Historic American Engineering Record Documentation of the High Energy Rocket Engine Research Facility (B–1) and Nuclear Rocket Dynamics and Control Facility (B–3)

Plum Brook Station
NASA Glenn Research Center
Sandusky, Erie County, Ohio

November 2010

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HISTORIC AMERICAN ENGINEERING RECORD
National Park Service
Great Lakes Support Office
1709 Jackson Street
Omaha, Nebraska 68102

November 2010

1.0 General Information

1.1 Overview of High Energy Rocket Engine Research Facility (B–1) and Nuclear Rocket Dynamics and Control Facility (B–3)

Location: National Aeronautics and Space Administration (NASA)
Plum Brook Station
John H. Glenn Research Center
6100 Columbus Road
Erie County, Sandusky, Ohio

The High Energy Rocket Engine Research Facility (B–1, Bldg. 3111) and the Nuclear Dynamics and Control Facility (B–3, Bldg. 3311) were located near the center of Plum Brook Station off Factory Road near its intersection with Fox Road. The B Complex included the Pump and Shop Building (Bldg. 3131), Substation D (Bldg. 3161), the Boiler Building (Bldg. 5231), the Valve House (Bldg. 5232), the B–3 Boiler House (Bldg. 3331), a 200,000-gal liquid-hydrogen storage dewar (Bldg. 5351), a liquid-hydrogen dewar control building (Bldg. 5335), and a steam ejector apparatus. B–1 and B–3 were operated remotely from the B Control and Data Building (Bldg. 5411).

Elevations: B–1, 651.5 ft; B–3, 655 ft; Pump House, 651.5 ft; liquid-hydrogen dewar, 651 ft; gas coolers, 651 ft; steam accumulators, 651 ft; B–3 Boiler House, 653.5 ft; B Control and Data Building, 662.5 ft (Refs. 1 and 2).

UTM Coordinates: B–1: 4581170N, 359420W B–3: 4580821N, 359573W
Latitude: B–1: 41.369778N B–3: 41.366667N
Longitude: B–1: –82.680944W B–3: –82.679036W

Owner: The NASA Lewis Research Center. In March 1999 the Center's name was changed to the NASA John H. Glenn Research Center.

Present Use: When Plum Brook was closed down in 1973 and 1974, the facilities were put in a second-tier standby condition. Despite efforts to determine alternative uses for the facilities in the mid-1970s, the test stands were not used after 1974. Between 1978 and 1982 the facilities were cannibalized for parts and further downgraded to a third tier of maintenance. When B–1 and B–3 were demolished in September 2010, the B–1 test stand had been inactive since June 1969 and the B–3 test stand had been inactive since May 1974.

Acronyms: Acronyms used in this document are defined in the appendix.

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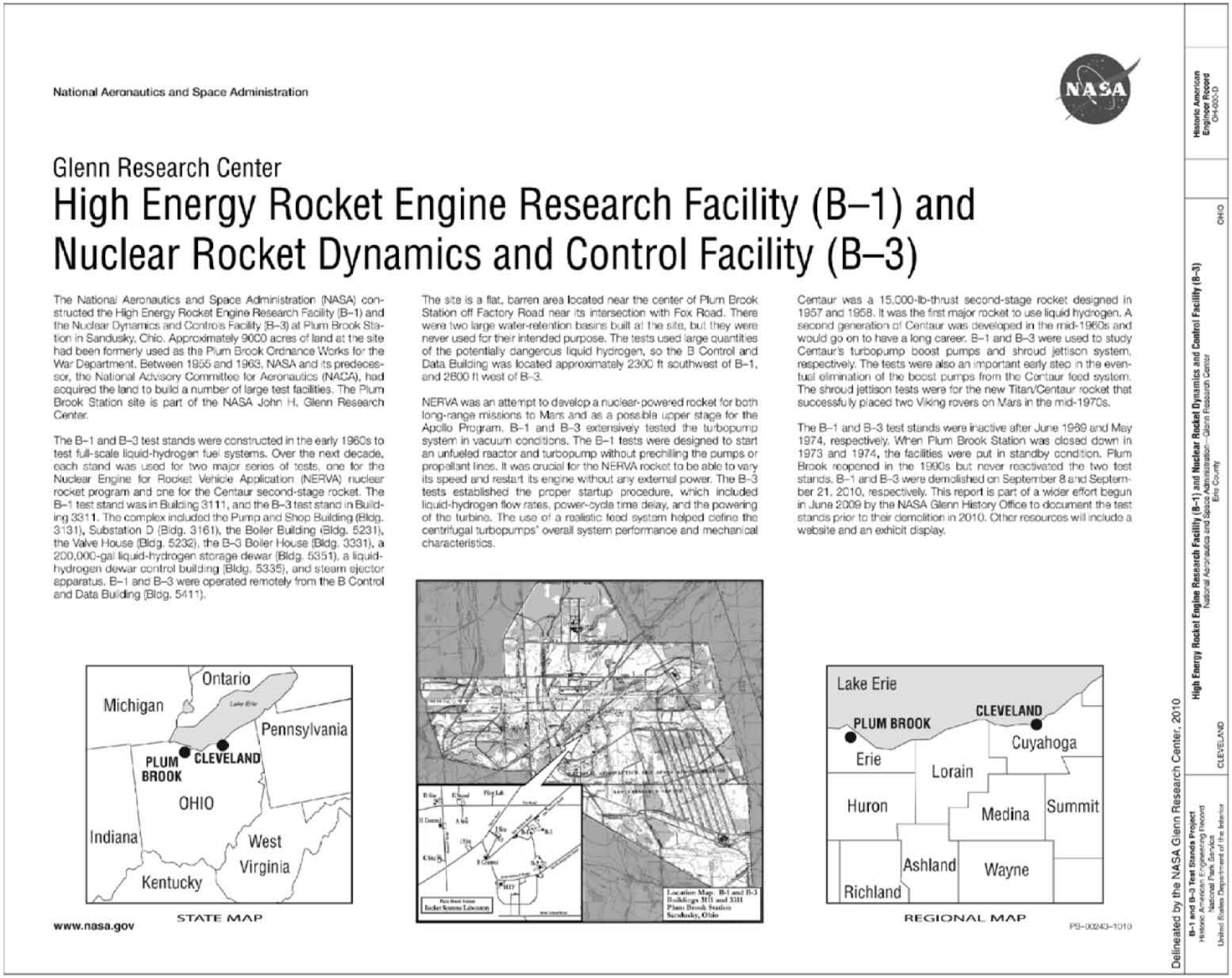
1.1.1 General Description and Photographs



National Aeronautics and Space Administration

Glenn Research Center

High Energy Rocket Engine Research Facility (B–1) and Nuclear Rocket Dynamics and Control Facility (B–3)

The National Aeronautics and Space Administration (NASA) constructed the High Energy Rocket Engine Research Facility (B–1) and the Nuclear Dynamics and Controls Facility (B–3) at Plum Brook Station in Sandusky, Ohio. Approximately 9000 acres of land at the site had been formerly used as the Plum Brook Ordnance Works for the War Department. Between 1955 and 1963, NASA and its predecessor, the National Advisory Committee for Aeronautics (NACA), had acquired the land to build a number of large test facilities. The Plum Brook Station site is part of the NASA John H. Glenn Research Center.

The B–1 and B–3 test stands were constructed in the early 1960s to test full-scale liquid-hydrogen fuel systems. Over the next decade, each stand was used for two major series of tests, one for the Nuclear Engine for Rocket Vehicle Application (NERVA) nuclear rocket program and one for the Centaur second-stage rocket. The B–1 test stand was in Building 3111, and the B–3 test stand in Building 3311. The complex included the Pump and Shop Building (Bldg. 3131), Substation D (Bldg. 3161), the Boiler Building (Bldg. 5231), the Valve House (Bldg. 5232), the B–3 Boiler House (Bldg. 3331), a 200,000-gal liquid-hydrogen storage dewar (Bldg. 5351), a liquid-hydrogen dewar control building (Bldg. 5335), and steam ejector apparatus. B–1 and B–3 were operated remotely from the B Control and Data Building (Bldg. 5411).

The site is a flat, barren area located near the center of Plum Brook Station off Factory Road near its intersection with Fox Road. There were two large water-retention basins built at the site, but they were never used for their intended purpose. The tests used large quantities of the potentially dangerous liquid hydrogen, so the B Control and Data Building was located approximately 2300 ft southwest of B–1, and 2600 ft west of B–3.

NERVA was an attempt to develop a nuclear-powered rocket for both long-range missions to Mars and as a possible upper stage for the Apollo Program. B–1 and B–3 extensively tested the turbopump system in vacuum conditions. The B–1 tests were designed to start an unfueled reactor and turbopump without prechilling the pumps or propellant lines. It was crucial for the NERVA rocket to be able to vary its speed and restart its engine without any external power. 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 use of a realistic feed system helped define the centrifugal turbopumps' overall system performance and mechanical characteristics.

Centaur was a 15,000-lb-thrust second-stage rocket designed in 1957 and 1958. It was the first major rocket to use liquid hydrogen. A second generation of Centaur was developed in the mid-1960s and would go on to have a long career. B–1 and B–3 were used to study Centaur's turbopump boost pumps and shroud jettison system, respectively. The tests were also an important early step in the eventual elimination of the boost pumps from the Centaur feed system. The shroud jettison tests were for the new Titan/Centaur rocket that successfully placed two Viking rovers on Mars in the mid-1970s.

The B–1 and B–3 test stands were inactive after June 1969 and May 1974, respectively. When Plum Brook Station was closed down in 1973 and 1974, the facilities were put in standby condition. Plum Brook reopened in the 1990s but never reactivated the two test stands. B–1 and B–3 were demolished on September 8 and September 21, 2010, respectively. This report is part of a wider effort begun in June 2009 by the NASA Glenn History Office to document the test stands prior to their demolition in 2010. Other resources will include a website and an exhibit display.

www.nasa.gov

PS-00243-1010

Delineated by the NASA Glenn Research Center, 2010

B–1 and B–3 Test Stands Project
Historic American Engineering Record
National Park Service
United States Department of the Interior

CLEVELAND

High Energy Rocket Engine Research Facility (B–1) and Nuclear Rocket Dynamics and Control Facility (B–3)
National Aeronautics and Space Administration—Glenn Research Center
Erie County

OHIO

Historic American Engineer Record
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Figure 1.1.—Map of Plum Brook Station showing its location within Ohio and Erie County. Overview and locations of the B–1 and B–3 test stands, 2010 (PS–00243–1010, NASA Glenn).

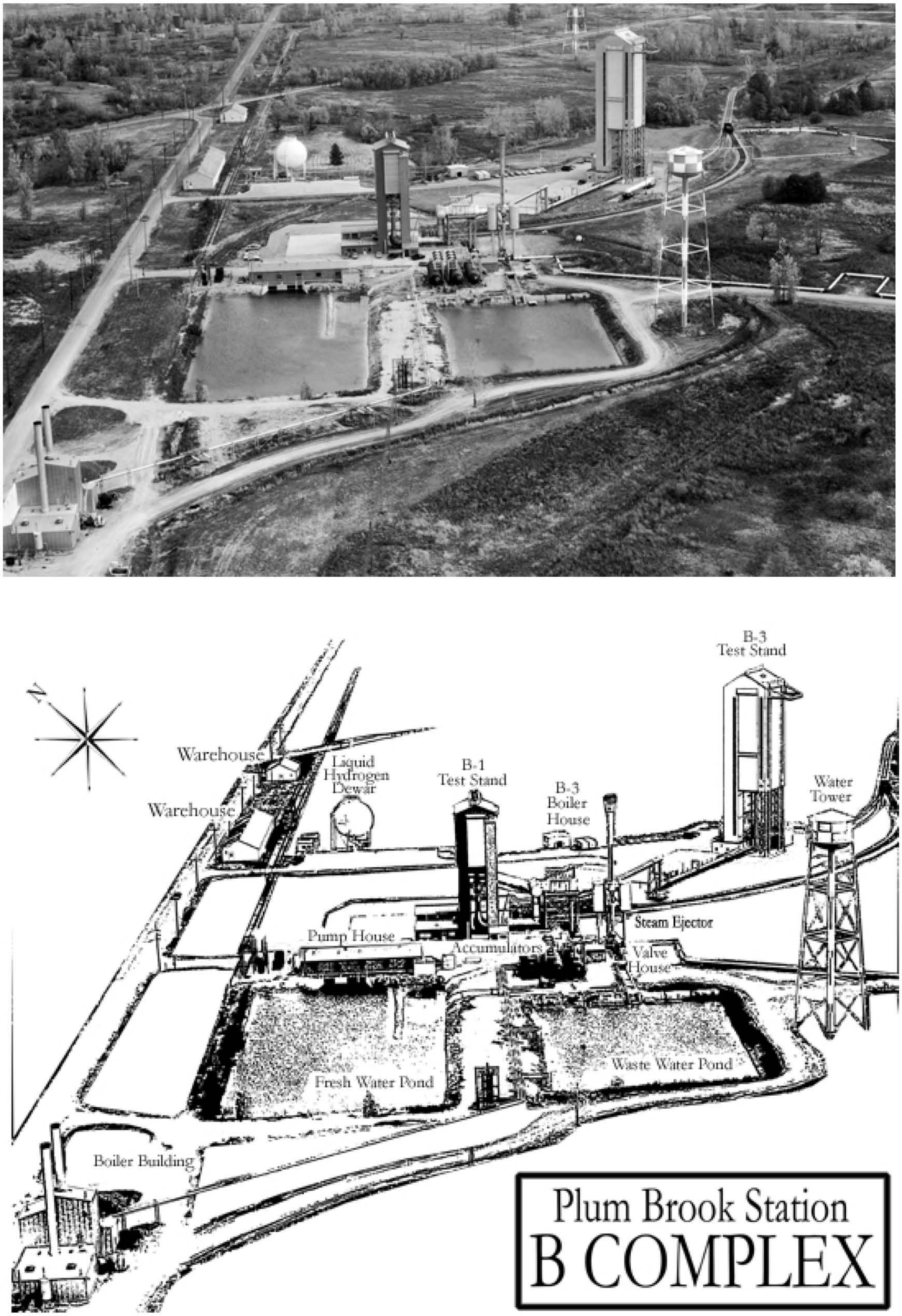


Figure 1.2.—B Complex with the B–1 and B–3 test stands and various support buildings, 1965 (C–1965–03012, NASA Glenn).

