Research Apparatus Description* (Washington, DC: NASA TM X–52043, 1964), <http://ntrs.nasa.gov>
462. Benjamin Colmery and Albert Powers, *Flow System Startup of a Full-Scale Simulated Nuclear Rocket Engine* (Washington, DC: NASA TM X–52139, 1965), <http://ntrs.nasa.gov>
463. Esterly, *Nuclear Rocket Simulator Tests*.
464. Lundin to Gerstein, “Turbopump and Nuclear Rocket Systems Evaluations.”
465. Thomas Biesiadny, Robert Coltrin, Albert Powers, et al., *Nuclear Rocket Simulator Tests, Flow Initiation With No Turbine Gas; Tank Pressure, 35 PSIA, Run 1* (Washington, DC: NASA TM X–52044, 1964), <http://ntrs.nasa.gov>
466. Richard Rudey, John Livingood, Thomas Litzler, et al., *Nuclear Rocket Simulator Tests Flow Initiation With Locked Rotor; Tank Pressure Ramp, 25 to 70 psi, Run 8* (Washington, DC: NASA TM X–52054, 1964), <http://ntrs.nasa.gov>
467. Heppler, *Startup Dynamics and Control*.

468. George Turney and Eileen Cox, *Cooldown Characteristics of Regenerative Nozzle Used in Full-Scale, Cold-Flow, Nuclear Rocket Test Facility* (Washington, DC: NASA TN D-3931, 1967), <http://ntrs.nasa.gov>
469. Roderick Spence, "Nuclear Rockets," *International Science and Technology* (July 1965).
470. David Robinson, Robert Coltrin, and Thomas Litzler, *Flow Initiation With Turbine Accelerated Tank Pressure 50 PSIA, Run 11* (Washington, DC: NASA TM-52066, 1964), <http://ntrs.nasa.gov>
471. James Dewar, *To the End of the Solar System: The Story of the Nuclear Rocket* (Lexington, KY: University Press of Kentucky, 2004).
472. Rocket Systems Division Reports, High Energy Rocket Engine Research Facility, 1964, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
473. David Straight and Thomas Biesiadny, *Effect of Feedline and Nozzle Insulation and Propellant Feedline Configuration on System Parameters That Affect Bootstrap* (Washington, DC: NASA TM X-52086, 1965), <http://ntrs.nasa.gov>
474. David Robinson, *Flow Initiation With Turbine Accelerated Tank Pressure 35 PSIA; Runs 12, 14-17* (Washington, DC: NASA TM X-52089, 1965), <http://ntrs.nasa.gov>
475. Clark, *Analytical and Experimental Study of Startup Characteristics*.
476. Rocket Systems Division Reports, High Energy Rocket Engine Research Facility.
477. Rocket Systems Division Reports, Nuclear Rocket Dynamics and Controls Facility, 1965, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
478. Wojciech Rostafinski, *An Analytical Method for Predicting the Performance of Centrifugal Pumps During Pressurized Startup* (Washington, DC: NASA TN D-4967, 1969), <http://ntrs.nasa.gov>
479. Guy Ribble and George Turney, *Experimental Study of Low-Speed Operating Characteristics of a Liquid Hydrogen Centrifugal Turbopump* (Washington, DC: NASA TM X-1861, 1969), <http://ntrs.nasa.gov>
480. Rocket Systems Division Reports, Nuclear Rocket Dynamics and Controls Facility, 1966, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
481. William Robbins and Harold Finger, *An Historical Perspective of the NERVA Nuclear Rocket Engine Technology Program* (Washington, DC: NASA CR-187154, 1991), <http://ntrs.nasa.gov>
482. Ribble and Turney, *Experimental Study of Low-Speed Operating Characteristics*.
483. Rocket Systems Division Reports, Nuclear Rocket Dynamics and Controls Facility.
484. Rocket Systems Division Reports, Nuclear Rocket Dynamics and Controls Facility, 1967, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
485. Roger Bilstein, *Orders of Magnitude: A History of the NACA and NASA, 1915-1990* (Washington, DC: NASA SP-4406, 1989), <http://ntrs.nasa.gov>
486. Portree, *Humans to Mars*.
487. T. A. Heppenheimer, *The Space Shuttle Decision: NASA's Search for a Reusable Space Vehicle* (Washington, DC: NASA SP-4221, 1999), <http://ntrs.nasa.gov>
488. Bilstein, *Orders of Magnitude*.
489. Portree, *Humans to Mars*.
490. "Plum Brook Station Senior Science Student Tour," 6 October 1965, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
491. "Ohio Firms Get Contracts," *Dover Daily Reporter* (26 July 1963).
492. Heath interview by Arrighi.
493. "\$2 Million Plum Brook Project Wins Approval," *Sandusky Register* (21 March 1966).
494. George H. Prueger, Morgan Williams, Wei-chung Chen, et al., *Unshrouded Centrifugal Turbopump Impeller Design Methodology* (Washington, DC: NASA/CP-2001-211141, 2001), <http://ntrs.nasa.gov>
495. "Site Building Active at Plum Brook," *Sandusky Register* (14 August 1965).
496. Plum Brook Rocket Systems Division, Test Operations Report for the Month of April 1964, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
497. George Sutton, *History of Liquid Propellant Rocket Engines* (Reston, VA: American Institute of Aeronautics and Astronautics, 2006).
498. Earl Logan and Ramendra Roy, editors, *Handbook of Turbomachinery, Second Edition* (New York, NY: Marcel Dekker, Inc., 2005).

499. Donald Urasek, *Investigation of Flow Range and Stability of Three Inducer-Impeller Pump Combinations Operating in Liquid Hydrogen* (Washington, DC: NASA TM X-1727, 1969), <http://ntrs.nasa.gov>
500. Calvin Ball, Phillip Meng, and Lonnie Reid, *Cavitation Performance on 84-Degree Helical Pump Inducer Operated in 37-Degree and 42-Degree R Liquid Hydrogen*, (Washington, DC: NASA TM X-1360, 1967), <http://ntrs.nasa.gov>
501. Douglas Anderson, Richard Soltis, and Donald Sandercock, *Performance of 84-Degree Flat-Plate Helical Inducer and Comparison With Performance of Similar 78-Degree and 80.6 Degree Inducers* (Washington, DC: NASA TN D-2553, 1964), <http://ntrs.nasa.gov>
502. Raymond Lacovic, *A Comparison of Experimental and Calculated Helium Requirements for the Pressurization of a Centaur Liquid Hydrogen Tank* (Washington, DC: NASA TM X-1870, 1969), <http://ntrs.nasa.gov>
503. Ball, *Cavitation Performance on 84-Degree Helical Pump Inducer*.
504. Phillip Meng and Robert Connelly, *Investigation of Effects of Simulated Nuclear Radiation Heating on Inducer Performance in Liquid Hydrogen* (Washington, DC: NASA TM X-1359, 1967), <http://ntrs.nasa.gov>
505. Robert Connelly and Phillip Meng, *Inducer Performance With Hydrogen Liquid-Vapor Mixtures* (Washington, DC: NASA TM X-523201, 1967), <http://ntrs.nasa.gov>
506. Robert Walter interview, Cleveland, OH, by Robert Arrighi, 5 November 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
507. Phillip Meng, *Change in Inducer Net Positive Suction Head Requirement With Flow Coefficient in Low Temperatures Hydrogen* (Washington, DC: NASA TN D-4423, 1968), <http://ntrs.nasa.gov>
508. Irving Pinkel, Melvin Hartmann, Cavour Hauser, et al., *Pump Technology* (Washington, DC: NASA N66-33672, 1966).
509. Walter interview by Arrighi.
510. Memorandum to Charles S. Moore, "Information for Yearly Experimental Facilities Operation Report for Plum Brook Station," 9 July 1962, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
511. Rocket Systems Division Test Operations Report, Turbine Test Facility, 1963, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, Ohio.
512. Walter interview by Arrighi.
513. Rocket Systems Division Test Operations Report, Turbine Test Facility, 1964, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, Ohio.
514. Rocket Systems Division Test Operations Report, Turbine Test Facility, 1964.
515. Rocket Systems Division Test Operations Report, Turbine Test Facility, 1965, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, Ohio.
516. Rocket Systems Division Test Operations Report, Turbine Test Facility, 1965.
517. Walter interview by Arrighi.
518. Thorvald Brink interview, Cleveland, OH, by Robert Arrighi, 29 November 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
519. Louis Russell, Harold Schmidt, and Robert Clarke, *Reaction Characteristics of Spills of Fluorine and Fluorine-Oxygen Mixtures Upon Various Materials* (Washington, DC: NASA TN D-3118, 1966), <http://ntrs.nasa.gov>
520. Russell, *Reaction Characteristics of Spills of Fluorine and Fluorine-Oxygen Mixtures*.
521. Russell, *Reaction Characteristics of Spills of Fluorine and Fluorine-Oxygen Mixtures*.
522. Brink interview by Arrighi.
523. Russell, *Reaction Characteristics of Spills of Fluorine and Fluorine-Oxygen Mixtures*.
524. Russell, *Reaction Characteristics of Spills of Fluorine and Fluorine-Oxygen Mixtures*.
525. Russell, *Reaction Characteristics of Spills of Fluorine and Fluorine-Oxygen Mixtures*.
526. Brink interview by Arrighi.
527. Harold Schmidt and Jack Harper, *Handling and Use of Fluorine and Fluorine-Oxygen Mixtures in Rocket Systems* (Washington, DC: NASA SP-3037, 1967), <http://ntrs.nasa.gov>
528. Walter Osborne, *Noncavitating and Cavitating Performance of a Liquid-Fluorine Pump Designed by Stream-Filament Method* (Washington, DC: NASA TM X-722, 1963), <http://ntrs.nasa.gov>
529. Schmidt, *Handling and Use of Fluorine and Fluorine-Oxygen Mixtures*.

530. John Kobak interview, Cleveland, OH, by Robert Arrighi, 9 September 2009, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
531. John Gibb, Glen Hennings, Harold Christianson, and Dave Fenn interview by John Sloop, May 1974, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
532. Schmidt, *Handling and Use of Fluorine and Fluorine-Oxygen Mixtures*.
533. Donald Perdue interview, Cleveland, OH, by Robert Arrighi, 12 November 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
534. “Plum Brook Tours Attract Students,” *Lewis News* (20 October 1972).
535. Walter interview by Arrighi.
536. William Gerber, NASA Lewis Research Center press release 66–67, 12 October 1966, NASA Glenn History Collection, Cleveland, OH.
537. “PB Invites Public,” *Lewis News* (6 October 1972).
538. Charles Kelsey, NASA Lewis Research Center press release 68–68, 25 October 1968, NASA Glenn History Collection, Cleveland, OH.
539. “Insuring Structural Integrity for Centaur,” *Lewis News* (1 June 1973).
540. Richard Martin, “The Atlas and Centaur ‘Steel Balloon’ Tanks a Legacy of Karel Bossart,” *40th International Astronautical Congress* (Malaga, Spain: IAA–89–738, 8–14 October 1989).
541. Robert P. Miller, *Experimental Bending Strength of an Atlas LV–36 Booster Beyond Compressive Skin Wrinkling* (Washington, DC: NASA TN D–5156, 1969), <http://ntrs.nasa.gov>
542. “Research and Technology on Propulsion, Space Power, and Space Vehicles,” *Inspection at the Lewis Research Center*, 4 October 1966, NASA Glenn History Collection, Inspections Collection, Cleveland, OH.
543. Theodore Gerus, John Housely, and George Kusic, *Atlas-Centaur-Surveyor Longitudinal Dynamics Tests* (Washington, DC: NASA TM X–1459, 1967), <http://ntrs.nasa.gov>
544. “Centaur Rocket Comes to Plum Brook Station,” *Sandusky Register* (18 December 1963).
545. “Plum Brook Gets Atlas,” *Sandusky Register* (17 August 1963).
546. Gerus, *Atlas-Centaur-Surveyor Longitudinal Dynamics Tests*.
547. Gerus, *Atlas-Centaur-Surveyor Longitudinal Dynamics Tests*.
548. Ted Gerus interview, Cleveland, OH, by Bonita Smith, 2 August 2002, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
549. Gerus, *Atlas-Centaur-Surveyor Longitudinal Dynamics Tests*.
550. Rocket Systems Division Reports, Dynamics Laboratory, March 1964, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
551. Robert P. Miller and Theodore Gerus, *Experimental Lateral Bending Dynamics of the Atlas-Centaur-Surveyor Launch Vehicle* (Washington, DC: NASA TM X–1837, 1969), <http://ntrs.nasa.gov>
552. Miller, *Experimental Lateral Bending Dynamics*.
553. Rocket Systems Division Reports, Dynamics Laboratory, 1964, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
554. Virginia P. Dawson and Mark D. Bowles, *Taming Liquid Hydrogen: The Centaur Upper Stage Rocket* (Washington, DC: NASA/SP—2004-4230, 2004), <http://ntrs.nasa.gov>
555. Robert P. Miller, *Experimental Bending Strength of an Atlas LV–36 Booster Beyond Compressive Skin Wrinkling* (Washington, DC: NASA TN D–5156, 1969), <http://ntrs.nasa.gov>
556. Roger Hershiser interview, Cleveland, OH, by Robert Arrighi, 17 December 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
557. Miller, *Experimental Bending Strength of an Atlas LV–36 Booster*.
558. Dawson, *Taming Liquid Hydrogen*.
559. Dawson, *Taming Liquid Hydrogen*.
560. “Research and Technology on Propulsion, Space Power, and Space Vehicles.”
561. Roger Bilstein, *Stages to Saturn : A Technological History of the Apollo/Saturn Launch Vehicles* (Washington, DC: NASA SP–4206, 1996), <http://ntrs.nasa.gov>

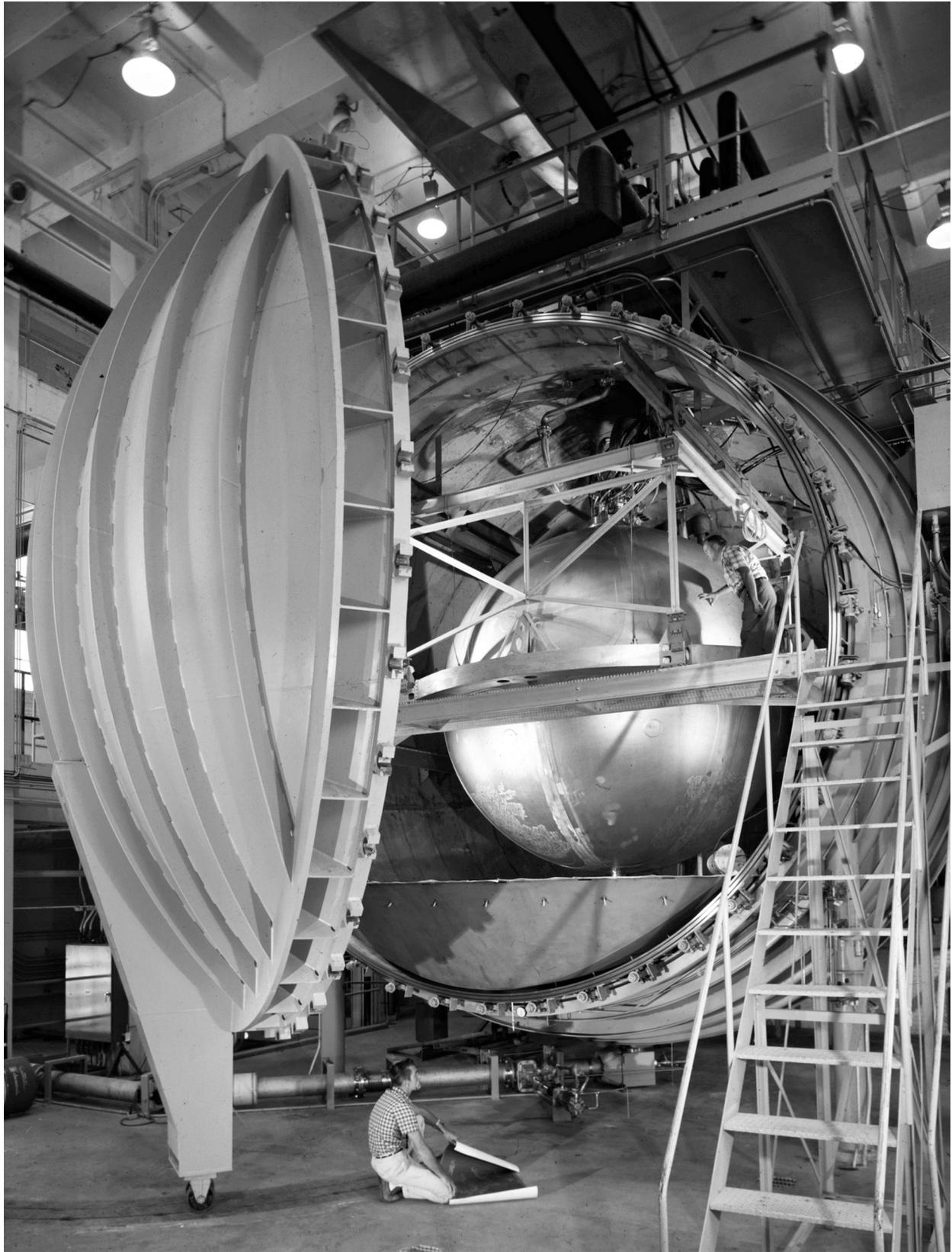


Image 129: A 13-foot-diameter propellant tank installed inside the Cryogenic Propellant Tank Facility (K Site) vacuum chamber (GRC-1967-C-03315).

◆ Chapter 7 ◆

Research for an Uncertain Future

On 9 November 1967 NASA successfully launched the first complete Saturn V/*Apollo* vehicle into space. Afterward, Wernher von Braun sent a signed photograph of the event to Lewis that included, “To Dr. Abe Silverstein, whose pioneering work in liquid-hydrogen technology paved the way to today’s success.” Although the Moon landing was still nearly two years away, liquid hydrogen had clearly proven itself and the United States had turned the corner in the Space Race. As the Agency neared its most notable achievement in the late 1960s, Congress slowly reduced its budget, downsized its workforce, and eliminated long-term missions. National concern for the Vietnam War and civil unrest overshadowed the space program.

The resolution of many of liquid hydrogen’s handling and storage issues had led to decreased rocket propulsion work at Lewis. Silverstein reorganized the Lewis staff in 1966 to focus more on aeronautics. The shift was most evident in the conversion of the Chemical Rocket Division into the Airbreathing Engines Division. As the larger facilities became operational at Plum Brook Station, utilization of the original Rocket Systems Area sites began ebbing. Nonetheless, the Rocket Systems Area remained active throughout the late 1960s with continued turbopump and heat transfer investigations, and a new wave of insulation and pressurization issues for propellant tanks.

Cryogenic Storage Issues

Rocket designers had a number of issues to address regarding tanks for cryogenic liquids, including strength, weight, fluid movement, pressurization, and insulation. (Lewis researchers also addressed the effect of microgravity on fluid behavior, but not at the Rocket Systems Area.⁵⁶²) Propellant tanks must be lightweight without compromising strength, pressurized to force the propellant out, designed to keep the fluids settled, and insulated to prevent the evaporation of the cryogenic liquids. Researchers used several Rocket Systems Area facilities for propellant tank investigations in the mid and late 1960s—particularly regarding pressurization and insulation.

The Hydraulics Laboratory (F Site) contained a high-pressure hydrogen tank for insulation studies and durability tests. The Tank Test Facility (J-4) was a semi-enclosed test stand used to study the loading of cryogenic propellants and insulation systems. The Vacuum Environment Facility (J-3) included a modest-sized vacuum chamber to test small fiber and resin liquid-hydrogen tanks. In addition, the staff could test entire propellant systems, including the tanks, in the High Energy Rocket Engine Research Facility (B-1 Stand) and Nuclear Rocket Dynamics and Control Facility (B-3 Stand).

The center’s premier tank testing facility, however, was the Cryogenic Propellant Tank Facility (K Site). K Site contained a 25-foot-diameter spherical vacuum chamber in which researchers could test tanks up to 18 feet in diameter. K Site also included cold wall^y equipment to create the temperatures of space and shakers to study the effect of launch vibrations.⁵⁶³ Glen Hennings terminated tank testing at J-4 and F Site once K Site began operation in the fall of 1965, but researchers continued to utilize J-3 for several more years.

^yA cold wall is a large capsule with ribbed walls through which a cryogenic fluid is flowed to create a cold environment.



Image 130: K Site test chamber with cryoshroud installed around the tank. The cryoshroud, or cold wall, subjected the tank to the low temperatures encountered in space (GRC-1971-P-01399).

Pressurization

Liquid-rocket-fuel tanks are pressurized with gases, referred to as pressurant, to naturally push the propellant toward the engine. The pressurant is usually a stable gas, such as helium, that possesses a higher pressure level than the liquid propellant. The pressure level must be high enough to push the cryogenic fluid toward the combustion chamber fast enough to prevent evaporation, but not so high as to require thicker tank walls. To avoid the extra weight of thicker tanks, engine designers seek to use the minimal amount of pressurant to meet the requirements.

Researchers developed methods to calculate the optimal pressurant level for any given set of tank parameters, such as gas temperature, liquid flow rate, and tank pressure. These theoretical predictions, however, required verification through actual tests of a tank in simulated space conditions. Robert Stochl, Philip DeWitt, and colleagues from Lewis's Chemical Rockets Division developed a test program to determine which factors had the most influence on pressurant performance during both the initial pressurization of the tank and the actual expulsion of the propellant. They first analyzed different injector designs on a small cylindrical tank at Lewis Field. The main portion of the test program, however, was run at K Site using two 5-foot-diameter spherical aluminum tanks—one with a slightly thicker wall than the other.⁵⁶⁴

K Site testing began with the evacuation of all air from the test chamber. This could take up to 24 hours, but once the vacuum was achieved multiple runs could be performed. The staff would partially fill the propellant tank with liquid hydrogen and let it settle. The operator then would activate the facility's timers, controls, and recording equipment and introduce the pressurant into the tank. Instrumentation inside the tank measured the concentration and distribution of the pressurant gas as it forced out the liquid fuel.



Image 131: A 13-foot stainless steel tank is brought to K Site for pressurization tests in August 1966 (GRC-1966-P-01861).

In the spring of 1966 the researchers tested both gaseous-helium and gaseous-hydrogen pressurants with the thicker-walled tank over 30 times while varying the temperatures, flow rates, and injector types.⁵⁶⁵ In the summer of 1966 the researchers investigated the effect of propellant motion, or sloshing, on the expulsion rate. Forces during the launch and coast phases of a mission can cause the propellants to slosh inside the tank. This can alter the rocket's course, cause the release of liquid out of the tank's vents, or move the propellant away from the outlet valve. Sloshing prematurely ended one of the early Centaur flights.⁵⁶⁶ The operators filled the tank about half way and used the K Site shaker equipment to slosh the liquid as it was pushed out of the tank. They repeated the tests that fall to determine the effect of antislosh baffles and different injectors on the expulsion rate.⁵⁶⁷

In January 1967 the K Site operators repeated the entire test program using the thin-walled tank.⁵⁶⁸ Overall Stochl and DeWitt tested three different types of injectors with the two 5-foot-diameter tanks at four different fluid levels, three gas temperatures, and different flow rates. They found that inlet gas temperatures and injector shape had the most effect on the temperature of the pressurant gas. The thickness of the tank did not influence the pressurant performance. They also determined that gaseous hydrogen required only half of the mass as gaseous helium to expel the same amount of liquid hydrogen from the tank. The findings were congruous with earlier analytical predictions.⁵⁶⁹

Stochl, DeWitt, and others expanded the test program to determine if their findings would translate to larger tanks.⁵⁷⁰ In May 1967 they repeated the test program in K Site using a 13-foot-diameter stainless steel tank.⁵⁷¹ They again found that the injector shape, gas temperature, and hydrogen pressure all influenced the pressurant's performance. Although the researchers felt confident that they could predict the behavior of the hydrogen gas pressurant with some injectors, the performance of the helium was much easier to forecast.⁵⁷²

Cold Shock

Certain materials, such as composites and plastics, are weakened by cryogenic temperatures, but the strength of proven materials such as stainless steel and aluminum alloys, however, requires verification at these low temperatures.

Engineers frequently use a method called cold shocking to verify that the tank's materials and equipment can withstand cryogenic temperatures. During cold shocking the tank is immersed in a cryogenic liquid. If immersion is not possible, a low-pressure cryogenic fluid is flowed into the tank. Liquid nitrogen, which is relatively easy to handle compared with other cryogenics, is the preferred medium. After the cold shock, technicians bring the tank back to ambient temperature, check all the welds, rethread the fasteners, and inspect the tank.⁵⁷³ The Rocket Systems Division conducted cold shocks on a variety of equipment in almost all of the Rocket System Area's test sites.



Image 132: A tank is cold shocked with liquid nitrogen at J-4 during April 1962 (GRC-1962-C-01046).

Methane Storage

Researchers considered methane as a possible alternative for hydrogen for long-term space missions. Methane, with its high density, requires smaller propellant tanks than hydrogen, burns well with liquid oxygen, and theoretically, could be manufactured from natural elements in the Martian atmosphere.⁵⁷⁴ Methane is also a good coolant for regeneratively cooled engines and a suitable lubricant for turbopump turbines.⁵⁷⁵ In the 1960s Lewis conducted extensive investigations of nozzles, injectors, cooling systems, and turbopumps for methane-fueled engines.⁵⁷⁶ Researchers used the Rocket Systems Area to compare pressurant gases for methane tanks and to test methane and fluorine/oxygen (FLOX) turbopumps.

Lewis's tank expulsion research continued at K Site in 1968 with the evaluation of pressurant options for a liquid-methane propellant. Philip DeWitt and Thomas McIntire sought to determine the applicability of liquid-hydrogen pressurization parameters to liquid methane. In November 1968 they began a five-month study of four different pressurant gases—methane, hydrogen, helium, and nitrogen—with the liquid-methane propellant at K Site under the same conditions as for the previous liquid-hydrogen studies.

The methane, hydrogen, and helium pressurants corresponded with DeWitt and McIntire's analytical predictions, but the researchers found nitrogen's performance difficult to measure. During the sloshing runs, less helium and hydrogen were needed to expel the fluid, whereas greater quantities of gaseous methane were required to complete the task.⁵⁷⁷ The K Site investigations provided basic data on various pressurant gases that could be employed if a new methane-fueled mission was identified.

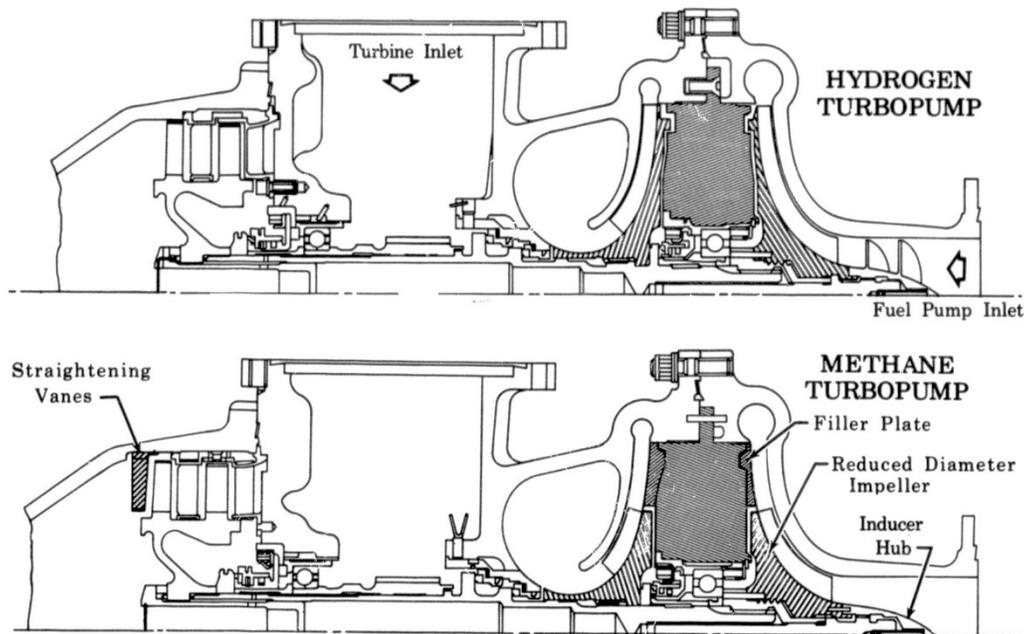


Figure 41. Comparison of Hydrogen and Methane RL10 Turbopump Assembly

FD 14533B

Image 133: Comparison of liquid-hydrogen and liquid-methane turbopump designs (NASA CR-72485, Fig. 41).



Researchers have been interested in using FLOX as an oxidizer since the 1950s. The addition of fluorine to the oxygen boosts performance and improves ignition. There was also interest in the use of a methane/FLOX propellant. In the mid-1960s Pratt & Whitney undertook a program to determine the feasibility of using the methane/FLOX propellant in its RL-10 engine. The effort included full-scale engine

tests at Pratt & Whitney and turbopump runs at Plum Brook's I Site. Pratt & Whitney had already successfully tested the RL-10 pumps with hydrogen and fluorine at the Rocket Systems Test Site (I Site).

Pratt & Whitney modified the RL-10's hydrogen turbopump to accommodate the higher pressure levels associated with methane and used its liquid-oxygen pump for the FLOX. The company shipped the RL-10 pumps to I Site in the summer of 1966.⁵⁷⁸ The I Site staff would run the pumps for 30 minutes to verify the integrity of the pumps and to gather data on the pressure increase and pump efficiency. Then they would put the pumps through two 5-minute runs to verify them for the full-engine tests at Pratt & Whitney.

The pump was first run at I Site on 30 September 1966 over various flow conditions. Although it performed well, the researchers found a crack in the main K-162B seal. The K-162B seals had proven reliable in previous investigations, so they surmised that the pump design was acceptable. They ran the RL-10 pump again for 5 minutes each in October and November. Pratt & Whitney then ran a full-scale engine test with the FLOX pump at its facilities. The main seal cracked again, causing the researchers to investigate its interference with the shaft.⁵⁷⁹

Nonetheless, Pratt & Whitney considered the overall methane/FLOX program successful. Although liquid methane has not yet been used as a rocket propellant, engineers still consider it as an option, particularly for Mars missions.

New Angles

In 1968 Phillip Meng and Royce Moore resumed their investigations of turbopump inducers in the Boiling Fluids Rig at the Turbopump Facility (C Site). Their earlier tests had verified the accurateness of a calculation to determine the minimal tank pressurization.⁵⁸⁰ They now set out to compare the performance of inducers with different blade angles. In the spring of 1968 they ran the Boiling Fluids Rig pump with an inducer with an 80.6-degree blade angle over a range of temperatures in cavitating liquid hydrogen. At a constant temperature the pump's required suction head increased as the rate of flow increased. At a constant flow the figure decreased as the temperature increased. Meng and Moore believed that the inducer could raise the pressure levels at the inlet even when the pump was operating at lower propellant flow rates and in cavitation.⁵⁸¹

Meng and Moore repeated the test in the fall of 1968 using an extended inlet line. They found the longer line decreased the flow rate. The pressure loss increased the inducer's required net positive suction head (NPSH). As in the previous investigation, the required NPSH for the inducer decreased with increasing temperature and increased as the flow velocity accelerated.⁵⁸²

The researchers then installed the same inducer at a different location on the inlet line. They discovered that the NPSH requirement was less in this configuration than that for the previous line-mounted arrangement but was greater than that for the original closely coupled configuration.⁵⁸³ The two researchers then put an inducer with a 78-degree blade angle through a similar analysis with the same results.⁵⁸⁴

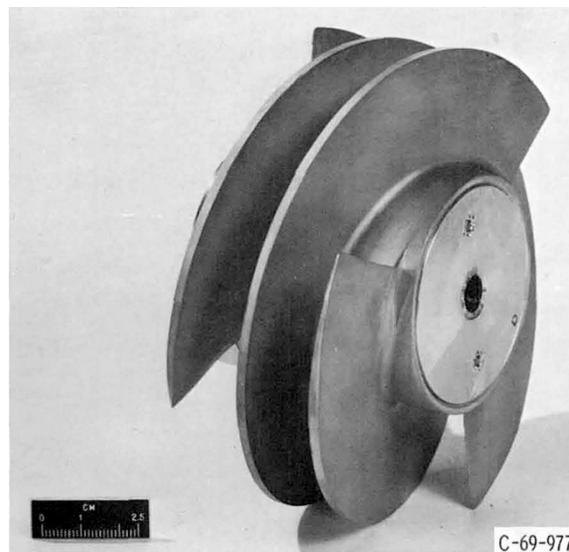


Image 134: An 80.6-degree inducer (GRC-1969-C-00977).

Cavitation Thermodynamics

The performance of an inducer in cavitation is influenced by the type of fluid, the rate of flow, and the interaction between the liquid and vapor. These combined elements were referred to as cavitation's thermodynamic effects.⁵⁸⁵ In 1968 Meng and Moore continued their cavitation studies at C Site's Boiling Fluids Rig, focusing on the effect of different inducer design elements, such as the inducer blade's surface, shape, thickness, and angle, on the liquid-hydrogen cavitation thermodynamics.

The researchers first compared the effects of placing the pump at three different positions on the inlet line. Then they operated the inducer and pump using three inlet line configurations. The thermodynamic effects were more evident when the temperature of the liquid was increased, but decreased as the fluid flow accelerated. Overall the predicted NPSH requirements were approximate to the actual performance.⁵⁸⁶

The inducer blades for these investigations had a sharp wedge shape. Meng and Moore were concerned that strain on the pump might damage these thin blades. So they designed an 80.6-degree inducer with blunt edges. They subjected this inducer to the same test parameters as the others in the Boiling Fluids Rig. Their findings again corroborated the theoretical predictions, and the thermodynamic effects of cavitation increased substantially as the liquid temperature rose and decreased when the flow rate accelerated.⁵⁸⁷

Meng and Moore then explored the effect of the inducer blade's thickness on the performance of an 80.6-degree inducer in cavitation. Three different inducers were tested with slightly varied thicknesses. The researchers were able to best predict the thermodynamic performance of the thickest blade, but they could not establish any overall tendencies that could be applied to all three. Each inducer had different NPSH requirements.⁵⁸⁸

They found that the inducer blade's angle, thickness, shape, and fairing all affected the inducer's suction performance and thermodynamics. Moore and Meng investigated the general performance of 78-, 80.6-, and 84-degree inducers in a cavitating environment in the Boiling Fluids Rig. They found that the 84-degree inducer was most influenced by cavitation thermodynamics. The 78-degree inducer was least affected by cavitation and possessed the highest noncavitating flow range.⁵⁸⁹

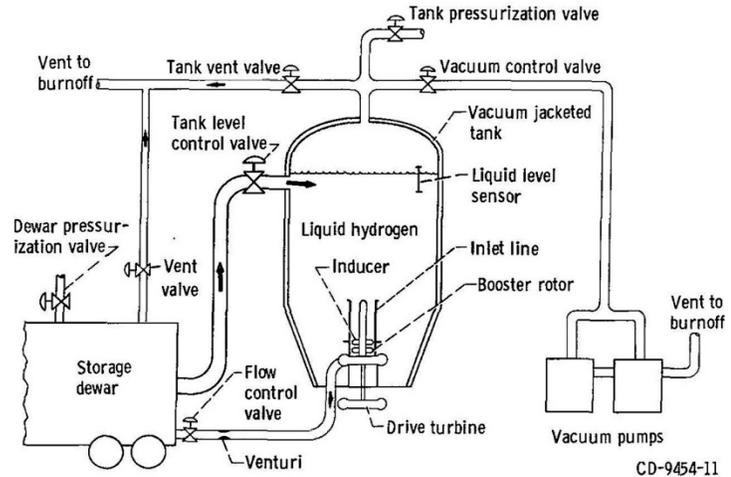


Image 135: Diagram of the Boiling Fluids Rig at C Site (NASA TN D-6361, Fig 3).



By the late 1960s Lewis's Fluid Systems Components Division had addressed most of the propellant pumping issues for chemical and nuclear rockets. Much of the work was performed at the Rocket Systems Area, including comprehensive analysis of inducer designs that confirmed NASA Marshall Space Flight Center's predictions that the device could ingest boiling hydrogen fast enough to lower the pressurization of the fuel tank.⁵⁹⁰

Turbopump performance in rocket systems increased nearly 500 percent between the 1950s and mid-1970s. NASA Lewis issued a massive summary of its development of liquid rocket engines that included eight volumes dedicated to the turbopump.⁵⁹¹ They felt that advances of rocket turbopumps, particularly

given their relatively small size, could be applied to other fields like the petroleum industry.⁵⁹² Lewis pump researchers turned their attention to new areas such as space power systems and advanced compressor design for aircraft engines.⁵⁹³ Turbopumps have continued to improve over the years with the emergence of new tools like computational fluid dynamics and composite materials.

Forging Their Own Community

During working hours the Plum Brook staff was fairly segregated between the rocket systems, reactor, and administrative areas. Access to the reactor complex was limited and required the use of radiation-monitoring devices. Plum Brook’s management and civil engineers were located near the main gate in the Engineering Building. The Rocket Systems Area staff spent a good deal of their time at the various test sites scattered across Plum Brook’s expanses. The physical isolation of the groups led to a certain level of ignorance regarding the activities of the other groups. This



Image 136: Dance inside the clubhouse at the picnic grounds (GRC-2016-C-05787).

was a new experience for Bill Brown, who had transferred to Plum Brook from Lewis Field in 1969. “They didn’t talk to each other very much,” he explained. “It was a very segregated operation. That surprised me when I came out here because back in Cleveland you got around more and knew more of what was going on in different areas.”⁵⁹⁴ Henry Pfanner laughed as he admitted, “We considered [the reactor personnel] a bunch of weird ducks, but they’re good friends.”⁵⁹⁵

Nonetheless the Plum Brook staff formed an enduring community in the 1960s that still meets regularly for breakfast. Many of them during this period were young transplants who had arrived in the rural Sandusky area with few, if any, connections. It is not surprising that the staff became close-knit and created lifelong friendships. Groups regularly went off on bowling, golfing, or fishing excursions. There were also dances, socials, and parties of all sorts, both at Plum Brook and in people’s homes.

Abe Silverstein had witnessed the effect of the staff’s camaraderie on the work during Lewis’s early NACA period. After becoming Center Director in 1961 Silverstein sought to instill that amity among new NASA personnel at Lewis Field and Plum Brook. He encouraged the creation of social committees and provided seed money for projects like the construction of a picnic ground area at Plum Brook.



Image 137: Pump house converted into employee clubhouse (GRC-2016-C-05791).

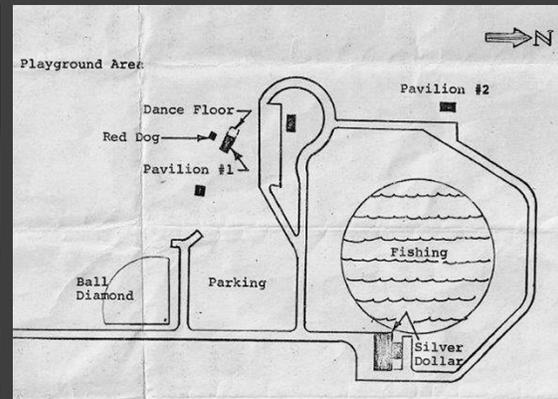


Image 138: Layout of the Plum Brook recreational area (NASA).

Bucky Walter was among those tasked with creating a new recreation park in the mid-1960s. He remembered Lewis management writing him a personal check for \$2,500 to fund the effort. Plum Brook civil engineers located an unused Plum Brook Ordnance Works (PBOW) pump house next to a large water retention pond in the woods just west of the Rocket Systems Area.⁵⁹⁶

The staff used a concrete platform for an old Dewar tank as the pad for the main pavilion and converted the pump house into a large clubhouse with a kitchen and bar. The site also included two pavilions, a fishing pond, baseball diamond, playground, and mobile bar. Employees performed the work during their off hours and contributed financially.⁵⁹⁷ Roger Hershiser remembers, “We built the building, wired it, and the coolers for beer. I don’t know where they got this stuff.”⁵⁹⁸

The new recreational area was very popular with the staff. “You could go down there any night of the week and somebody would be there with their family having a cookout on the grills,” Walter recalled. We had swings and all that. We had a wonderful [merry-go-round] that had an actual turbine in it. It sat there for years, and no one even had to grease it in the winter or rain. A lot of drinking went on down there.”⁵⁹⁹

Plum Brook also hosted four or five annual picnics, each of which drew well over 1,000 employees and families from Plum Brook and Lewis Field. Walter coordinated these all-day events, which included multiple bands, airplane rides, hot air balloons, hay rides, and other entertainment. In 1975, Lewis decided to have its annual picnic at Plum Brook. That event drew 2,500 attendees.⁶⁰⁰



Image 139: Families fishing at the recreational area (GRC-2016-C-05784).

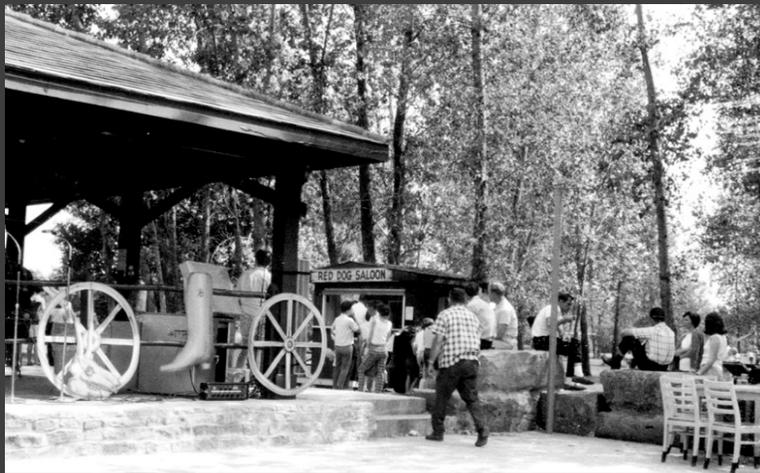


Image 140: Pavilion area at the picnic grounds (GRC-2016-C-05792).

New Tensions

Although the threat of conflict with the Soviet Union had receded in the late 1960s, the nation had new concerns that seemed to come to a head in 1968. The North Vietnamese invasion of South Vietnam in February brought an almost immediate escalation of U.S. involvement in the conflict. President Lyndon Johnson's announcement of his impending retirement in March was followed by the assassinations of Martin Luther King and Robert Kennedy and a summer of urban unrest and antiwar protests.

In the midst of this NASA successfully launched its first crewed Saturn V vehicle in October. NASA decided to redirect the ensuing *Apollo 8* flight from Earth orbit to a stunning flight around the Moon on 24 December 1968. *Apollo 8* brought NASA the most attention from the public and media since the *Mercury* flights.

It was also during this period, however, that NASA was dealing with the first significant cuts to its budget in its 10-year history. The intensification of the Vietnam War and President Johnson's social programs had created large deficits 1967. The deficit, in conjunction with concerns about NASA's competency following the death of three astronauts in January 1967, led to the first real tightening of Agency's belt during fiscal year 1968. Congress continued to support the Apollo Program at its full request, but introduced reductions in almost all post-Apollo efforts, which included the Saturn V and Nuclear Rocket for Rocket Vehicle Application (NERVA) rockets as well as proposed missions like the human exploration of Mars and a series of lunar and Earth-orbit efforts collectively referred to as Apollo Applications. NASA was forced to cancel Voyager's ambitious human missions to Mars, and replace them with a robotic program that became Viking. NASA proposed substantial numbers of new Saturn and Apollo hardware for extended lunar visits, but received only about a third of its request. This however included funds for what would become Skylab.⁶⁰¹

Nuclear Nozzles

By now the NERVA vehicle was tied to the human exploration of Mars. Like any major space program, Project Rover was expensive on its own. Sending humans to Mars, however, would be even more costly. The cancellation of Voyager in 1968 left NERVA without a mission at a time of decreasing budgets. Nonetheless the ground research continued at Los Alamos, and Nevada and Lewis researchers Ralph Schacht and Richard Quentmeyer carried on their nuclear rocket heat transfer studies at J-1.

They sought to determine data for the heat transfer from the nozzle to the liquid-hydrogen coolant. The correlations from previous studies were limited to a specific set of conditions. They now sought to create a universal equation that took into account all the related nuclear rocket input. This could only be verified with a test with liquid hydrogen as the coolant.

The convergent-divergent shape of the nozzle was the same as for the earlier set of J-1 tests, but this engine was stainless steel, not copper. The setup permitted the researchers to manipulate the cooling variables while maintaining the hot gas levels.⁶⁰² The installation and checkout of the site's liquid-hydrogen system began in late 1963 and was completed six months later. The Rocket Systems Division staff, however, took over two years to install the test equipment and cooling system on the stainless steel stock engine.⁶⁰³

Finally in August 1966 the operators were able to fire the engines for up to 10 seconds at a time. The tests continued throughout 1967 and 1968. Quentmeyer remembered a gigantic explosion blowing an engine off the stand in April 1967. “We were running at night, and we were looking at the TV [monitor], ‘Where is the engine?’ We looked at the engine, and we’re looking at it, but couldn’t figure out what was wrong.... all that was there was the injector. The steel engine that we were using at the time was blown into a million pieces. They went out the next day with a broom to sweep up the pieces.”⁶⁰⁴

Quentmeyer and Schacht developed a new correlation for determining the nozzle-to-coolant heat transfer rate for nuclear rockets. The equation was unique in its ability to calculate both subcritical and supercritical^z temperatures. They continued their heat transfer studies at Lewis’s Rocket Engine Test Facility at Lewis Field in the 1970s using ceramic composite coatings for the thrust chambers.⁶⁰⁵

Meanwhile, in February 1969 the Atomic Energy Corporation (AEC) began testing a second-generation NERVA engine, the XE, in Nevada. Unlike the tests of the initial NERVA NRX engine in 1966, the XE was in its true flight configuration. Over the next eight months the AEC successfully fired the XE 40 times and demonstrated new startup techniques.⁶⁰⁶ It was a validation of the entire Rover Program. The next phase should have been the flight test, which had been canceled in 1964. Instead the ground technology program continued. Congressional support and funding remained relatively static funding in the late 1960s, although the budget was nearly half the level received at the peak in 1964.⁶⁰⁷

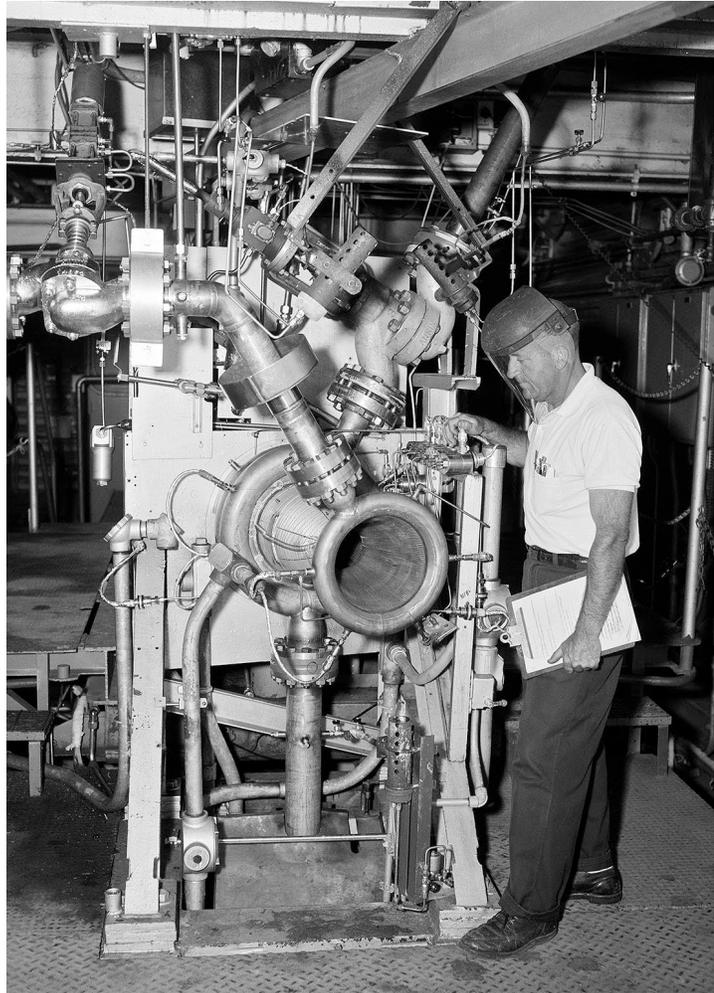


Image 141: A technician checks the installation of a steel engine in J-1 during November 1966. It was a 28,000-pound-thrust gaseous hydrogen-fluorine/oxygen (FLOX) engine (GRC-1967-P-01281).

^zThe critical temperature is the temperature at which vapor can no longer be liquefied no matter how much pressure is applied.

The Rocket Systems Area contributions to the nuclear rocket program included the engine startup tests at the B-1 and B-3 stands, the nozzle heat transfer tests at the Rocket Systems Test Site (J Site), and heat exchanger investigation at F Site. These activities were part of a larger effort by Lewis to apply its liquid-hydrogen experience to both the current Rover programs and undetermined future nuclear missions. Other Lewis contributions to nuclear propulsion included hydrogen heat transfer, materials durability, and fuel element design.⁶⁰⁸

Can Centaur Handle the Pressure

The seven *Surveyor* flights to the Moon completed Centaur's primary mission, but the program did not fade away. Instead, Centaur blossomed into the nation's primary vehicle for launching spacecraft and satellites. NASA relied on the Atlas/Centaur to launch a number of interplanetary missions in the late 1960s and early 1970s, including the *Mariner 6* and *7* flybys of Mars, the *Mariner 9* orbit of Mars, and *Pioneer 10*—the first spacecraft to visit Jupiter and the first to exit the solar system. Centaur also launched a series of Orbiting Astronomical Observatory satellites from which retrieve ultraviolet data from stars and view galaxies not visible by Earth-bound telescopes.

Lewis, which maintained responsibility for Centaur Program, created the Launch Vehicle Division in 1969 to oversee the additional launches planned for the coming years. Lewis also worked with General Dynamics to improve and upgrade the Centaur vehicle with a new computer system and an equipment module to store the electronics. In 1973, this new Centaur D-1A sent *Pioneer 11* by Jupiter and launched *Mariner 10*, the first spacecraft to use the gravitation pull of a planet (*Venus*) to reach another (*Mercury*). The D-1A also launched four Intelsat IV communication satellites.

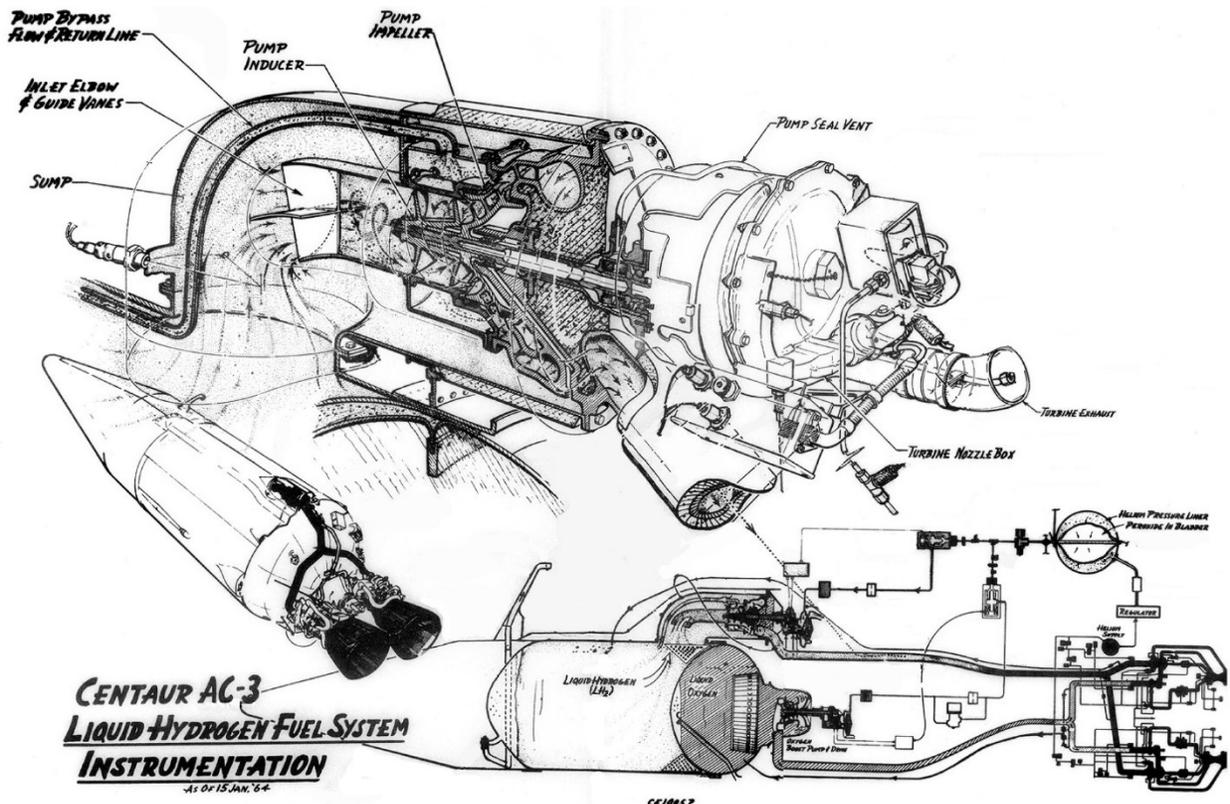


Image 142: Schematic drawing of the hydrogen boost pump for the Atlas/Centaur 3 (AC-3) vehicle (NASA).

Rocket Systems Area testing played a key role in two of Centaur’s most significant changes of the 1970s—the removal of the boost pumps and the incorporation of a new shroud for Titan/Centaur. The removal of the boost pumps was one of the more ambitious engineering proposals to emerge in the mid-1960s for Centaur. The boost pumps increased the propellant’s pressure as it traveled from the tanks to the turbopumps. The boost pumps, which were sometimes larger than the turbopumps, however, increased the complexity and cost of the vehicle.⁶⁰⁹ By the mid-1960s engineers had reduced the required propellant pressure levels for Centaur’s RL-10 engines and reduced the amount of pressure necessary in the both the tank and the propellant line, making the eradication of the boost pumps possible for the first time.⁶¹⁰ The Rocket Systems Area’s B-1 Stand was critical to the ultimate decision to go forward with the removal of the boost pump from the Centaur design.



The first step was to determine how much pressurization was required to maintain performance. Lewis researchers, who were already studying the effectiveness of different pressurant gases with 5-foot-diameter tanks at K Site, were able to develop computer programs to predict the precise levels of tank pressurization for all phases of a mission. The tanks used in the K Site tests, however, differed from the Centaur tank in shape, injector design, and level of heat exposure. Ray Lacovic of the Centaur Program Office undertook a study with a full-scale Centaur tank in the B-1 Stand to verify the computer models.⁶¹¹

In August 1967 Plum Brook technicians began readying the B-1 Stand for a series of “Advanced Centaur” tests with a bimodal “battleship” propellant tank. Centaur’s liquid-hydrogen tank required helium pressurization during the activation of the turbopump just prior to ignition, but it could use gaseous hydrogen from the engines during normal operation. Centaur’s liquid-oxygen tank, however, required helium during pre-ignition and operation.⁶¹² Centaur’s hydrogen and oxygen tanks were unique in that they shared a common bulkhead to minimize weight. The tank was similar in size and weight to an actual Centaur tank, but it was heavily insulated and roughly 10 times thicker. Because only the propellant or the oxidizer would be outflowed during a particular run, the engineers substituted liquid nitrogen for the missing fluid.⁶¹³

In December 1967 Lacovic obtained the tank’s baseline data by allowing the liquid hydrogen to evaporate from the tank over a period of nearly 8 hours. Over the next two months the researchers tested the hydrogen tank 36 times in simulated startup conditions with varied liquid and pressurization levels. Lacovic found that additional helium was required as the liquid level decreased.⁶¹⁴ On 1 March, the Centaur tank underwent 10 expulsion tests during normal engine operation—three tests simulating a single-burn mission and seven tests in a two-burn configuration. The average deviation between the computer prediction and actual expulsion requirements was only 5.1 percent.⁶¹⁵



Image 143: B-1 Stand firing in preparation for Centaur's pressurization system tests. Steam is emitted from the ejector of the facility's altitude exhaust system. The B-3 Stand is in the background (GRC-1966-C-04025).

In May 1968 Lacovic initiated the pressurization tests of the oxidizer tank at the B-1 Stand. Over the next three months the staff conducted 14 liquid-oxygen pre-ignition pressurization and 22 expulsion runs. Again the tests were conducted over a range liquid-and pressure levels. In some runs, the helium was injected directly into the liquid-and in others it entered into the empty space. Again there were only minor differences between the computer models and the actual pressurant behavior. Lacovic felt confident that the computer programs could be used to successfully predict helium requirements for both Centaur's liquid-hydrogen and liquid-oxygen tanks.⁶¹⁶

The tank pressurization studies at the B-1 Stand confirmed that computer predictions regarding the system's ability to function without a boost pump were correct. Engineers then used computer models to accurately generate the pressurant levels required for the Centaur propellant system without boost pumps. They verified these predictions two years later with the test of an actual Centaur vehicle under full simulated space conditions in the new Spacecraft Propulsion Research Facility (B-2). The B-2 studies demonstrated that Centaur's RL-10 engines could start and operate reliably without the boost pumps.⁶¹⁷ The first flight of a Centaur without the boost pumps took place in June 1984.⁶¹⁸ Although it would take 15 years for the boost-pump-less Centaur to begin operating, the new configuration improved the simplicity and reliability of the pumping system.

Perimeter Property Problems



Image 144: Plum Brook and its buffer zone seen in the context of the Sandusky area in 1960 (GRC-1960-C-55682).

“Silverstein Insulted Us” screamed the headline of the 17 June 1969 *Sandusky Register*, reflecting the feeling of many Sandusky-area residents that the federal government was taking advantage of a technicality to seize private property.

In 1941 the War Department had seized 9,000 acres of private property to build the PBOW. After World War II the military decided to lease 3,000 acres of property around the PBOW’s perimeter to private individuals. Members of the local community—many of whom had lost property in 1941—purchased these parcels and used them almost exclusively for agricultural purposes. After 20 years, the individuals would take full possession of the property and could do with it as they saw fit. The agreement, however, contained a clause that stated during the lease the government retained the right to reacquire this property for “national defense” purposes.⁶¹⁹

These leases, which were set to expire in the late 1960s, presented a problem for NASA. Lewis had acquired Plum Brook specifically to provide a safe location for potentially hazardous research involving radiation, flammable and toxic propellants, and noise. Lewis claimed that the loss of the buffer zone property would reduce its use of hydrogen-fluorine and nitrogen tetroxide by a factor of three; elevate the noise levels at the boundary to 100 decibels; and increase concern about explosion hazards.⁶²⁰

Nonetheless, the community was irate in January 1967 when NASA announced its plans to buy up the leases. The Agency’s image was not helped by allegations the previous week regarding corruption with construction contracts. Congressman Charles Mosher attempted to mitigate the complaints while fully supporting NASA’s decision. Despite the protests, Congress allocated \$2.1 million to purchase the lands in August 1967.⁶²¹ The decision created bad press for NASA and uncomfortable situations for local politicians who wanted to retain NASA’s investment, but also stem the growing tide of resentment in the community.

NASA offered a five-year lease to the 55 affected families to ease the transition, but the government eventually purchased the properties. Plum Brook’s fortunes would change in the 1970s, however, and many residents were later able to reacquire the land in the 1980s as NASA sought to reduce its holdings.

Blanket Coverage

The Rocket Systems Division continued their tank insulation testing during this period at the new K Site facility. Researchers in the mid-1960s were examining options for multimission space tug vehicles, including an inexpensive reusable, easily applied insulation system. It was clear that multilayer designs were the most promising for long-duration missions, but there was concern that the pressure changes of repeated launches and reentries would damage the inner layers of multilayer insulation.⁶²² Richard DeWitt and Max Mellner of the Chemical Rocket Division were particularly interested the effects of repeated heating and cooling cycles on the multilayer insulation's integrity and its performance after it had been removed and reapplied, as in the case of a tank repair.

In 1968 Lewis procured an insulated 7-foot-diameter tank from Lockheed and installed it in K Site's vacuum chamber. Lockheed created the insulation in blankets consisting of a clear plastic film over a single one-half-inch-thick layer of fiberglass, which was covered with 10 layers of Mylar- (DuPont Teijin Films) encapsulated aluminum. Nitrogen or helium was used to purge any air from the system. Technicians installed different numbers of blankets for different portions of the tests.⁶²³

In the spring and summer of 1968 DeWitt and Mellner conducted seven runs at K Site which simulated space conditions and six in a ground-hold configuration. Once vacuum conditions were achieved, the tank was filled with liquid hydrogen, which was allowed to slowly evaporate. The first three space-hold runs, which employed three layers of blankets, revealed no significant wear over the consecutive tests. The procedure was then repeated with four, five, and six layers of blankets. The heat loss decreased proportionally with each new layer. During the ground hold tests DeWitt and Mellner found that the condensing and freezing of nitrogen in the blankets caused excessive heat penetration.⁶²⁴

In April 1968 technicians stripped the insulation from initial test off the tank and reapplied it. Over the next few months they retested the Lockheed tank with between three and six layers of insulation blankets. They found that there were greater thermal losses in some areas than predicted and that the adhesive regularly deteriorated.⁶²⁵

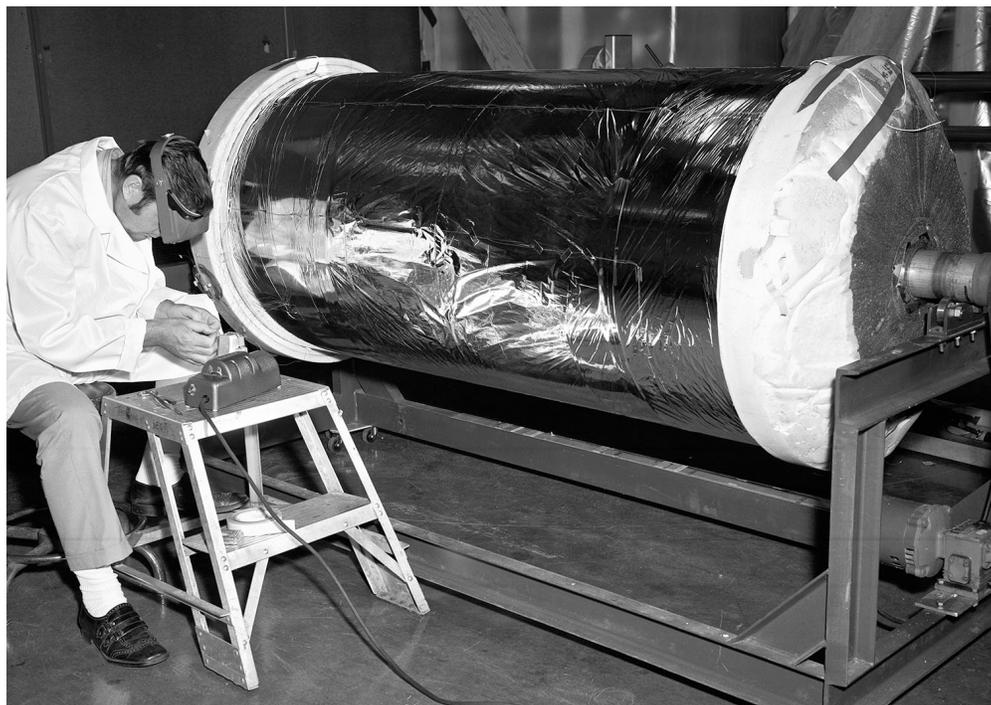


Image 145: A technician installs insulation on a calorimeter for testing in K Site (GRC-1971-P-01416).