1.1.2 Location Map

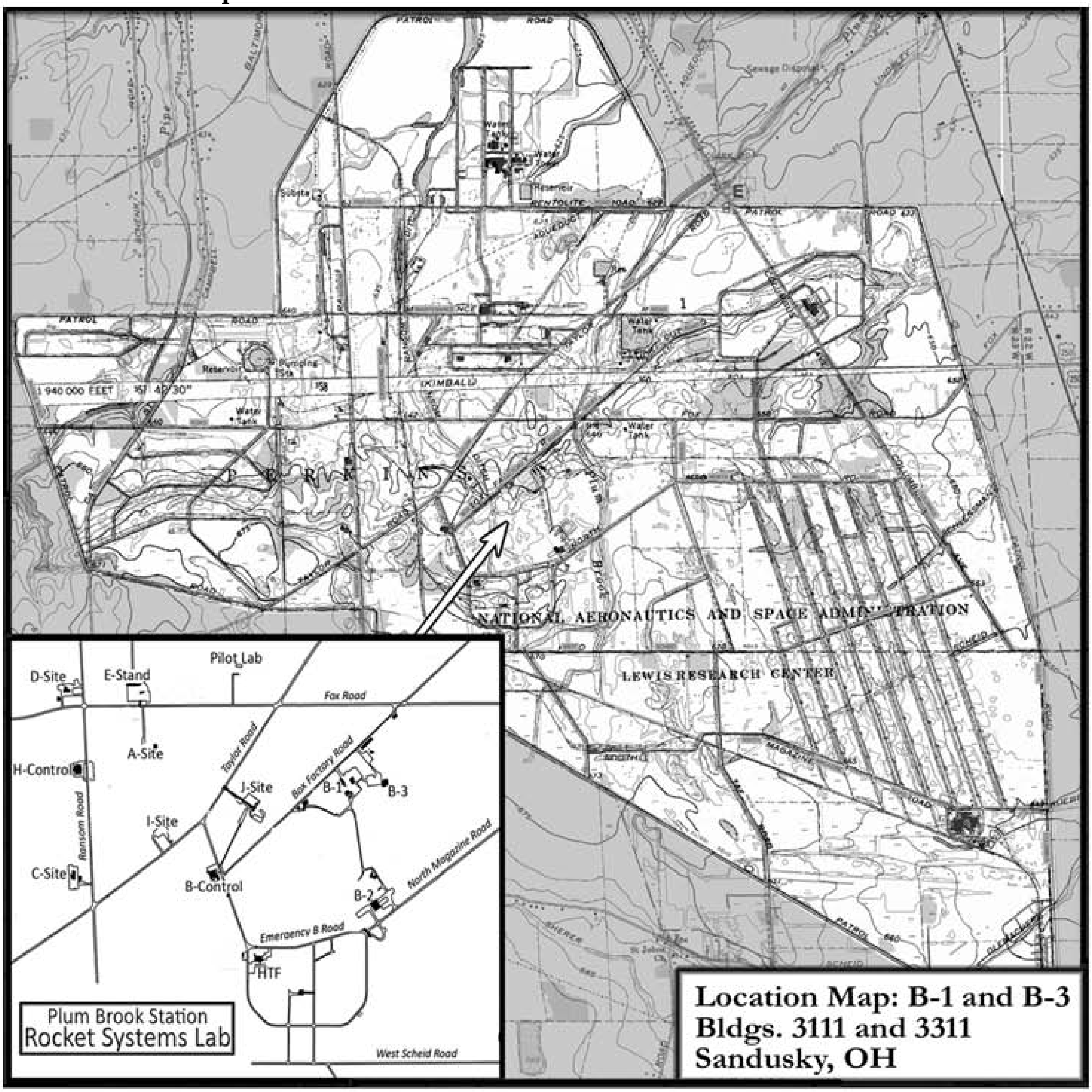


Figure 1.3.—Map of Plum Brook showing locations of B–1 (Bldg. 3111) and B–3 (Bldg. 3311).

1.1.3 Original Plans

The B–1 and B–3 test stands were constructed in the early 1960s to test full-scale liquid-hydrogen fuel systems. Over the next decade, each test stand was used for two major series of tests, one for the Nuclear Engine for Rocket Vehicle Application (NERVA) nuclear rocket program and one for the Centaur second-stage rocket.

B–1 was designed to test propellant systems in simulated altitude conditions. This test stand, also referred to as the NERVA Stand, was used for extensive study of the NERVA propellant feed system, particularly the operation of its turbopumps, fluid instability in flow passages, and evaluation of equipment performance. A nearby steam plant supplied the steam for the facility's ejector, which produced the simulated altitude conditions in the test section (Ref. 3). The facility could be used to test engines up to 6000 lb thrust for 6 minutes. The Plum Brook Station Review reported that this capacity could have been increased fivefold with minor modifications. B–1 included cryogenic run tanks, exhaust gas scrubbers, and large gaseous and cryogenic storage trailers. The facility was tied into Plum Brook's H Control and Data Building (Ref. 4).

B–3 was also used to study tanking and flow processes for complete rocket systems. The rocket's combustion chamber was pressurized to simulate an actual launch, but the engines were not fired. Researchers could study the effect of combustion chamber pressure on flow dynamics. B–3 had its own gas and cryogenic supply systems, including a 200,000-gal liquid-hydrogen dewar located 300 ft from B–3. It could utilize B–1's scrubber system and water systems but never did. It did use the B–1's steam system and ejector to simulate altitude conditions. The facility was tied into Plum Brook's H Control and Data Building (Ref. 5).

The B Complex included the two test stands, two large retention basins, the B–1 steam ejectors, the Pump and Shop Building, Substation D, the Valve House, the Boiler Building, the B–3 Boiler House, and the Hydrogen Gas Handling Building (Bldg. 5333). Other related structures in the general vicinity included the Space Propulsion Research Facility (B–2, Bldg. 3211), the B–2 Refrigeration Building (Bldg. 3231), the B Control and Data Building, and the Hypersonic Tunnel Facility (HTF, Bldg. 3411). The infrastructure built to support the two test stands was utilized by other facilities at Plum Brook, including B–2.

Figure 1.4.—Plum Brook and the surrounding farmland (viewed from the west). Lake Erie is visible to the north, and downtown Sandusky is out of view to the northwest, 1960 (C–1960–55682, NASA Glenn).

1.2 Topography

The B–1 and B–3 test stands were located near the center of 6400 acres of land at NASA Glenn's Plum Brook Station near Sandusky, Ohio. The War Department originally seized 9000 acres of flat farmland in 1941 to construct a large ordnance manufacturing center. The land was relatively level and cleared for farming but had scattered clusters of trees. The farmers were given weeks to vacate the land, and soon the property was fenced in, plowed over, and populated by over 600 buildings. The Plum Brook Ordnance Works closed suddenly in August 1945 and remained vacant for the next 10 years. In 1955 the National Advisory Committee for Aeronautics (NACA) Lewis Flight Propulsion Laboratory purchased 500 acres at the western edge to construct a nuclear test reactor. Between 1958 and 1963, the laboratory (which had changed its name to the NASA Lewis Research Center) acquired the entire 9000 acres to construct a number of sites to test high-energy rocket propellants and engines. B–1 and B–3 were among these test facilities.

Figure 1.5.—Typical Plum Brook farm before the Government seized the land, 1941 (PBOW414E, NASA Glenn).

Figure 1.6.—Construction of the Plum Brook Ordnance Works, 1941 (PBOW484, NASA Glenn).

The majority of the old military structures were burned by the NACA between 1958 and 1963, but many still exist. Since the end of the War, the fenced-off site has become a sanctuary for the natural world. Forests and savannahs have developed, and wildlife has flourished. Over 521 plant, 125 breeding bird, 21 amphibian or reptile, 16 fish, 53 butterfly, 450 moth, and 8 bat species live there, including 20 plant, 8 bird, 3 amphibian or reptile, and 1 moth species protected by the Endangered Species Act. In recent years a pair of eagles has returned annually to raise its young (Ref. 6).

B–1 and B–3 were located near the center of Plum Brook near the intersection of Box Factory Road and Fox Road. The elevation in the general area is approximately 651 ft, but it rises to 655 ft in some points. During the 1960s, while B–1 and B–3 were operating, the area around the test stands was flat and treeless. Outcrops of trees existed across Box Factory Road and between the site and other test sites. In recent years the vegetation had spread up to the test stands and other structures, and additional trees had entered the area.

Figure 1.7.—B Complex encompassing B–1 and B–3 as it appeared while the test stands were operating, 1964 (C–1964–72620, NASA Glenn).

Figure 1.8.—B–1 and B–3 test stands after years of neglect, 2007 (C–2007–01959, NASA Glenn).

1.3 Project Information

This report is part of a wider effort to document the B–1 and B–3 test stands prior to their 2010 demolition. Documentation formally began in October 2009 after a Statement of Work for the NASA Glenn History Program was finalized with the Facilities Division. The project included the gathering of documents, photographs, drawings, and films; researching the facility's physical and operational history; interviewing retirees; and photographing the site. The resulting information is being disseminated via a website and this report.

B–1 and B–3 were unique to Glenn and contributed to two large space programs in the 1960s. Maintenance of the facilities was neglected following the closure of Plum Brook in 1973 and 1974. Although Plum Brook's larger facilities were restored once Plum Brook reopened, B–1, B–3, and the other small rocket sites were left fallow. B–1 and B–3 were unique in appearance, but they eventually became safety hazards. Glenn decided to document the facilities thoroughly before their September 2010 demolition and to share the information with the public and within the Agency.

2.0 History

2.1 Historical Context

NASA Glenn has been an important leader in rocket propulsion since the 1940s. In the 1950s the Center was at the vanguard of developing high-energy fuels for rocket engines. With the advent of the national space program in the late 1950s, the Center established the Plum Brook auxiliary site to build numerous large test facilities. During the 1960s, the Center was heavily involved with the development of a nuclear rocket engine and the Centaur second-stage vehicle. B–1 and B–3 were used to test the performance of both of these engines.

Figure 2.1.—High-energy rocket propellant test runs in the Lewis Rocket Lab, 1955 (C–1955–37428, NASA Glenn).

2.1.1 NACA Rocket Research

NASA Glenn was established in 1941 by the NACA in Cleveland, Ohio. Originally called the NACA Aircraft Engine Research Laboratory (AERL), the Center was the NACA's third research laboratory, but the only one dedicated to propulsion. Congress approved funds for the AERL in 1940 as it became apparent that the United States would soon become embroiled in World War II. The NACA spent the war years resolving problems on existing piston military aircraft, but the AERL also became involved in the new types of propulsion that emerged during the war—the turbojet, ramjet, and rocket.

AERL researchers in the rocket field concentrated on the study of fuels or propellants. Because the NACA officially considered rockets as artillery and not in the scope of its aeronautics mission, the AERL researchers kept their work under wraps and appeared as the High Pressure Combustion Section on the organization chart. A group of small test cells, referred to as the Lewis Rocket Lab, was built in a remote corner of the AERL to carry out their investigations. The research concentrated on fuels, many of them exotic high-energy fuels.

NACA veteran Abe Silverstein was named Director of Research at NACA Lewis in 1949 (the AERL had been renamed the NACA Lewis Flight Propulsion Laboratory) and was named Associate Director in 1953. Under Silverstein's leadership, NACA Lewis was at the vanguard of new fields such as nuclear propulsion and electric propulsion, while it expanded existing rocket work. Silverstein elevated the rocket group on the organizational chart and renamed it the Rocket Research Branch (Ref. 7).

By the early 1950s, the researchers had determined that liquid hydrogen and liquid oxygen was the optimal propellant combination and concentrated their efforts there. Silverstein spearheaded the construction of the new Propulsion Systems Laboratory (1952) and the Rocket Engine Test Facility (1957), which could fire 15,000- and 20,000-lb thrust rockets, respectively. Initially the work was on small in-house rocket engines used to test different propellant mixtures as well as different nozzles, turbopumps, and other components. By the early 1960s, however, the facilities were testing full-scale engines such as Pratt & Whitney's RL–10.

Silverstein also sought a test reactor to study the effects of radiation on materials that would be used to construct a nuclear-powered aircraft engine. After several sites were examined, 500 acres at the 9000-acre Plum Brook Ordnance Works in Sandusky, Ohio, were selected for the reactor in September 1955. During the 6 years that it took to build the reactor, it became apparent that NASA Lewis (NACA Lewis had been renamed the NASA Lewis Research Center in October 1958) needed additional facilities to test rocket engines and their components. The large unused tracts of land at Plum Brook were perfect for the dangerous fuels work.

An additional 3000 acres were acquired from the Army to build two test facilities—the Pilot Lab (later called the Pilot Plant) and the multifacility Rocket Systems Laboratory, which would eventually include B–1 and B–3. In the fall of 1959 NASA requested the use of another 3500 acres (Ref. 8). The Pump Research Laboratory (A Site), the Turbopump Facility (C Site), the Turbine Test Facility (D Site), Pilot Plant (G Site), and Central Control (later called the H Control and Data Building) were operational in September 1961. The Dynamics Laboratory (E Stand) began testing in February 1962, the Liquid Fluorine Pump Laboratory (I Site) began testing in March, and the Rocket Test Area (J Site)'s five test cells began testing throughout the 1962 fiscal year (Ref. 9).

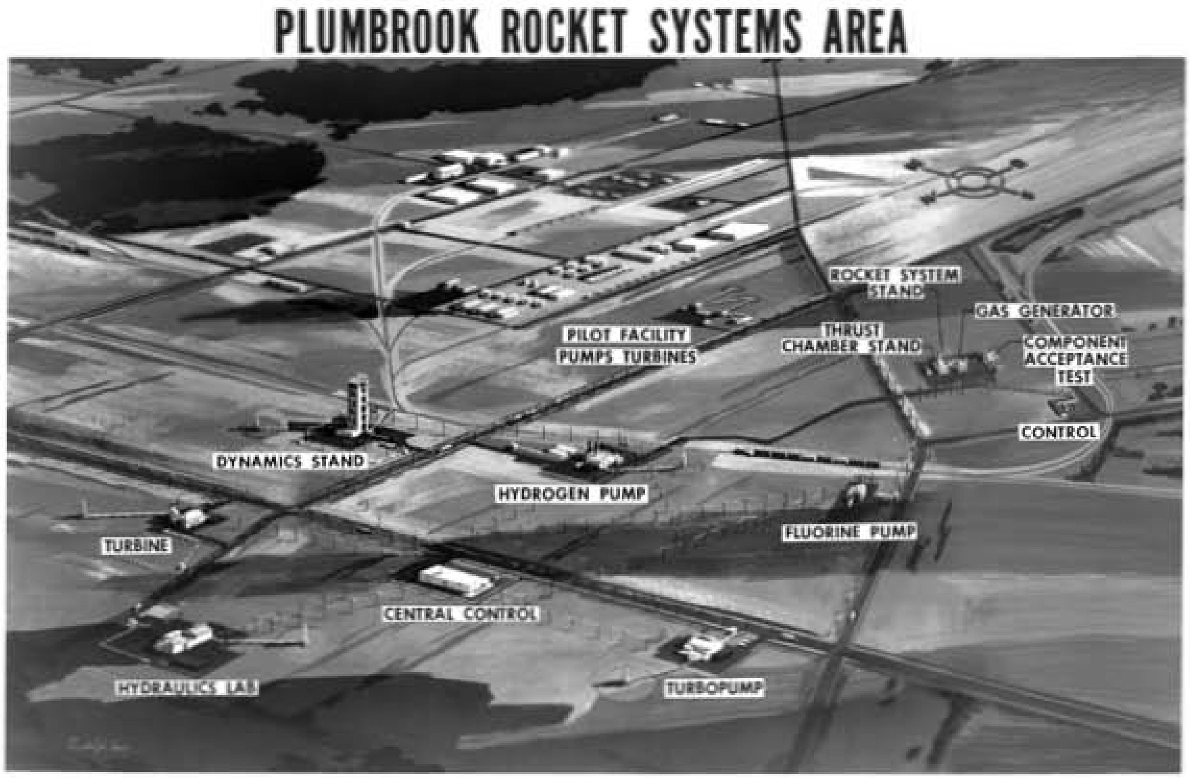


Figure 2.2—Early drawing of the anticipated Rocket Systems Laboratory, 1960 (C–1960–53497, NASA Glenn).