Too Much of a Good Thing

The number and density of layers were considered the most important aspect to the success of multilayer insulation systems, but designers needed to determine the optimal combination. Some predicted that anywhere from 100 to 200 layers of insulation might be required for long-duration missions. There was concern that compression, trapped gases, or application methods could skew these predictions. Fifty-two layers of the thin double-aluminized Mylar with silk net spacers was 1 inch thick. Researchers had not previously tested more than 30 layers or developed calculations to predict more than 112 layers.⁶²⁶

In 1969 Robert Stochl undertook a study at K Site to determine if predictive equations could be used for greater numbers of layers. Stochl tested 20, 40, 60, 100, and 160 layers on a 30-inch-diameter calorimeter placed inside an 8-foot cryoshroud^{aa} that created the cold temperatures of space. To improve uniformity the staff applied the insulation spirally instead of using the blanket technique used in previous studies.⁶²⁷

The staff struggled to wrap the calorimeter with enough tension to prevent slipping and sagging. By April 1969 the technicians had successfully wrapped the device with 160 layers of insulation. The initial tests revealed a higher evaporation rate than expected. Follow-up runs with 60 and 100 layers convinced Stochl that there were an optimum number of layers. He concluded that 20 to 60 layers provided the best thermal protection. Increasing the number of layers beyond 60 did not provide any additional thermal protection.⁶²⁸

Stochl resumed the K Site studies in the spring of 1970 to study the lower end. He found that at least 30 layers were required for adequate protection. Stochl determined that the methods for forecasting the effectiveness of the insulation underestimated the heat transfer in almost all configurations.⁶²⁹ Though the predictive techniques needed further work, the K Site test data were available to assist designers of insulation systems for deep space missions.⁶³⁰

The Ultimate Solution

Multilayer insulation systems required a vacuum around the tank. This was not an issue in space, but was difficult to address on the launch pad, where atmospheric air could enter breaches in the insulation and degrade the thermal protection.⁶³¹ NASA and its industry partners investigated several methods to prevent gaps in the insulation such as purging the layers with a gas or encapsulating the insulation in an airtight vacuum. They found that the former created excessive heat along the tank, and that the latter required extra equipment and weight.⁶³²

In the end, researchers from Lewis and Union Carbide developed a novel technique that maintained the vacuum without the use of extra equipment or gases. This Self-Evacuating Multi-Layer Insulation (SEMI) was suitable for use on the ground, in the atmosphere, and in space. The SEMI system utilizes shingled panels of multilayer aluminized Mylar to prevent heat transfer. A laminated Mylar wrap vacuum seals the panels to the tank. SEMI required lightweight and flexible materials that could withstand the vacuum of space, the elimination of off-gasing, and a method of evacuating the system prior to its use.⁶³³

^{aa}Cryoshrouds are large capsules with ribbed walls through which a cryogenic fluid is flowed to create a cold environment.

In the fall of 1970 the staff mounted large SEMI panels on a liquid-hydrogen-cooled calorimeter that was installed inside an 8-foot cryoshroud at K Site. The researchers analyzed the insulation, the self-evacuation, the vacuum casing, and off-gasing in December 1970. They concluded that the panels were suitable for both ground and space storage tanks.⁶³⁴ NASA claimed that the SEMI insulation reduced heat transfer by 90 percent in atmospheric conditions and 99 percent in a space environment.⁶³⁵

In the early 1970s, NASA considered using the SEMI system for the space shuttle's external tank. Union Carbide conducted an initial study for Lewis that showed the SEMI system could be applied to the shuttle. To produce a temperature-resistant and formable material, the designers had to sacrifice some of the impermeability of the SEMI system. This meant that the system would occasionally have to be manually evacuated. This could compromise the system's self-evacuation ability. The shuttle designers eventually decided to use a spray-foam technique to insulate the tank.⁶³⁶

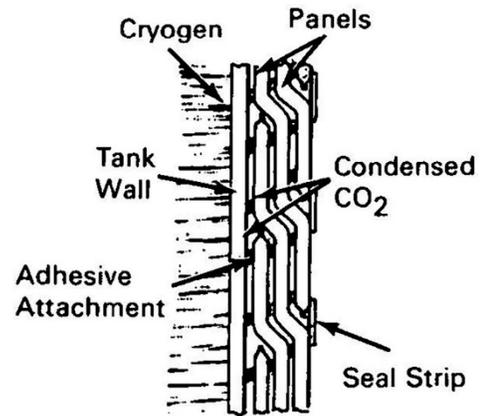


Image 146: Schematic view of SEMI insulation system (NASA Tech Brief 40-10646).



Image 147: K Site during the testing of the SEMI insulation. The cryoshroud is visible inside the test chamber (GRC-1971-P-1401).

Apollo Achievements

On 16 July 1969 a Saturn V sent the fifth Apollo crew into space. Three days later Neil Armstrong stepped onto the surface of the Moon. It was the climax of NASA's intense eight-year rush to place the first human on another planet. Lewis's early work with liquid hydrogen led to the selection of hydrogen for the Saturn V upper stages; Lewis engineers served as technical consultants for both the F-1 and J-2 engines; and turbopump testing at C Site's Boiling Fluids Rig proved that inducers increased flow enough to keep the hydrogen tank at low pressures.⁶³⁷

Even before *Apollo 11*, the United States had soundly established its technical superiority over the Soviet Union.⁶³⁸ A primary technical reason was that the Soviets did not use liquid hydrogen. Chief Designer Sergei Korolev knew of hydrogen's capability, and despite opposition from rivals, had his engineers work on hydrogen-oxygen upper stages from the massive new N-1 rocket in the early 1960s. The nation, however, did not have large-scale hydrogen production facilities or testing sites.⁶³⁹ Although Korolev's team created several hydrogen engines in the late 1960s and 1970s, the first Soviet hydrogen rocket did not fly until 1987. In addition, the Soviets attempted to launch their massive N-1 rocket four times between 1969 and 1972 without success.⁶⁴⁰

NASA's *Apollo 11* achievement was arguably surpassed nine months later in April 1970 when the Agency was able to safely bring the wounded *Apollo 13* capsule back to Earth. After the four-day crisis had passed, NASA launched an investigation into the cause of the oxygen tank's debilitating explosion. The six-week investigation included nearly 100 tests conducted at five NASA centers and several private companies.⁶⁴¹ NASA Lewis participated with the investigation in several ways: Irving Pinkel, who had led the Fluid Systems Components Division for a number of years, was an official observer of the Apollo 13 Review Board; investigators used the Zero Gravity Facility at Lewis Field to study the burning of Teflon-(Chemours) insulated wires in microgravity; and the Rocket Systems Area simulated the tank rupture and later studied liquid-oxygen flow through a choked passage.

A test program was hurriedly set up at the B-3 Stand in the spring of 1970 to simulate the tank rupture.⁶⁴² The researchers sought to determine the effects of sudden oxygen venting in the vacuum of space.⁶⁴³ Henry Pfanner recalled that engineers located a tank that was similar in shape to the *Apollo* tank and set it on the 5-foot diameter exhaust line, which tied into the B-1 vacuum system. "We'd get the conditions inside this tank to what they supposedly were," Pfanner explained, "and then blow this thing down and see what happened inside the tank." They ran the test under several different conditions. The effort was set up and run very quickly. Abe Silverstein personally approved the expanded use of Lewis's computing systems so that the engineers could calculate their data quickly. Pfanner remembered there was another reason to rush. "[Bob] Smalley and I had a reservation to go fishing up in Canada, and we had three weeks to get this thing done."⁶⁴⁴

New World Class Facilities

In December 1969 Plum Brook began operating its two largest facilities—the B–2 Stand and the Space Power Facility (SPF). These world-class facilities would come to define Plum Brook and were still in operation in 2016. B–2 and SPF are outside of the scope of this project, so their research activities are not described in detail.

At the time, B–2 was the only facility in the world capable operating a full-scale rocket stage with engines up to 100,000 pounds of thrust in a simulated space environment. The facility has the unique ability to maintain a vacuum while operating a rocket engine. The rocket fires into a 120-foot-deep spray chamber which cools the exhaust before it is ejected outside the facility. The B–2 Stand uses giant diffusion pumps to reduce chamber pressure, nitrogen-filled cold walls create cryogenic temperatures, and quartz lamps to replicate the radiation of the Sun to simulate space conditions.⁶⁴⁵ Lewis used B–2 to test the Centaur D–1A extensively in the early 1970s. Lewis has fired more than 100 Pratt & Whitney RL–10 engines in B–2 for Centaur, 80 current RL–10B–2 engines for Delta-3 development, and another 12 RL–10B–2s for the Delta 3 Upper Stage.

SPF’s 100-foot-diameter, 120-foot-high tank is the largest high-vacuum chamber ever built. SPF was originally designed to test nuclear propulsion and power hardware, but it was never used for that purpose. Lewis has used the SPF to test space power systems, shroud jettison systems, Mars lander airbags, deployable solar sails, and solar arrays for the International Space Station.



Image 148: B–2 as it becomes operational in the fall of 1969 (GRC–1969–C–03154).



Image 149: SPF as it becomes operational in the fall of 1969 (GRC–1969–C–03155).

References

562. John Aydelott, Michael Carney, and John Hochstein, *NASA Lewis Research Center Low-Gravity Fluid Management Technology Program* (Washington, DC: NASA TM–87145, 1985), <http://ntrs.nasa.gov>
563. Lewis Research Center, “Capabilities and Facilities of the Plum Brook Station,” c1970, NASA Glenn History Collection, Plum Brook Collection, Cleveland, OH.
564. Robert Stochl, Philip Masters, Richard DeWitt, and Joseph Malloy, *Gaseous-Hydrogen Requirements for the Discharge of Liquid Hydrogen From a 1.52-Meter- (5-ft-) Diameter Spherical Tank* (Washington, DC: NASA TN D–5336, 1969).

565. Stochl, *Gaseous-Hydrogen Requirements for the Discharge of Liquid Hydrogen*.
566. Raymond Lacovic, Frederick Yeh, Steve Szabo, et al., *Management of Cryogenic Propellants in a Full-Scale Orbiting Space Vehicle* (Washington, DC: NASA TN D-4571, 1968), <http://ntrs.nasa.gov>
567. Rocket Systems Division Reports, Cryogenic Propellant Tank Site, 1966, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
568. Rocket Systems Division Reports, Cryogenic Propellant Tank Site, September 1967, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
569. Robert Stochl, Philip Masters, Richard DeWitt, and Joseph Malloy, *Gaseous Helium Requirements for the Discharge of Liquid Hydrogen From a 1.52-Meter- (5-ft-) Diameter Spherical Tank* (Washington, DC: NASA TN D-5621, 1970), <http://ntrs.nasa.gov>
570. Robert Stochl, Phillip Masters, Richard DeWitt, and Joseph Malloy, *Gaseous-Hydrogen Pressurant Requirements for the Discharge of Liquid Hydrogen From a 3.96-Meter- (13-ft-) Diameter Spherical Tank* (Washington, DC: NASA TN D-5387, 1969), <http://ntrs.nasa.gov>
571. Rocket Systems Division Reports, September 1967.
572. Robert Stochl, Phillip Masters, Richard DeWitt, and Joseph Malloy, *Gaseous-Helium Pressurant Requirements for the Discharge of Liquid Hydrogen From a 3.96-Meter- (13-ft-) Diameter Spherical Tank* (Washington, DC: NASA TN D-7019, 1970).
573. NASA Research Center, “Glenn Safety Manual” (2012), <http://smad-ext.grc.nasa.gov/shed/pub/gsm/gsm-manual.pdf> (accessed 28 May 2014).
574. Robert Braeunig, “Rocket Propellants,” *Rocket and Space Technology* (2008), <http://www.braeunig.us/space/propel.htm> (accessed 28 May 2014).
575. J. E. Colbert, S. A. Mosier, and T. E. Bailey, *FLOX/Methane Pump-Fed Engine Study* (Cleveland, OH: NASA CR-72485, 1969), <http://ntrs.nasa.gov>
576. John Gregory, *FLOX/Methane Pump-Fed Engine Technology* (Washington, DC: NASA TM X-52796, 1970), <http://ntrs.nasa.gov>
577. Richard DeWitt and Thomas McIntire, *Pressurant Requirements for Discharge of Liquid Methane From a 1.52-Meter- (5-ft-) Diameter Spherical Tank Under Both Static and Slosh Conditions* (Washington, DC: NASA TN D-7638, 1974), <http://ntrs.nasa.gov>
578. Colbert, *FLOX/Methane Pump-Fed Engine Study*.
579. Colbert, *FLOX/Methane Pump-Fed Engine Study*.
580. Irving Pinkel, Melvin Hartmann, Cavour Hauser, et al., *Pump Technology* (Washington, DC: NASA N66-33672, 1966).
581. Phillip Meng and Royce Moore, *Cavitation Performance of an 80.6-Degree Helical Inducer in Liquid Hydrogen* (Washington, DC: NASA TM X-1808, 1969), <http://ntrs.nasa.gov>
582. Royce Moore and Phillip Meng, *Cavitation Performance of Line-Mounted 80.6-Degree Helical Inducer in Hydrogen* (Washington, DC: NASA TM X-1854, 1969), <http://ntrs.nasa.gov>
583. Phillip Meng and Royce Moore, *Hydrogen Cavitation Performance of 80.6-Degree Helical Inducer Mounted in Line With Stationary Centerbody* (Washington, DC: NASA TM X-1935, 1970), <http://ntrs.nasa.gov>
584. Royce Moore and Phillip Meng, *Cavitation and Noncavitation Performance 78-Degree Helical Inducer in Hydrogen* (Washington, DC: NASA TM X-2131, 1970), <http://ntrs.nasa.gov>
585. Royce Moore and Phillip Meng, *Thermodynamic Effects of Cavitation of an 80.6-Degree Helical Inducer Operated in Hydrogen* (Washington, DC: NASA TN D-5614, 1970), <http://ntrs.nasa.gov>
586. Moore, *Thermodynamic Effects of Cavitation*.
587. Phillip Meng and Royce Moore, *Hydrogen Cavitation Performance of 80.6-Degree Helical Inducer With Blunt Leading Edges* (Washington, DC: NASA TM X-2022, 1970), <http://ntrs.nasa.gov>
588. Royce Moore and Phillip Meng, *Effect of Blade Leading Edge Thickness on Cavitation Performance of an 80.6 Helical Inducer in Hydrogen* (Washington, DC: NASA TN D-5855, 1970), <http://ntrs.nasa.gov>
589. Royce Moore and Phillip Meng, *Comparison of Noncavitation and Cavitation Performance for 78, 80.6, and 84-Degree Helical Inducers Operated in Hydrogen* (Washington, DC: NASA TN D-6361, 1971), <http://ntrs.nasa.gov>

590. Charles Kelsey, NASA Lewis Research Center press release 69–36, 14 July 1969, NASA Glenn History Collection, Cleveland, OH.
591. *Turbopump Systems for Liquid Rocket Engines* (Washington, DC: NASA SP–8107, 1974), <http://ntrs.nasa.gov>
592. Pinkel, *Pump Technology*.
593. “Pump and Compressor Branch,” *Lewis News* (19 January 1968).
594. William Brown interview, Cleveland, OH, by Robert Arrighi, 17 December 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
595. Henry Pfanner interview, Cleveland, OH, by Robert Arrighi, 6 September 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
596. Robert Walter interview, Cleveland, OH, by Robert Arrighi, 5 November 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
597. Walter interview by Arrighi.
598. Roger Hershiser interview, Cleveland, OH, by Robert Arrighi, 17 December 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
599. Walter interview by Arrighi.
600. “A Good Time Was Had by All at PB’s Picnic,” *Lewis News* (5 September 1975).
601. David Portree, *Humans to Mars: Fifty Years of Mission Planning, 1950–2000* (Washington, DC: NASA/SP—2001-4521, 2001), <http://ntrs.nasa.gov>
602. Ralph Schacht and Richard Quentmeyer, *Coolant-Side Heat-Transfer Rates for a Hydrogen-Oxygen Rocket and a New Technique for Data Correlation* (NASA TN D–7207: Washington, DC, 1973), <http://ntrs.nasa.gov>
603. Lewis Research Center, “Capabilities and Facilities of the Plum Brook Station.”
604. Richard Quentmeyer interview, Cleveland, OH, by Virginia Dawson, 22 January 2003, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
605. Schacht, *Coolant-Side Heat-Transfer Rates for a Hydrogen-Oxygen Rocket*.
606. James Dewar, *To the End of the Solar System: The Story of the Nuclear Rocket* (Lexington, KY: University Press of Kentucky, 2004).
607. Steven Howe, *Assessment of the Advantages and Feasibility of a Nuclear Rocket for a Manned Mars Mission* (Los Alamos, NM: LANL LA–UR–85–2442, 1985).
608. H. S. Bloomfield and R. J. Sovie, *Historical Perspectives: The Role of the NASA Lewis Research Center in the National Space Nuclear Power Programs* (Washington, DC: NASA TM–105196, 1991), <http://ntrs.nasa.gov>
609. George Sutton, *History of Liquid Propellant Rocket Engines* (Reston, VA: American Institute of Aeronautics and Astronautics, 2006).
610. Charles Kelsey, NASA Lewis Research Center press release 69–76, NASA Glenn History Collection, Centaur Collection, Cleveland, OH.
611. Raymond Lacovic, *A Comparison of Experimental and Calculated Helium Requirements for the Pressurization of a Centaur Liquid Hydrogen Tank* (Washington, DC: NASA TM X–1870, 1969), <http://ntrs.nasa.gov>
612. Raymond Lacovic, *Comparison of Experimental and Calculated Helium Requirements for Pressurization of a Centaur Liquid Oxygen Tank* (Washington, DC: NASA TM X–2013, 1970), <http://ntrs.nasa.gov>
613. Lacovic, *A Comparison of Experimental and Calculated Helium Requirements for the Pressurization of a Centaur Liquid Hydrogen Tank*.
614. Rocket Systems Division Test Operations Report, High Energy Rocket Engine Research Facility, February 1968, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
615. Lacovic, *A Comparison of Experimental and Calculated Helium Requirements for the Pressurization of a Centaur Liquid Hydrogen Tank*.
616. Lacovic, *Comparison of Experimental and Calculated Helium Requirements for Pressurization of a Centaur Liquid Oxygen Tank*.
617. Steven Szabo, *Centaur Space Vehicle Pressurized Propellant Feed System Tests* (Washington, DC: NASA TN D–6876, 1972), <http://ntrs.nasa.gov>
618. Thomas Rudman and Kurt Austad, “The Centaur Upper-Stage Vehicle,” 4th International Conference on Launcher Technology Space Launcher Liquid Propulsion (3–6 December 2002).

619. Charles Mosher to Mrs. Richard Fries, 3 May 1967, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
620. Thomas Paine to Jackson Betts, 3 December 1968, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
621. Ron Coffman, “NASA Agents Seek Land Buys in Month,” *Sandusky Register* (18 October 1968).
622. Richard Knoll and Richard DeWitt, *Thermal Performance of a Modularized Replaceable Multi-Layer Insulation System for a Cryogenic Stage* (Washington, DC: NASA TN D-8282, 1977), <http://ntrs.nasa.gov>
623. Richard DeWitt and Max Mellner, *Experimental Evaluation of a Purged Substrate Multilayer Insulation System for Liquid Hydrogen Tankage* (Washington, DC: NASA TN D-6331, 1971), <http://ntrs.nasa.gov>
624. DeWitt, *Experimental Evaluation of a Purged Substrate Multilayer Insulation System*.
625. Rocket Systems Division, Test Operations Report, Vacuum Environment Facility, 1968, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
626. Robert Stochl, *Basic Performance of a Multilayer Insulation System Containing 20 to 160 Layers* (Washington, DC: NASA TN D-7659, 1974), <http://ntrs.nasa.gov>
627. Stochl, *Basic Performance of a Multilayer Insulation System*.
628. Stochl, *Basic Performance of a Multilayer Insulation System*.
629. Stochl, *Basic Performance of a Multilayer Insulation System*.
630. “Looks to 1971 Accomplishments,” *Lewis News*, 29 January 1971.
631. Porter Perkins, L. S. Smith, and M. A. Colaluca, *Preliminary Test Results on a Compressed Multi-Layer Insulation System for a Liquid Hydrogen Fueled Rocket* (Washington, DC: NASA N65-88890, 1963).
632. Porter Perkins, R. P. Dengler, L. R. Niendorf, et al., *Self-Evacuating Multilayer Insulation of Lightweight Prefabricated Panels for Cryogenic Space Propulsion Vehicles* (Washington, DC: NASA TM X-52266, 1967), <http://ntrs.nasa.gov>
633. NASA Tech Brief, *Lightweight, Self-Evacuated Insulation Panels* (Washington, DC: NASA Brief 70-10646, 1970).
634. Porter Perkins, Robert Dengler, and L. R. Niendorf, *Self-Evacuated Multilayer Insulation of Lightweight Prefabricated Panels for Cryogenic Storage Tanks* (Washington, DC: NASA TN D-4375, 1968), <http://ntrs.nasa.gov>
635. NASA Tech Brief, *Lightweight, Self-Evacuated Insulation Panels*.
636. K. F. Burr, *Reusable Lightweight Modular Multi-Layer Insulation for Space Shuttle* (Washington, DC: NASA CR-121166, 1973), <http://ntrs.nasa.gov>
637. “Apollo Mans Moon,” *Lewis News* (18 July 1969).
638. Charles D. Benson and William Barnaby Faherty, *Moonport: A History of Apollo Launch Facilities and Operations* (Washington, DC: NASA SP-4204, 1978), <http://ntrs.nasa.gov>
639. Asif Siddiqi, *Challenge to Apollo: The Soviet Union and the Space Race, 1945-74* (Washington, DC: NASA/SP-2000-4408, 2000), <http://ntrs.nasa.gov>
640. George Sutton, “History of Liquid-Propellant Rocket Engines in Russia, Formerly the Soviet Union,” *Journal of Propulsion and Power* 19, No. 20 (November-December 2003).
641. Hearing Before the Committee on Aeronautical and Space Sciences, Apollo 13 Mission Review, United States Senate, 30 June 1970.
642. Robert Graham, “A Summary of the Research Activities of the Experimental Section, Physics and Chemistry Division,” 1970, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
643. Apollo 13 Review Board, “Report of Apollo 13 Review Board: Appendices F, G, H,” 1970.
644. Pfanner interview by Arrighi.
645. Szabo, *Centaur Space Vehicle Pressurized Propellant Feed System Tests*.



Image 150: The Centaur D-1T's interstage adapter is lifted into the Nuclear Rocket Dynamics and Control Facility (B-3 Stand) during August 1972. The staff was preparing for upcoming Centaur Standard Shroud tests (GRC-1972-C-02855).

◆ Chapter 8 ◆

Completing the Mission

In the late morning on 5 January 1972, President Richard Nixon met NASA Administrator James Fletcher and his deputy George Low at Nixon's sprawling coastal estate in San Clemente to discuss the final details of NASA's new endeavor in space. The President announced to the press, "I have decided today that the United States should proceed at once with the development of an entirely new type of space transportation system designed to help transform the space frontier of the 1970's into familiar territory, easily accessible for human endeavor in the 1980's and '90's."⁶⁴⁶ Although not immediately apparent, the decision to proceed with the new "space shuttle" program set in motion a series of events that led to the termination of research at Plum Brook one year later.

Although the shuttle's main engines were fueled by liquid hydrogen, Lewis would play only a minimal role in the design of the new vehicle. NASA's budget, which had been ebbing since the mid-1960s, began declining dramatically. The 1970s were a bleak period in the history of the NASA Lewis Research Center. NASA separated hundreds of staff members from the Agency, cut programs, and closed Plum Brook Station. Dick Heath surmised, "They were looking for what they could rid of [to fund the shuttle], and somebody in Washington saw this little obscure thing sitting out in the middle of a cornfield. 'Why, there's 750 people there. We can get a lot of money. Close it!'"⁶⁴⁷ The staff worked to mothball Plum Brook's facilities in 1973 and 1974 while conducting the final test programs at the Rocket Systems Area and seeking new employment. The Rocket Systems Area's final contribution was a key shroud test for the new Titan/Centaur vehicle. The six Titan/Centaur missions were a high point of NASA's space program in the 1970s.



Image 151: President Richard Nixon and NASA Administrator James Fletcher discuss a model of the space shuttle in January 1972 at the "Western White House" in San Clemente (NASA).

Demise of the Nuclear Rocket Program

After taking office in January 1969 President Nixon's administration took steps to make up for budget shortfalls by reducing federal expenditures. U.S. involvement in the Vietnam War was at its peak, and social unrest was widespread. In 1969 NASA issued a report that once again recommended sending humans to Mars as well as developing a new orbiting spacecraft, a space station, and a large space telescope, but public enthusiasm for the space program faded rapidly after *Apollo 11*'s successful lunar landing in July.⁶⁴⁸

President Nixon issued his own policy in March 1970. It confirmed that the United States will always be active in space but stated that the activities must fit "within a rigorous system of national priorities."⁶⁴⁹ The President did not endorse sending humans to Mars or the space station, but he allowed the continuation of Saturn-based missions—including Skylab, nuclear propulsion, and basic studies of a reusable shuttle vehicle. It is worth noting that he also approved sending two spacecraft on a multiplanet journey and sustained the robotic exploration of Mars. Lewis Field and its Rocket Systems Area at Plum Brook would play key roles in developing the Titan/Centaur vehicle to launch these missions.



As NASA's annual budget continued to slide in the early 1970s, there was intense debate in Washington, DC, regarding NASA's two most expensive endeavors: the space shuttle and the Nuclear Rocket for Rocket Vehicle Application (NERVA) rocket. The shuttle was seen as a tool to build a space station, whereas NERVA was necessary for the human exploration of other planets.⁶⁵⁰ With the cancellation of Voyager and a general fear of investing in the human exploration of Mars, the need for the NERVA engine diminished. In addition, Congress's decision to cease production of the Saturn V in fiscal year 1971 meant that there was no way of launching the NERVA stage into space. NASA would have no method of sending humans beyond low Earth orbit for the foreseeable future.

President Nixon significantly reduced NERVA funding for fiscal year 1972. In an effort to save some portion of the program, the Space Nuclear Propulsion Office (SNPO) redesigned NERVA as a smaller nuclear engine to power a stage that could be launched from the shuttle.⁶⁵¹ The Office of Management and Budget wanted to cut the program outright, but debate continued within Congress and at NASA. Key Congressmen threatened to retract support for the shuttle if NERVA was discontinued. The President's official approval of the shuttle in January 1972, however, left NERVA in a precarious position.⁶⁵² The program's budget was now at the same level it had been before President Kennedy's expansion of the space program.⁶⁵³ Although Administrator Fletcher continued to publicly support the smaller NERVA engine, he did not include any nuclear propulsion or power programs when submitting NASA's fiscal year 1973 budget request in September 1972. The Agency had made the decision to cease its nuclear activities, but for months it did not inform those directly involved with the efforts—the Atomic Energy Commission (AEC), SNPO, and Lewis management.⁶⁵⁴



Image 152: Exhibit at Lewis's 1973 Inspection featuring NASA's recently approved space shuttle (GRC-1973-C-03426).

Black Friday

On 26 December 1972 NASA Headquarters notified Lewis Center Director Bruce Lundin^{bb} of the impending termination of its nuclear programs. The decision would have immediate repercussions at Lewis, NASA's lead center for nuclear programs, including its Plum Brook Station, but Lundin was instructed to keep the news to himself until a formal announcement could be made in January.⁶⁵⁵

NASA management planned to inform a local Congressman, Charles Mosher, of the closure at noon on Friday 5 January 1973 and issue a press release at 4 p.m. It was one year to the day after the approval of the shuttle and just 17 days after the splashdown of the final *Apollo* capsule. Lundin called an all-hands meeting in the Plum Brook cafeteria that coincided with the congressional announcement.

After a long preamble regarding NASA's overall budget concerns, Lundin finally got to the specifics. "Long-range research and technology work that cannot be expected to have a real need or application until the 1980's must be terminated at this time and priority given to more shorter range activities in say the 3 to 5 year time span. This means that essentially all nuclear power and nuclear propulsion R&D [research and development] work will be terminated this fiscal year." The room grew restless as Lundin continued, "This means, of course, that the reactor here at Plum Brook will be closed down during the remainder of this current fiscal year."⁶⁵⁶

Lundin was not finished, "Further, because NASA finds it simply does not have the dollars and the money in its place in the national scene to run major and expensive facilities on a continuing basis just because they're there, and they're doing interesting and hopefully useful things; because it can't run facilities that it doesn't clearly need, the rest of the Plum Brook will have to be closed down at the end of fiscal 1974."⁶⁵⁷



Image 153: Plum Brook's Engineering Building where Lundin made his announcement to the staff. It was the last day to spend the previous year's annual leave, so many had to be called in from home for the meeting (GRC-2016-C-05192).

^{bb}Lundin, a Lewis engineer and manager since 1942, replaced Abe Silverstein as Center Director in 1969.



Image 154: The staff gathers in the control room on 5 January 1973 to permanently shut down the Plum Brook Reactor (GRC-2003-C-00847).

The news came as a shock and a disappointment to most of the staff. Bill Brown recalled, “We were busy out here. I call us fat, dumb, and happy.”⁶⁵⁸ Others were less surprised. Plum Brook Director Hap Johnson, who retired in June 1974, later admitted, “The handwriting was on the wall in a certain sense because the space program, particularly the shuttle, was sucking up every dime. We were not the only ones who were caught in that; [the NASA] Ames, Langley [research centers] were all being dimed to death, too. Good programs that had to be shut down lots of places in order to support the shuttle. So you could see that it was gradually going to erode, but I didn’t expect it to be absolutely shut down.”⁶⁵⁹ Bucky Walter remembered the reactor staff leaving the cafeteria to shut down the reactor for the final time. “What a waste of talent.”⁶⁶⁰

Meanwhile, there were several key research programs under way at the Rocket Systems Area that had to be completed before Plum Brook was shut down. The staff was put in the position of completing these efforts while mothballing the facilities and searching for new jobs.