Two rocket programs dominated the B–1 and B–3 test stands: NERVA and Centaur. The two rockets shared several common traits: they were upper-stage rockets, they were originally designed for the Saturn booster, and most importantly, they used the high-energy cryogenic liquid hydrogen as a propellant. Centaur would burn the hydrogen in liquid oxygen, and NERVA would heat it in its reactor. The Atomic Energy Commission (AEC) designed NERVA's nuclear engine and General Dynamics designed the Centaur rocket in the late 1950s, when many in the field were not convinced of the benefits of the then-unproven liquid hydrogen.

NASA Lewis's critical role in demonstrating the potential of liquid hydrogen in the 1950s led to requests to extensively test both of these rockets in the 1960s. Full-scale tests of the NERVA engine were conducted at the AEC's Nevada Test Site, and full-scale tests of the Centaur's RL–10 engine were conducted at Lewis's Rocket Engine Test Facility and Propulsion Systems Laboratory. There was a need, however, to test the propellant feed system and the turbopump hardware. Lewis engineers designed the B–1 and B–3 test stands for just that purpose. These tests were a less expensive method of analyzing engine components and systems. When problems were resolved, the entire engine could be tested at a larger test facility. Centaur's development proceeded more rapidly than NERVA's, and Centaur continues to operate to this day. The NERVA program, however, was cancelled for budgetary reasons in 1973.

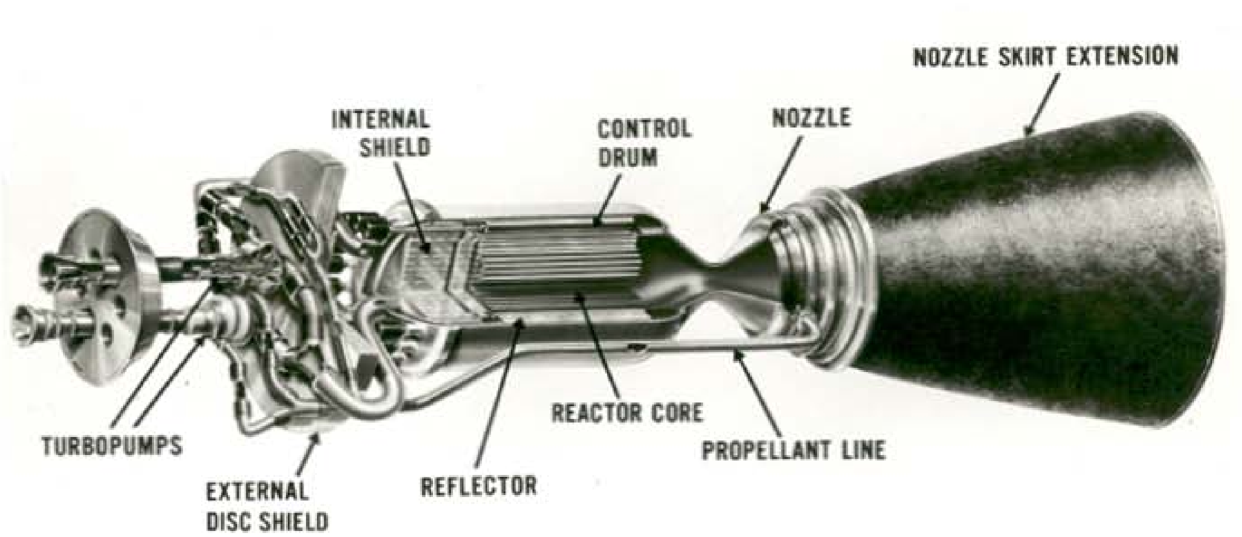


Figure 2.3.—Explanatory drawing of the Nuclear Engine for Rocket Vehicle Application (NERVA) thermodynamic nuclear rocket engine (GPN–2002–000144, NASA Headquarters).

2.1.2 Nuclear Rocket Program

The concept of a nuclear-powered aircraft had fallen from favor before construction of the Plum Brook Reactor Facility was completed, but it was quickly supplanted by a new nuclear-powered rocket program. NERVA was a joint NASA–AEC endeavor to develop a nuclear-powered rocket for both long-range missions and as a possible upper stage for the Apollo Program. NERVA not only provided the Plum Brook Reactor Facility with a new mission but required the construction of new facilities to test the engine. NERVA began as Project Rover in 1955 when the AEC instituted a study to develop nuclear-powered missiles for the U.S. Air Force.

In June 1955, NACA Lewis presented the Air Research & Development Command with a research proposal for manned air-breathing nuclear engine applications and began a study comparing chemical and nuclear propulsion for missiles (Ref. 10). In November the AEC approved the program, termed Project Rover, and research began immediately at their Los Alamos laboratory. The initial studies focused on developing components and systems for a nuclear engine.

In Cleveland, Frank Rom and other NACA Lewis researchers began investigating the use of tungsten-based nuclear engines in 1957. The Los Alamos researchers preferred a graphite-based reactor, but the graphite reactor that was chosen yielded mixed results (Ref. 10). In both concepts, liquid hydrogen entered the engine through a tube encircling the nozzle. This cryogenic fuel flowed through the nozzle tubes back up to the reactor so that it could serve as a coolant for both the nozzle and engine. The feed line then entered the reactor core to be heated. The reactor heated the hydrogen to 2000 °C before expelling it through the nozzle (Ref. 11).

In May 1958 NACA Lewis announced that it would build rocket-testing sites at Plum Brook. The first two sites would be the Pilot Lab and the multifacility Rocket Systems Laboratory

(Ref. 12). The B–1 test stand at the Rocket Systems Laboratory was to be used to study the hydrogen propellant feed system for the nuclear rocket in simulated altitude conditions.[1]

During 1958, negotiations were underway to create the new NASA space agency incorporating the NACA labs. One of the main concerns would be NASA's increased role in Rover and its relationship with the AEC. Influential New Mexico Senator Clinton Anderson was perhaps the leading nuclear rocket proponent in Washington, DC, but he was very protective of Los Alamos. Despite his general backing of NASA, he was wary of their partnership in the Rover/NERVA program (Ref. 13).

On December 19, 1959, Rover was officially transferred from the Air Force to NASA, with the AEC remaining an equal partner. The mission changed from a nuclear missile to a nuclear rocket for long-duration space flight. In August 1960, a joint AEC–NASA Space Nuclear Propulsion Office (SNPO) was created to oversee the program. It was headed by Lewis veteran Harry Finger and consisted of three offices: one in Albuquerque for the Los Alamos reactor design work, one in Nevada for the testing of the reactors and engines, and one in Cleveland to oversee NASA Lewis's hydrogen engine work (Refs. 11 and 14). Since Lewis was the primary NASA center involved and the joint SNPO commission was headed by Finger, Senator Anderson rebuffed Lewis's efforts at the time as much as possible (Ref. 13).

There were several stages in the overall nuclear rocket development program beginning with basic reactor design research. This was followed by the Kiwi series of reactors built to test basic nuclear rocket principles in a nonflying reactor. Kiwi spawned both a larger version, Phoebus, and a smaller version, Pewee. The next phase, NERVA, would create an entire flyable engine. Several variations were developed, but the Kiwi-B4-based NERVA Reactor Experiment (NRX) design proved to be the most successful. The final phase of the program would flight test the reactor as the third stage on a Saturn V booster. This was called the Reactor In Flight Test (RIFT). The test was postponed indefinitely in 1964 before any flights were attempted (Ref. 15).

Researchers at Los Alamos worked on developing basic reactor designs from 1955 to 1959. A prototype of the first Rover reactor, Kiwi-A, was unveiled at Jackass Flats, Nevada, in early October 1958. The 100-MW Kiwi-A was first tested in Nevada on July 1, 1959. In addition to operating the reactor, the researchers created basic design methods, acquired information on controls and materials, and developed methods of making fuel elements (Refs. 11 and 14).

A second and third Kiwi-A were tested in July and October 1960, this time at full power. The Kiwi-A tests were useful to the engineers but revealed severe structural problems with the graphite reactor core (Refs. 11 and 14). Nonetheless, the SNPO felt confident enough with the progress to move on to the next phase, which would result in a flyable engine. A request for bids for the industrial development of a nuclear rocket was released on October 19, 1960. This was the beginning of NERVA. On June 7, 1961, Westinghouse's Aerojet-General was selected to build the NERVA engine (Ref. 16).

In May 1962, Congress approved $40 million for the construction of a second wave of test facilities for Plum Brook. The new construction would include the large Space Power Facility

[1]Details of the B–1 construction are given in Section 2.2.2.

vacuum chamber to study a NERVA engine, a Hydrogen Transfer Facility to test systems for storing liquid hydrogen, the B–3 test stand to operate NERVA motors, the enlargement of the B–1 test stand, and improvement of the general infrastructure (Ref. 17). Abe Silverstein, who was now Center Director at NASA Lewis, set up a design group to plan a $15 million facility for testing a nuclear rocket engine at Plum Brook. At the time, the Plum Brook Reactor Facility was just beginning to operate, and Plum Brook began a wave of hiring (Ref. 18).

2.1.3 Centaur Program

In May 1962, the same month that funds for B–3 and other new Plum Brook facilities were approved by Congress, the first attempted launch of an Atlas-Centaur rocket exploded in the skies above Cape Canaveral. NASA intended to use Centaur to carry the *Surveyor* spacecraft into space in its efforts to soft land on the Moon. The Surveyor missions would be a key step in the fulfillment of the incipient Apollo Program. The failure of the first launch, however, jeopardized the entire Centaur Program.

The 15,000-lb-thrust second-stage Centaur rocket was developed by General Dynamics in 1957 and 1958 for the military. It was the first rocket to use liquid hydrogen as a fuel and had unique balloonlike propellant and oxidizer tanks that shared a common bulkhead. Its use of liquid hydrogen was a result of the research conducted at NACA Lewis in the mid-1950s. The Centaur Program was managed by Werner von Braun at the Army Ballistic Missile Agency. At the time, Von Braun was exploring upper stages for the Atlas, Titan, and Jupiter missiles.

There was internal debate at that time over the selection of the upper stage for the new Saturn booster. A 1959 committee led by Abe Silverstein reviewed the options and concluded that a stage using high-energy propellants such as liquid hydrogen was the only solution. Von Braun was skeptical but approved their decision. The Army Ballistic Missile Agency was absorbed into NASA as the Marshall Space Flight Center in July 1960.

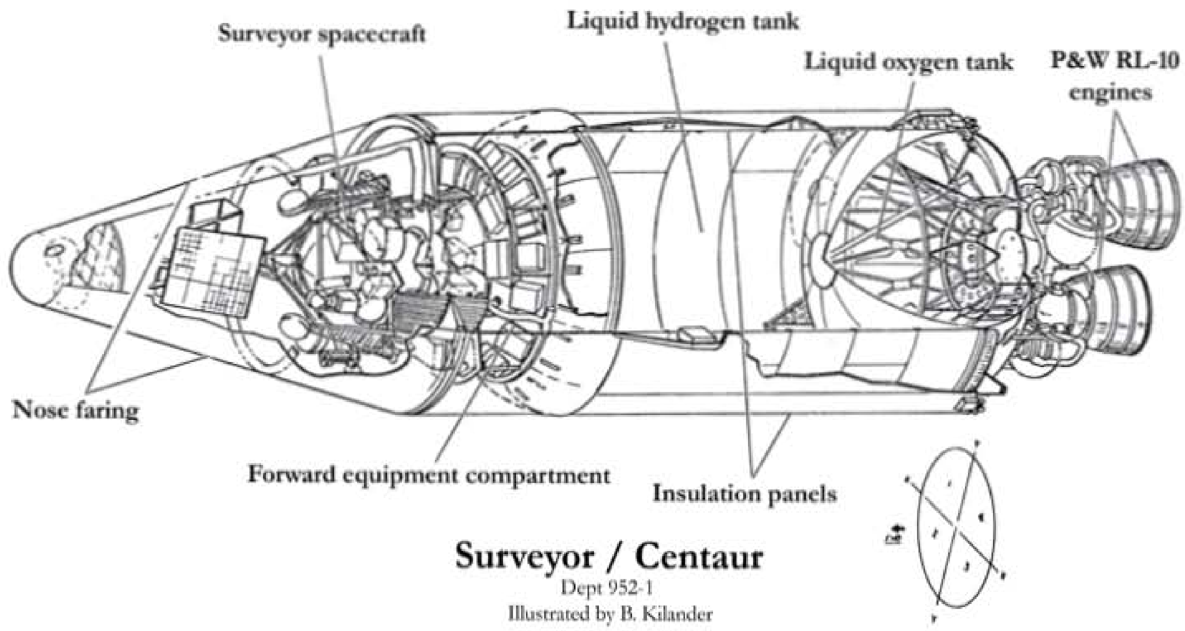


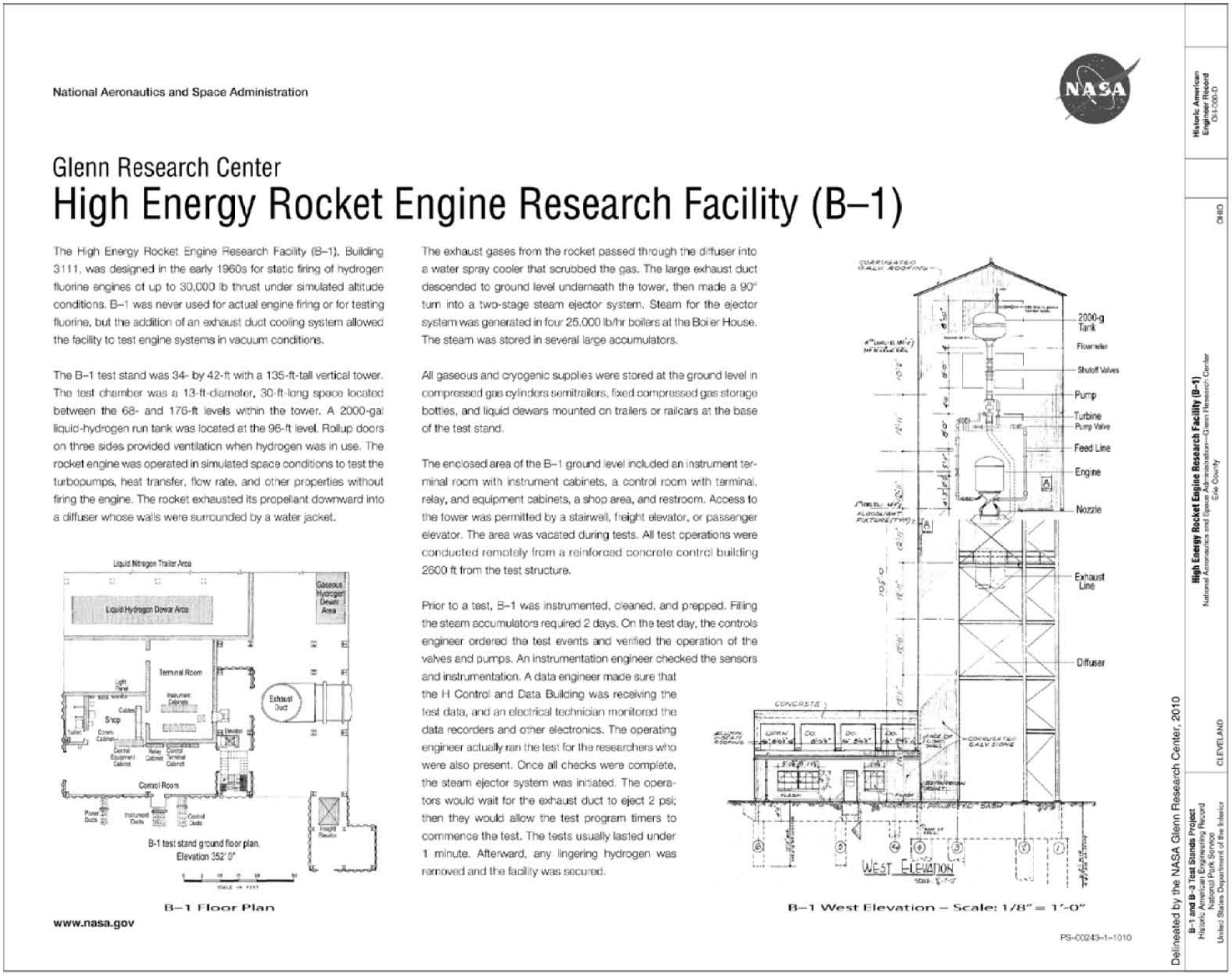
Figure 2.4.—Centaur rocket with its Surveyor payload (952–1, NASA Glenn History Collection). P&W, Pratt & Whitney.