Cryogenic Storage Test Vehicle

As NASA was pushing its complex, long-duration exploration into the distant future, Lewis researchers continued their study of advanced cryogenic propellant storage systems. Engineers had determined that extremely long missions required thermal protection systems that included a combination of multilayer insulation, shadowshields, and nonconductive supports and wiring. Richard DeWitt, Robert Boyle, and Richard Knoll of the Chemical Propulsion Division developed the Cryogenic Storage Test Vehicle (CSTV)

to investigate the integration of these tools with full-scale hydrogen and fluorine tanks and a fiberglass support structure.⁶⁶¹

The researchers planned to use K Site and a cryoshroud to simulate a theoretical 1,200-day mission to Saturn. Technicians installed a 13- by 13-foot cryoshroud around the test hardware to simulate the cryogenic temperatures of space. They selected the liquid-hydrogen/liquid-fluorine propellant combination for the program because it posed the most questions.⁶⁶² Preparations for the CSTV tests had a discouraging start in June 1970 when the plastic tarp covering the delicate cryoshroud became dislodged during the journey from the manufacturer in Massachusetts to Sandusky. It took Plum Brook technicians three months to clean and repaint the damaged surfaces.⁶⁶³ It was just the first of many problems that delayed the testing for almost two years.

DeWitt and Boyle divided the CSTV test program into two phases—one using only the multilayer insulation and another with the insulation and shadowshields in place. They tested the article in three different temperature fields—near Earth, deep space, and null—which was produced by keeping both the payload and shroud at cryogenic temperatures.⁶⁶⁴ In September 1973 the researchers subjected the CSTV to all three scenarios using only the multilayer insulation. They added the shadowshields to the vehicle in the spring of 1974 and repeated the tests.⁶⁶⁵ They found the propellant tank supports and other penetrations diminished the performance of the multilayer insulation for the near-Earth missions. The results were better for the deep space configurations with and without the shadowshields.⁶⁶⁶

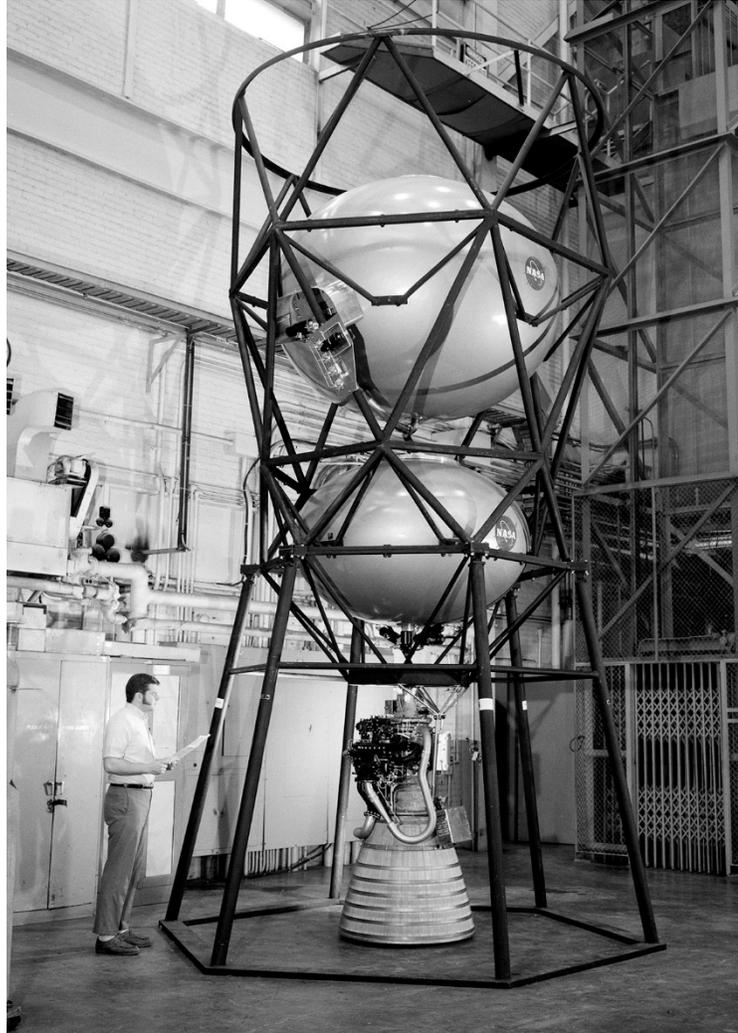


Image 155: CSTV prior to installation of the thermal protection system. The entire framework was sprayed with high-emissivity white paint. The oval 73- to 88-inch-diameter aluminum tank was supported by 12 fiberglass struts. It had two 116-inch-diameter double-sheeted shadow shields and two blankets of multilayer insulation. Each blanket contained 15 layers of double aluminized Mylar (DuPont Teijin Films) with silk net spacers. The CSTV included a simulated payload and an equipment box⁶⁶⁷ (GRC-1971-C-00149).

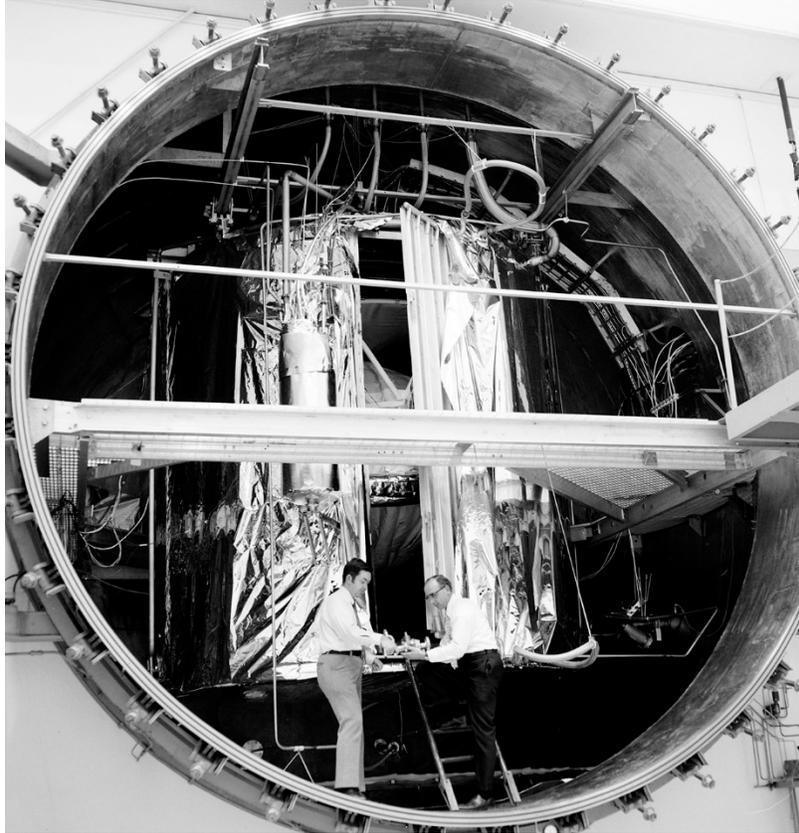


Image 156: Researchers with the CSTV, which is enveloped in a cryoshroud, in the Cryogenic Propellant Tank Facility (K Site) vacuum chamber (GRC-1974-C-03471).



DeWitt and Knoll also used the CSTV to expand on the 1968 tests of reusable insulation blankets at the Cryogenic Propellant Tank Facility (K Site). The insulation proved to be robust and easily applied to the tank. The tests showed that the heat transfer to the tanks in low Earth orbit was 2.6 times greater than anticipated. The performance of the insulation degraded as the number of cycles increased, but DeWitt and Knoll surmised that this may have been a result of leaks underneath the insulation rather than external heat sources. In general they concluded that the concept was applicable to space-tug-types of vehicles.⁶⁶⁸

Although NASA canceled plans for long-duration human exploration missions by the time that the CSTV tests were run, the cryogenic storage technology was on the shelf for future applications. The center resumed its cryogenic fluids research in the late 1980s.

Choked Flow at the Hydraulics Laboratory (F Site)

Any movement of cryogenic fluids can result in some vaporization, referred to as two-phase flow. The rate and pressure of the propellant flow were key elements in the design of turbopumps, tanks, and handling equipment for cryogenic engine systems.⁶⁶⁹ “We make all kinds of computational works,” researcher Robert Hendricks explained, “yet without thermophysical properties and understanding of fluid similitudes, they are worthless.”⁶⁷⁰

In the early 1960s Hendricks and his colleagues in the Fluids and Physics Chemistry Branch developed Fortran computer codes such as GASP (an acronym for “gas properties”) that enabled researchers to analyze the relationship between fluid types and behaviors that effect propellant flow.⁶⁷¹ One such issue was choked flow, which occurs when this liquid/vapor mixture enters a nozzle or other restrictive space.⁶⁷² The breach in *Apollo 13*’s oxygen tank in 1970 spurred additional research in this area.

Lewis researchers believed that they could calculate the amount of liquid and vapor based on the type of fluid, its temperature and pressure, and the shape of the passage, but this theory needed to be verified.⁶⁷³ At Lewis Field, Robert Simoneau mapped the choked flow of liquid nitrogen and a liquid-nitrogen and liquid-methane mixture through different restrictive passages. After reducing the flow rate and pressure to individual curves, the researchers concluded that the nitrogen data could be extended to the more difficult liquid oxygen.⁶⁷⁴

Hendricks recalled, “We were very sure of our GASP and two-phase choked flow codes, as well as the similitudes we projected, yet there was no corroborating proof that they would work in a real system.”⁶⁷⁵ Hendricks and Simoneau proposed a series of flow tests with a liquid-oxygen/liquid-nitrogen mixture to determine if their code could predict the behavior of other fluids.

The researchers submitted their proposal through the Lewis management chain. Later, Hendricks was walking along a road through the valley that divided Lewis Field. A car stopped beside him just long enough for Henry Barnett, Deputy Director of Management, to call out, “We have approved your project,” before continuing on its way up the hill. Hendricks and Simoneau explored options at the soon-to-be-closed Rocket Systems Area for running the tests. They initially considered the High Energy Rocket Engine Research Facility (B–1 Stand) and the Nuclear Rocket Dynamics and Control Facility (B–3 Stand), but these facilities proved to be too expensive to run for such a risky test.⁶⁷⁶ F Site, which had been idle since January 1968, was selected instead.



Image 157: Hendricks in 1971 (GRC–1971–C–03181).

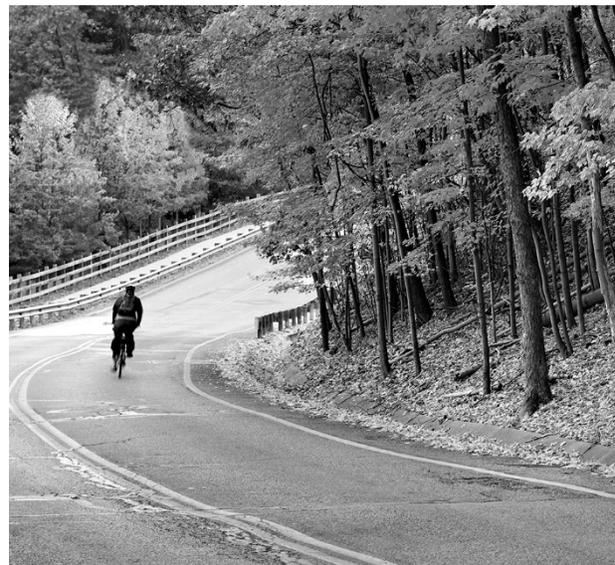


Image 158: Lewis Field’s West Area Road (as seen in 2009), where Hendricks was informed that the F site testing had been approved (GRC–2009–C–03907).

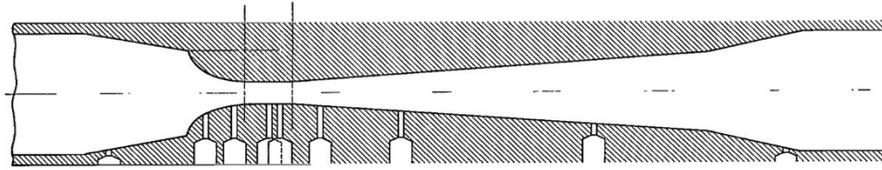


Figure 4. - Elliptical-convergence test section.

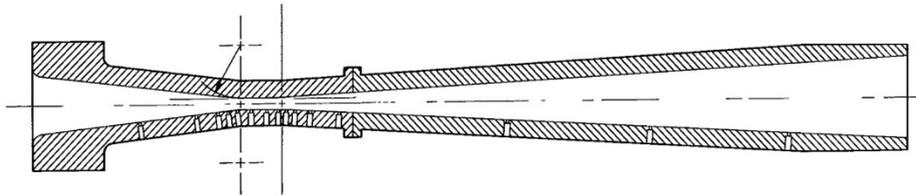


Figure 3. - Conical-convergence test section.

Image 159: F Site test sections used to study choked oxygen flow. The choking occurred in the restrictive throat section (NASA TN D-8169, Fig. 3-4).

Hendricks and Simoneau traveled from Lewis Field to Plum Brook in late May 1974 to witness the eight runs at F Site.⁶⁷⁷ Liquid oxygen with either gaseous or liquid nitrogen was passed through pinched converging-diverging nozzles to produce the choking effect under varied conditions.⁶⁷⁸

The researchers were able to tabulate the extensive choked flow data for the fluid mixture. They concluded that two-phase choked flow rates and pressure ratios for the nitrogen and oxygen were not influenced by the nozzle shape and could be standardized. This process served as the basis for creating new tools to predict the flow characteristics of other liquids.⁶⁷⁹ Hendricks and Simoneau went on to repeat the tests at Lewis Field using liquid nitrogen, methane, and hydrogen with similar results.⁶⁸⁰ The test program, however, was the end of F Site. The facility was deactivated immediately after the tests ended.

Shuttering the Station

“You couldn’t just turn the lights out, lock the door, and go away,” explained Gordon MacKay. “A lot of preparations to prevent [the systems] from freezing and just a lot of things you had to clean in case they ever did want to come back.”⁶⁸¹ Throughout 1973 and 1974 the Plum Brook staff methodically deenergized electrical systems, deactivated boilers, depressurized the air service, and took other safeguards for each of the test sites. Afterward, the engineers issued End Condition reports for each facility, enumerating the steps that had been taken to deactivate the various systems. In some cases test hardware was left in place. It was not unusual for calendars, coffee mugs, and other personal items to remain with the facility.

Lewis considered 64 structures to be still active and maintained them as such. Fifty-five buildings were put in standby condition, including the Spacecraft Propulsion Research Facility (B-2), the Space Power Facility (SPF), the Hypersonic Tunnel Facility (HTF), K Site, and the reactor. These buildings were secured, protected from the weather, and received enough heat and power to prevent the systems from deteriorating. Theoretically, these facilities could be put back into operation within three months. Lewis felt that the cost of maintaining 31 structures outweighed the benefit of bringing them back online at a later date. They were secured, but not maintained. Most of the Rocket Systems Area fell into this category.⁶⁸² “When we shut the place down,” Bob Kozar explained, “we said that the small test cells were, in fact, duplicated elsewhere, at the [NASA] Marshall Spaceflight Center, in industry now, and we weren’t going to spend a lot of money maintaining what already existed.”⁶⁸³



Image 160: Rocket Systems Service Team. Left to right: Carlton Baker, Theodore Klonk, Edwin Graebner, Ellsworth Kissick, Dale McCutcheon, Richard Harris, John Baughman, Kenneth Burrows, and Gary Proy (GRC-2016-C-05118).

Thinning the Herd

After peaking at 5,100 in 1966, Lewis's personnel complement began subsiding rapidly. The center lost 700 positions between 1966 and 1970, 208 positions in 1971, and another 120 in 1972.⁶⁸⁴ The reductions announced by Bruce Lundin in January 1973 resulted in the loss of another 600 employees. The center met the target number of reductions through a combination of retirements, layoffs, and transfers. For many Plum Brook mechanics and technicians, the writing had appeared on the wall several years before. Roger Hershiser was among 15 or 20 technical people from the Rocket Systems Area that reluctantly left the Agency on their own accord in 1969 as their positions became more and more tenuous. "I had a young family I had to take care of," he explained. "I just loved this job. I hated like heck to leave."⁶⁸⁵ Many of the NACA veterans who had begun their careers at the lab in the 1940s decided to retire. The younger generation hired in the early 1960s did not have that luxury.

Lewis's reductions hit Plum Brook the hardest. By the spring of 1974 Plum Brook's staff had declined from 600 to 54. The center's 5 January 1973 press release announcing the closure of Plum Brook stated, "The special skills and experience of employees to be separated can be of great benefit to the nation in other areas of technical interest."⁶⁸⁶ Within days, Lewis created an employment assistance office that, in its first six months, facilitated the transition of 232 employees, including 117 from Plum Brook, to new careers.⁶⁸⁷

Lewis subsequently established a second job placement office in the Engineering Building at Plum Brook to assist the remaining employees losing their jobs. These ranged from mechanics to engineers and even Plum Brook Manager Hap Johnson. Bill Brown oversaw a 10-person staff that contacted hundreds of possible external employers, aligned skill sets with employer needs, mailed thousands of resumes, and set up interviews.⁶⁸⁸ Lewis maintained the Plum Brook office until mid-1974.⁶⁸⁹

In addition, regional companies, including Ford and Delphi, briefed the staff on the types of positions that were available at their facilities. The University of Toledo offered review classes for engineers seeking their Professional Engineer certificates.⁶⁹⁰

“NASA did everything in their

power,” recalled former Plum Brook engineer Jim Greer. “Starr Truscott did so much out here in contacting industries and telling what these people were like. Helping all the people get a position.”⁶⁹¹

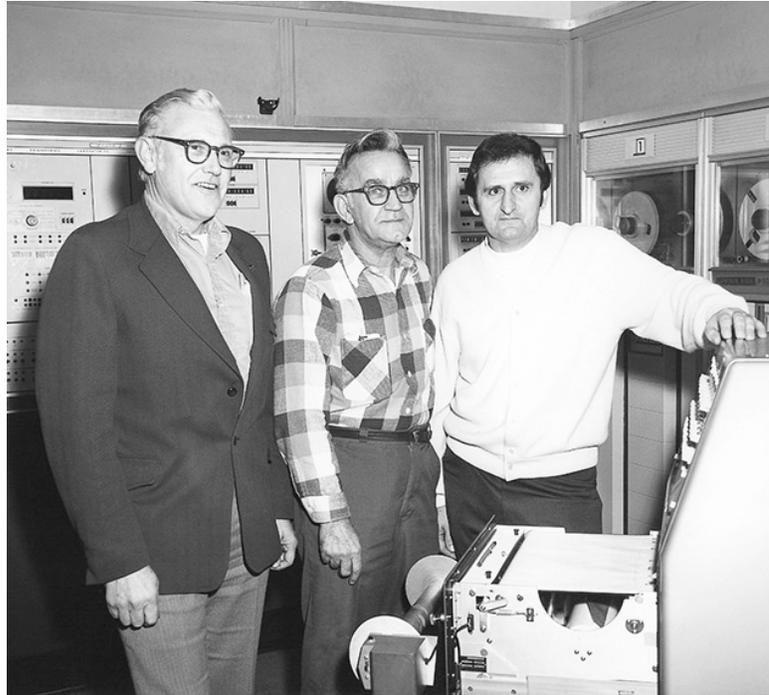


Image 161: Members of the Rocket Systems Service Team. Left to right: James Freyberg, James Wohlever, and Donald Gresh (GRC-2016-C-05117).

Centaur’s New Missions

In the mid-1960s NASA began taking steps to pair the Centaur stage with Lockheed Martin’s Titan III booster to provide service in the range between the Atlas/Centaur and Saturn vehicles. Lockheed originally developed the Titan in parallel with General Dynamics’s Atlas in the mid-1950s to launch the U.S. Air Force’s missiles. Lockheed created the three-stage Titan III version in 1962 specifically to launch military satellites.⁶⁹² In the late 1960s General Dynamics created the Centaur D-1T to serve as the Titan’s fourth stage.

In 1968 NASA canceled the Mars Voyager proposal to send humans on a flyby of Mars but approved sending twin robotic *Viking* solar-powered orbiters and nuclear-powered landers to study the Martian surface.⁶⁹³ The *Viking* payloads were the heaviest objects ever attempted to be launched into space. Each was over three times the weight of the heaviest Atlas/Centaur payload. NASA decided to launch *Viking* on the Titan/Centaur, and Lewis engineers had the difficult task of integrating Centaur with both the Titan III and the *Viking* payload.⁶⁹⁴ A failure of the \$1 billion mission would not only jeopardize future planetary missions but the Agency itself. The Soviet Union had rushed to send several orbiters and twin landers to Mars in 1973. The first crashed into the surface, but the second successfully landed in a major sandstorm and, during its 20 seconds of life, transmitted an image back to Earth.

NASA also coopted the *Voyager* name for the most ambitious Mariner-type flyby missions to date. NASA scientists at the Jet Propulsion Laboratory designed the twin *Voyager* spacecraft to take advantage of a unique alignment of the planets in the late 1970s. They were able to design a mission that used the gravitational pull of certain planets to increase the spacecraft's speed enough to reach the next planet. This particular arrangement occurred only every 175 years, so there was pressure to meet the launch window.

Centaur Standard Shroud

The new Centaur D-1T was similar in size and design to the recently upgraded D-1A vehicle for Atlas. The most significant difference for the D-1T was a completely new shroud, called the Centaur Standard Shroud (CSS). *Viking* required a wide aerodynamic shield for its descent onto Mars. The 56-foot-tall CSS was 4 feet larger in diameter than the Titan booster. This gave the 160-foot-tall Titan/Centaur stack its unique bulbous shape.⁶⁹⁵

The shroud is a critical component on any launch vehicle mission. The conical two-piece covering encapsulates the payload to protect it against adverse conditions and improve aerodynamics as the launch vehicle passes through the atmosphere. The shroud is jettisoned once the vehicle is at the edge of space. Even a minor error in this process could cause the launch to fail.

Testing of the shroud jettison system was critical to the mission. Lewis researchers accumulated a good deal of shroud testing experience during the previous decade at Lewis Field. Researchers there had verified the shroud jettison systems for the Atlas/Centaur 4 (AC-4) and AC-6 Surveyor missions (1964 and 1965) and the Atlas/Agena and Centaur shrouds for three Orbiting Astronomical Observatory missions (1965, 1968, and 1972). Lewis researchers also had tested the shroud for the *Apollo-Skylab* launch in Plum Brook's new SPF vacuum chamber (1971).⁶⁹⁶

Lockheed designed the CSS so that the shell, not the supports, carried most of load so that the Centaur would not be overburdened. The shroud's cylindrical section had internal fiberglass insulation panels to keep the Centaur from freezing during the 2-hour liquid-hydrogen tanking and to prevent external heat from warming the propellants during the launch.⁶⁹⁷ A series of pyrotechnics along the seam were fired to release the shroud halves, which were pushed away from the vehicle by springs.⁶⁹⁸

In July 1970, Plum Brook management agreed to support the Titan/Centaur effort by testing the CSS tests in its B-3 Stand and SPF. The CSS test program would verify the shroud's strength, jettison system, and insulation, as well as the Centaur ground-hold purge system and the hydrogen tank venting system.⁶⁹⁹ The CSS assessment consisted of two tests at the B-3 Stand and the third in SPF. The first was a series of



Image 162: A Centaur D-1T is prepared for mating with the Titan III booster in 1974 (NASA 101-KSC-74P-302).

shroud unlatching tests conducted with the tanks filled with liquid hydrogen and liquid nitrogen. These would verify that the insulation, purge vent, and jettison systems worked in cryogenic temperatures. The next was a two-phase structural test to validate the structural strength of the CSS, the vehicle's interstage adapter and forward bearing, and the vehicle's interaction with the Titan skirt. The SPF tests would jettison the shroud in temperature and pressure conditions that simulated space. Aerodynamic heating would be simulated to ensure that the shroud did not bind up during the launch.⁷⁰⁰

Jack Humphrey, a veteran of the earlier Centaur shroud tests, managed the CSS test program and Bill Klein oversaw the Plum Brook operations. Rocket Systems Division Chief Glen Hennings appointed Henry Pfanner as the test conductor for the B-3 tests. It was unusual for a Controls person to manage a test program, but Hennings felt that Pfanner's knowledge of the servo control system would be crucial.⁷⁰¹ Dick Heath conducted the CSS testing in the SPF space tank.

Final Preparations

The B-3 Stand was not designed for shroud testing, but at 210 feet, it was the tallest structure at Plum Brook and could easily accommodate the 58-foot-long CSS. In January 1971 the Rocket Systems Division began installing new work platforms, designing a catchnet system, and making other modifications to the B-3 Stand.⁷⁰²

The B-3 test program ran into problems almost immediately when the Area Safety Committee rejected the program's application for a safety permit. The researchers wanted to keep the stand's roll-down doors closed to prevent the wind from affecting the shroud temperature. Lewis's safety guidelines, however, clearly stated that facilities using hydrogen had to be open to the atmosphere to prevent gas buildup and reduce the possibility of explosions. Committee chairman Bill Brown later explained, "You always assumed that you were going to have a spark capability, an ignition capability. You always assumed that was possible. Even though they took every precaution you can imagine."⁷⁰³

John Gibb, head of the Rocket Systems Division's Propulsion Section, protested that having the doors up would skew the results. Brown and Gibb met with the upper management team on the Executive Safety Board to discuss the issue. The board supported Brown's decision. The doors would have to remain open. Gibb and his engineers modified the doors so that they could be opened quickly when the propellant tanking began. The test was then run, and the doors were promptly lowered back down. This allowed the researchers to achieve the desired test conditions while meeting the safety requirements.⁷⁰⁴

Rocket Systems Division staff members also were forced to deal with Lewis's evolving test requirements and Lockheed's delays in creating the shroud. A November 1971 report stated, "Design information we request from Cleveland is almost always later than the original request date and usually received at the last possible date to meet the schedule. There have been several instances where the final information is significantly different than preliminary information received at an earlier date. The catcher system has probably been the worst example of this. In addition, the program objectives and effort required have multiplied over the original estimates based on information received more than a year ago. All of the above changes have been absorbed without changing the end date. The schedule is now so tight that no further schedule perturbations can be tolerated without changing the date."⁷⁰⁵



Image 163: Preparations at the B-3 Stand for the structural test of the CSS in early 1973. The test setup included the Centaur, its interstage adapter, a flight-weight propellant tank, and a Viking model (GRC-1973-P-01383).

Confirmation

The CSS validation program commenced on 28 September 1972 with the first of three separation runs. The test engineers evacuated the site and loaded the propellants into the tanks. They allowed the hydrogen to settle and then measured to rate of evaporation to determine the performance of the shroud's insulation during a simulated ground hold. They then pumped the remainder of the propellants out and jettisoned the two shroud halves into the catchnets.⁷⁰⁶

There were difficulties pressurizing the shroud with liquid hydrogen in the Centaur tanks, and posttest inspections of the CSS revealed a crack in the liquid-hydrogen vent sleeve and a rupture of the shroud's pyrotechnics casing, which could have damaged the payload. During the follow-up test, the forward seal tore and both shroud halves impacted the simulated payload. Engineers modified the pyrotechnics, seals, and insulation, but the difficulties continued during November and December.⁷⁰⁷

Although conspicuously absent from the monthly Test Operations Report, the CSS efforts were disrupted by the January 1973 announcement of the impending Plum Brook closure and layoffs. As some staff members began leaving for other employment opportunities, NASA management realized that a failure to complete the CSS validation testing would impact the 1975 launch dates for *Viking*—arguably the Agency's highest profile mission of the 1970s.

Lewis quietly offered permanent positions to several of those running the CSS program if they stayed to complete the tests.⁷⁰⁸ "Guys were flying out of there in 1973 getting jobs," recalled Henry Pfanner. "Who's going to come in there and run. Not that it is very complicated for somebody who designed it, but it would be very difficult for somebody who didn't design it. So we stayed on and did the test."⁷⁰⁹ There was no reversing the closure of Plum Brook, however, and the staff continued to mothball the facilities and search for new employment during the CSS testing.

The CSS testing resumed at 9:20 p.m. on 7 February 1973 when the shroud underwent its first successful unlatch test. A *Lewis News* article states, "In a split second during the quiet evening hours last Wednesday, two latches unfastened, hinges rotated, and a 6,500-pound aluminum cover on a rocket broke loose at Plum Brook Station."⁷¹⁰ The successful test convinced the researchers to cancel the remaining unlatch tests.



Image 164: CSS installed in the B-3 Stand (GRC-1973-C-01373).



Image 165: B-3 Rocket Systems Team with Glen Hennings seated at desk. Left to right: Richard Barrows, John Gibb, Mario Miraldi, William Rice, George Wildschrey, Donald Weikle, Norman Schoeder, and John Sholes (GRC-2016-C-05116).

The next series of CSS tests, which began in April 1973, sought to demonstrate the structural integrity of the CSS and Centaur D-1T systems. The researchers subjected the CSS hardware to a horizontal force and found that the shroud bent 50 percent more than predicted and that the forward seal loosened. The engineers resolved the problem and successfully conducted two additional runs. The test series, which concluded July 1973, verified the shroud's overall structural strength, demonstrated the need for load-sharing supports between the Centaur and the shroud, and confirmed that the insulation did not degrade over time.⁷¹¹

The staff removed the Centaur, CSS, and test equipment from the B-3 Stand by mid-July 1973 and installed them at SPF for the heated jettison tests. The SPF provided a much more realistic analysis of the shroud's performance in simulated space conditions and offered a large enough area that the shroud could be completely jettisoned, not just popped open. Heath and the engineers conducted the first two SPF jettison tests at temperatures that simulated the aerodynamic heating that occurred during a launch and then a third at ambient temperatures to provide baseline data for analysis. The three successful separations provided the researchers with data on payload clearances and the separation system's effectiveness.⁷¹² The B-3 and SPF tests verified Lockheed's calculations of the flight performance of the CSS. The new shroud was ready for a real test—Titan/Centaur's single development launch.

Titan/Centaur Successes

NASA scheduled a development launch for Titan/Centaur to verify its performance prior to the six planned missions. On 12 February 1974, the first Titan/Centaur lifted off from Cape Canaveral and smoothly jettisoned the CSS. The failure of Centaur's engines to start, however, forced the range safety officer to destroy the vehicle. NASA and General Dynamics engineers identified a problem with the boost pumps and concluded that the issue was not unique to the Titan/Centaur and could have occurred on any of the previous Atlas/Centaur missions. All of the critical interface issues between Titan and Centaur had been demonstrated, so no additional test flights were required.⁷¹³ Nonetheless, there was tremendous pressure to keep the high-profile program on schedule. Tensions were relieved in December 1974 when Titan/Centaur successfully launched the German spacecraft *Helios 1* on its mission to the Sun. The Titan, Centaur, and CSS performed perfectly.

The Centaur Office worked feverishly to prepare for the five additional Titan/Centaur launches over the next two and a half years. The *Viking* orbiters and landers were launched in August and September 1975 and arrived at Mars in the summer of 1976. The two orbiters and landers operated on the Martian surface for between two and six years. Besides being the first U.S. spacecraft to land on Mars, *Viking* provided several other firsts, including the first classification of Mars's physical conditions and the first high-resolution images of Mars. NASA would not return to the Martian surface until the 1997 Pathfinder mission.