NASA Marshall was preoccupied with the Saturn booster and wary of Centaur's unconventional design. Von Braun recommended canceling the program before a single flight. The loss of the first launch only deepened his doubts. As the complexity of the *Surveyor* design increased, however, it became apparent that Centaur was the only vehicle capable of hauling the spacecraft.

Following Congressional hearings and internal NASA debate, the Centaur Program was transferred to NASA Lewis in September 1962. Lewis had been the primary proponent of liquid hydrogen and already had experience testing Centaur's RL–10 engines. In addition, Silverstein was now Lewis's Center Director and would personally oversee the program. Numerous test facilities were built or modified at both Lewis's main campus and Plum Brook specifically for Centaur. The rocket was put through an intensive 2-year checkout. The electronics, shroud jettison system, hydrogen venting, propellant flow system, and a myriad of other components were examined.

The next Centaur launch in November 1963 was a success. By the seventh launch in April 1966, Centaur's initial problems had been resolved. On May 30, 1966, Centaur successfully sent the first *Surveyor* spacecraft on its way to the Moon. Three days later it became the first spacecraft to soft land on an extraterrestrial surface.

Although the *Surveyor* flights completed Centaur's primary mission, the success led to the planning of further launch assignments and upgraded versions of the rocket. This required additional tests and studies during the late 1960s and early 1970s at NASA Lewis's Cleveland campus and at Plum Brook. NERVA and Centaur would be the basis for most of the testing at Plum Brook during the 1960s.



National Aeronautics and Space Administration

Glenn Research Center

High Energy Rocket Engine Research Facility (B–1)

The High Energy Rocket Engine Research Facility (B–1), Building 3111, was designed in the early 1960s for static firing of hydrogen fluorine engines of up to 30,000 lb thrust under simulated altitude conditions. B–1 was never used for actual engine firing or for testing fluorine, but the addition of an exhaust duct cooling system allowed the facility to test engine systems in vacuum conditions.

The B–1 test stand was 34- by 42-ft with a 135-ft-tall vertical tower. The test chamber was a 13-ft-diameter, 30-ft-long space located between the 68- and 176-ft levels within the tower. A 2000-gal liquid-hydrogen run tank was located at the 96-ft level. Rollup doors on three sides provided ventilation when hydrogen was in use. The rocket engine was operated in simulated space conditions to test the turbopumps, heat transfer, flow rate, and other properties without firing the engine. The rocket exhausted its propellant downward into a diffuser whose walls were surrounded by a water jacket.

The exhaust gases from the rocket passed through the diffuser into a water spray cooler that scrubbed the gas. The large exhaust duct descended to ground level underneath the tower, then made a 90° turn into a two-stage steam ejector system. Steam for the ejector system was generated in four 25,000 lb/hr boilers at the Boiler House. The steam was stored in several large accumulators.

All gaseous and cryogenic supplies were stored at the ground level in compressed gas cylinders semitrailers, fixed compressed gas storage bottles, and liquid dewars mounted on trailers or railcars at the base of the test stand.

The enclosed area of the B–1 ground level included an instrument terminal room with instrument cabinets, a control room with terminal, relay, and equipment cabinets, a shop area, and restroom. Access to the tower was permitted by a stairwell, freight elevator, or passenger elevator. The area was vacated during tests. All test operations were conducted remotely from a reinforced concrete control building 2600 ft from the test structure.

Prior to a test, B–1 was instrumented, cleaned, and prepped. Filling the steam accumulators required 2 days. On the test day, the controls engineer ordered the test events and verified the operation of the valves and pumps. An instrumentation engineer checked the sensors and instrumentation. A data engineer made sure that the H Control and Data Building was receiving the test data, and an electrical technician monitored the data recorders and other electronics. The operating engineer actually ran the test for the researchers who were also present. Once all checks were complete, the steam ejector system was initiated. The operators would wait for the exhaust duct to eject 2 psi; then they would allow the test program timers to commence the test. The tests usually lasted under 1 minute. Afterward, any lingering hydrogen was removed and the facility was secured.

B–1 Floor Plan

B–1 West Elevation – Scale: 1/8" = 1'-0"

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PS-00243-1-1010

Delineated by the NASA Glenn Research Center, 2010

Historic American Engineer Record OH-000-D

High Energy Rocket Engine Research Facility (B-1)
National Aeronautics and Space Administration—Glenn Research Center
Erie County

CLEVELAND

OHIO

B-1 and B-3 Test Stands Project
Historic American Engineering Record
National Park Service
United States Department of the Interior

Figure 2.5.—B–1 test stand drawing and overview, 2010 (PS–00243—1–1010, NASA Glenn).

2.2.1 B–1 Construction Data Sheet

Dates of Construction: 1959 to 1964
Excavations for B–1 likely began sometime in 1959, and the test stand and its water tower were visible in aerial photographs by late 1960. By May 1961 the test stand was in place and most of the infrastructure complete. In the summer of 1961 NASA Lewis management decided to alter the design for the facility in order to handle a NERVA nuclear engine (Ref. 19). By July 1962 the new design work was mostly complete and the contracts were let. Delays in obtaining the test equipment from the manufacturer kept the facility from being completed until January 1964, 1 year after its scheduled completion (Ref. 20).

Engineers: The B–1 test stand was designed by NASA Lewis engineers. Certain components and subsystems were designed by external firms.

Contractors: Thermal Products Company and the Gundlach Sheet Metal Company manufactured some components. Goodyear Aircraft Corporation created the seal for the test stand, and the Elwin G. Smith Company assembled the test stand. John Naumann and Sons installed the elevator shaft, and the Taylor Elevator Service Company Inc. installed the elevator (Ref. 21). Rudolph-Libbee, Inc., built the original B Control and Data Building (Ref. 22), and R.G. Beer Corp. built the addition to the B–1 Boiler House (Ref. 23).

Owners: The NASA Lewis Research Center. In March 1999 the Center's name was changed to the NASA John H. Glenn Research Center. The property for Plum Brook was incrementally acquired by NASA and its predecessor, the NACA, from the Department of Defense between 1955 and 1963.

Original Cost: $2,201,000/$2,415,000

Significance: The B–1 test stand was designed for hot-firing tests on a variety of engine systems 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. The different components could be studied and adjusted without having to fire the engine. Once the B–1 studies were complete, the entire engine could be fired in larger facilities such as B–2. B–1 contributed to two major NASA programs during the 1960s: NERVA and the Centaur second-stage rocket.

B–1 was used for extensive study of the Mark IX turbopump for the Kiwi phase of the NERVA program. The B–1 tests focused on the propellant feed system, including the turbopumps, fluid instability in flow passages, and evaluation of equipment performance (Ref. 3). The tests demonstrated that the reactor could be bootstrapped, or started on its own without any external input. This ability to restart the engine without external power was crucial to long-duration space flight. In addition, B–1 testing verified the performance of the valves, seals, bearings, and other basic components that would have to function in a radiation environment in order for the propellant system to work properly. The researchers found that the Mark IX turbopump accelerated as needed and did not stick, that the expected pressure fluctuations in the reflector and nozzle were not as severe as in other tests, and that the separation of flow from the nozzle surface resulted in a large-amplitude vibration in the nozzle (Ref. 24).

The B–1 test stand was overhauled in the fall of 1967 and spring of 1968 for a series of liquid-hydrogen outflow and tank-pressurization tests for the Centaur Program. These Advanced Centaur tests were run throughout the year and into 1969. They led to a redesign of the tank insulation that was eventually the standard used on the Centaur D. The Centaur D was used on over 65 successful launches between 1966 and 1989. The tests were also an important early step in the eventual elimination of the boost pumps from the Centaur feed system. Follow-up full-scale tests were conducted in B–2, and the boost pumps were eventually removed from the design. This produced a less complicated system and significantly reduced the cost of a Centaur rocket (Ref. 4).

Figure 2.6.—B–1 test stand nears completion, 1962 (P62–01858, NASA Glenn).

2.2.2 B–1 Original Construction and Startup

NASA engineers developed the design for the B–1 test stand during 1959. A local Cleveland engineering firm, Addache & Associates, Inc., was hired to produce the drawings: the first phase of which was completed in March 1960. It is likely that excavations and work on the related infrastructure were well underway by that point. B–1 and its water tower are visible in photographs from late 1960. By May 1961 the test stand was in place and most of the infrastructure complete. In April 1961 the massive 140-ton steam accumulators arrived by rail from New Jersey. The size and weight of the accumulators required that the train keep its speed to 25 mph and travel only during daylight. The accumulators were a major component of the steam system used to simulate altitudes at the test stand (Ref. 25).

Figure 2.7.—Steam ejector exhaust stack is lifted into place, 1962 (P62–01511, NASA Glenn).

Figure 2.8.—B–1 test stand nears completion in March 1961. Connecting it to the other infrastructure, installing the test equipment, and checking out the operation would require another 2 years, 1961 (C–1961–56203, NASA Glenn).

Figure 2.9.—Steam accumulators are put into place, 1962 (P62–01276, NASA Glenn).

Figure 2.10.—Construction of the B–1 control room in the B Control and Data Building, 1962 (P62–01700, NASA Glenn).

The diaphragm seal, designed by NASA engineer A.R. Troots, was one of the more important components of the test stand. It was manufactured by Goodyear Aircraft Corporation. The seal had to be suitable for 10-psid[2] pressure in a –320 °F hydrogen gas atmosphere and be flexible enough to allow movement in all directions with no strain on the material (Ref. 26).

In the summer of 1961, NASA Lewis management decided to alter the design for the new B–1 test stand specifically to handle turbopump testing of a NERVA nuclear engine. By July 1962 the design work was mostly completed and the contracts were let. The initial call was for the facility to be completed by January 1963, but construction continued well into 1963 (Ref. 19). In February and March, the steam system and ejectors were being tested and tweaked (Ref. 27). During the first week of February 1963, Warren Jones and Thomas Shiplet of the Mechanical Engineering Branch observed test runs of the B–1 steam systems. They reported seeing several problems involving valve operation, flooding, frozen lines, improper water level in the accumulators, ejector swaying, and water hammering. These were due in part to poor operating instructions, issues not addressed in the design, and lack of calibration (Ref. 28).

[2]Pounds per square inch differential.

Figure 2.11.—Kiwi-B reactor nozzle is prepared for installation in B–1, 1964 (C–1964–69681, NASA Glenn).

The Aerojet Kiwi-B reactor, nozzle, and Mark IX turbopump arrived at Plum Brook in mid-April 1963, and installation in B–1 began immediately. The problems with the steam system and ejectors continued to be unresolved (Ref. 29). There were also difficulties getting the support pads into the 0.003-in. specification (Ref. 29). The hydraulic system, helium purge, accumulator catwalks, and a liquid-nitrogen pump were installed in July, but delays continued because of lack of manpower (Ref. 30). Instituting overtime and hiring contractors in August accelerated the work by 3 to 5 weeks (Ref. 31). The helium system checkout runs were completed on September 20, and research was set to begin on November 18, but several problems were still unresolved (Ref. 32).

Figure 2.12.—Kiwi-B reactor with its Mark IX turbopump is transported from a warehouse at Plum Brook to the B–1 test stand, 1963 (P63–01348, NASA Glenn).

Eight data runs in October 1963 using helium gas revealed unforeseen accelerations through the nozzle. All of the instrumentation had to be reinstalled and calibrated before the final checkout. Tests using liquid hydrogen were pushed back until mid-December (Ref. 33). Final preparations were made to the setup in November. The reactor core was stabilized, the nozzle pressure checked, thermocouples added, and electronics verified (Ref. 34). The first attempted run on December 18 was scrapped because of instrument noise levels and monitor problems. The latter problems were quickly rectified, but the former required an extensive investigation. Mechanical work on B–1 continued in preparation for the planned January 17 second test (Ref. 35).

Figure 2.13.—B–1 test stand as it appeared in September 1964 (C–1964–72617, NASA Glenn).

The first actual liquid-hydrogen test run took place on January 17, 1964. Excess instrument noise from the power supply for a Rosemont temperature sensor caused problems with some of the data channels. A second attempted run on January 28 was also unsuccessful because of excess noise in 60-percent of the instrumentation channels, failure of a hydraulic pumping unit, and a leaking turbopump discharge valve (Ref. 20).

The second successful test run was accomplished on February 12. The instrument transmission cable grounding system was modified to fix the data noise problem, and most of the data channels performed well. In addition, several modifications were made to the valves and sensors (Ref. 36). The problematic data channels were improved, and several valves were reconfigured. An error-free liquid-hydrogen test was run on March 25, 1964 (Ref. 37).

The April 7 run was scrubbed when a run tank valve could not be sealed. A follow-up test on April 22 was successful, but there remained problems with the run tank valve. Again several valves were switched. Also, television cameras and recorders were permanently installed in the test section (Ref. 38). Two more successful tests were run on May 6 and May 22. The exterior of the building was painted, and a reheater system was installed to warm the engine after the test runs (Ref. 39).

Additional liquid-hydrogen runs were accomplished on June 3 and 17, 1964. Again, the engineers tinkered with the setup to improve minor problems. Larger modifications included the rehabilitation of two units in the B–1 Boiler House to double its capacity (Ref. 40). After another test run on July 1, the pump rotor was locked and the test was run again on July 15 to determine the torque produced by the liquid-hydrogen flow. Approximately 8 hours were spent during a run on July 29 trying to define the performance requirements for the pump discharge servovalve. The remainder of the test was cancelled because of the time spent establishing those requirements (Ref. 41). NASA awarded a $1.3 million contract to Rocketdyne in July 1964 to supply four RN–6 liquid-hydrogen chilled nozzles to be tested for the NERVA program. One of these nozzles was destined for Plum Brook (Ref. 42).