Titan/Centaur sent a second *Helios* toward the Sun in January 1976. In August and September 1977, the Titan/Centaur launched the twin *Voyager* spacecraft. Collectively, the *Voyagers* investigated Jupiter, Saturn, Uranus, Neptune, and 48 of their moons before leaving the solar system in the 2010s. The spacecraft continue to return data regarding the stars and the frontier between the Sun and interstellar space.⁷¹⁴



Image 166: Titan/Centaur launch of Viking 1 on 20 August 1975 (NASA LRC-1975-L-06432).

Despite the successes, the Titan III/Centaur combination had a relatively short career. The Centaur rocket, however, has launched nearly 200 missions and is still going strong. During its perilous formative years, NASA Lewis went to extraordinary efforts to ensure the success of the program. The dynamics load testing in the Dynamics Stand (E Stand) at Plum Brook was a critical element of this effort. The pressurant studies at the B-1 and B-2 stands resulted in the removal of the boost pumps and a creation of a new propellant system design that continues to be used today. The CSS jettison tests in the B-3 Stand and SPF were critical to the new Titan/Centaur vehicle. During the 1970s, when most Lewis research divisions suffered from budget reductions and shrinking research programs, the Launch Vehicle Division thrived.



Plum Brook, however, was closed down. The final Rocket Systems Area facilities were mothballed in the spring of 1974, and hundreds of employees had been let go. By 1975 there were only a half dozen of NASA staff members in Sandusky.⁷¹⁵ Henry Pfanner recalled, “Total time from when Bruce [Lundin] announced that Plum Brook was closing until there was only a handful of us left, meaning five, was a little under two years.”⁷¹⁶ Several of the facility engineers accepted posts at Lewis Field in new research fields such as renewable energy and pollution reduction. Jim Cairelli, Bucky Walter, and Gordon MacKay and others were placed in Lewis’s automotive Stirling program. Don Perdue became a systems engineer for the Centaur Program. The new commuters formed carpools for the 55-mile trek to Cleveland. Meanwhile management pursued alternative uses for Plum Brook.

References

646. “President Nixon’s 1972 Announcement on the Space Shuttle” (5 January 1972), <http://history.nasa.gov/stsnixon.htm> (accessed 28 May 2014).
647. Richard Heath interview, Cleveland, OH, by Robert Arrighi, 15 August 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
648. Ihor Gawdiak and Helen Fedor, *NASA Historical Data Book vIV* (Washington, DC: NASA SP-4012, 1994), <http://ntrs.nasa.gov>
649. John Logsdon, *After Apollo?: Richard Nixon and the American Space Program* (London: Palgrave Macmillan, 2015).
650. T. A. Heppenheimer, *The Space Shuttle Decision: NASA’s Search for a Reusable Space Vehicle* (Washington, DC: NASA SP-4221, 1999), <http://ntrs.nasa.gov>
651. John M. Logsdon, editor, *Exploring the Unknown, Selected Documents in the History of the U.S. Civil Space Program, Volume IV: Accessing Space* (Washington, DC: NASA/SP-1999-4407, 1999), chap. 1, <http://ntrs.nasa.gov>
652. James Dewar, *To the End of the Solar System: The Story of the Nuclear Rocket* (Lexington, KY: University Press of Kentucky, 2004).
653. Steven Howe, *Assessment of the Advantages and Feasibility of a Nuclear Rocket for a Manned Mars Mission* (Los Alamos, NM: LANL LA-UR-85-2442, 1985).
654. Dewar, *To the End of the Solar System*.
655. Memorandum to Bruce Lundin, 26 December 1972, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
656. Bruce Lundin, Untitled Talk at Plum Brook Station, 5 January 1973, NASA Glenn History Collection, Bruce Lundin Collection, Cleveland, OH.
657. Bruce Lundin, Untitled Talk at Plum Brook Station.
658. William Brown interview, Cleveland, OH, by Robert Arrighi, 17 December 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.

659. Alan Johnson interview, Cleveland, OH, by Mark Bowles, 20 March 2002, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
660. Robert Walter interview, Cleveland, OH, by Robert Arrighi, 5 November 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
661. Richard DeWitt and Robert Boyle, *Thermal Performance of an Integrated Thermal Protection System for Long-Term Storage of Cryogenic Propellants in Space* (Washington, DC: NASA TN D-8320, 1977), <http://ntrs.nasa.gov>
662. DeWitt, *Thermal Performance of an Integrated Thermal Protection System*.
663. Rocket Systems Division Reports, K Site, 1970-1974, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
664. DeWitt, *Thermal Performance of an Integrated Thermal Protection System*.
665. Rocket Systems Division Reports, K Site, 1970-1974.
666. DeWitt, *Thermal Performance of an Integrated Thermal Protection System*.
667. DeWitt, *Thermal Performance of an Integrated Thermal Protection System*.
668. Richard Knoll and Richard DeWitt, *Thermal Performance of a Modularized Replaceable Multi-Layer Insulation System for a Cryogenic Stage* (Washington, DC: NASA TN D-8282, 1977), <http://ntrs.nasa.gov>
669. Yih-Yun Hsu, *Review of Critical Flow Rate, Propagation of Pressure Pulse, and Sonic Velocity in Two-Phase Media* (Washington, DC: NASA TN D-6814, 1972), <http://ntrs.nasa.gov>
670. Robert Hendricks email to Robert Arrighi, 10 July 2013, NASA Glenn History Collection, Cleveland, OH.
671. Robert C. Hendricks, Anne K. Baron, and Ildiko C. Peller, *GASP—A Computer Code for Calculating the Thermodynamic and Transport Properties for Ten Fluids* (Washington, DC: NASA TN D-7808, 1975), <http://ntrs.nasa.gov>
672. Robert Simoneau and Robert Hendricks, *Two-Phase Choked Flow of Cryogenic Fluids in Converging-Diverging Nozzles* (Washington, DC: NASA TP-1484, 1979), <http://ntrs.nasa.gov>
673. Robert Simoneau, F. F. Simon, and Robert Hendricks, "Discharge Rates From Cryogenic Vessels," *Lewis Basic Research Review* (Cleveland, OH: NASA, 1972).
674. Robert Hendricks, Robert Simoneau, and Richard Barrows, *Two-Phase Choked Flow of Subcooled Oxygen and Nitrogen* (Washington, DC: NASA TN D-8169, 1976), <http://ntrs.nasa.gov>
675. Hendricks email to Arrighi.
676. Hendricks email to Arrighi.
677. Rocket Systems Division Reports, F Site, 1974, NASA Glenn History Collection, Plum Brook Collection, Cleveland, OH.
678. Hendricks, *Two-Phase Choked Flow of Subcooled Oxygen and Nitrogen*.
679. Hendricks, *Two-Phase Choked Flow of Subcooled Oxygen and Nitrogen*.
680. Simoneau, *Two-Phase Choked Flow of Cryogenic Fluids*.
681. Gordon MacKay interview, Cleveland, OH, by Robert Arrighi, 14 January 2014, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
682. "Plum Brook Station Review," 30 December 1976, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
683. Robert Kozar interview, Cleveland, OH, by Virginia Dawson, 30 March 2000, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
684. Bruce Lundin, Memorandums to Lewis Employees, 5 August 1970, 21 January 1971, 29 January 1971, 14 March 1972, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
685. Roger Hershiser interview, Cleveland, OH, by Robert Arrighi, 17 December 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
686. NASA press release, 5 January 1973, NASA Glenn History Collection, Plum Brook Collection, Cleveland, OH.
687. "Office Finds Jobs for Many," *Lewis News* (27 July 1973).
688. "Outplacement Office Opens," *Lewis News* (5 April 1974).
689. "Plum Brook Phased Down," *Lewis News*, (July 12, 1974).
690. MacKay interview by Arrighi.

691. Jim Greer interview, Cleveland, OH, by Mark Bowles, 6 September 2002, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
692. “Atlas vs. Titan,” *Aircraft and Missiles* (July 1960).
693. David Portree, *Humans to Mars: Fifty Years of Mission Planning, 1950–2000* (Washington, DC: NASA/SP—2001-4521, 2001), <http://ntrs.nasa.gov>
694. Virginia P. Dawson and Mark D. Bowles, *Taming Liquid Hydrogen: The Centaur Upper Stage Rocket* (Washington, DC: NASA/SP—2004-4230, 2004), <http://ntrs.nasa.gov>
695. NASA Lewis Research Center Press Release 70–28, 25 June 1970, NASA Glenn History Collection, Press Release Collection, Cleveland, OH.
696. Robert Arrighi, *Revolutionary Atmosphere: The Story of the Altitude Wind Tunnel and Space Power Chambers* (Washington, DC: NASA/SP—2010-4319, 2010), <http://ntrs.nasa.gov>
697. “Centaur Shroud Passes Cryo Test,” *Lewis News* (23 February 23 1973).
698. Titan/Centaur Project Office, *Centaur Standard Shroud (CSS) Cryogenic Unlatch Tests* (Washington, DC: NASA TM X–71455, 1973), <http://ntrs.nasa.gov>
699. Titan/Centaur Project Office, *Centaur Standard Shroud (CSS)*.
700. NASA Lewis Research Center, *Centaur Standard Shroud Static Ultimate Load Structural Tests* (Washington, DC: NASA TM X–71823, 1975), <http://ntrs.nasa.gov>
701. Henry Pfanner interview, Cleveland, OH, by Robert Arrighi, 6 September 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
702. Rocket Systems Division Reports, Rocket Dynamics and Control Facility, 1971, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
703. Brown interview by Arrighi.
704. Brown interview by Arrighi.
705. Rocket Systems Division Reports, Rocket Dynamics and Control Facility.
706. Titan/Centaur Project Office, *Centaur Standard Shroud (CSS)*.
707. Rocket Systems Division Reports, Rocket Dynamics and Control Facility, 1972, Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
708. Heath interview by Arrighi.
709. Pfanner interview by Arrighi.
710. “Centaur Shroud Passes Cryo Test.”
711. Charles Eastwood, G. Sarvey, Jack McArdle, and M. C. Seaver, *Centaur Standard Shroud Static Limit Load Structural Tests* (Washington, DC: NASA TM X–71727, 1975), <http://ntrs.nasa.gov>
712. NASA Lewis Research Center, *Centaur Standard Shroud Heated Altitude Jettison Tests* (Washington, DC: NASA TM X–71814, 1975), <http://ntrs.nasa.gov>
713. R. J. Rolbuhler, *Centaur Boost Pump Turbine Icing Investigation* (Washington, DC: NASA TM X–73221, 1976), <http://ntrs.nasa.gov>
714. Dawson, *Taming Liquid Hydrogen*.
715. “NASA to Ax Jobs at Lewis Center.”
716. Henry Pfanner interview, Cleveland, OH, by Mark Bowles, 26 September 2002, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.



Image 167: High Energy Rocket Engine Research Facility (B-1 Stand) in 2007 after years of neglect (GRC-2007-C-01907).

◆ Chapter 9 ◆

Aftermath

On 5 February 1973 NASA Headquarters instructed Bruce Lundin to write a memorandum for the record formally requesting that Plum Brook Station be put into standby mode and submit a phase-out plan.⁷¹⁷ To delay the removal of its resources, Lundin's request stated that Plum Brook Station would be closed for only a few months. In response NASA Administrator James Fletcher instructed Lundin to find new, non-NASA applications for Plum Brook. The Agency hoped that other agencies, universities, or industry would assume control of some of the test sites. Lundin hesitated before beginning the effort. He recalled receiving "vigorous phone calls" from headquarters over the ensuing days asking why he had not initiated the search. The Agency appointed an advisor to spur Lundin's efforts.⁷¹⁸ There was no turning back. NASA would never use the Rocket Systems Area again.

NASA futilely attempted to find alternative uses for Plum Brook Station in the 1970s. During the development of the shuttle, the Agency's most impressive achievements in space were probes to the outer planets. As the shuttle began flying missions in the 1980s, NASA initiated plans for a large space station. In the late 1980s and early 1990s NASA restored the larger facilities at Plum Brook to support a short-lived effort to return humans to the Moon and possibly Mars. Although such missions would require advanced technologies explored at the Rocket Systems Area in the 1960s, the center only reactivated one Rocket Systems Area facility—the Cryogenic Propellant Tank Facility (K Site). Instead the center built new facilities to study cryogenic fluids management. After nearly 40 years of abandonment, the Agency demolished the Rocket Systems Area facilities in the 2000s.

For Sale

In March 1973 electric propulsion specialists Jack Dugan and John Shannon were asked to testify before Congress to remind the House Authorization Subcommittee on Aeronautics and Space Technology that NASA was full of intelligent and enthusiastic young researchers. "One must realize that the cuts of talented scientific and engineering talent constitute a serious national problem," Dugan warned. "The continued cutbacks have already triggered an irreversible trend in university enrollments by discouraging people from majoring in engineering and the physical sciences. It's particularly tragic when the country faces an energy crisis and environmental problems that cry for new technology."⁷¹⁹

Lundin was impressed by Dugan's remarks regarding the effects of NASA's cutbacks on the nation's future capabilities. In April 1973 Lundin asked Dugan to lead the effort to find external interest in Plum Brook's facilities.

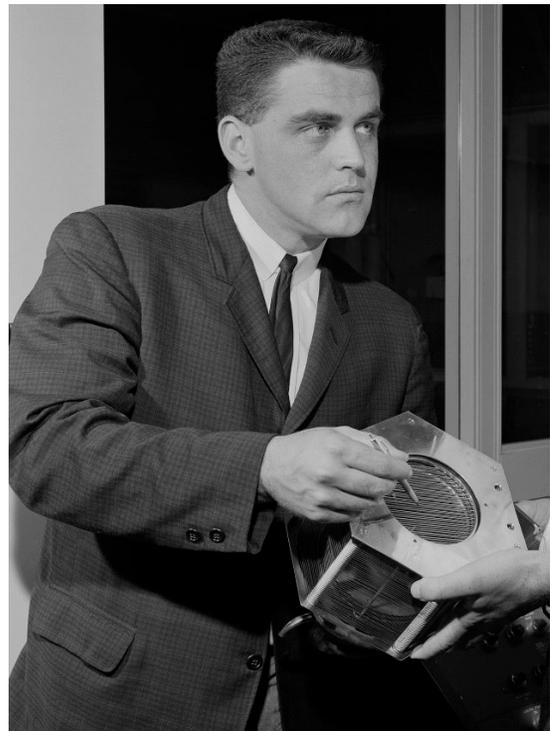


Image 168: Dugan displaying an ion thruster in 1963, shortly after joining NASA and 10 years before he took on the Plum Brook repurposing effort (GRC-1963-C-65280).

Dugan quickly requested the design of a 20-page booklet that highlighted the potential uses of both Plum Brook’s test sites and open lands. Not surprisingly, the brochure featured the largest sites—the reactor, the Spacecraft Propulsion Research Facility (B–2), and Space Power Facility (SPF)—most prominently, but it also carefully noted potential uses of the Rocket Systems Area sites. Some examples: the High Energy Rocket Engine Research Facility (B–1 Stand) was “ideally suited for testing large turbopump systems such as those used in the electric power industry”; the Liquid Hydrogen Pump facility (A Site) and Turbopump Facility (C Site) could be used for component research for “the hydrogen economy”; the Controls and Turbine Test Facility (D Site) could be applied to automotive engines, and the Dynamics Stand (E Stand) was “well suited for structural testing of large equipment or structures subject to vibration loads.”⁷²⁰

Dugan also organized a symposium at Plum Brook on 23 and 24 April 1973 to introduce prospective clients to Plum Brook. During the introductory dinner, Lundin explained three possible scenarios to attendees—Plum Brook could be operated as a NASA nonprofit organization, it could be transferred to another institution, or the sites could be mothballed. Congressman Charles Mosher expressed his frustration, “We’ve put all of this money into [Plum Brook]. This policy of stop and go seems terribly inefficient. But the problems of Plum Brook do seem to illustrate a whole realm of other problems regarding federal use of facilities such as this.”⁷²¹

The frustration was shared by the other guests. The local newspaper reported that half of the 80 visitors held science or engineering doctorate degrees, yet they could not generate any ideas for alternative uses for Plum Brook. The common sentiment was “the facilities and equipment should be utilized by someone, but not by my institution.” Norman Phillips, head of the Sandusky Chamber of Commerce, compared the tour of the sites the following morning to “attending a wake for a close friend. The last time I was here there were people all over the place. Now there are so few.”⁷²²

Over the next year Dugan expended a great deal of energy writing letters, attending meetings, and traveling around the country to advertise Plum Brook’s assets. He was able to identify six potential projects for Plum Brook involving NASA, the air force, navy, National Science Foundation, and the National Oceanographic and Atmospheric Administration, with only the latter coming to fruition in SPF.⁷²³

It was a difficult period in U.S. history. The nation dealt with a recession, high unemployment, the Oil Embargo, Watergate, and the negotiated end of the Vietnam War. NASA’s human space program was transitioning from Apollo to the shuttle, and NASA funding was declining sharply. Lewis, which did not have a direct role in the shuttle program, was particularly impacted. Although the center pivoted into new fields like renewable energy, there was not enough work to sustain Plum Brook.

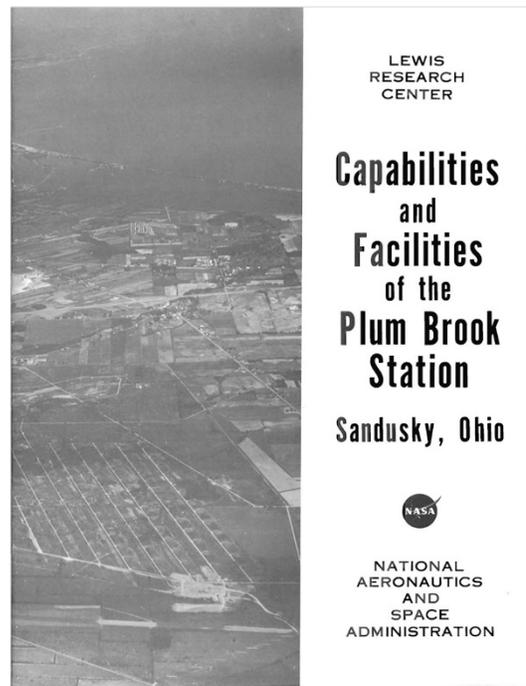


Image 169: NASA publication highlighting potential uses of Plum Brook and its facilities for non-NASA users (NASA).

Standing By

Meanwhile, the transition from operational status to standby was not going smoothly. In the spring of 1974 Lewis still maintained a staff of 50 at SPF with the hope that Dugan's marketing would bring in addition work.⁷²⁴ Plum Brook Manager Ray Koch and SPF Chief Dwight Reilly met with Bruce Lundin in April 1974 to express their frustration with the lack of planning for the standby period and the undetermined status of the remaining staff. Koch drafted a detailed list of suggested actions and requested the establishment of a new organizational structure to reflect the current situation.⁷²⁵

Any prospect of keeping Plum Brook open soon faded, however, and Lewis pared the staff down substantially. NASA retained five civil servant staff members as Plum Brook caretakers, including Koch and his assistant Jean Fox. James Brichacek maintained Plum Brook's electrical and communications systems. Alan Duncan monitored the mothballed test sites. Robert Kanney inventoried and arranged the transfer of the NASA equipment left in place when Plum Brook was shut down.⁷²⁶ There were also approximately 30 contractors on site to provide security and maintenance.⁷²⁷

Over the next few years there was some interest in adapting the B-1 Stand and the Nuclear Rocket Dynamics and Control Facility (B-3 Stand) to test engines for Vertical Take-off and Landing aircraft and C Site to study combustor emissions. These plans fell through, however, and the facilities remained shuttered. During this period, Plum Brook's primary office space, the Engineering Building, was occupied by the Environmental Protection Agency (EPA), the Federal Bureau of Investigation, and the Department of the Interior, and the army. By late 1976 Lewis management had stopped promoting D Site, the Hydraulics Laboratory (F Site), and the Rocket Systems Test Site (J Site), and had decreased its efforts with A Site, E Stand, and the Fluorine Pump Facility (I Site). The EPA used the structures at D Site and F Site to support a new test track used to analyze noise from automobiles. The U.S. Army Reserve utilized J Site structures to store equipment for their occasional training exercises at the south end of the Plum Brook property.⁷²⁸



Image 170: Liquid-chemical trailers sit idle at Plum Brook (GRC-2016-C-05189).

The Wind Turbine

Plum Brook's most successful effort during this period had nothing to do with space, propulsion, or liquid hydrogen. In the 1970s Lewis expanded its research activities to include nonaerospace endeavors such as environmental monitoring, energy efficient power systems, and renewable energy sources. The Arab Oil Embargo of 1973 left the United States without enough energy to meet its needs. This led to the establishment of the Energy Research and Development Administration (ERDA) in 1974 and the Department of Energy in 1977. Lewis researchers began applying their experience with aerodynamics, turbomachinery, and energy conversion systems to energy problems on Earth.⁷²⁹ Wind energy was a major component of this effort, and Plum Brook's open spaces were perfect for the research.

Lewis sponsored an international conference on wind energy in 1973 that led to a joint NASA and ERDA effort to develop efficient and cost-effective wind energy systems. The Wind Energy Program included a small experimental wind turbine at Plum Brook and a series of increasingly powerful machines built at sites across the nation. Lewis engineers designed Plum Brook's 100-kilowatt turbine (referred to as Mod-0) to be large enough to obtain useful data, but small enough to facilitate frequent updates and modifications.⁷³⁰

In 1975 Plum Brook engineers supervised the construction of the Mod-0 turbine and prepared it for operation. Bucky Walter was responsible for establishing operating procedures for the various systems, and Henry Pfanner worked on the servocontrols.

In 2013 Walter recalled some hesitation when it was time to activate the device, "I was at the control panel and asked the Division Chief, Branch Chief, and the Project Engineer to give me permission to rotate the turbine. There was dead silence. I waited and again there was no response from anyone. I said, 'oh hell,' and rotated the pitch control knob, the 125-foot wind turbine turned, and they all cheered. I think if I waited for a response I might be sitting at that control panel today!"⁷³¹

On a cool, windy 29 October 1975 hundreds of people traveled to Sandusky to witness the turbine's official dedication. After a local high school band played "Windmills of Your Mind" and NASA and ERDA officials gave talks and held a press conference, NASA Administrator Fletcher and Robert Seamans, the head of ERDA, depressed the red button on the podium to activate the wind turbine. As the turbine began rotating a loud, repeating thud was heard. The machine was quickly shut down. Lewis inspectors later discovered that one of the manufacturer's employees had accidentally left a flashlight inside one of the hollow blades.⁷³²



Image 171: Installation of the Mod-0 wind turbine at Plum Brook in September 1975 (GRC-1975-C-03114).

David Spera and Darrell Baldwin conducted most of the Mod-0 research while Henry Pfanner managed the facility's day-to-day operations. Pfanner explained, "It was myself, a good mechanic, and good electrician. We'd figure out what in the hell we'd have to do, and we'd get it done."⁷³³ The turbine was brought down over a dozen times for modification, including new blades, towers, controls, and generators.⁷³⁴

The Mod-0 device provided NASA researchers with basic experience in operating wind turbines and integrating them into the utility grid. Operators could vary the pitch of the blade to control the turbine power and synchronize the power generator with the utility company when the wind turbine was run at a constant speed. The staff overcame early difficulties with reliability, rotor durability, and turbulence caused by the tower's staircase. Lewis researchers used the Mod-0 testbed to study different blade materials, anchoring techniques, and rotor types.⁷³⁵

In November 1985 over 100 people attended a ceremony at Plum Brook to mark 10 years of Mod-0 operation. Baldwin presented Pfanner with a citation for his efforts and remarked, "Hank [Henry Pfanner] and his operations team carried out pioneering research testing for which there was little or no precedent. Hank's example was always one of dedication, efficiency, and friendship."⁷³⁶

In the early 1980s, NASA decided to deemphasize Lewis's energy research programs and focus again on aeronautics and space. NASA turned the Mod-0 machine over to the Colorado-based Solar Energy Research Institute in 1986. The institute's interest in a hands-on test facility quickly faded, however, and the turbine was shut down not long afterward.⁷³⁷

Throughout the program, NASA and ERDA built 13 wind turbines at sites ranging from Hawaii to Rhode Island and Puerto Rico. Each generation proved more successful than the previous and decreased the cost of electricity generation.⁷³⁸ The 3.2-megawatt facility in Oahu, which was transferred to a private utility company in 1988, was the culmination of the previous 15 years of research.⁷³⁹ It all started at Plum Brook at a time when everything else was dying.



Image 172: Single-bladed rotor. One of the most successful configurations used a lone blade with a counterweight on the other side. Despite concerns about the evenness and level of its power output, the single-bladed wind turbine generated over 200 kilowatts of power, twice the facility's original design capacity⁷⁴⁰ (GRC-1985-C-05882).

Rocket Systems Area Succumbs

The center conducted a formal review of Plum Brook's assets in late 1976. The report offered four options—continue the current efforts; retain SPF, B-2, the Hypersonic Tunnel Facility (HTF), the reactor, K Site, C Site, and the B-3 Stand; maintain SPF, B-2, and HTF; or excess all facilities and property except the wind turbine.⁷⁴¹ In February 1977 headquarters opted to keep presently used structures operational, continue maintaining the reactor, SPF, B-2, HTF, and K Site in standby, and release excess equipment and land.⁷⁴²

The decision affected all of the Rocket Systems Area facilities except K Site. NASA left these structures intact, but inventoried the research equipment for use at other sites. In 1977 and 1978 key components of the B-1 Stand were removed for use at other centers. Lewis began using the A, C, D, and F sites as storage space. The A Site shop building and I Site Boiler Building were relocated and converted into a guard station.⁷⁴³

In September 1977 NASA notified Congress that it wanted to excess 2,150 acres at Plum Brook. The Agency transferred 600 of those acres to the EPA as buffer for its Noise Enforcement Test Facility near D Site.⁷⁴⁴ The property owners who had had land seized in the late 1960s campaigned to have the first options on the newly available property. After several delays, the transfer of the property was finally completed in 1985.⁷⁴⁵ In addition the Agency gave modest parcels to the army, the Ohio Historical Association, and the Perkins School System. The latter included the Plum Brook Ordnance Works (PBOW) administrative buildings near the gate.⁷⁴⁶



Image 173: B-1 (left) and B-3 (right) stands as they appeared in 2007 (GRC-2007-C-01959).

In October 1978 Garrett Corporation requested to use the vacant SPF to test a new method of manufacturing gas centrifuges for the Department of Energy. Garrett was interested in SPF for its size, not for its vacuum chamber capabilities. In 1980 NASA and Garrett agreed to a five-year lease, and the facility was brought back online, albeit with major physical modifications.⁷⁴⁷ Plum Brook's other test facilities remained idle.



Image 174: Abandoned railroad tracks at Plum Brook in 2003 (GRC-2016-C-05783).



Image 175: Materials Compatibility Laboratory (J-5) in 2007 (GRC-2007-C-02026).



Image 176: I Site in 2007 (GRC-2007-C-02024).

Plum Brook's Rebirth

In 1978 NASA appointed John McCarthy to succeed recently retired Bruce Lundin as Lewis's Center Director. McCarthy introduced long-term institutional planning in an effort to stabilize Lewis's budget and capitalize on the center's strengths. His successor Andy Stofan reorganized the staff in 1982 and implemented Lewis's first official master plan, which led to several major new programs for the center and a role in NASA's human space program.

It was a period of transition for NASA. As the space shuttle began operations in 1981, the Agency reintroduced initial plans for an orbiting space station. Lewis would play a major role in creating experiments for the shuttle missions and designing the power system for what would become the International Space Station.⁷⁴⁸ Lewis had turned a corner.

Nonetheless, in 1985 the Office of Management and Budget (OMB) recommended that NASA excess Plum Brook and decommission its remaining facilities. A multiagency commission was formed to review the OMB proposal. Bob Kozar, who had worked for five years in the reactor facility, served as Lewis's representative on the commission. The committee ultimately came to the conclusion that the Plum Brook facilities were too valuable to lose, and in 1986 convinced the OMB to reverse its recommendations.⁷⁴⁹ NASA Administrator James Fletcher stated, "It is my opinion that this capability must be preserved, and the option should be retained of making PBS [Plum Brook Station] a national aerospace test site for use by NASA, DOD [Department of Defense], industry, and other government agencies."⁷⁵⁰

Although most of the Rocket Systems Area was beyond restoration, NASA decided that it would reactivate SPF, B-2, K Site, and HTF as needed. The customer, however—either external groups or specific NASA programs—was required to completely fund all activities involving the activation and operation of the facility. Kozar was responsible for managing Plum Brook and restoring the four large sites.⁷⁵¹ NASA engaged Sverdrup Corporation to operate the sites. Sverdrup hired several of the former Rocket Systems Area facility engineers to serve as consultants, but only six civil servants and 55 contractors were left manning the Plum Brook sites during this period.⁷⁵²



During the summer of 1987 Plum Brook engineers restored the B-2 Stand for acceptance testing of a space plasma experiment designed by the University of Utah.⁷⁵³ This was followed by extended vacuum testing of the Space Power Experiments Aboard Rockets (SPEAR) plasma experiments for the military. The multiyear effort to restore the B-2 Stand's engine testing capability was completed in 1996. The firing of a Boeing Delta 3 rocket with its modified RL-10 engines in 1998 was the B-2 Stand's first new propulsion testing since the early 1970s.⁷⁵⁴ The facility has tested numerous hydrogen engines and upper-stage vehicles.

The staff began reactivating SPF in 1987. Unlike the reactivation of the B-2 Stand, this required significant repairs to reverse the

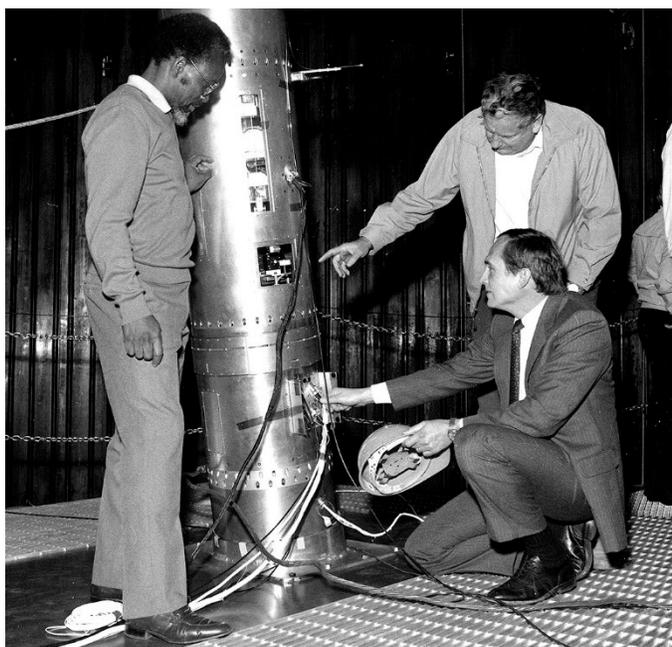


Image 177: Bob Kozar (kneeling) and Henry Pfanner (above) examine the SPEAR experiment in the B-2 Stand during November 1987 (GRC-1987-C-10612).

modifications that Garrett Corporation had made to the test chamber in the early 1980s. Operators successfully pumped down the vacuum chamber for the first time in the fall of 1988.⁷⁵⁵ The first test in the restored SPF was a jettison of an Atlas/Centaur shroud in December 1989. NASA has since tested shroud jettison systems for the Atlas, Titan, and Ariane rockets; solar arrays for the space station; and airbags for the Mars Pathfinder.