Before the next runs, two high-speed Fastex cameras and a gaseous nitrogen heater were installed. Temperatures of the reactor, nozzle, and propellant system were measured to form a baseline during warm up. A new control system for the engine's turbine and a flight-weight piping system were installed before the next test (Ref. 41). The final practice test was run on August 12. A test scheduled for August 26 was deemed to be superfluous and cancelled. B–1 was ready for its NERVA test program. During this time the B–1 exhaust system was beginning to be linked to the new B–3 system (Ref. 43).

2.2.3 B–1 Alterations

Most of the NERVA equipment was removed in May 1965 and installed in B–3. In August 1967 preparations began at B–1 for a series of Advanced Centaur tests that November: a pressurized gas-conditioning system, a liquid-oxygen system with a 13,000-gal dewar, a liquid-hydrogen system, a hydrogen burn-off and liquid-oxygen dump line, a new patchboard and digitizer for the instrumentation system, and a trailer for the high-pressure helium supply (Ref. 44). In October 1967, NASA engineers discovered that the preparations required more time than was planned, so the testing was put off until early December. The Plum Brook controls engineers designed a back-pressure control system since flight-weight vehicle vent valves could not be procured. Also in October 1967, the inspection of the Centaur 5C tank to be used for the tests began with a pressure test and a cryogenic test (Ref. 45).

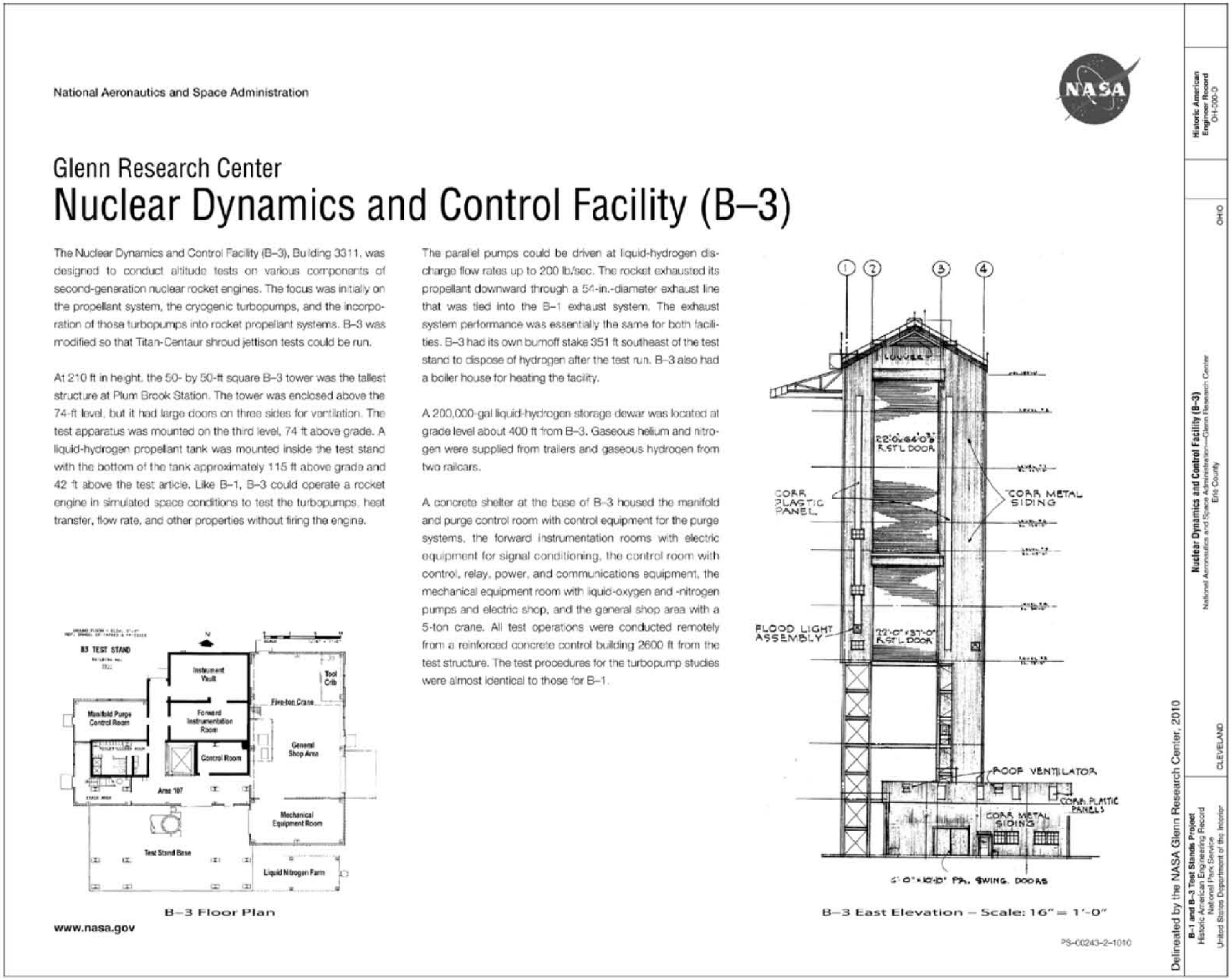
In January 1973 NASA cancelled the NERVA program and decided to shut down Plum Brook. Over the next 18 months, Plum Brook's staff was reduced from 600 to 54 and the facilities were put into mothball condition (Ref. 46). B–1 had completed its last test in July 1969. An End Condition Statement report was issued for each facility stating what steps had been taken to deactivate the various systems. Electrical systems were deenergized, boilers deactivated, the gas system shut down, the air service depressurized, and so forth. Technically, the mothballed B–1 could be put back into operation within 3 months. The structures were grouped into three categories to prioritize their readiness for reactivation, with Readiness Category 1 being the most important. The shutdown steps were well documented along with procedures to start up the facilities again.

In the mid-1970s, NASA decided not to keep all the facilities in standby condition. Those not preserved were cannibalized for research and test equipment, but the overall structure and systems remained in place. B–1 was initially placed in Readiness Category 2, but its Pump and

Shop Building was placed in Readiness Category 1. In December 1977, B–1's freight elevator was removed for NASA's new Michoud Assembly Facility in New Orleans. In January 1978, B–1's 300-ft liquid-hydrogen vacuum-jacketed transfer line was removed for a Langley Research Center hydrogen spill test conducted by the Jet Propulsion Laboratory at China Lake Naval Facility. In 1982 the B–1 test stand was demoted to Readiness Category 3 (Ref. 4).

Figure 2.14.—B–1 after the freight elevator and liquid-hydrogen transfer line had been removed, 1984 (C–1984–05694).

2.3 B–3 Test Stand Physical History



National Aeronautics and Space Administration

Glenn Research Center

Nuclear Dynamics and Control Facility (B–3)

The Nuclear Dynamics and Control Facility (B–3), Building 3311, was designed to conduct altitude tests on various components of second-generation nuclear rocket engines. The focus was initially on the propellant system, the cryogenic turbopumps, and the incorporation of those turbopumps into rocket propellant systems. B–3 was modified so that Titan-Centaur shroud jettison tests could be run.

At 210 ft in height, the 50- by 50-ft square B–3 tower was the tallest structure at Plum Brook Station. The tower was enclosed above the 74-ft level, but it had large doors on three sides for ventilation. The test apparatus was mounted on the third level, 74 ft above grade. A liquid-hydrogen propellant tank was mounted inside the test stand with the bottom of the tank approximately 115 ft above grade and 42 ft above the test article. Like B–1, B–3 could operate a rocket engine in simulated space conditions to test the turbopumps, heat transfer, flow rate, and other properties without firing the engine.

The parallel pumps could be driven at liquid-hydrogen discharge flow rates up to 200 lb/sec. The rocket exhausted its propellant downward through a 54-in.-diameter exhaust line that was tied into the B–1 exhaust system. The exhaust system performance was essentially the same for both facilities. B–3 had its own burnoff stake 351 ft southeast of the test stand to dispose of hydrogen after the test run. B–3 also had a boiler house for heating the facility.

A 200,000-gal liquid-hydrogen storage dewar was located at grade level about 400 ft from B–3. Gaseous helium and nitrogen were supplied from trailers and gaseous hydrogen from two railcars.

A concrete shelter at the base of B–3 housed the manifold and purge control room with control equipment for the purge systems, the forward instrumentation rooms with electric equipment for signal conditioning, the control room with control, relay, power, and communications equipment, the mechanical equipment room with liquid-oxygen and -nitrogen pumps and electric shop, and the general shop area with a 5-ton crane. All test operations were conducted remotely from a reinforced concrete control building 2600 ft from the test structure. The test procedures for the turbopump studies were almost identical to those for B–1.

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Historic American Engineer Record OH-200-D

OHIO

Nuclear Dynamics and Control Facility (B–3)
National Aeronautics and Space Administration—Glenn Research Center
Erie County

CLEVELAND

B–1 and B–3 Test Stands Project
Historic American Engineering Record
National Park Service
United States Department of the Interior

Figure 2.15.—B–3 test stand drawing and overview, 2010 (PS–00243–2–1010, number, NASA Glenn).

2.3.1 B–3 Construction Data Sheet

Dates of Construction: 1963 to 1965
Excavations for B–3 began in March 1963. The framework for the test stand began going up that July and was largely in place by early September. The exterior walls were in place by late October 1963, and photographs show that the test stand itself was mostly complete in January 1964 (Ref. 47). The next year and a half would be spent connecting B–3 to the B–1 Boiler House, the hydrogen tank, and other infrastructure needed for operation. In March 1965 the planned NERVA tests for B–3 were cancelled. Instead, another set of NERVA tests would be transferred from B–1. The transfer of the test equipment extended the initial construction until December 1965 (Ref. 48).

Engineers: NASA Lewis engineers developed the B–3 design, but they hired a local engineering firm, Osborn Engineering Company, to create the blueprints.

Contractors: E.T. Browder Construction Company of West Virginia performed most of the construction (Ref. 49), but Potomac Metal Products Company fabricated and erected the steel frame, and Bay Construction, Inc., excavated and laid the foundation (Ref. 22). Boonshaft and Fuchs supplied the actuators, Acme Construction Company built the railroad sidings leading to B–3 (Ref. 50), and Annin Company supplied the control valves. John W. Danforth Company installed the propellant support systems, Technician, Inc., installed the altitude exhaust system (Ref. 21), Lake Erie Electric Company installed the electrical control system (Ref. 23), and Valley Electric Company installed the instrumentation system (Ref. 51).

Owners: The NASA Lewis Research Center. In March 1999 the name was changed to the NASA John H. Glenn Research Center. The property for Plum Brook was acquired incrementally by NASA and its predecessor, the NACA, from 1955 to 1963.

Original Cost: $1,878,000

Significance: B–3 was used to study tanking and flow systems for complete rocket systems in simulated altitude conditions. The rocket's combustion chamber was pressurized to simulate an actual launch, but the engines were not fired. Researchers could study the effect of combustion chamber pressure on flow dynamics (Ref. 5). B–3 ran two series of tests during its operational years: one for the NERVA nuclear engine and one for the Centaur engine.

The B–3 NERVA tests established the proper startup procedure, which included liquid-hydrogen flow rates, power-cycle time delay, and the powering of the turbine. The use of a realistic feed system helped define the centrifugal turbopump's overall system performance and mechanical characteristics. The turbopump was installed directly under the scale representation of a propellant tank. Engineers designed a reheat system for B–3 that saved $50,000 worth of propellants and allowed engineers to perform six series of two back-to-back tests (Ref. 52).

B–3 conducted a number of tests leading up to the first Titan-Centaur launch and the Viking mission to Mars. Unlike previous B–1 or B–3 studies, these focused on the protective shroud not the turbopumps. Unlatch tests verified that the shroud would jettison in a cold space environment, structural load tests determined the structural integrity of the shroud in a cold environment, and insulation tests led to a redesign of the insulation system (Ref. 4).

2.3.2 B–3 Original Construction and Startup

NASA Lewis engineers likely began planning the B–3 test stand, along with HTF, B–2, and other improvements, shortly after President Kennedy's "Urgent National Needs" speech in late May 1961. The new facilities were in a budget approved by the President in January 1962. By the time that Congress approved the budget that September, NASA had developed a schedule for B–3 through 1966.

Cleveland-area Osborn Engineering Company created the initial drawings in February 1963. Bay Construction Company and Potomac Metal Products Company were contracted in March 1963 to perform the excavation and steelwork, respectively. In July 1963, NASA hired E.T. Browder Construction Company of St. Albans, West Virginia, to build B–3 (Ref. 22). The work included enclosing the test stand, extending electric power and utilities to the site, and constructing the heating plant and a substation. The contract also included equipping B–3 with heat, light, power, ventilation, plumbing and special services, as well as installing the elevator and shop crane and completing the facility (Ref. 26).

Figure 2.16.—Ground is excavated for the B–3 test stand, 1963 (P63–01266, NASA Glenn).

Excavations for the B–3 test stand and its infrastructure began in mid-March 1963 and were completed by early April. Supports were placed into the earth, and some concrete was poured at the base in early May (Ref. 50). By May 24, the area had been graded, a railroad line was being run to the site, a concrete apron was being laid to the west of the test stand, and a large tank for liquid hydrogen was delivered to the site. The latter two items were completed in June. Also in June, the concrete base of the test stand was put in place. B–3 steel framework began to be assembled in early July. The framework was approximately 50-percent complete by the end of the month, another 25-percent complete by August 6, and in place by mid-August. The framework for the adjacent shop was built, and the entire steel structure was painted in early September. The siding and platforms were being added in October, and the structure itself was complete in mid-November 1963.

Figure 2.17.—Construction workers set the supports for the B–3 test stand into the ground, 1963 (P63–01405, NASA Glenn).

Figure 2.18.—Train carries the steel framework for B–3 to the construction site, 1963 (P63–01565, NASA Glenn).

Figure 2.19.—Construction of the B–3 control room in the B Control and Data Building, 1963 (P63–01559, NASA Glenn).

Figure 2.20.—First girders are erected for the B–3 test stand, 1963 (P63–01606, NASA Glenn).

Figure 2.21.—Paul R. Jeffers, Inc., construction crew assembles the B–3 test stand, 1963 (P–1963–01661, NASA Glenn).