The restoration of K Site began in 1988. Researchers used the facility to study slush hydrogen to support the National Aerospace Plane (NASP) program.⁷⁵⁶ NASA constructed a large slush hydrogen generator at K Site in August 1989 to facilitate the research. In the early 1990s K Site provided the most significant slush hydrogen studies to date. Engineers brought the HTF facility back online from 1990 to 1993. The first research run was conducted in 1996. NASA has tested rocket-based combined-cycle engines and combustors in the HTF.⁷⁵⁷

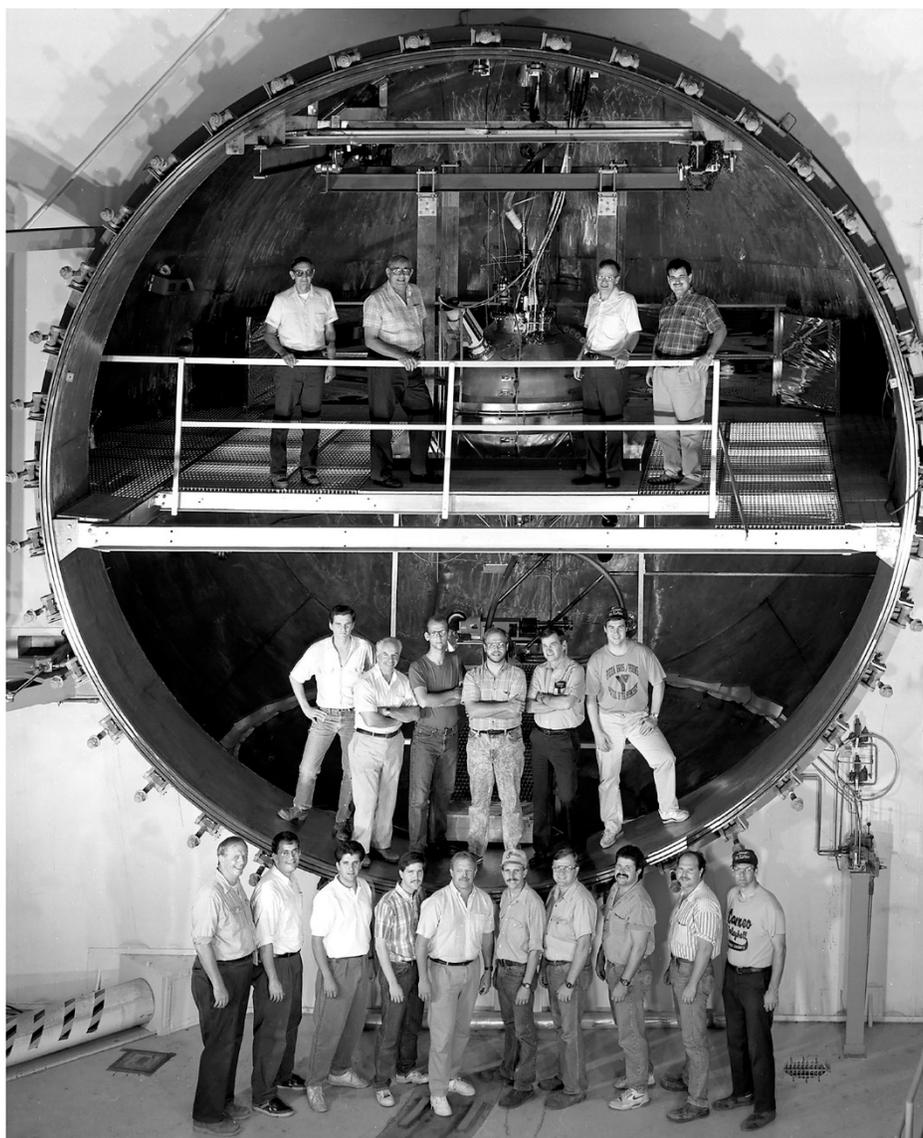


Image 178: Staff poses in the K Site vacuum chamber after the installation of a new slush hydrogen rig. A small propellant tank is installed between the four men on the upper level (GRC-1991-C-07453).

Space Exploration Revival

As Plum Brook returned to service in the late 1980s, the Soviet Union began disintegrating. General Secretary Mikhail Gorbachev eased restrictions on the nation's satellite states and forged a new arms agreement with the United States. The United States saw the end of the Cold War as an opportunity to increase its space exploration activities. Although NASA struggled during this period with the *Challenger* accident and wrangling over the design of the space station, there was increased public interest in NASA's space program. NASA began resurrecting some of its more ambitious plans from the 1960s.

On 20 July 1989 President George H. Bush visited the National Air and Space Museum to mark the 20th anniversary of *Apollo 11* and announce a new national space effort, referred to as the "Space Exploration Initiative (SEI)." The initiative called for NASA to proceed with the space station in the 1990s, establish a base on the Moon in the 2000s, and send humans to Mars within 30 years.⁷⁵⁸ It was the Agency's first proposal to send humans beyond low Earth orbit since the late 1960s.

President Bush then asked NASA to develop options to fulfill these goals. In the fall of 1989 NASA responded with a costly, inflexible long-range plan without alternatives. Congress and the public quickly pushed back against the \$500 billion proposal, and the SEI soon faded away.⁷⁵⁹

Despite its termination, SEI restored the Agency's interest in long-term human exploration missions. It would require several technologies that had been first explored by Lewis researchers and tested at the Rocket Systems Area in the 1960s—including nuclear propulsion and cryogenic fluid management systems.⁷⁶⁰ In 1991 Lewis created a Nuclear Propulsion Office to analyze different nuclear thermal rocket options and identify issues that needed research.

Lewis also partnered with the NASA Marshall Space Flight Center to establish a Cryogenic Fluids Management program for the Agency. The program studied issues related to the acquisition, transfer, and storage of cryogenic propellants for long-duration space missions. Lewis focused on basic research issues, conducted tests with tanks to verify computer modeling, and developed small fluids experiments to be conducted on the space shuttle.⁷⁶¹ Lewis also proposed a large in-space fluids experiment called the Cryogenic On-Orbit Liquid Depot Storage, Acquisition, and Transfer Satellite (COLD-SAT). Although, NASA decided not to pursue the \$300 million experiment, the center continues work in this field.

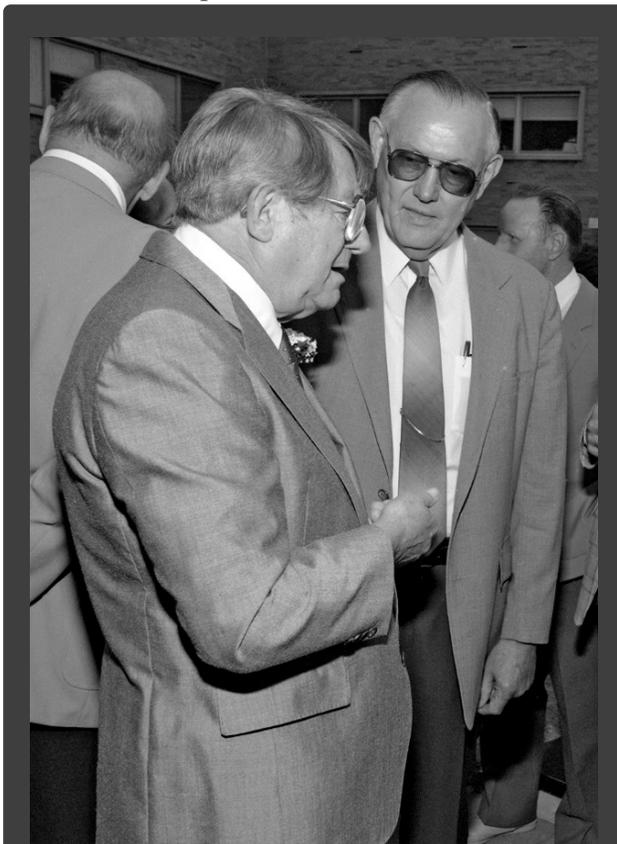


Image 179: Abe Silverstein (left) and Glen Hennings. On 13 July 1989 Lewis, in conjunction with several engineering societies, held a formal dinner to mark the 20th anniversary of the Apollo 11 lunar landing. Abe Silverstein, the keynote speaker, was joined by Neil Armstrong and Buzz Aldrin.⁷⁶² Silverstein retired from NASA in 1969 and served as an industry consultant for several years. After Plum Brook's closure in 1974, Hennings took a position in Lewis's Facilities Engineering Division until he retired in 1980 (GRC-1989-C-07750).

It was during this period that Lewis restored K Site. The Rocket Systems Area's other tank sites, the Vacuum Environment Facility (J-3) and F Site, could not be brought back online, so the center built the Supplemental Multilayer Insulation Research Facility (SMiRF) and the Cryogenic Components Laboratory (CCL) at Lewis Field to study tank insulation, pressurization, and propellant dumping in simulated space environments.⁷⁶³

In 2004, President George W. Bush resurrected the goals of the SEI with the Vision for Space Exploration (VSE). To support the effort, the center expanded its cryogenic fluids development and verification capabilities by relocating two of the CCL's seven test cells to Plum Brook Station and adding a Fuels Densification Test Site. Although the VSE, like its predecessor, proved to be fiscally unsustainable, Lewis continues its cryogenic fluids management work. In recent years, the center has sponsored the development of new spacer materials for insulation systems and has contributed to the development of cryocoolers to maintain temperature levels during multimonth space missions.⁷⁶⁴ The focus is on the use of lightweight composite materials and a zero boiloff tank.⁷⁶⁵



Image 180: Cryogenics Components Lab at Plum Brook. The complex includes test cells (some of which were moved from Lewis Field) to study liquid oxygen, nitrogen, and hydrogen; a hydrogen densification area; and an area for the high-pressure testing of tanks (GRC-2004-C-01205).

Demolition

In the 1990s the government sought to reduce expenditures in all of its agencies. NASA, which was struggling to fund its \$30-billion space station, was hit particularly hard. The Agency eliminated several major programs and underwent a concerted effort to consolidate its activities, plan smaller missions, and reduce its overhead.⁷⁶⁶ By the mid-1990s there were again calls to close Plum Brook. Although Lewis chose to maintain Plum Brook, it did initiate efforts in 1998 to decommission the inactive test reactor. Lewis^{cc} had studied the removal of the facility several times previously, but had balked at the associated costs, which only escalated over the years. By 2012 the reactor site was replaced by a green field.⁷⁶⁷

In the meantime, NASA's annual budget continued to drop, and the General Accounting Office persisted in its call for the Agency to eliminate underutilized or duplicative structures from its books. In 2004, NASA Headquarters allocated funds for the demolition of unused facilities and asked its centers to submit lists of candidate buildings. Lewis proposed the removal of nine buildings at its Lewis Field campus in Cleveland.⁷⁶⁸ Since that time the center has demolished several formerly important test facilities, including the Rocket Engine Test Facility.

In 2007 Lewis made plans to eliminate the vacant Rocket Systems Area from Plum Brook. The center considered the move necessary for health, safety, economic, and potential development reasons.⁷⁶⁹ In November 2004, E Stand became the first facility to fall. Construction crews smote the remainder of the Rocket Systems Area sites in three bursts. A Site, C Site, F Site, and I Site were demolished in the late summer and fall of 2009; the Gas Handling Area and the B-1 and B-3 stands in 2010; and the Control and Data Building (H Control Building), K Site's control building, and the Materials Compatibility Laboratory (J-5) hortonosphere in late 2012.⁷⁷⁰ In addition, in 2013 the center decided remove K Site, which had been reactivated in 1987. Although the housing structure—originally a PBOW building—was demolished, Plum Brook decided to keep the K Site test chamber for possible future use.⁷⁷¹



Image 181: E Stand is dismantled in 2004 (GRC-2004-C-01213).



Image 182: B-1 Stand is demolished in 2010 (GRC-2010-C-04960).



Image 183: B-3 Stand is destroyed in 2010 (GRC-2010-C-0497).

^{cc}Lewis was renamed the John H. Glenn Research Center in 1998. The center will continued to be referred to as “Lewis” in this document.



Image 184: Deer gather in the field next to the B-1 stand (GRC-2016-C-05790).

Rocket Systems Area Legacy

The Rocket System Area at Plum Brook was an unassuming, yet comprehensive group of test facilities designed to tackle a broad spectrum of hydrogen-related propulsion research. When Lewis engineers conceived the sites in early 1957 there was a paucity of data available on the pumping, insulation, and storage of liquid hydrogen. The Rocket Systems Area provided Lewis researchers with safe, adaptable, and remote laboratories to study the behavior of high-energy propellants on full-scale components.

Most of the Rocket Systems Area sites were not intended to be permanent, though. By the 1970s hydrogen was a proven propellant and aerospace companies such as Pratt & Whitney and Rocketdyne built their own facilities. Bob Kozar, explained, “They don’t need NASA. Where back in the very beginning, nobody’s ever built [hydrogen propulsion system] before. They needed the federal government to drive the process. Today they don’t, but they still need support.”⁷⁷²

Another factor leading to the downfall of the Rocket Systems Area was NASA’s cancellation of its advanced missions. As funds became scarce in the late 1960s and early 1970s, dreams of sending humans to Mars or Venus quickly faded. In-space cryogenic storage systems and nuclear rockets for these long-duration missions would not be required in the foreseeable future. Nonetheless, there are continued calls to send humans to Mars—most notably the SEI in 1989 and the Vision for Space Exploration in 2004. NASA continues to study tanks for cryogenic fluids for future propellant depots, landers, and heavy-lift launch vehicles.

The Rocket Systems Area provided Lewis researchers with the tools to conduct basic cryogenic fluid handling research that helped establish liquid hydrogen as a reliable fuel, allowed them to test hardware to support specific programs like Centaur and the Nuclear Rocket for Rocket Vehicle Application (NERVA), and enabled them to study technologies for future long-term missions to other planets. Although the Rocket Systems Area has not received as much recognition as Lewis’s larger test facilities, its contributions to spaceflight are tangible and continue to endure.

References

717. Roy Jackson to Bruce Lundin, "Decision To Place the Plum Brook Station of LeRC in Standby Condition," 5 February 1973, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
718. Bruce Lundin, Untitled Talk at Plum Brook Station, 1974, NASA Glenn History Collection, Bruce Lundin Collection, Cleveland, OH.
719. "Two Testify for Lewis Before House Committee," *Lewis News* (6 April 1973).
720. Lewis Research Center, "Capabilities and Facilities of the Plum Brook Station," c1970, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
721. John Hammack, "Plum Brook's Future: Private Use or Disuse?" *Sandusky Register* (25 April 1973).
722. Hammack, "Plum Brook's Future."
723. Lundin, Untitled Talk at Plum Brook Station.
724. Lundin, Untitled Talk at Plum Brook Station.
725. Dwight Reilly and Raymond Koch to Bruce Lundin, "Operation of Plum Brook After July 1, 1974," 17 April 1974, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
726. "Tenants Keep Plum Brook Staff Active," *Lewis News* (1 April 1977).
727. "Script for Ray Koch," 27 April 1979, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
728. "Plum Brook Station Review," 30 December 1976, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
729. Virginia Dawson, *Engines and Innovation: Lewis Laboratory and American Propulsion Technology* (Washington, DC: NASA SP-4306, 1991), <http://ntrs.nasa.gov>
730. David Spera, "Ten-Year Wind Turbine Program Sets Stage for Future," *Lewis News* (29 November 1985).
731. Robert Walter interview, Cleveland, OH, by Robert Arrighi, 5 November 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
732. Walter interview by Arrighi.
733. Henry Pfanner interview, Cleveland, OH, by Robert Arrighi, 6 September 2013, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
734. Spera, "Ten-Year Wind Turbine Program."
735. James Schefter, *Capturing Energy From the Wind* (Washington, DC: NASA SP-455, 1982), <http://ntrs.nasa.gov>
736. Spera, "Ten-Year Wind Turbine Program."
737. Pfanner interview by Arrighi.
738. Ronald Thomas, *DOE/NAA Lewis Large Wind Turbine Program* (Washington, DC: NASA TM-82991, 1982), <http://ntrs.nasa.gov>
739. "NASA Sells World's Largest Wind Turbine to Hawaiian Electric," *Lewis News* (5 February 1988).
740. C. B. F. Ensworth III and R. D. Corrigan, *Testing of a One-Bladed 30-Meter-Diameter Rotor on the DOE/NASA Mod-0 Wind Turbine* (Washington, DC: NASA TM-100274, 1988), <http://ntrs.nasa.gov>
741. "Plum Brook Station Review."
742. "Plum Brook Chronology," c1980s, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
743. Harrison Stamm Gowdy, Patrick O'Bannon, Leah Konicki, et al., "Phase I Architectural Survey of the NASA Plum Brook Station, Erie County, Ohio," 12 April 2002, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
744. "Script for Ray Koch."
745. "Plum Brook Station Briefing," 19 May 1982, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
746. "Plum Brook Chronology."
747. "Nuclear-Plant Equipment to Be Built at Plum Brook," *The Toledo Blade* (12 March 1980).
748. Dawson, *Engines and Innovation*.

749. Robert Kozar interview, Cleveland, OH, by Virginia Dawson, 30 March 2000, NASA Glenn History Collection, Oral History Collection, Cleveland, OH.
750. “Strategies for Closing Plum Brook Station,” 1995, NASA Glenn History Collection, Plum Brook Station Collection, Cleveland, OH.
751. Kozar interview by Dawson.
752. “Strategies for Closing Plum Brook Station.”
753. “Well Preserved Plum Brook Facilities Could be Used for Space Station and Aerospace Plane Testing,” *Lewis News* (11 December 1987).
754. Michael Meyer, Kevin Dickens, Tony Skaff, et al., *Performance of the Spacecraft Propulsion Research Facility During Altitude Firing Tests of the Delta III Upper Stage* (Washington, DC: NASA/TM—1998-208477, 1998), <http://ntrs.nasa.gov>
755. Roger Smith, *Space Power Facility Readiness for Space Station Power System Testing* (Washington, DC: NASA TM–106829, 1995), <http://ntrs.nasa.gov>
756. “Plum Brook’s K Site Facility Reactivated for Slush Hydrogen Tests,” *Lewis News* (11 May 1990).
757. Scott Thomas and Jinho Lee, *The Mothball, Sustainment, and Proposed Reactivation of the Hypersonic Tunnel Facility (HTF) at NASA Glenn Research Center Plum Brook Station* (Washington, DC: NASA/TM—2010-216936, 2010), <http://ntrs.nasa.gov>
758. Thor Hogan, “Lessons Learned From the Space Exploration Initiative,” *News & Notes* (November 2007).
759. Hogan, “Lessons Learned From the Space Exploration Initiative.”
760. Hogan, “Lessons Learned From the Space Exploration Initiative.”
761. James Faddoul and Stanley McIntyre, *NASA Cryogenic Fluid Management Technology Program Plan* (Washington, DC: NASA TM–105256, 1991), <http://ntrs.nasa.gov>
762. “Apollo Lunar Landing Commemoration Planned,” *Lewis News* (7 July 1989).
763. P. J. Dempsey and R. J. Stochl, *Supplemental Multilayer Insulation Research Facility* (Washington, DC, NASA TM–106991, 1995), <http://ntrs.nasa.gov>
764. Michael L. Meyer, David J. Chato, David W. Plachta, et al., “Mastering Cryogenic Propellants,” *Journal of Aerospace Engineering* 26 (2013).
765. Office of the Chief Technologist, “Composite Cryogenic Technologies and Demonstration Project” (2012), http://www.nasa.gov/offices/oct/stp/game_changing_development/composite-cryotank.html (accessed 5 June 2016).
766. Laurie Boeder and Dwayne Brown, “Review Team Proposes Sweeping Management, Organizational Changes at NASA,” NASA press release 95–73, 19 May 1995, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
767. Mark Bowles, *Science in Flux: NASA’s Nuclear Program at Plum Brook Station 1955–2005* (Washington, DC: NASA SP–2006–4317, 2006), <http://ntrs.nasa.gov>
768. NASA Glenn Facilities Division, “Project Requirements Document for Demolition of the Altitude Wind Tunnel Building 7 at Glenn Research Center. Project No. 9395,” September 10, 2004, NASA Glenn History Collection, Altitude Wind Tunnel Collection, Cleveland, OH.
769. Ramon Lugo and Mark Epstein, “Programmatic Agreement Between NASA and the Ohio State Historic Preservation Office Regarding Facilities, Infrastructure, and Sites at the NASA Plum Brook Station, Erie County, Ohio,” 11 July 2012, NASA Glenn History Collection, Directors Collection, Cleveland, OH.
770. Glenn Research Center, Facilities Division, Master Plan Demolition Log Book, 12 December 2013, Facilities Collection, Directors Collection, Cleveland, OH.
771. Andy Ouriel, “Big Bang at Plum Brook,” *Sandusky Register* (17 June 2013).
772. Kozar interview by Virginia Dawson.

◆ Appendix A ◆ The Facilities

NASA Lewis Research Center engineers quickly designed a series of comparatively small test facilities known as the Rocket Systems Area at Plum Brook Station in the late 1950s and early 1960s to study the handling and storage of liquid hydrogen and other cryogenic fluids. The three primary areas of study for the facilities were experimental rocket components, turbopumps, and propellant tanks. The researchers also created one facility to verify the structural dynamics of launch vehicles. The names of the sites, which often included more than one test rig, frequently changed over the years, so the staff assigned each an alphanumeric name (A Site, B-3, etc.) to clarify the situation.

The operations engineers could conduct tests at multiple sites from a single control building. Each facility included its own explosion-proof wiring, burnoff stacks, shop areas, locker rooms, and remote television monitoring system. The sites utilized Plum Brook's digital computer, service air, communications, warning, and other systems. The Gas Handling Area supplied the liquids and gases necessary to operate the sites and conduct the tests.



Image 185: Facilities at Plum Brook's Rocket Systems Area.

A Site—Liquid Hydrogen Pump Facility

1961–68

Purpose

A Site was designed to test impellers and inducers for high-flow hydrogen and oxygen pumping systems. The facility included separate test loops for hydrogen and oxygen turbopumps. Researchers utilized these test loops to determine the performance of high-power turbopumps with experimental inducers and impellers in conditions comparable to those experienced when integrated into a liquid chemical rocket engine.

Site Description

A Site was located on Fox Road near the northwest corner of the Rocket Systems Area. The A Site test loops were contained in a single 1,605-square-foot Butler Building that included a 3-ton overhead crane and large access doors on the north and south ends. Hardware included gas turbines, gearboxes, and bedplates. An addition along the east wall contained an Instrument Room, Controls Room, and Electrical Mechanical Room. NASA added a large shop building just east of the facility to prepare test articles. Twelve tubular storage Dewars and a small pump house were located just north of the facility. Propellant trailers connected to the facility along the west wall, and a gaseous-hydrogen line ran south from the building to a small burnoff stack.

Operation

The staff installed the experimental turbopump on the drive shaft of either the hydrogen or oxygen test loop with an automatic thrust-balance compensator. The pump then transferred the fluid through a 3-inch stainless steel pipe from one 6,000-gallon Dewar to another. A gaseous-hydrogen-powered three-stage axial-flow turbine spun the drive shaft at up to 60,000 rpm to operate the pump. The hydrogen and oxygen loops could pump up to 20,000 and 1,500 gallons/minute, respectively. To facilitate photographic analysis of the pump flow, designers gave the turbopump a transparent casing and put viewing ports in the test loop. The staff operated the tests and recorded the data from the Control and Data Building (H Control Building) about a quarter mile from the site.



Image 186: A Site (GRC-1962-P-01542).



Image 187: Mechanic overhauls test loop at A Site (GRC-2016-C-05096).

Tests

Lewis researchers used A Site's liquid-hydrogen loop to study centrifugal and multistage axial-flow pump designs incorporating several different types of impellers and inducers. Researchers were only able to use the oxygen test loop, which suffered from many technical problems, for one series of tests. Its basic contribution was the problem-plagued testing of four NASA-designed impellers to support the M-1 engine program.

Hydrogen Test Loop

- 1961–62 Liquid-hydrogen centrifugal pump
- 1963–64 Impeller designs for liquid-hydrogen centrifugal pump
- 1965–66 Inducer blade loadings on a liquid-hydrogen centrifugal pump
- 1967–68 Four-stage axial-flow hydrogen pump

Oxygen Test Loop

- 1964 Oxygen turbopump for the M-1 engine

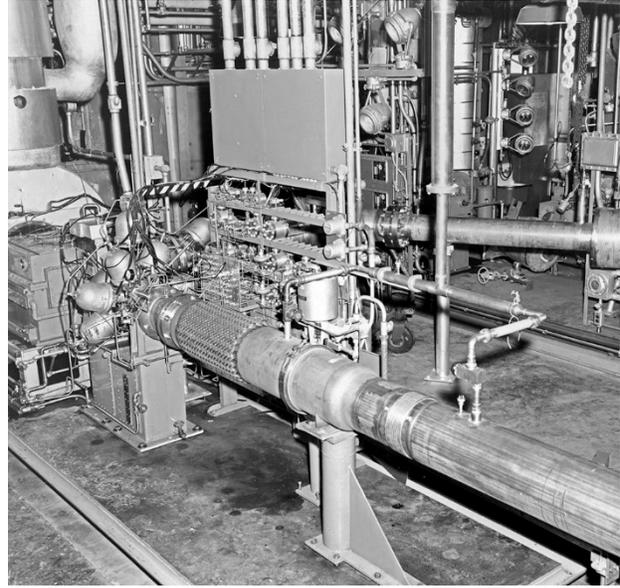


Image 188: Liquid-hydrogen test loop at A Site (GRC-1965-P-02010).

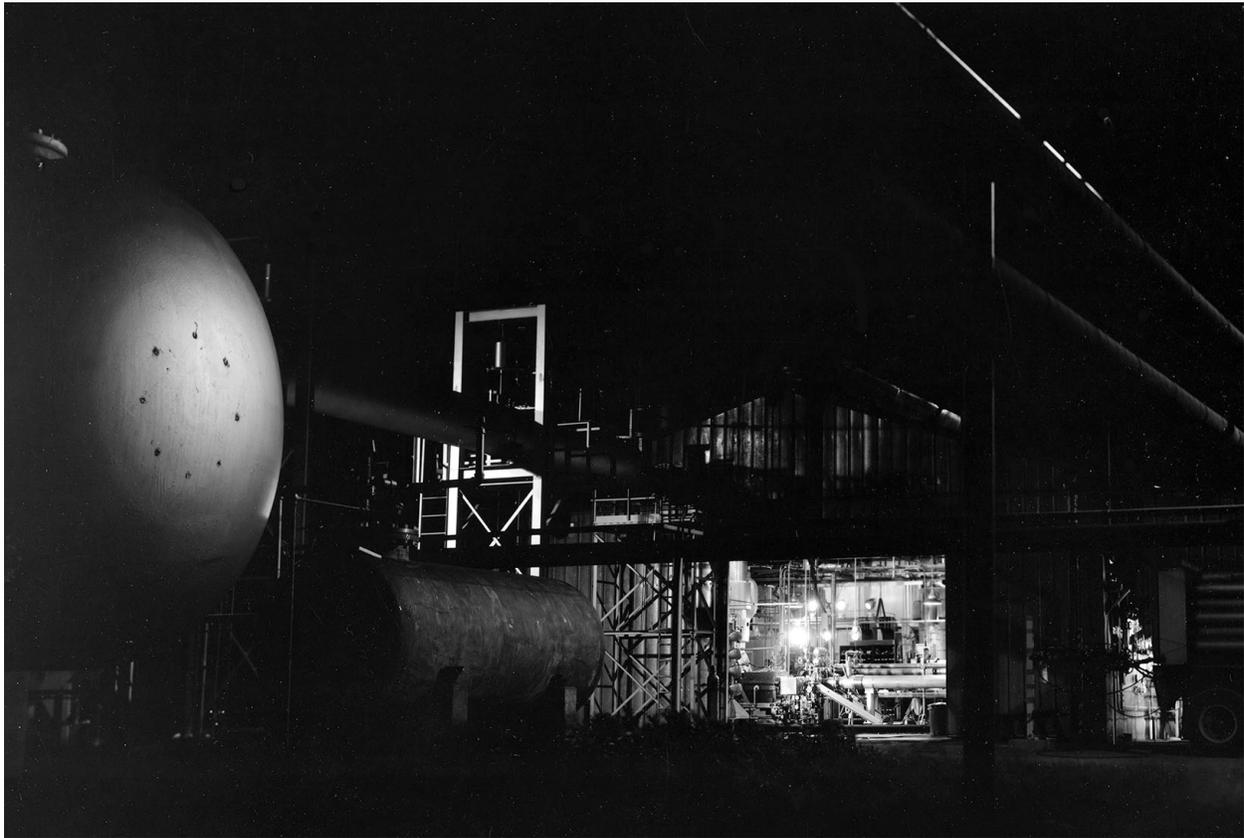


Image 189: Operation of A Site at night (GRC-1963-P-01193).

B-1 Stand—High Energy Rocket Engine Research Facility

1962–69

Purpose

The B-1 Stand was designed for hot-firing tests of hydrogen and fluorine engines with up to 30,000 pounds of thrust at altitude conditions, although it was never used in this capacity. It had a vacuum capsule for testing entire engines in a space environment, and a steel test carriage for cold-flow tests. Researchers never utilized its engine firing capability, but they did test full-scale hydrogen pumping systems for simulated missions.

Site Description

B-1 was located with the Nuclear Rocket Dynamics and Control Facility (the B-3 Stand) off of Box Factory Road near the southern end of the Rocket Systems Area. The 135-foot-tall vertical tower was enclosed above the 68-foot level. By 1964 the facility included roll-up doors on three sides to provide ventilation in the event of a hydrogen leak. The B-1 tower faced two rectangle retention ponds to the southwest. The steam accumulators and a steam ejector stack were linked to the southeast wall of the test stand. A rectangular single-story Pump House and a smaller Valve House stood between the test stand and the large retention ponds. A water tower was to the west of the ponds. The B-1 Stand included cryogenic fuel tanks, exhaust gas scrubbers, and large storage trailers for gaseous and cryogenic materials.

The test chamber was a 13-foot-diameter, 30-foot-tall space within the tower. The B-1 Stand included cryogenic fuel tanks, exhaust gas scrubbers, and large storage trailers for gaseous and cryogenic materials. A two-stage steam ejector provided vacuum pumping to create the low pressures of space. The facility was tied into Plum Brook's data acquisition system

Operation

It took two days for the Boiler House to fill the steam accumulators needed to operate the two-stage steam ejector that provided vacuum pumping to create the low pressures of space. During this period the staff installed the instrumentation, purged and chilled the propellant lines, and sequenced the run program equipment. When this was complete, the operator initiated the steam ejector system. Once the exhaust duct



Image 190: B-1 Stand (GRC-1962-P-01859).

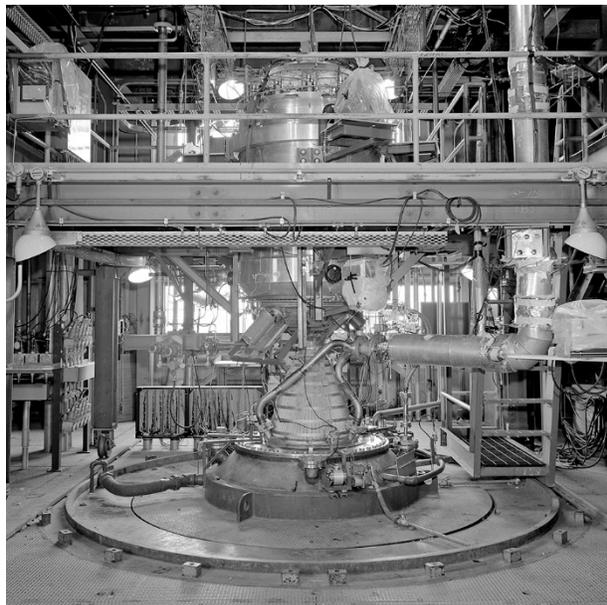


Image 191: Kiwi-B engine inside the B-1 Stand (GRC-1964-P-01347).

pressure reached 2 pounds per square inch, the operator commenced the test run, which usually lasted under 1 minute. The tests were run from the B Control Building located approximately 2,500 feet from the facilities. The facility was tied into Plum Brook’s data acquisition system in H Control.

Tests

The B-1 Stand was used for extensive study of the Mark IX turbopump for the Kiwi phase of the Nuclear Engine for Rocket Vehicle Application (NERVA) program. The B-1 tests focused on the propellant feed system, including the turbo-pumps, fluid instability in flow passages, and evaluation of equipment performance. Researchers also used the B-1 Stand for a series of liquid-hydrogen outflow and tank-pressurization tests for the Centaur Program. The tests led to a redesign of the tank insulation that was eventually the standard used on the Centaur D, and they were an important early step in the eventual elimination of the boost pumps from the Centaur feed system.



Image 192: Kiwi-B reactor is lifted into the B-1 Stand (GRC-1963-P-01358)

- 1964–66 NERVA engine propellant feed tests
- 1967–69 Advanced Centaur tests



Image 193: Aerial view of the B-1 Stand (GRC-1966-C-04025).

B-3 Stand—Nuclear Rocket Dynamics and Control Facility

1966–74

Purpose

The B-3 Stand was used to study tanking and flow systems for complete nuclear rocket engine systems in simulated altitude conditions. The rocket's combustion chamber was pressurized to simulate an actual launch, but the engines were not fired and the reactor was not operated. The B-1 Stand facilitated the study of propellant flow systems and turbopumps.

Site Description

The B-3 Stand was located with the B-1 Stand off of Box Factory Road near the southern end of the Rocket Systems Area. At 210 feet in height, the 50- by 50-foot tower was the tallest structure at Plum Brook. The upper section, 32 by 27.5 feet in area, was enclosed above the 74-foot level. The first floor contained a shop area, mechanical equipment room, tool crib, manifold-purge control room, and instrumentation rooms. The shop and mechanical equipment room were adjacent to the east side of the test stand. The forward instrument room was adjacent to the north side of the test stand.

Operation

The operations of the B-3 Stand were similar to those of the B-1 Stand. It took two days for the Boiler House to fill the steam accumulators needed to operate the two-stage steam ejector that provided vacuum pumping to create the low pressures of space. During this period the staff installed the instrumentation, purged and chilled the propellant lines, and sequenced the run program equipment. When this was complete, the operator initiated the steam ejector system. Once the exhaust duct pressure reached 2 pounds per square inch, the operator commenced the test run, which usually lasted under 1 minute. The tests were run from B Control located approximately 2,500 feet from the facilities. The facility was tied into Plum Brook's data acquisition system in H Control.



Image 194: B-3 Stand (GRC-1964-C-72621).



Image 195: Centaur Standard Shroud (CSS) in the B-3 Stand (GRC-1973-P-01373).

Tests

Researchers used the B-3 Stand for two extended test programs: the startup of the propellant flow system for the Kiwi-B nuclear engine and jettison tests of the CSS for the new Titan-Centaur vehicle. The B-3 tests established the proper startup procedure, which included liquid-hydrogen flow rates, power-cycle time delay, and the powering of the turbine. The B-3 Stand conducted a number of tests of the CSS for the new Titan-Centaur vehicle. Unlike previous B-1 or B-3 studies, these tests focused on the protective shroud, not the turbopumps. Unlatch tests verified that the CSS would jettison in a cold space environment, structural load tests determined the structural integrity of the CSS in a cold environment, and insulation tests led to a redesign of the insulation system.

1966 Kiwi-B engine propellant feed tests
1972–74 CSS jettison and tanking tests



Image 196: CSS being loaded into the B-3 Stand (GRC-1973-P-01377).



Image 197: CSS shown in the B-3 Stand along with support structures (GRC-1973-P-01379).

C Site—Turbopump Facility

1962–68

Purpose

C Site was designed to study pump inducers that operate in boiling hydrogen and to test experimental turbopumps. C Site contained two test setups—a liquid-hydrogen turbopump and the Boiling Fluids Rig. Researchers used the former to investigate the matching of inducer and impeller stages for high-speed liquid-hydrogen turbopumps. The Boiling Fluids Rig allowed the analysis of experimental pumps at the near-boiling temperatures often found in hydrogen rocket systems.

Site Description

C Site was located on Ransom Road along the western portion of the Rocket Systems Area. The 2093-square foot test area was contained in a Butler Building, with the vertical tank for the Boiling Fluids Rig at the south end and the hydrogen pump loop on a steel plate at the north. The instrument, control, mechanical, and electrical rooms were in an annex off the north end. The portals and pumps used to transfer the propellants from portable 6,000-gallon trailers into the test Dewar were along the south wall. A vacuum pump room and two tank storage areas were in an extension of the western wall. A small pump house further east of the facility supplied high-pressure hydrogen gas to drive the turbine. C Site had a large shop building just to the east of the facility to prepare test articles.



Image 198: C Site (GRC-1960-C-54928).

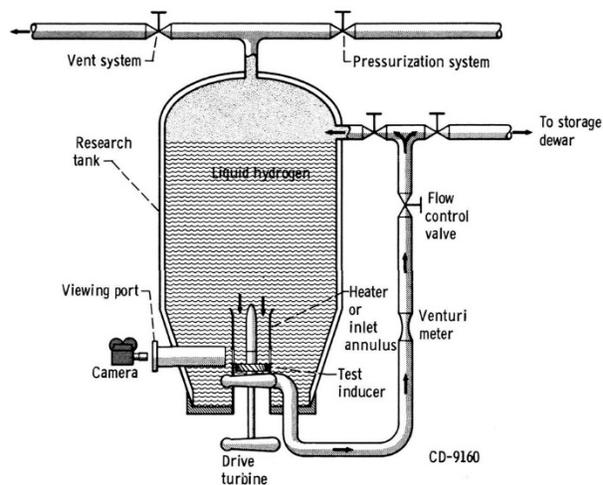


Image 199: Boiling Fluids Rig (NASA TM X-52320, Fig. 1).

Operation

The liquid-hydrogen turbopump at C Site—the *Hydrogen Turbopump Rig*—worked similarly to the turbopumps in the A Site loops. High-pressure hydrogen gas powered the turbine, which in turn spun the drive shaft connected to the experimental pump. The turbopump rapidly pumped the fluid from one 6,000-gallon tank to another. The rig accommodated run durations up to 5 minutes. Test engineers, who operated C Site remotely from H Control, could independently adjust the fluid flow, speed, and pressure.

The *Boiling Fluids Rig* was a 2,500-gallon stainless-steel hydrogen tank with a transparent turbopump submerged at the bottom. The gaseous-hydrogen-powered drive turbine was located beneath the tank, whereas the pump's inducer and impeller were in the tank. A shaft penetrating the bottom of the tank connected the pump and the turbine. The experimental pump recirculated the fluid out the bottom of the

tank and into the top. The tank included viewing ports and a strobe lighting system that permitted the filming. Engineers added a cylindrical heater at the inlet to simulate temperatures in a nuclear engine.

Tests

Researchers used C Site's Hydrogen Turbopump Rig to study inducers with angles of varying degrees as well as their performance in cavitation. Researchers used the Boiling Fluids Rig to study the rates of net positive suction head at the turbopump inlet when the liquid hydrogen was at higher temperatures and the effect of temperature, pressure, and flow rate on cavitation. Researchers also explored the use of slush hydrogen to reduce the size of the propellant tanks.

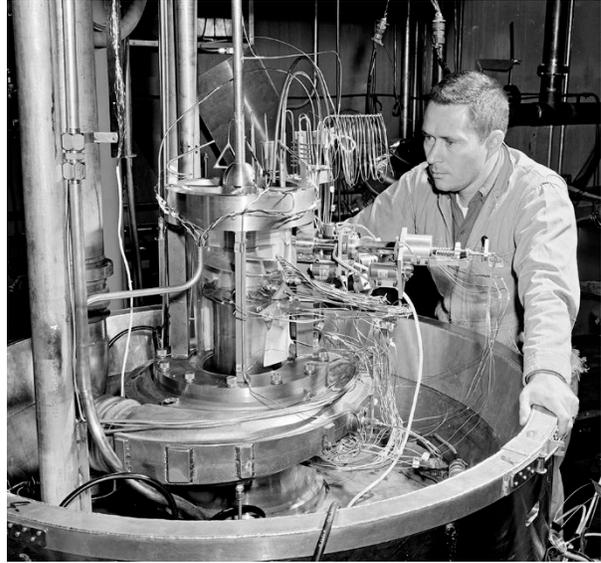


Image 200: A technician inspects the Boiling Fluids Rig (GRC-1961-C-58537).

Hydrogen Turbopump Rig

1963–66 Impeller matching with centrifugal hydrogen pump

Boiling Fluids Rig

1962 Liquid-hydrogen pump

1963–64 Inducer performance in heat from nuclear rocket

1964 Inducer performance in slush hydrogen

1966 Minimal pressure required to pump hydrogen

1968 Comparison of different inducer blade shapes and angles



Image 201: C Site at night (with hydrogen burnoff line to the left (GRC-2016-C-05798).

D Site—Controls and Turbine Test Facility

1963–65

Purpose

D Site consisted of two test rigs for testing multistage turbines that powered turbopumps on chemical and nuclear rocket engine systems. The staff unsuccessfully struggled for several years to get the facility to operate properly.

Site Description

D Site was located at the intersection of Ransom and Fox roads at the northwest corner of the Rocket Systems Area. The test equipment was contained in a 1,511 square foot rectangular Butler Building with mechanical, control, and instrument rooms added along the east end. Liquid-oxygen and liquid-hydrogen tank pits with their respective gas generator rooms were located outside the north wall. The main test area included a large office and electronic shop and two overhead cranes (5 ton and 1.5 ton). A shop building and a small pump house were located to the southeast, and a hydrogen burnoff line extended from the facility to the north.

Operation

The staff installed two 15,000-horsepower, 60,000-rpm turbines simultaneously at D Site. Each rig included its own gas generators, high-speed gearbox, and eddy-current dynamometers. The gas generators converted the liquid propellants into gas to operate the turbines. The dynamometers, also mounted to the bedplate, acted like brakes on the turbine and measured the turbine's output. The staff operated D Site from H Control.



Image 202: Aerial view of D Site (GRC-1960-C-54888).

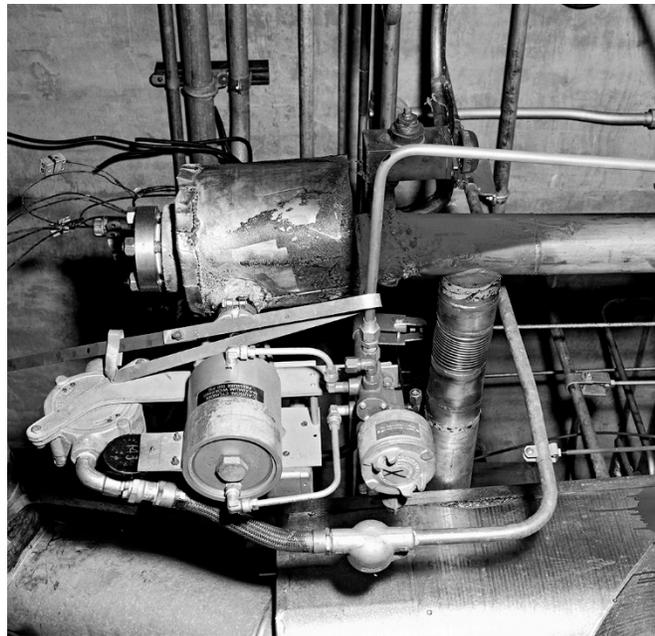


Image 203: A 60,000-rpm turbine at D Site (GRC-1962-C-59323).

Testing

Researchers installed an eight-stage turbine in one of D Site's test rigs and a three-stage turbine in the other. The turbines were intended for a 100,000-lb-thrust hydrogen-oxygen engine and a nuclear rocket engine. Delays and equipment problems prevented successful testing for several years. Lewis management decided to permanently shut down the two rigs in 1964 and 1965.

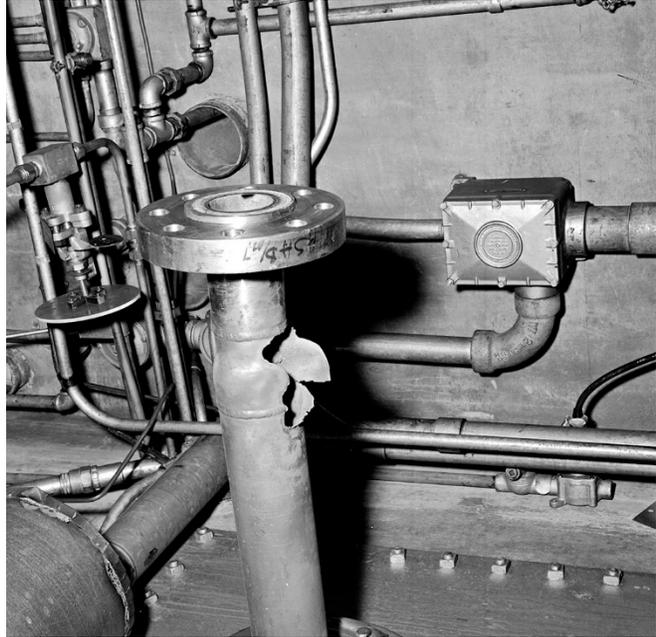


Image 204: Damaged equipment in D Site ((GRC-1962-C-59320).



Image 205: Exterior of D Site (GRC-1960-C-54888).

E Stand—Dynamics Stand

1962–68

Purpose

E Stand was designed to verify the structural integrity of missiles in launch conditions and to study full-scale vehicle pressurization and propellant flow systems. The tower simulated the vibrations and forces that occur during launches without having to fire the engines. Lewis Research Center used it primarily to test the Atlas-Centaur vehicle.

Site Description

The seven-story E Stand was located on Fox Road in the northwest region of the Rocket Systems Area. It had a 14-ft-diameter test section that ran the length of the seven-level tower. NASA extended the height of the stand from its original 117 feet to 144 feet to accommodate the new Atlas/Centaur vehicle with its payload. There were several work platforms at different levels in the stand. E Stand included an electrodynamic shaker and an I-beam support frame at its base and four spring boxes and load cells that were connected to cables that supported the rocket vertically. A spring at the bottom of the tower supported the rocket from below, and cables supported it from the sides to replicate free flight. The stand included several fluid systems to study the effect of vibrations on pumping systems. Adjacent to the base of the stand were instrument, control, and mechanical rooms. The tower included a large overhead crane, a 125-foot-tall door, and an elevator. The site also contained a small shop and a large deionized water tank.

Operation

The vehicle was secured to the frame with horizontal and vertical stabilization springs connected to cables that were suspended from the top of the tower. Four spring boxes and load cells were connected to cables that supported the rocket vertically. A large vibrational exciter shook the rocket from below with 15,000 pounds of force, and a 200-pound exciter provided horizontal force. The exciters were actuated by a power amplifier in a concrete block house beside the tower. The facility was operated from the Central Control Building located 1000 feet away.



Image 206: Aerial view of E Stand (GRC-1960-C-54932).



Image 207: Installation of the Atlas stage into E Stand (GRC-1963-P-01701).

Tests

Researchers used E Stand extensively to subject the Atlas/Centaur launch vehicle and its *Surveyor* payload to dynamic lateral and longitudinal forces. Notable achievements include verification that the Atlas could support the Centaur stage and testing the vehicle's resilience after purposely bending the vehicle. Researchers also used E Stand for the vibration testing of smaller items, including the Mercury Evaporation and Condensing Analysis (MECA) payload, instrumentation for the Sky Bolt rocket, and a *Ranger* payload accelerometer.

- 1962 Vibrational analysis on the *Space Electric Rocket Test (SERT) I*, *Ranger* accelerometer, and Sky Bolt instrumentation
- 1962–63 Vibrational analysis on MECA program
- 1963 Atlas load tests
- 1964 Atlas/Centaur longitudinal and latitudinal dynamics
- 1965 Centaur fairing loads
- 1966 Atlas/Centaur postwrinkling strength
- 1967 Atlas/Centaur bulkhead and duct dynamics
- 1968 Atlas/Centaur duct dynamics

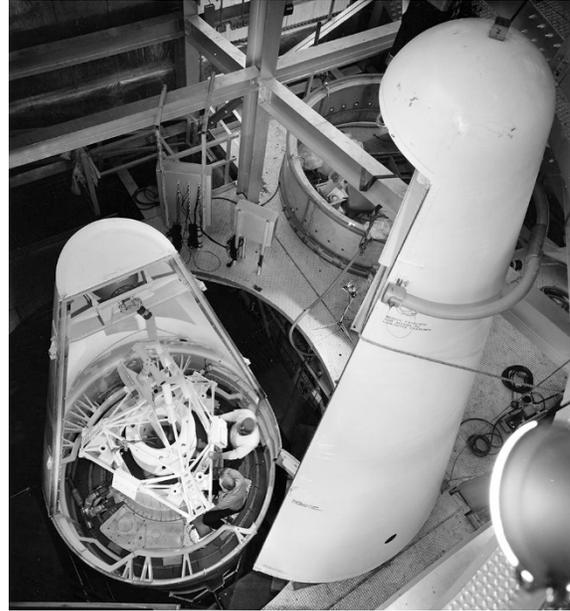


Image 208: *Surveyor* model added to the Atlas/Centaur in E Stand (GRC-1964-P-01237).



Image 209: Installation of the Atlas stage into E Stand (GRC-1963-P-01703).

F Site—Hydraulics Laboratory

1963–74

Purpose

F Site, known primarily as the Hydraulics Laboratory but also referred to as the Hydrogen Flow Facility, was designed to study the flow conditions of cryogenic fluids as they passed through an experimental turbopump. Researchers also used the facility to study a liquid-hydrogen heat exchanger for nuclear rockets.

Site Description

F Site, located on Fox Road, was the western-most Rocket Systems Area facility. The primary structure was a rectangular Butler Building that had a hydrogen test area in the west section, another test area to the east, and a third test area on the mezzanine level. The Instrument Room, the Control Room, and the Electric Mechanical Room were located between the two test sections. A rectangular shop area abutted against the north side of the structure. F Site contained a liquid-hydrogen storage vessel and a catch basin with the experimental flow hardware set up in between. A small pump house was located to the north of the structure, and a hydrogen burnoff line was located to the south.

Operation

The experimental component, usually a turbopump, was installed in the test loop between the two hydrogen tanks. The operator pressurized the propellant run tank and stabilized the system. The valves were then released as the pump transferred the fluid from one tank to the other. The staff could modify the fluid temperature during the test by introducing ambient gas into the liquid. The operators conducted the tests from H Control.



Image 210: Aerial view of F Site (GRC-1959-C-51682).



Image 211: Mechanic adjusts test setup at F Site (GRC-1961-C-57557).

Tests

Researchers used F Site to analyze a triangular hydrogen heat exchanger for a nuclear rocket, to cold shock a Centaur 5-C tank, and to study the choked flow of liquid oxygen.

- 1963–66 Hydrogen-water heat exchanger for a nuclear rocket
- 1963–64 External insulation system for a Centaur tank
- 1968 Centaur tank cold shock
- 1974 Liquid-oxygen choked flow

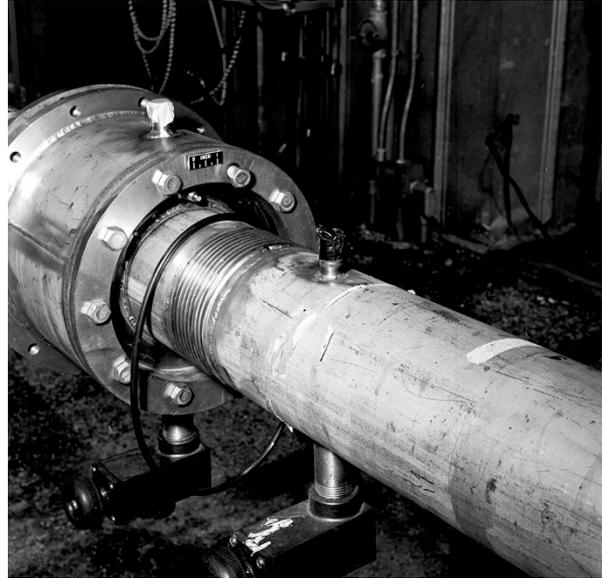


Image 212: Test setup at F Site (GRC—1961-C-57574).

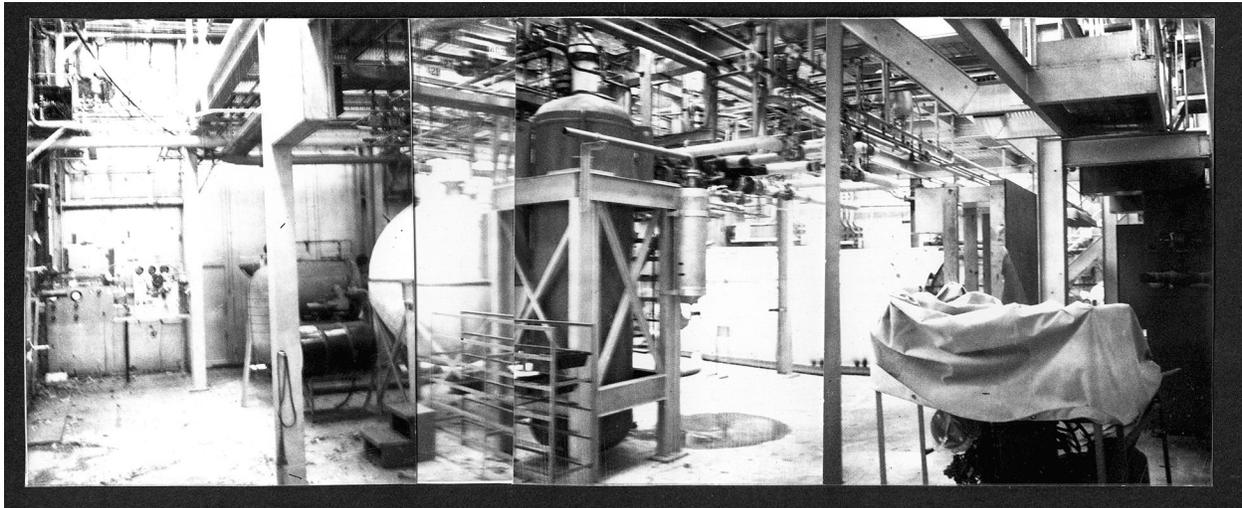


Image 213: Work areas inside of F Site (GRC—2016-C-05112).

G Site—Pilot Plant/Pump and Turbine Facility

1958–64

Purpose

The Pilot Plant, also known as the Pump and Turbine Facility, was designed to test models of Lewis-designed rocket pumps and turbines with cryogenic propellants before the designs were provided to manufacturers for production.

Site Description

The Pilot Plant was located on Fox Road in the north central portion of the Rocket Systems Area. The site had two test facilities—the Liquid Hydrogen Pump and the Turbine Test Facility—located 350 feet north from its control and instrument rooms. These rooms were repurposed 9-foot-diameter steel tanks from the Plum Brook Ordnance Works (PBO) that were covered with an earthen mound. The Turbine Test Facility contained a test section for the experimental turbines, a pressure-controlled inlet duct system, and an exhaust duct that vented directly to the atmosphere. The test equipment included the turbine, the housing, and the dynamotor. There was a shop building to the east of the two test facilities and a pump house to the south.

Operation

The staff installed the model pump or turbine in the corresponding test building, connected a roadable hydrogen Dewar to the equipment, and stabilized the pressure and temperature levels. The pump circulated the gaseous hydrogen or nitrogen propellant from the Dewar and back into a catch basin. The operator, located in the onsite underground control room, could control the inlet flow and exhaust with valves in the test apparatus. Strain gauges measured the torque, and a tachometer measured the turbine speed.



Image 214: Aerial view of the Pilot Plant (GRC-1960-C-54924).

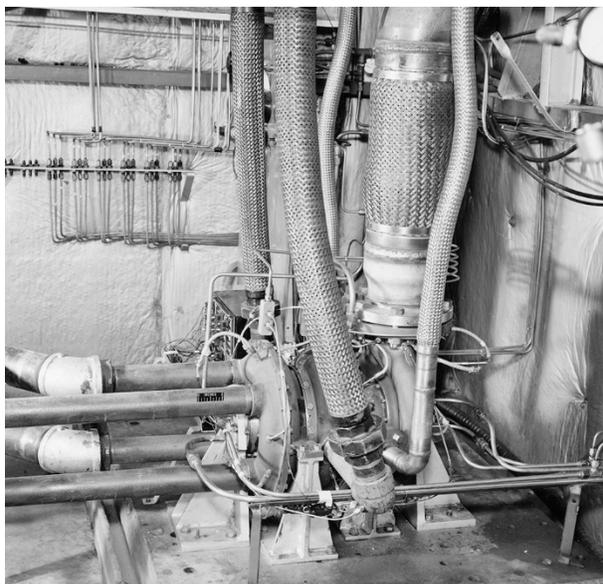


Image 215: Air brake at the Pilot Plant (GRC-2016-C-05134).

Tests

Researchers used the Pilot Plant’s Turbine Test Facility to test the performance of experimental axial-flow turbines for nuclear rocket engines and to test liquid-hydrogen-cooled bearings. The Liquid Hydrogen Pump was used to test small-scale axial-flow turbopumps.

Liquid Hydrogen Pump

- 1961 15,000-rpm hydrogen axial-flow pumps
- 1964 Small-scale axial-flow hydrogen pump

Turbine Test Facility

- 1961 Three-stage NERVA turbine and six-stage Hy-Nut Turbine
- 1963–64 Three-stage axial-flow hydrogen pump for hydrogen-cooled bearings



Image 216: Damaged equipment at the Pilot Plant (GRC-1964-P-01571).



Image 217: Pilot Plant structures (GRC-2016-C-05796).

HHTF—Hydrogen Heat Transfer Facility

Purpose

HHTF was designed to study nozzles and other nuclear rocket engine components with hot hydrogen gas at similar temperatures as those found in a nuclear reactor. NASA reconfigured the HHTF into the Hypersonic Tunnel Facility (HTF) before any test programs were conducted with the original design.

Site Description

The HHTF was located on Emergency B Road in the south central portion of the Rocket Systems Area. The facility was enclosed in rectangular building that included several small shop areas. The heart of the HHTF was its 40-foot-deep, 10-foot-diameter pebble bed heater located 50 feet below the test section. The heater could supply large quantities of 4200°R hydrogen gas to the test section at a rate of 12,000 feet per second. The heater was a cylindrical silicon carbide brick structure with baseball-size carbon pebbles at the bottom. Lewis engineers redesigned the heater replacing the balls with stacks of graphite rings. Hydrogen gas was supplied by a railcar Dewar, and the liquid hydrogen by a 6000-cubic-foot tank. The facility's exhaust stack was 88 feet tall.

Operation

The carbon pebbles (and later, graphite rings) were electrically heated over a period of several days. The gas flowed upward through the test section and was expelled through the stack on top of the facility. Several days were required to bring the pebble bed up to the high temperatures required for the tests. The facility drew an enormous amount of electricity that required coordination with the local power company. The site was operated from B Control, and data were recorded at H Control.

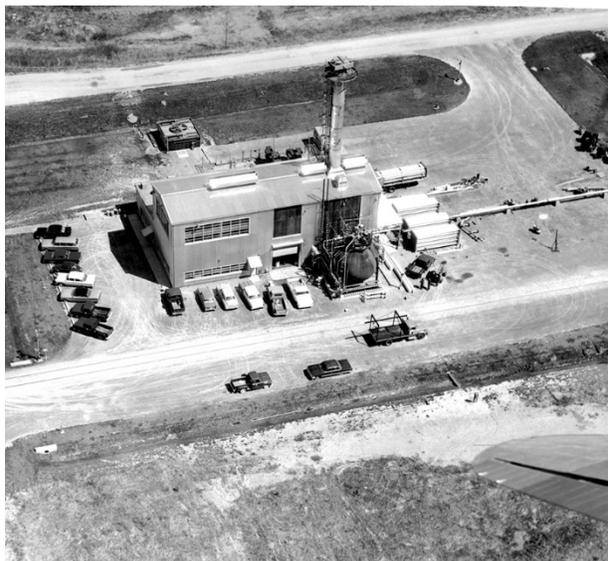


Image 218: Aerial view of HHTF (GRC-1965-C-01675).



Image 219: Pellets inside HHTF's pebble bed heater (GRC-1966-P-01889).

Tests

Lewis engineers and local construction teams struggled for six years to bring the facility online. In 1966, management decided to convert the facility into the HTF.



Image 220: Pebble bed heater inside HHTF (GRC-1966-P-01879).



Image 221: Exterior of the HHTF (GRC-1967-P-01291).

I Site—Fluorine Pump Facility

1962–67

Purpose

I Site was designed to test liquid-fluorine turbopumps that operate at 20,000 rpm and produce flow rates up to 50 pounds per second.

Site Description

I Site was located on Taylor Road near the center of the Rocket Systems Area. The main structure was a rectangular Butler Building with an open interior in which the test loop was set up. The actual pump test section was in an 855-square foot annex along the southeastern wall that opened to the exterior. The I Site setup was a closed-loop system in which liquid fluorine was circulated by the research turbopump. This pump was enclosed inside a 9500-pound stainless steel containment vault and wrapped in what was called a “burn wire,” which automatically closed emergency valves in the case of a fire. Trailer tankers supplied the facility through ports in the northeastern wall. Small instrument, control, and mechanical equipment rooms lined the northwest wall of the building. A large shop building was located to the east of the primary I Site structure.

Operation

The staff passivated the system before the test with a gaseous-fluorine system. The liquid fluorine was stored in a 600-gallon run tank that was pressurized with helium. A heat exchanger maintained the fluid temperature to extend run times. The operator, located 1,200 feet away in H Control, opened the valves to allow the fluorine to flow into the loop. Then the experimental pump circulated the fluorine through the loop and back into the Dewar. The pump, powered by an air-breathing turbine, initially operated at lower speeds then increased until it reached normal operating speeds.



Image 222: Aerial view of I Site (GRC-1959-C-51684).



Image 223: Fluorine equipment at I Site (GRC-1962-C-59408).