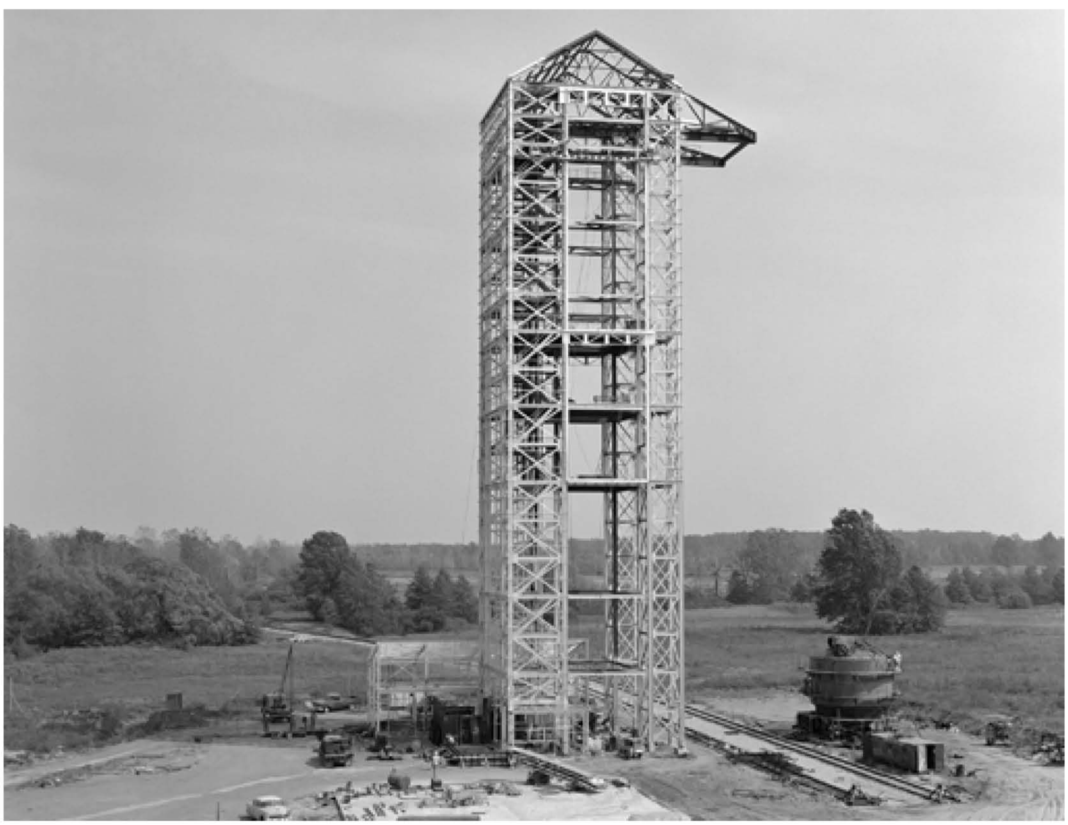

Figure 2.22.—Framework for the B–3 test stand nears completion, 1963 (P63–01807, NASA Glenn).

The next year and a half were spent installing the other infrastructure and support systems. In December 1963 NASA awarded contracts for installing the control valves, propellant support systems, and altitude exhaust system at B–3. Work on those components began soon thereafter (Ref. 21). The electrical control system contract was let in April 1964 (Ref. 23). The altitude exhaust piping was only partially installed by September. Photographs show that by March 1965 the B–3 altitude exhaust system had been connected to the B–1 system and the facility was nearly complete.

In April 1965 NASA Lewis management decided to transfer the NERVA Mark IX tests from B–1 to B–3. Plans indicated that the transfer of equipment and modifications to B–3 would take up to 5 months (Ref. 53). The construction of the liquid-hydrogen centrifugal pump stands and instruments was finished in early June 1965. After some delays and extensive testing, the system was ready for operation by the first week of July (Ref. 54). The reactor, carriage, and new instrumentation cabinets were installed in July, and preliminary flow tests were successful for the altitude exhaust purge system. The B–3 nozzle access platform was completed in August, and the reactor piping, camera supports, signal-conditioning equipment, and exhaust purge system were being worked on. However, hydraulic fluid contaminated the steam-pressure control system, leaks were found on two large valve actuators, and leaks were found between the nozzle and mylar seal adapter ring (Ref. 55). The first tests were run in March 1966.

2.3.3 B–3 Alterations

In February 1966, a reheater system was installed that brought the equipment back to ambient temperatures after it had been filled with cryogenic fuels. This allowed two tests to be run in a single day.

In 1974, after Plum Brook was closed, B–3 and the B–3 Boiler House were placed in Readiness Category 2. When B–3 was downgraded to Readiness Category 3 in 1982, the architectural survey noted that the shop area was being used as a warehouse and that aircraft warning lights would remain active (Ref. 26).

2.4 Nuclear Engine for Rocket Vehicle Application (NERVA) Tests

In the late 1950s, the Project Rover phase of the nuclear rocket program was being carried out both at Los Alamos and at NACA Lewis's Cleveland campus. The 300-MW Kiwi-A reactors were developed to study instrumentation, control, fuel element types and fabrication, and structural design. The Kiwi-B reactors were intended to dramatically increase power without increasing overall size. Like Kiwi-A, the early Kiwi-B reactors' graphite fuel elements were damaged because of harsh internal vibrations during the firing. Aerojet was selected in July 1961 to design the NERVA engines that would incorporate the Kiwi-B reactor. The Los Alamos group was pushing ahead, incorporating advanced design elements such as the Rocketdyne turbopump, the liquid-hydrogen-cooled nozzle, and the automatic bootstrap start. Although they were trying to accelerate the schedule, the Los Alamos team blanched at testing the new reactor with liquid hydrogen (Ref. 13). Instead they used gaseous hydrogen in a successful 300-MW run of the Kiwi-B1 in December 1961 at the Nevada Test Site (Refs. 11 and 14).

While work progressed on the reactor itself, other nonnuclear components and systems for the engine also had to be checked and studied. In May 1958, NACA Lewis announced that it would build rocket testing facilities at Plum Brook (Ref. 12). One of the facilities, B–1, was a tall test stand to be used to test the turbopumps and propellant feed system for the Kiwi-B reactor (Ref. 56). Much would change in the program between 1958 and 1964 when B–1 became operational.

The engine's propellant feed system consisted of a Rocketdyne Mark IX pump driven by a Mark III turbine. The turbine received its power via hot gas from the nozzle. It was cooled by cold hydrogen, which then passed through the turbine to spin the pump (Ref. 57). The liquid-hydrogen turbopump was one of the most important components of the engine. Low-pressure liquid hydrogen flowed from the Kiwi engine propellant tank to the turbopump. The pump increased the pressure and pumped the fuel through the nozzle and reflector, cooling those components on its way to the top of the reactor. The hydrogen expanded as it was heated in the reactor core and then was exhausted out the nozzle (Ref. 58).

Changes in fluid pressure, flow, and friction result in vibration, cavitation, stalls, or instabilities in turbopumps. Turbopumps require lubrication, but in nuclear engines, radiation turns most lubricants to sludge. Radiation also damages the materials from which the turbine and turbopump are constructed. The delicate texture of the liquid hydrogen made it more difficult to pump and increased the odds for cavitation, particularly when heated by radiation (Ref. 13).

Rocketdyne and Aerojet began exploring turbopumps for the nuclear engine as early as 1955. In 1958 Aerojet recommended a centrifugal pump, but Rocketdyne proposed an axial-flow design. In June 1958 the Air Force accepted Rocketdyne's version, but the NACA, which was about to assume the Air Force's role in Rover, did not care for either design (Ref. 13).

Rocketdyne began working on its liquid-hydrogen turbopump for Project Rover in 1956. When NASA became more involved with Rover in 1958, its two leaders with the most technical acumen, Hugh Dryden and Abe Silverstein, pressed to have the unproven turbopump removed from the design. Instead Silverstein suggested using pressurized gas to move the propellant through the system. This method was generally utilized for low-speed and lightweight applications. Researchers at Los Alamos later determined that this method could affect the steel's molecular composition and make it brittle. NASA cancelled the proposal and recommissioned Rocketdyne's turbopump. This required a redesign of Test Cell C at Los Alamos and pushed its completion date from 1960 to 1962 (Ref. 13).

This misjudgment by Dryden and Silverstein resulted in anger by the AEC and Senator Anderson who believed that NASA's 10-plus-year estimate for completion of the NERVA program was inaccurate. Anderson pressed for a flight test on a Saturn booster in the mid-1960s. NASA agreed to form a joint managerial structure to oversee the program. This became the Space Nuclear Propulsion Office (SNPO) (Ref. 13).

Despite the planning changes, Rocketdyne's development of the Mark IX turbopump, which used liquid hydrogen as a lubricant for its bearings, proceeded rapidly. Rocketdyne determined that either an axial-flow or centrifugal design would work, and each had benefits for certain types of missions. The turbopump technology developed for NERVA in the late 1950s would ultimately be used for the Saturn V rocket. James Dewar wrote, "If this [turbopump] work had not started in 1956, the J–2 might have been unavailable for the Saturn V, jeopardizing the lunar landing or perhaps requiring the giant Nova." (Ref. 13).

Before the entire NERVA engine could be studied, the components, reactor, turbopump, nozzle, and fuel elements were tested independently at Los Alamos, Aerojet, the Nevada Test Site, and NASA Lewis. This was followed by testing of the major subsystems at Los Alamos, Aerojet, and Rocketdyne (Ref. 57). Servoloops controlled the pump speed, the mass flow rate to the reactor, and the specific speed. A venturi downstream from the pump measured the flow rate to the reactor and compared it with the rate demanded by the reactor. A flow-rate meter compared the two figures and adjusted the turbopump speed by varying the turbine throttle valve (Ref. 59).

In a February 1962 letter to NASA Headquarters, NASA Lewis researcher John Povolny outlined the extensive plans to test the NERVA engine in the B–1 test stand. There were several aspects to the planned tests: engine startup transients of a Rocketdyne Mark IX turbopump, Kiwi-B nozzle, pressure vessel, core, and reflector; mapping of the Mark IX pump and turbine, including cavitation and stall characteristics; and a repeat of the Mark IX tests using an Aerojet turbopump instead of the Mark IX. Povolny included some possible future tests: including a Mark IX startup test using a boost pump, a Mark IX startup test using an electrically heated reflector, a Mark IX engine mapping test at different engine speeds with and without a boost pump, shutdown transients, and heat propellant system requirements (Ref. 60).

Figure 2.23.—NASA Lewis technician inspects the cooling tubes on a Kiwi-B nozzle, 1963 (C–1963–66543, NASA Glenn).

The first Kiwi-B run with liquid hydrogen at the Nevada Test Site took place in September 1962. The core disintegrated, proving that the design was inadequate, but the anticipated hydrogen flow problems never materialized. Another core design, Kiwi-B4, was tested in November 1962. Vibration resulting from dynamic instability from the hydrogen flow caused several of the fuel elements to break. Researchers analyzed and tested the reactor's components and subsystems throughout 1963. The engineers addressed the problem and retested the Kiwi-B4 design in May 1964, just as the B–1 test stand was completed. The reactor operated smoothly, but difficulties with the nozzle ended the test. In July 1964, the design was finally run successfully at full power for 8 minutes (Refs. 11 and 14).

2.4.1 Nuclear Engine for Rocket Vehicle Application (NERVA) Propellant Feed System Tests (B–1)

The NERVA rocket had to be able to restart on its own using a preprogrammed startup system. At NASA Lewis, researchers were seeking to create a safe programmable startup system for the nuclear rocket engine. Control system parameters needed to be specified and heat-transfer behavior had to be determined in order to have a reliable programmed startup. Lewis was using analog computer programs to create the programmed startup, but they were not able to successfully simulate all startup conditions. The B–1 cold-flow nuclear rocket simulation test program was created to obtain the data at the initiation of flow and immediately afterward. This information could be used for other computer simulations (Ref. 61).

The tests were designed to start an unfueled Kiwi-B1B reactor and its Aerojet Mark IX turbopump without any prechilling of the pumps or propellant lines. The key elements of the study would be startup dynamics and control, heat transfer and flow, mechanical phenomena, and turbopump characteristics. A more detailed breakdown included the issues of two-phase flow oscillations, required chilldown length prior to bootstrapping, turbine flow for bootstrapping, temperature-time variations in all components, choking in the nozzle cooling passages, state of the hydrogen during startup and as it entered the core, turbopump operating characteristics, vibration characteristics throughout the system, heat transfer and flow between the pump discharge and nozzle inlet, and improved methods for calculating pressure drop, fluid temperatures, and material temperatures (Ref. 24).

The B–1 test stand was operated with liquid nitrogen and gaseous hydrogen during the initial facility checkout, but the use of liquid hydrogen during the actual tests would present many of its own problems. The first run in January 1964 was designed to work through those problems. That run included 290 measurements of various data recorded on magnetic tape. A 1103 computer program converted the signals to engineering units and calibrated the equipment (Ref. 24).

It was crucial for the planned long-term missions that the NERVA rocket be able to vary its speed and restart its engine without any external power. The latter was called bootstrapping. This was accomplished by allowing a small amount of liquid hydrogen to flow through a valve into the reactor. The hydrogen vaporized and started the turbine, which drove the turbopump. The turbopump then pumped additional liquid hydrogen to the reactor. On September 21, 1964, the first NERVA run was conducted at B–1. It had been more than 6 years since the facility's conception. The engine did indeed start up at altitude conditions, but the test was shortened when key instrumentation channels were not recorded and an insufficient amount of liquid hydrogen was in the NERVA propellant tank. A follow-up bootstrap test on September 30 was more successful (Ref. 62). The test determined that the turbine could achieve bootstrap acceleration during flow initialization.

Figure 2.24.—Aerojet Kiwi-B reactor is lifted up into the B–1 test stand, 1963
(P63–01352, NASA Glenn).

Almost simultaneously, the first NERVA reactor test, NRX–A2, was successful on September 24, 1964, in Nevada. It was a tremendous success, and Aerojet took out a full page ad in the Wall Street Journal to tout its accomplishment (Refs. 11 and 14). The engine was successfully bootstrapped at Los Alamos in October 1964. The same test revealed that the turbopump could control the rate of propellant flow at all levels, thus operating the engine at virtually any speed. James Dewar described it, “Unglamorous compared to a roaring full-power run, this was actually a major milestone: 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.” (Ref. 13).

The third bootstrap test at B–1 was successfully completed on October 15. All the test objectives were met. That very same day, the first demonstration of a bootstrap startup of a NERVA reactor occurred at Los Alamos. It was an underappreciated but major test for the program. The same test revealed that the turbopump could control the rate of propellant flow at all levels, thus operating the engine at virtually any speed (Ref. 13).

The B–1 runs were followed by a sequence of steam ejector tests during the week of October 22, 1964, that determined the ejector air pumping capacity at various steam pressures. A chilldown test was run on October 30 without powering the engine's turbine (Ref. 63). The chilldown test determined the heat-transfer rate and pressure drop in the propellant feed system components. Hydrogen's unique characteristics included the convective boiling of two-phase liquid hydrogen. The B–1 test adequately simulated the first 15 seconds of the nuclear engine startup (Ref. 64).

The electronics were calibrated, the system was purged with helium, the liquid-hydrogen tank for the NERVA engine was filled, and the turbopump assembly was chilled before the test run. The exhaust system was then purged by steam flowed through the ejectors. A sequencer control circuit automatically initiated the test conditions when the exhaust system reached its preset pressure level. When the run conditions were achieved, a valve was opened below the turbopump to release the liquid hydrogen to the engine. This was considered considered to be T–0 (time zero). The hydrogen was gradually vaporized as it flowed through the feed line to the nozzle. Initially gaseous hydrogen would enter the nozzle, but over time the system would cool and the gaseous hydrogen would be replaced by liquid hydrogen. Bootstrap ignition of the engine was started simultaneously. This increased the pressure and flow through the system. Soon the entire engine was cooled, and liquid and two-phase hydrogen were throughout the system. The B–1 tests ended when the propellant entered the core. It took only 4 seconds for the nozzle tubes to cool down (Ref. 64).