Tests

Researchers established a test program at I Site to obtain the performance characteristics of NASA-designed fluorine pumps during cavitation, study the effect of cavitation on the fluoride surface coating, and analyze rotating shaft seal designs. Pratt & Whitney researchers also used I Site to determine if fluorine could be used in their RL-10 engines and to explore the use of a methane-fluorine/oxygen (FLOX) propellant in the engine.

- 1962–64 Lewis liquid-fluorine centrifugal turbopumps
- 1963–65 Pratt & Whitney RL-10 fluorine turbopumps
- 1964 Fluorine turbopump seals
- 1966 Pratt & Whitney methane/FLOX turbopump

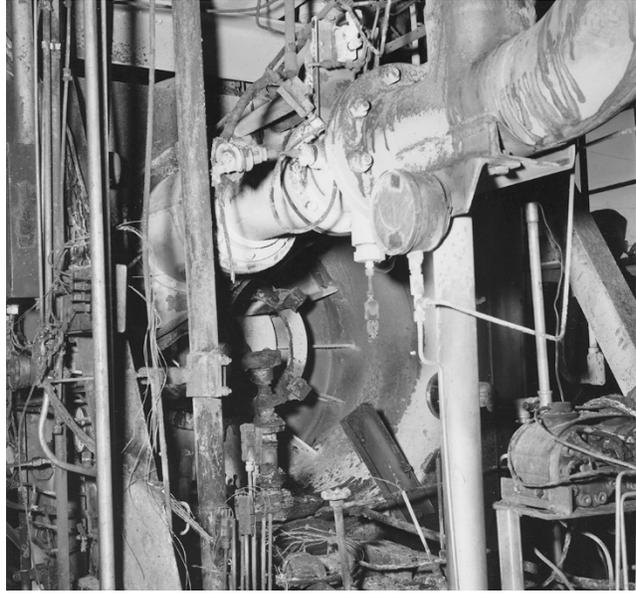


Image 224: Damaged I Site test equipment (GRC-2016-C-05797).



Image 225: Exterior of I Site (GRC-2016-C-05170).

J Site—Rocket Systems Test Site

J Site, which was located on Taylor Road near the center of the Rocket Systems Area, consisted of five different test facilities used to investigate issues regarding rocket combustion, propellant storage, heat transfer, and fluorine handling. The main structure was a C-shaped building that housed two test rigs with an external liquid-hydrogen tank between them. The vertical test stands were located just off the north and east sides of the building. A large round tank was nearby further east. The main control room for the site was located in portable trailers behind earthen mounds to the southwest.

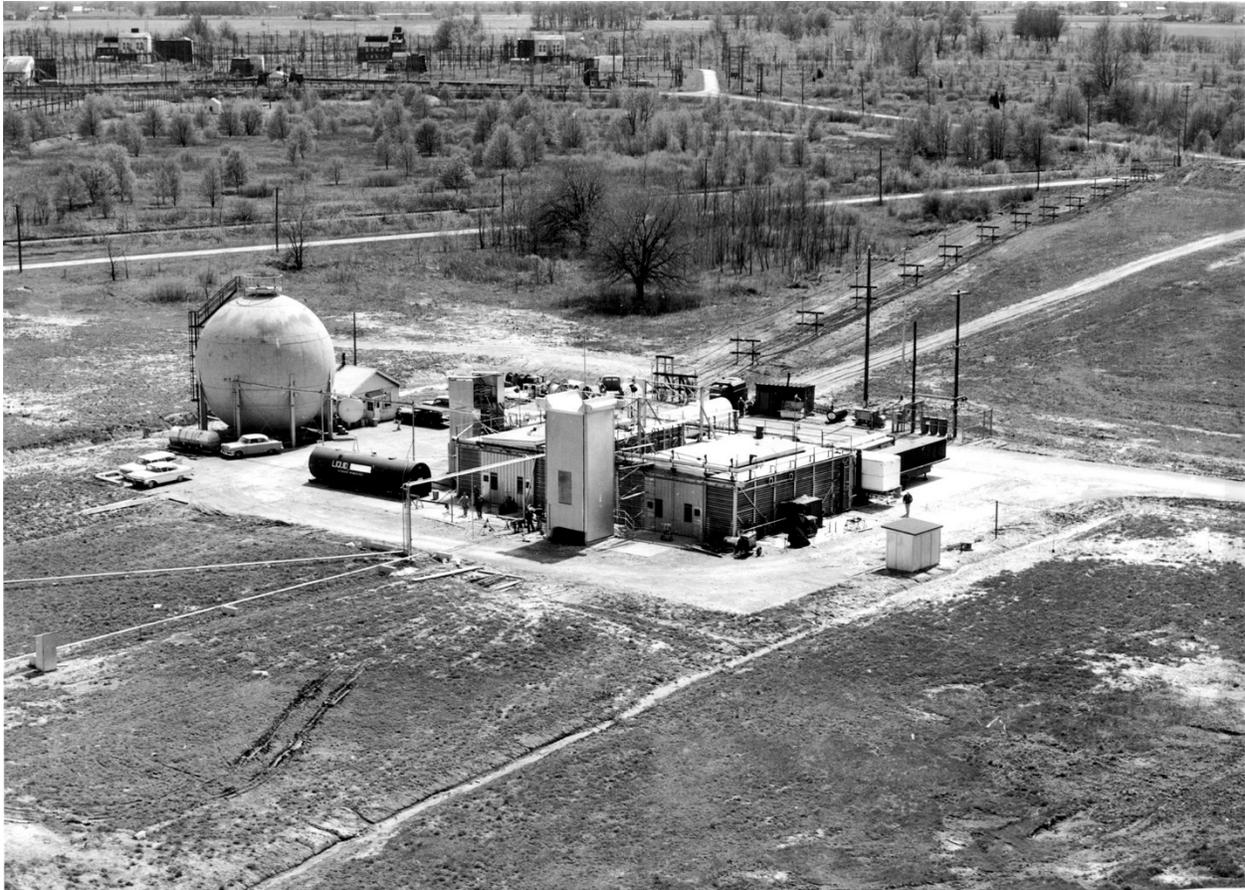


Image 226: Aerial view of the J Site Complex (GRC-2016-C-05795).

J-1

1961–68

Purpose

The J-1 rocket stand was built to study heat transfer between a nuclear engine's hot exhaust gases and its nozzle.

Site Description

J-1 was a horizontal rocket test stand located in the northwest half of J Site's main structure. The structure's walls consisted of earth encased in metal siding. Mobile propellant tanks fed the facility from the south wall, and there was a permanent liquid-hydrogen tank just outside the east wall. The J-1 rig was elevated approximately 5 ft above the ground and fired horizontally through a large door in the north wall.

Operation

The staff installed the experimental engine and opened the building's sliding doors. The operators, located in the J Control trailers, adjusted the propellant and coolant pressure to the desired levels. They then initiated the test, which automatically opened the supply valves and fired the engine. The runs typically lasted only a few seconds. The coolant flow was sent to a burnoff system instead of to the injector so that it did not influence the nozzle's heat transfer data.

Tests

Researchers used J-1 for a multiyear study of the heat transfer to and from liquid hydrogen in regeneratively cooled nuclear rocket nozzles and basic hydrogen-oxygen engine tests.

- 1961–62 Gaseous-hydrogen/liquid-oxygen rocket engine
- 1963 Hydrogen burnoff tests for the HHTF design
- 1962–63 Copper hydrogen-oxygen engine for nuclear rocket heat transfer
- 1964–68 Injectors for steel hydrogen-oxygen engines
- 1964–68 Regeneratively cooled liquid-hydrogen engines



Image 227: Rocket firing at J-1 (GRC-2016-C-05793).

J-2

1961–66

Purpose

J-2 was a rocket test stand designed to study throttling and heat transfer in rocket engines that used high-energy propellants such as liquid hydrogen and liquid fluorine.

Site Description

The J-2 vertical stand was located outside of the northeastern wall of the main J Site structure. The approximately 25-ft-high stand allowed the oxidizer tank to be mounted above the fuel tank for a more realistic simulation. The tower had roll-up doors on either side to provide ventilation during the tests. The engine fired downward into a U-shaped duct, which directed the exhaust horizontally out into the atmosphere.

Operation

The operation of J-2 was similar to that of J-1. The test engineers in the control trailers adjusted the propellant pressure rates then initiated the test. The propellant flow and chamber pressure were closed-loop systems with automatic controls. The engine fired briefly and expelled its exhaust into the atmosphere.

Tests

Researchers ran a gaseous-hydrogen/liquid-fluorine engine at J-2 and studied throttling and combustion instability in a liquid-oxygen/liquid-hydrogen pressure-fed engine. Researchers also used J-2 to study the heat transfer to and from the hydrogen in regeneratively cooled nuclear rocket nozzles.

1961	Gaseous-hydrogen/liquid-fluorine engine
1962	Liquid-oxygen/liquid-hydrogen pressure-fed engine
1963	Throttling of a liquid-oxygen/liquid-hydrogen engine
1965	K Site 13-foot tank system



Image 228: J-2 rocket stand (GRC-1960-C-54834).

J-3—Vacuum Environment Facility

1961–68

Purpose

J-3 was designed to test liquid-hydrogen propellant tank durability and insulation systems in simulated space conditions. This test stand was initially the center's only facility capable of rapid pumpdown testing.

Site Description

J-3 was located in the southeastern half of J Site's main building. This stand contained a modest-sized cylindrical zero-leak high-vacuum chamber in which small propellant tanks were installed. The fill line and vent line entered from the top. J-3 and J-4 shared the same hydrogen flow system.

Operation

The staff hung the experimentally insulated tank from its neck inside the J-3 vacuum chamber. After purging the tank, they filled it with liquid hydrogen and allowed it to stabilize. A mechanical pump reduced the chamber's pressure level to simulate high altitudes. Infrared lamps simulated solar heating on one side of the tank. The operator then allowed the propellant to boil off to measure the performance of the insulation system.

Tests

Researchers used J-3 to test the thermal retention capability of various tank insulation systems, including the Linde superinsulation, Lewis Research Center's constrictive wrap and self-evacuating insulation, and foil systems from the Arthur D Little Company (ADL).

- 1963–64 Linde superinsulation
- 1963–64 Centaur constrictively wrapped tank
- 1964 ADL gold Mylar (DuPont Teijin Films) insulation
- 1966–67 Linde Self-Evacuating Multilayer Insulation (SEMI)
- 1966–68 ADL insulation
- 1968 Copper heat transfer tank



Image 229: J-3 test chamber opened (GRC-1963-P-01655).

J-4—Tank Test Facility

1962–64

Purpose

J-4 was a vertical test stand designed to study loading issues and the performance of various insulation systems in ground-hold situations.

Description

J-4 was a vertical semi-enclosed test stand located off the eastern corner of the main J Site structure. The approximately 25-foot-tall stand contained experimental oxidizer and fuel tanks mounted above one another. The tank structure consisted of an inner shell, insulation, and outer shell. J-4 and J-3 shared the same hydrogen flow system.

Operation

The staff loaded the experimental tank into the stand and purged it with nitrogen gas and helium. Next they flowed the liquid hydrogen and opened the tank's vent valve. Then they allowed the liquid to boil off to measure the insulation system's effectiveness. The operators conducted the tests from the J Site control trailer.

Tests

Researchers used J-4 used to test Goodyear, Linde, and ADL insulation systems, and they proposed jettisonable and constrictively wrapped insulation for the Centaur rocket.

1962	Goodyear insulation system
1963	Linde superinsulated tank
1963	Centaur constrictively wrapped tank
1964	ADL gold Mylar insulation
1964	Centaur jettisonable insulation system



Image 230: J-4 at night (GRC-1963-C-01117).

J-5—Materials Compatibility Laboratory

1961–65

Purpose

J-5, known primarily as the Materials Compatibility Laboratory and also known as the Fluorine Hydraulics Laboratory, was designed to test the durability of materials subjected to high-pressure fluorine or fluorine-oxygen flow. NASA added a stand outside of the facility to study fluorine's interaction with other materials in spill conditions.

Site Description

The J-5 dynamic materials compatibility test rig was enclosed in a 38-foot-diameter steel horton-sphere that had a poured-concrete floor to provide a level working surface. The rig's test section was located between a supply and receiver tank. External to the facility were a separate control room, shop, safety showers, and gas storage. The control room, which was located just east of the facility, was inside a cylindrical tank buried in an earthen mound for protection. NASA added an elevated stand northeast of the facility for spill testing. This stand included an elevated 3.5-gallon stainless steel tank with a 4-inch-diameter spill pipe that traveled downward through an aluminum blast shield and into a spill pan.

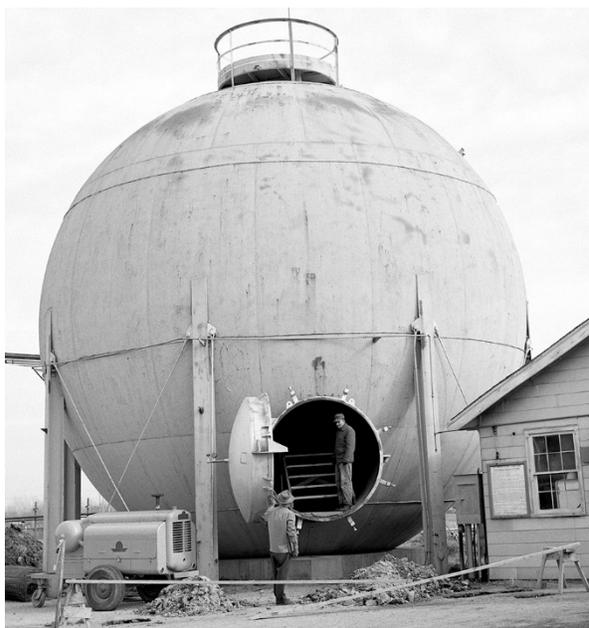


Image 231: J-5 containment vessel (GRC-1960-C-54830).

Operation

Two flanges secured the materials sample in the test section, which was immersed in liquid nitrogen. The staff wrapped burn wire around the test section to automatically shut down the run if fire was present. The operators, located nearby in the J-5 control room, controlled the flow rate as the liquid fluorine passed from the supply tank, through the test section, and into the receiver tank. The spill tower tests released the liquid fluorine from an elevated tank and allowed it to splash into a pan filled with various materials to document the reaction.

Tests

Researchers used J-5 for two series of tests. One studied the ability of different materials to withstand high-pressure fluorine flow to determine if they were suited for use in seals for fluorine engines. The other analyzed fluorine's reaction with materials typically found near storage tanks to determine what would happen with a major fluorine spill.

1963–64 Fluorine/FLOX materials compatibility

1964 Fluorine/FLOX spills

K Site—Cryogenic Propellant Tank Facility

1965–73

Purpose

K Site was designed to test cryogenic propellant tanks up to 18-ft-diameter in a simulated space environment. These studies included proof testing ground storage devices, investigating tank pressurization issues, and developing long-term insulation systems.

Description

K Site was located on Ransom Road just northwest of the main Rocket Systems Area. The facility had a 9500-cubic-foot, 25-foot-diameter spherical chamber with a 20-foot-diameter access door. The facility's main structure was a two-story concrete building that formerly served as a boiler plant for the PBOW. The test chamber occupied the western half of the building. The eastern half was a large clean area and overhead crane for test preparation. A small addition was added to the north wall for instrumentation equipment. NASA built an external 626-square foot semicircular control room southwest of the main building and a shop and burnoff line to the west.

Operation

The staff installed the experimental tank into the test chamber, filled the tank with hydrogen, allowed it to settle, and adjusted the pressure and temperature to the researcher's specifications. They then opened the tank vents, activated the data-recording equipment, and initiated the test. K Site included a large hydraulic actuator that could simulate launch vibrations and a cryo-shroud that simulated the cold temperatures of space. Data-recording equipment tracked the hydrogen boiloff rate to determine the effectiveness of the insulation.



Image 232: Aerial view of K Site (GRC-1966-C-04048).

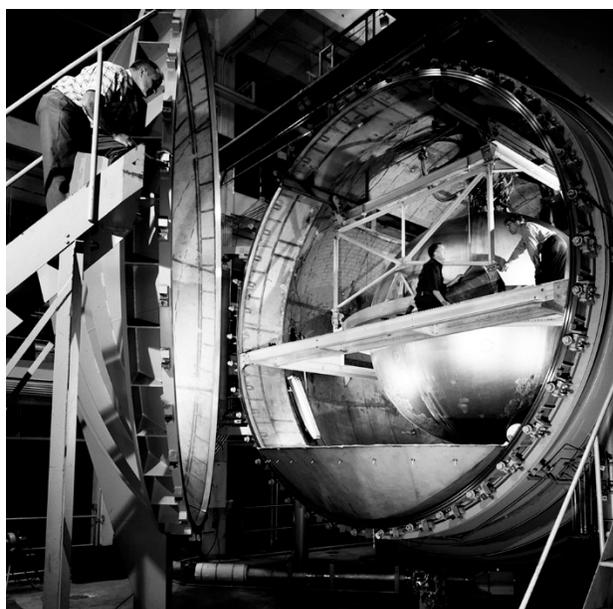


Image 233: Researchers install an experimental tank in K Site (GRC-1967-C-03314).

Tests

Researchers used K Site to determine the boiloff rates of different size tanks; to study insulation methods such as use of multilayer blankets, self-evacuating layers, spray-on materials, and shadowshields; and to test propellant transfer between two tanks.

- 1966–67 5-foot tank expulsion
- 1967 Boeing 9-foot tank acceptance test
- 1967 13-foot tank expulsion
- 1968 Lockheed 7-foot tank multilayer insulation
- 1968–69 5-foot tank methane expulsion
- 1969 Calorimeter with spiral-wrapped multilayer insulation
- 1969 ADL 8-foot cryoshroud leak test
- 1969–70 Calorimeter with self-evacuating multilayer insulation
- 1970–71 Calorimeter with self-evacuating multilayer insulation
- 1970–71 ADL shadowshield in 8-foot cryoshroud
- 1971–72 Vertical calorimeter with 160-layer insulation
- 1973–74 Cryogenic Storage Test Vehicle (CSTV)

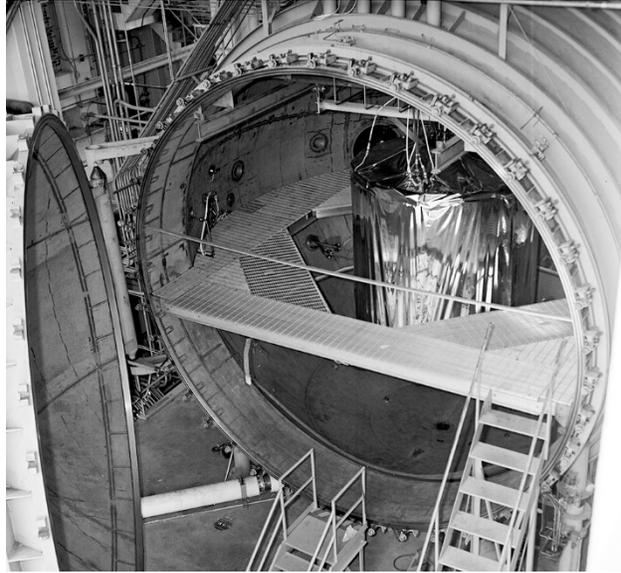


Image 234: Cryoshroud in the K Site test chamber (GRC–1971–P–01400).

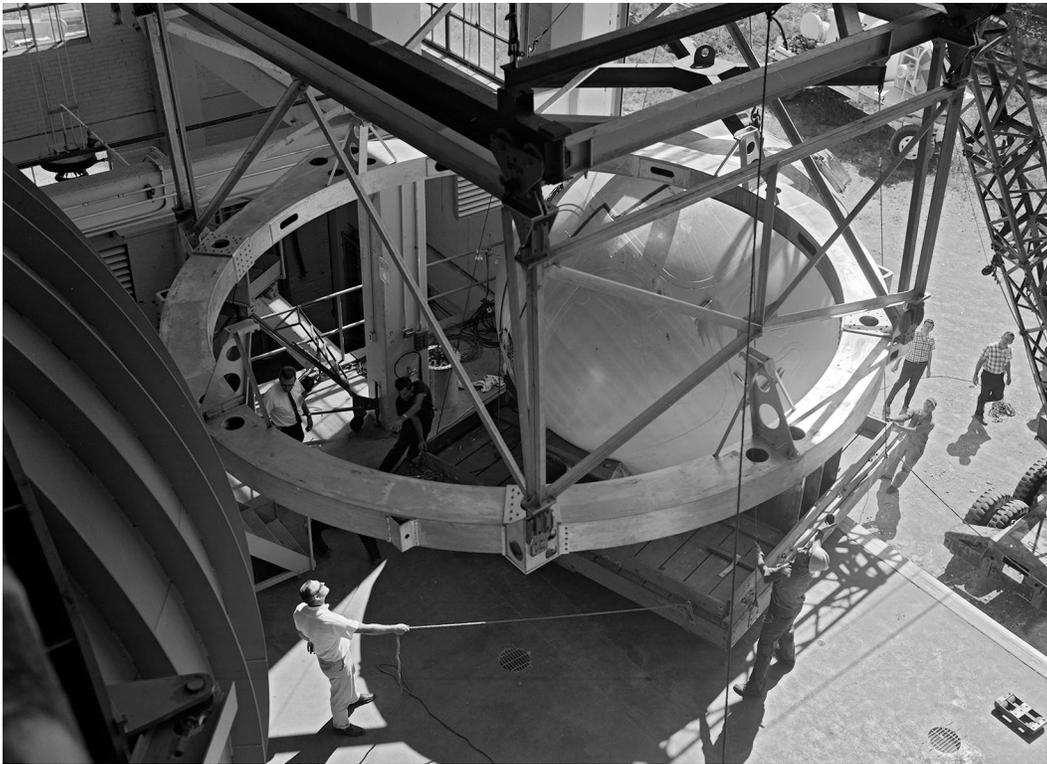


Image 235: Experimental tank brought into K Site (GRC–1966–P–01859).

Support Buildings

Testing at the Rocket Systems Area would not have been possible without the services of an extensive team of individuals and support facilities. Researchers at Lewis Field, Lewis's main campus in Cleveland, generally conceived the ideas for the test programs. They worked with Plum Brook's Rocket Systems Division to determine the best site and establish the parameters for the test. Management required a safety permit before it would approve a test. The researchers then worked with a site's facility engineer, electricians, and mechanics to install the equipment, instrumentation, and data-recording equipment. The test was preprogrammed on computer punch cards. The Gas Handling Unit supplied the facilities with the necessary propellants and pressurized gas. The tests were conducted from remote control rooms, primarily the Control and Instrument Building, to mitigate the danger of high-energy propellants.

Administration and Engineering Buildings

The Rocket Systems Area was supported by the staff in Plum Brook's Rocket Systems Division and Facilities Division. These people, along with the Plum Brook's management and civil engineers, were initially located in the former PBOW's 25,700-square-foot Administration Building located near the main gate at the north end of Plum Brook. The single-story wooden E-shaped building contained 53 modest offices, four conference rooms, and a cafeteria in the basement. The Administration Building also housed the printing and computing machines.

In the mid-1960s Plum Brook constructed the two-story 57,625-square-foot Engineering Building to house personnel. The L-shaped building had 69 offices, four conference rooms, a library, a cafeteria, and a large assembly area. NASA continued to use the Administration Building even after the new structure was complete. Test engineers had offices in these buildings but spent much of their time out at the test sites.



Image 236: PBOW's Administration Building (GRC-1960-C-53826).

H Control Building—Control and Instrument Building

H Control was located on Ransom Road in the northwest region of the Rocket Systems Area. This 12,258-square-foot reinforced-concrete building contained the control panels and data-recording devices for A Site, C Site, D Site, E Stand, F Site), and I Site. H Control contained the data-recording equipment for all the Plum Brook facilities. The rectangular structure sent and received data from the test sites through over 13,000 overhead lines. Although the building supplied many sites, it could record data from only one test at a time and could swap interchangeable patchboard panels to

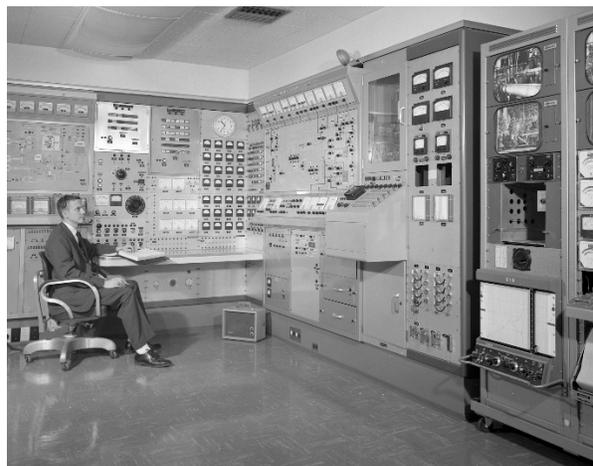


Image 237: Inside H Control (GRC-1963-P-01437).

decrease the lag time between tests. The staff could remotely view testing at the sites via closed-circuit television systems.

B Control Building

The 11,508-square-foot B Control was located near the center of the Rocket Systems Area. NASA added the building to provide safe operation of the B-1 and B-3 test stands and, later, of the HTF and the B-2 Stand. Each of these sites had its own control room. B Control had a number of data recording systems. J Site, K Site, and the Pilot Plant had their own on-site small control structures. H Control recorded the test data for these sites.



Image 238: B Control room (GRC-1965-P-02150).

Gas Handling Area

The Rocket System Area required large quantities of hydrogen, oxygen, fluorine, nitrogen, and helium. The Gas Handling Area, which was near a major railway route, consisted of four small structures and two permanent Dewars located on Ransom Road just northwest of the Rocket Systems Area. These buildings created gaseous nitrogen, hydrogen, and helium, and they provided a storage structure. In addition, the Gas Handling Unit purchased liquid hydrogen from industrial suppliers. The center owned four railcar tanks that transported liquid hydrogen to Plum Brook from other states. The unit supplied the sites with the required gases or liquids via rail or truck-based storage tanks. A massive 200,000-gallon liquid-hydrogen storage vessel was located near the B-1 and B-3 stands.



Image 239: Gas Handling Area (GRC-2016-C-05788).

◆ Appendix B ◆

Glossary

- Blade loading:** The load placed on the rotor blades. It is calculated by dividing the rotor's weight by the total combined areas of all of the blades.
- Bootstrapping:** The self-generating restart of an engine by flowing gaseous fuel into the gas turbine. The turbine drives the turbopump which draws liquid propellant towards the combustion chamber.
- Butler buildings:** Prefabricated ready-to-assemble structures manufactured by the Butler Manufacturing Company. *Butler building* has become a generic term for a variety of premade structures.
- Calorimeter:** Tool designed to measure the production and transfer of heat and energy. Calorimeters are basically insulated tanks with temperature measurement devices inside.
- Cavitation:** The creation and collapse of vapor pockets in low-speed two-phase fluid flow.
- Cold flow:** A test in which the propellant is pumped through the system but the engine is not fired.
- Cold shock:** Subjecting a component to cryogenic temperatures, usually using a liquid nitrogen bath, to verify its integrity before introducing liquid hydrogen.
- Cold wall:** Enclosure with ribbed walls through which a cryogenic fluid is flowed to create a cold environment.
- Critical temperature:** The temperature at which vapor can no longer be liquefied no matter how much pressure is applied.
- Cryogenic:** Relating to extremely cold temperatures. In their liquid form, elements such as hydrogen, oxygen, and nitrogen are considered cryogenics because their boiling temperature is extremely low (−297°F to −423°F).
- Cryoshroud:** Large enclosures with ribbed walls through which a cryogenic fluid is flowed to create a cold environment.
- Cryostat:** A refrigeration device that compresses gases, regeneratively cools them, and then expands them until portions of the gas liquefy.
- Damping:** The suppression of oscillations or disturbances; the dissipation of energy with time.
- Dewar:** A glass or metal container made like a vacuum bottle that is used especially for storing liquefied gases.
- Expulsion:** Forcing of propellant from the tank using a gas with density greater than that of the propellant.
- Hortonsphere:** A large, strong spherical pressurized tank used to store liquids or gases without vaporization.
- Impeller:** A rotor that significantly increases the pressure and drives the propellant toward the engine. Axial-flow pumps employ a series of impellers, whereas centrifugal pumps use one large rotor.
- Inducer:** A spiral-shaped turbopump stage that raises the propellant pressure just enough to prevent cavitation in the impeller.
- Liquefaction:** The process of converting a solid or gas into liquid.
- Net positive suction head (NPSH):** The difference between the pump inlet's pressure level and the pressure at which the propellant will vaporize. In order to avoid cavitation, the Available NPSH—the liquid's pressure level, must be higher than the pump's pressure reduction, referred to as the Required NPSH.
- Nuclear Engine for Rocket Vehicle Application (NERVA):** was a joint NASA and Atomic Energy Commission effort to develop a nuclear-propelled rocket in the 1960s and early 1970s.
- Oxidizer:** Chemical used to combust with fuel in the vacuum of space. Air-breathing engines use atmospheric air as the oxidizer.

Passivation: The floating of unpressurized fluorine into the system and allowing it to build up a layer along the interior of the piping. This coating provided some protection against the general corrosiveness of high-pressure liquid hydrogen.

POGO: Vibrations in rocket systems that cause variations in propellant flow. These variations cause the rocket to jump forward and backwards like a pogo stick. These self-perpetuating variations can result in serious structural damage to the vehicle.

Pressurant: Gas contained in a tank that naturally pushes the propellant toward the engine. The pressurant is a stable gas, such as helium, that possesses a higher pressure level than the propellant.

Propellant: The combination of the fuel and the oxidizer.

Regeneratively cooled engine: An engine that uses the cryogen liquid hydrogen as both the propellant and the coolant to prevent the engine from burning up. The fuel was fed through rows of narrow tubes that surrounded the combustion chamber and nozzle before it was ignited inside the combustion chamber.

Shadowshield: An externally mounted guard deployed to block solar radiation once a vehicle is in space.

Solid rocket: A rocket engine fueled with a solid propellant. Such motors consist essentially of a combustion chamber containing the propellant, and a nozzle for the exhaust jet, although they often contain other components (such as grids, liners, etc.).

Specific impulse: A measurement of engine efficiency. The greater the specific impulse, the less propellant is required for a specific velocity.

Steady state: When a system reaches a point where its various properties remain unchanged over a period of time.

Thermodynamics: The study of heat and temperature in relationship to the energy or work of a system.

Torr: A unit of pressure used to measure air pressure. One torr equals 1/760th of a standard atmosphere.

Turbopump: A propellant pump that increases the pressure of the fluid and feeds the fluid to the engine's combustion chamber.

Ullage: The area inside a tank that does not contain liquid.

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The Rocket System Area at Plum Brook Station—an unassuming, yet comprehensive, group of test facilities—provided researchers with the tools to conduct basic cryogenic fluid handling research. The facilities helped to establish liquid hydrogen as a reliable fuel that could be safely stored, pumped, and burned. They also allowed researchers to test hardware for the Centaur and the Nuclear Rocket for Rocket Vehicle Application (NERVA) programs and to study technologies for future long-term missions to other planets.



Back cover: Hydrogen is burned off during a run at the Turbopump Facility, also known as C Site (GRC-2016-C-05178).

Front cover: Firing of a gaseous-hydrogen engine at the J-1 Rocket Systems Test Site (GRC-2016-C-05793).