During a November 6 meeting between the Plum Brook operations people and the NASA Lewis researchers, a test schedule was developed for the next 5 months. The Mark IX turbopump would be tested every 2 weeks during that period. The B–1 instrument terminal room would have to be expanded, a burnoff line from the pump discharge would be added, a transfer line from the 200,000-gal liquid-hydrogen storage dewar would be linked to B–1, and a new steam-pressure control system would have to be installed (Ref. 65).

A successful November 12 test was the first of several bootstrap tests with lightweight piping between the pump discharge and nozzle inlet. The ensuing run was delayed when a defective turbine sprayed lube oil (Ref. 65). The runs were short, usually about 1 minute.

Sixteen seconds into the December 9 test, the engine was shut down because of uncontrolled turbine speed. A faulty feedback signal was found to be the problem. The December 22 run was mostly error-free except for unstable pump speed and flow control (Ref. 66). Two more successful runs followed in January 1965, and plans for reactor structural tests were added to the program for March. Work on the test stand heating system started (Ref. 67) and was completed in February. Two more good runs were accomplished in February. Meanwhile design work for the second series of runs was underway (Ref. 68).

Attempts to predict system dynamics and component performance of the NERVA nuclear rocket simulator were undertaken in B–1. Previous tests started with 10-percent propellant flow and 1-percent of power. Researchers wanted to specify control-system parameters to make sure that the system functioned correctly during a programmed startup. This test attempted to include the startup of the engine. Cold-flow tests were run in B–1 to study the system dynamics and component behavior during startup (Ref. 24).

The dynamics, control, heat transfer, flow, mechanical phenomena, and turbopump behavior during startup were studied. This included the severity of two-phase flow oscillations, chill-down time to smooth flow instabilities, turbine flow required, temperature/time variations for all components, and determining if choking occurs in the nozzle coolant passages. Of particular interest was the behavior of the liquid hydrogen during startup—throughout the system but especially as the liquid hydrogen entered the reactor core. The overall flow density and heat transfer of the liquid hydrogen throughout the system was also important. Any vibrations from the system were noted, and methods of measuring pressure drop and temperatures were improved (Ref. 24).

Figure 2.25.—Operator at the B–1 controls in the B Control and Data Building during Nuclear Engine for Rocket Vehicle Application (NERVA) tests, 1965 (P65–02149, Plum Brook).

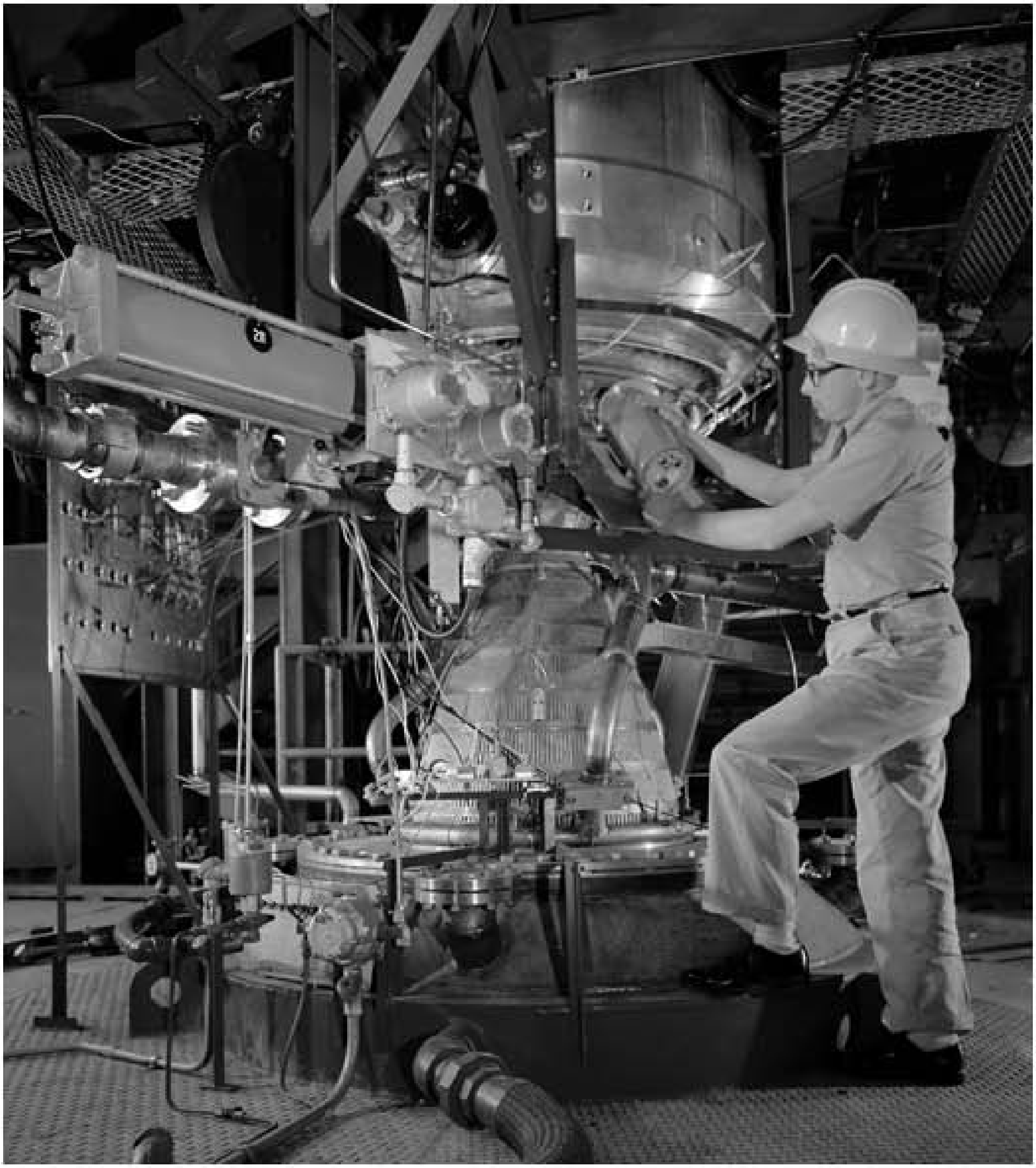

Figure 2.26.—Technician installs test equipment on the Kiwi-B reactor, 1964 (P64–01290, NASA Glenn).

The tests showed that the Mark IX turbopump accelerated as needed and did not stick, the expected pressure fluctuations in the reflector and nozzle were not as severe as in other tests, and the separation of flow from the nozzle surface resulted in a large-amplitude vibration in the nozzle (Ref. 24).

B–1 anticipated further testing of the Mark IX turbopump, but that was cancelled on March 31, 1965. On April 13, NASA Lewis management decided to transfer the second series of NERVA tests to B–1's new sister stand, B–3. B–1 would be put on standby status. At B–3, the second series of NERVA tests from B–1 were to be alternated with full-scale pump tests and system dynamics tests. The research hardware and instrumentation would be transferred to B–3. This transfer and B–3 modifications would take up to 5 months. Test runs of the facility were planned for October. The new tests would use an Aerojet Mark III, Mod 4 turbopump, a Kiwi-B1B reactor with mock fuel cells, and several servocontrol systems (Ref. 53).

Figure 2.27.—President John F. Kennedy visits the Nevada Test Site with Atomic Energy Commission (AEC) Chief Glenn Seaborg at his right and Space Nuclear Propulsion Office (SNPO) Head Harold Finger leading the way, 1962 (Harold Finger photograph).

2.4.2 Nuclear Engine for Rocket Vehicle Application (NERVA) Pump-Down and Cold-Flow Tests (B–3)

Even before its official inception in 1961, the NERVA program was constantly battling for Federal funds. As early as October 2, 1957—2 days before the Sputnik I launch—Congress proposed reducing the Rover budget. Sputnik changed everyone's outlook on space, and funding was increased in February 1958 (Ref. 13). Sputnik also brought about the Nation's manned space program, which NERVA would have to compete with for funding throughout the decade.

In May 1961, as the SNPO was deciding which aerospace firm would be selected to design the NERVA engine, President Kennedy gave his famous address to Congress vowing to land on the Moon. The second item on his space agenda was Project Rover. He promised, "An additional

23 million dollars, together with 7 million dollars already available, will accelerate development of the Rover nuclear rocket. This gives promise of some day providing a means for even more exciting and ambitious exploration of space, perhaps beyond the moon, perhaps to the very end of the solar system itself." (Ref. 69).

Two and a half years later, President Kennedy's successor, President Lyndon Johnson significantly reduced the NERVA budget, resulting in the cancellation of the planned Reactor In Flight Tests. The ground testing phase was then extended. The Vietnam War and President Johnson's war on poverty were costly efforts that resulted in NASA Administrator James Webb and AEC Chief Glenn Seaborg having to justify their budgets. Funding for both NASA's manned missions and the joint agency NERVA rocket plateaued in the mid-1960s and declined thereafter (Ref. 70).

As stated earlier, in April 1965 NASA Lewis management decided to transfer the second series of NERVA tests from B–1 to the newly completed B–3, with runs scheduled for that November. These tests would use an Aerojet Mark III, Mod 4 turbopump, a Kiwi-B1B reactor with mock fuel cells, and several servocontrol systems. The research hardware and instrumentation would be transferred from B–1 to B–3 (Ref. 53).

The new reactor nozzle arrived at B–3 in mid-May, and most of the equipment transfer was completed by the end of the month. A new steam regulating system was successfully tested. Reactor carriage modifications, fabrication of the 54-in. adapter for the nozzle, installation of servovalves, and hookup of new instrumentation equipment continued (Ref. 71).

The construction of the liquid-hydrogen centrifugal pump stands and instruments was finished in early June 1965. After some delays and extensive testing, the system was ready for operation by the first week of July (Ref. 54). The reactor, carriage, and new instrumentation cabinets were installed during July, and preliminary flow tests were successful for the altitude exhaust purge system. NASA was informed that Aerojet could not supply the Mark III reactor until late August, thus delaying the startup of the test program until November (Ref. 72).

Figure 2.28.—Engineers inspect the Kiwi-B reactor outside the B–3 test stand, 1967 (P67–01290, NASA Glenn).

The B–3 nozzle access platform was completed in August 1965. Reactor piping, camera supports, signal-conditioning equipment, and the exhaust purge system were being worked on. However, hydraulic fluid contaminated the steam pressure control system, leaks were found on two large valve actuators, and leaks were found between the nozzle and mylar seal adapter ring. Delivery of the reactor was now delayed until late September (Ref. 55). The leak problem was resolved, and the pressure transducers and cameras were installed in September. All the data channels that could be installed without the equipment were installed (Ref. 73).

The Mark III reactor was finally delivered the week of October 4. The turbopump and liquid-hydrogen-level probe were quickly installed and instrumented. Problems continued with the actuators (Ref. 74).

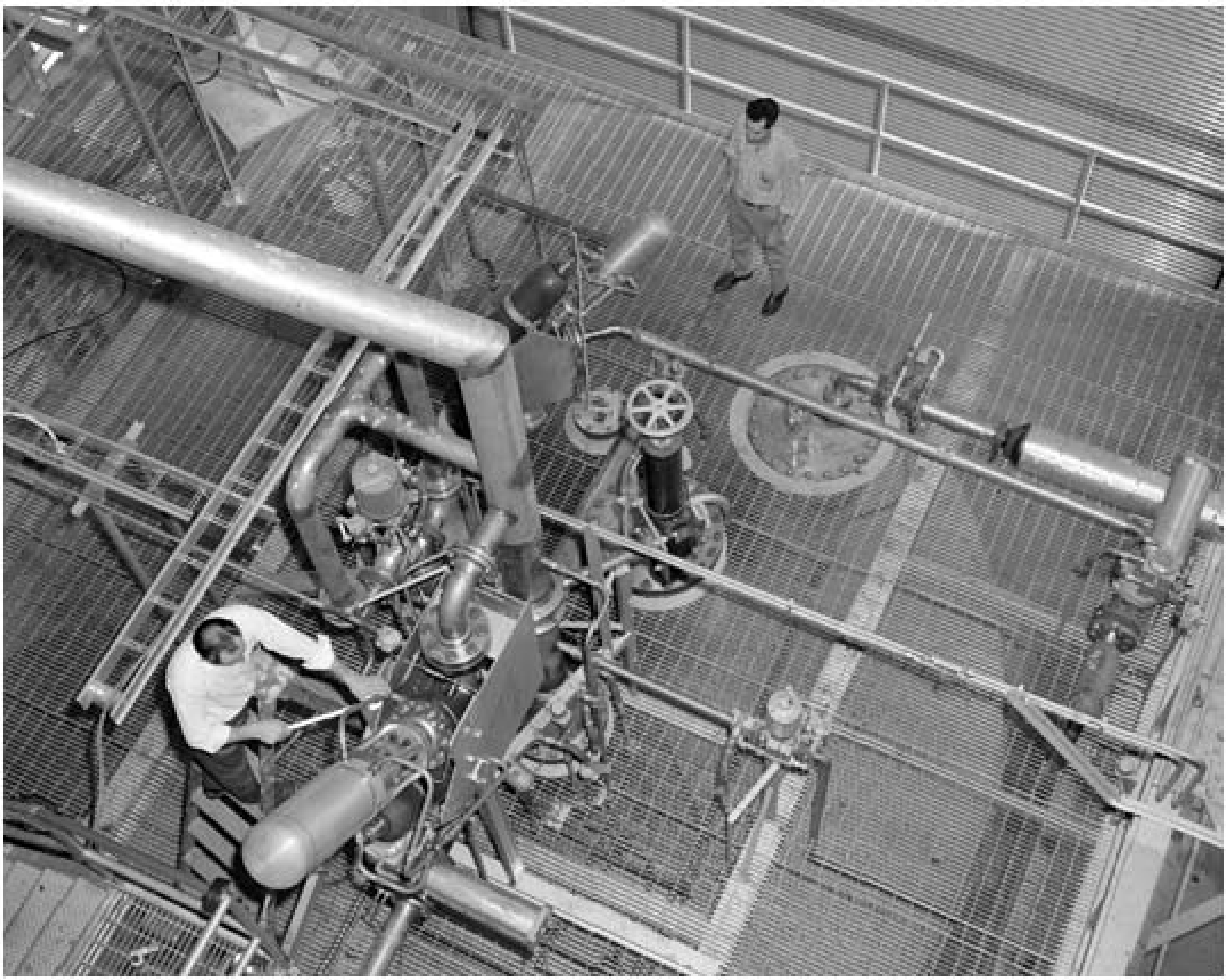

Figure 2.29.—Technicians work on Mark IX turbopump in the B–3 test stand, 1966 (P66–01663, NASA Glenn).

The first liquid-nitrogen pretest run was made on November 17. There was noise on the instrumentation channels, the liquid-level probe failed, the burnoff flame was extinguished by the flow of purged gas, and the tank shutoff valve failed to close. There were also problems with the data-recording equipment (Ref. 75). A second liquid-nitrogen run was conducted on December 7 and 21, 1965. There were only minor data-transmission problems (Ref. 48).

A test with a prechilled pump took place on February 3, 1966, and a second test without chilling the pump was run on February 25. Both were successful except for problems with several data channels because of noise from the recently installed Fastex high-speed cameras. Several additional problems with the data recording were discovered after the test. The crew began installing a reheat system to return the reactor and its components to ambient temperatures immediately after a test run. This would allow two tests in a single day and would likely reduce the amount of days between test runs (Ref. 76).

Meanwhile at the Nevada Test Site, a major test of the NERVA NRX engine also took place in February. The test was the first time that all the engine components were integrated. The components were arranged in an unrealistic manner, but all functioned as they would on a flight. The test showed that the reactor could be bootstrapped, automatically controlled, and prove itself stable in a wide range of conditions. It also proved that the reactor, turbopump, and other components were reliable. Harry Finger wrote, “The NRX/EST test program was important in that it was the culmination of a long line of Rover research and development tasks.” (Ref. 57).[3]

A test at B–3 was run on March 10 to determine the chilldown dynamics for a specific tank pressure. It was also the first time that researchers attempted to use the reheat system. Although it worked well, another operational problem prevented a second test on March 10. The first of a series of turbopump tests was performed on March 30 to map the lower speed range of the Mark III’s pump performance. The flow was purposely not powered through the engine, and the test objectives were accomplished (Ref. 77).

The next turbopump test was successfully run on April 27. It was the first time that the railcar tank for gaseous hydrogen was used (Ref. 78). The final turbopump test was run on May 19 to test the pump at various speeds and flow rates. NASA Lewis researchers determined that the pump speed, pressures, and flow rates oscillated during the run (Ref. 79).

The turbopump test was rerun on June 9 to test corrections to fix the vibrations and oscillations experienced on May 19. A malfunction of the run tank vent servovalve and in a helium purge regulator caused the rerun to be aborted. When the test was retried on June 14, the oscillations had decreased. Although the researchers were satisfied with the results, they decided to modify B–3 for the chilldown tests. The first of the chilldown tests was run on June 30 from an unchilled startup. The reheater brought the reactor back to ambient temperatures in 3 hours, permitting a second run. The second test that day prechilled the system first (Ref. 80).

[3]NRX/EST, NERVA Reactor Experiment/Engine System Test.

Figure 2.30.—B–3 as it appeared during the Nuclear Engine for Rocket Vehicle Application (NERVA) tests, 1967 (C–1967–01766, NASA Glenn).

The facility was modified for a series of nine bootstrap tests. The first prechilled bootstrap test was run on July 26, 1966. The first attempt failed when the controls programmer failed to start. Once the problem was rectified and systems were reset, the reactor was successfully run for 23 seconds (Ref. 81).

After a 3-week cleaning and inspection of the Boiler Building, the second prechilled bootstrap test was run on August 25. The test opened the turbine power-control valve simultaneously with the pump's main discharge valve. The second test that day was cancelled after the flowmeter was found to be inoperable (Ref. 82).

In September an evaporation test was run on the 200,000-gal liquid-hydrogen storage dewar. The dewar could not be used for 2 weeks afterward. In addition, the steam system could not be used while two new steam accumulators were installed at B–2. No research test runs were made because of these activities (Ref. 83).

October was a busy month at B–3. Four bootstrap tests were run—two on October 5 and two on October 12. During the second test, the turbopump did not start successfully despite some acceleration. The data channels were extremely noisy during the last two tests. Regulators for the hydrogen railcar were satisfactorily tested on October 26 over a number of flow rates (Ref. 84).

Again in November 1966, four bootstrap tests were run on 2 days—November 9 and 22. The last run failed during an attempt to shorten the delay time on the pump speed for ambient startup by throttling the discharge flow. This resulted in erratic pump speed and head rise (Ref. 85).

Two additional bootstrap runs were successfully carried out on December 14. This completed the bootstrap portion of the test program. The $3000 reheater shortened the estimated length of the program by 3 months and saved $50,000 worth of propellants. A series of cavitation tests were being planned, so January 1967 would be spent overhauling B–3's subsystems and removing the test hardware (Ref. 86).

The first tests at B–3 began in December 1966. These were full-scale propellant feed system startup tests for the NERVA program. The goal was to identify the best way to start a nuclear reactor in space. Twenty-three startup tests were performed with the Aerojet Mark III, Mod 4 turbopump. The turbopump supplied liquid hydrogen to an unfueled Kiwi-B1 reactor. The reactors would not be operated until the spacecraft was out of the atmosphere, but starting the reactor in space was a complicated process. In addition, the liquid-hydrogen propellant was used to cool the reactor. Consequently, liquid hydrogen had to be pumped through the engine starting before liftoff, but it could not enter the reactor core until the spacecraft was in space (Ref. 52).

The B–3 tests established the proper startup procedure, which included liquid-hydrogen flow rates, power-cycle time delay, and powering the turbine. The use of a realistic feed system helped to define the centrifugal turbopump's overall system performance and mechanical characteristics. The turbopump was installed directly under the scale representation of the NERVA propellant tank (Ref. 52).

Despite several months of preparation for a series of cavitation tests, the B–3 NERVA tests were finished. It is unclear why they were cancelled, but it was likely due to lack of funding of the overall program. The B–3 test stand would not be used again for another 5 years.

2.5 Centaur Tests

In April 1961, I. Abbott at NASA Headquarters asked NASA Lewis if the B–1 test stand, which was then still under construction, could be used to conduct an altitude evaluation of the Centaur second-stage rocket. Centaur was being managed at NASA Marshall, and Marshall wanted to test the vehicle in altitude conditions either in Arnold Engineering Development Center's J–3 test stand or in Plum Brook's B–1. There was some hesitation at NASA Lewis to approve the tests because they could not be completed until after Centaur's first two launches. Lewis also was reluctant because they were gearing up to test the NERVA nuclear rocket engine at B–1 (Ref. 87). Nonetheless Lewis supplied a cost breakdown for the modifications necessary to prepare B–1 for the Centaur tests. These modifications included a new test capsule, a rocket-driven exhaust ejector, and modeling tests to determine the ejector design. Instrumentation for the tests was estimated at $900,000, and the total cost was almost $1.4 million. The modifications would take 1 year to complete after the construction of B–1 was completed (Ref. 88). In the end NASA decided to forgo the tests, and B–1 proceeded with its original nuclear rocket engine mission.

The entire Centaur Program, however, was transferred to Cleveland in the fall of 1962. After 2 years of intensive checkouts and testing in a variety of facilities, including Plum Brook's E Stand, Centaur began a string of successful launches in 1965. These included sending the *Surveyor* spacecraft to the Moon in early summer 1966. During this period, General Dynamics was busy designing the second-generation Centaur, the D–1A. These Centaurs would have a more sophisticated computer system, a universal equipment module, and an updated propellant feed system. One issue that was critical was determining if a boost pump was needed in the feed system. NASA Lewis management decided to use B–1 to conduct some of these pump tests.

Figure 2.31.—Atlas-Centaur rocket is delivered to Plum Brook for testing in the E Stand, 1963 (1963–65589, NASA Glenn).

2.5.1 Advanced Centaur Tests (B–1)

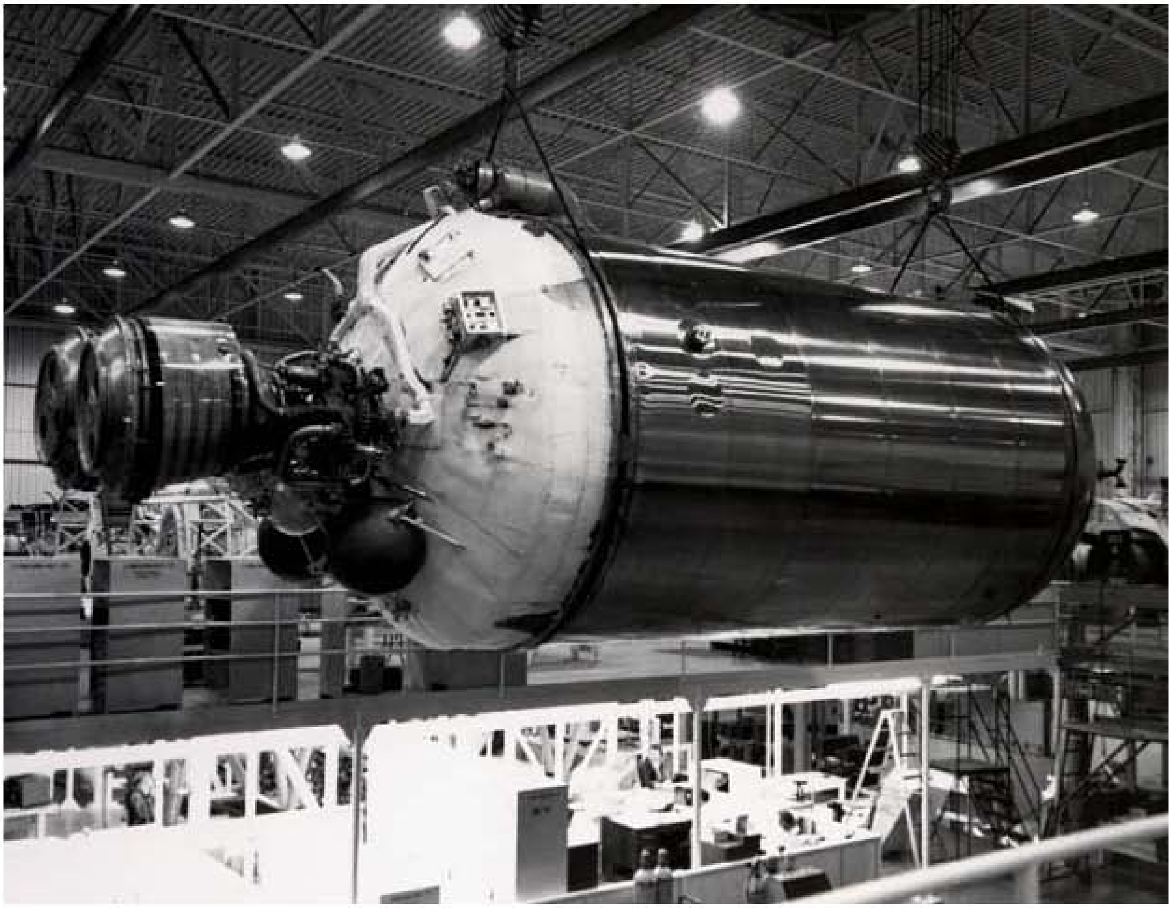

Figure 2.32.—Centaur second-stage rocket being manufactured at General Dynamics plant, 1962 (C–1962–62409, NASA Glenn).

In August 1967 Plum Brook technicians began readying B–1 for Centaur testing in November. The test series, referred to as the "Advanced Centaur" tests, obtained data on the pressurization and outflow of propellants from a "battleship type" Centaur tank. Since only the propellant or oxidizer would be outflowed in each test run, liquid nitrogen would be substituted for the missing element. The tests would focus on tank outflow and tank pressurization to determine if the boost pumps could be removed from the system.

The preparations—which included testing the pressurizing gas conditioning system, a liquid-oxygen system with a 13,000-gal dewar, a liquid-hydrogen system, a hydrogen burnoff and liquid-oxygen dump line, a new patchboard and digitizer for the instrumentation system, and a trailer for the high-pressure helium supply—proceeded through October (Ref. 44). In October, Plum Brook engineers discovered that more time than anticipated would be needed for the checkout. The Centaur testing was put off until early December. Flight-weight vehicle vent valves could not be procured, so the Plum Brook controls people designed a back-pressure control system. Also in October, the inspection of the Centaur 5C tank to be used for the tests began with a pressure test and a cryogenic test (Ref. 45).

All of the facility systems were verified during the first 2 weeks of December 1967, and several preparatory tests were run. On December 21 five pressurized tests and five helium burp tests of NERVA's liquid-hydrogen tank were performed (Ref. 89). Five series of helium burp tests, each consisting of four runs, were conducted in January 1968. The tank insulation had not chilled properly, resulting in an accelerated boil-off rate, and the tests were considered to be invalid. For the next test on February 1, the tank was chilled for 12 hours after it was filled. Ten series of the burp tests were run that day with 36 successes. That portion of the testing was considered to be complete (Ref. 90).

Problems with the gaseous-helium chilling system postponed the next series of tests until March 1. Again, the filled liquid-hydrogen tank was chilled for 12 hours before the test. All of the liquid-hydrogen outflow tests were run that day. There was one single-burn test and seven double-burn runs, thus completing that phase of the testing (Ref. 91). On March 14 and 19, a series of Centaur liquid-oxygen tank tests were run with liquid nitrogen. The six burp tests and five outflow tests were intended to shorten the testing with actual liquid oxygen. Preparing the facility for the actual liquid-oxygen testing took 4 to 6 weeks (Ref. 91). Three liquid-oxygen test days were completed in May: two burp and three outflow tests on May 2, two burp and four outflow tests on May 16, and four burp and three outflow tests on May 24 (Ref. 92). These continued in June with four burp and three outflow tests on June 5, and four burp and four outflow tests on June 19 (Ref. 93).

B–1 was modified during the first week of July for the Centaur liquid-oxygen tank pressurization tests. The burp and outflow block of tests were completed on July 9 and 12 (Ref. 94). In early July, a helium test rig was transferred from the Rocket Test Area to B–1 for testing with the Centaur tank system. Five helium blowdown tests were run on August 27 using one Centaur bottle (small tank), which was tested with four different orifices. Also during August, engineers developed a technique for insulating flight-weight ducts for upcoming tests (Ref. 95).

Figure 2.33.—B–1 (left) and B–3 (right) during the Advanced Centaur tests, 1967
(P–1967–1287, NASA Glenn).

The first test investigating the NERVA propellant tank duct redesign and tank pressurization hardware was conducted on November 20, 1968. A second outflow test 2 days later was aborted after an operator misprogrammed the test, causing the pressure to decrease quickly (Ref. 96). The third outflow test was run on December 3 (Ref. 97).

The first run of the second phase of the Block II liquid-hydrogen program was run on January 22, 1969, to study the pressure drop across the duct during outflow and to verify that the helium was not trapped over the engine inlet valves during the liquid-hydrogen transfer. The tests verified the pressure-drop calculations and that helium was not trapped over the inlet valves (Ref. 98).

The next series was liquid-hydrogen tests with a flight-type pressurization panel that was chilled to simulate test conditions for similar tests in B–2 (Ref. 98). A failure of the pressurization valves at the vendor set back the tests. During February almost the entire instrumentation pressure panel was installed, and tubing was installed from the helium tanks to the panel and then to the hydrogen and oxygen tanks. The entire B–1 operational staff was temporarily transferred to B–2 while waiting for the pressure valves to arrive. B–2 had been recently completed and was gearing up for its first tests (Ref. 99).

The tank pressurization panel, which was not received until April 15, 1969, was installed and checked on April 22. Plum Brook engineers decided to run the tests at ambient temperatures so that the valve would not be stressed. The valve tests were completed on April 28 (Ref. 100).

The Centaur tank was filled on May 1, and the Centaur liquid-hydrogen outflow tests were run on May 2. Two two-burn and one single-burn test were run, as well as two helium burps. The liquid-hydrogen cut and outflow connections were then removed, and the liquid-oxygen duct and outflow were installed. On May 14, four successful outflow tests were run: two single-burn and two two-burn. Three more outflows were run on May 28, using different valves in the pressurization panel. All were successful. These would be the last tests ever run at B–1 (Ref. 101).

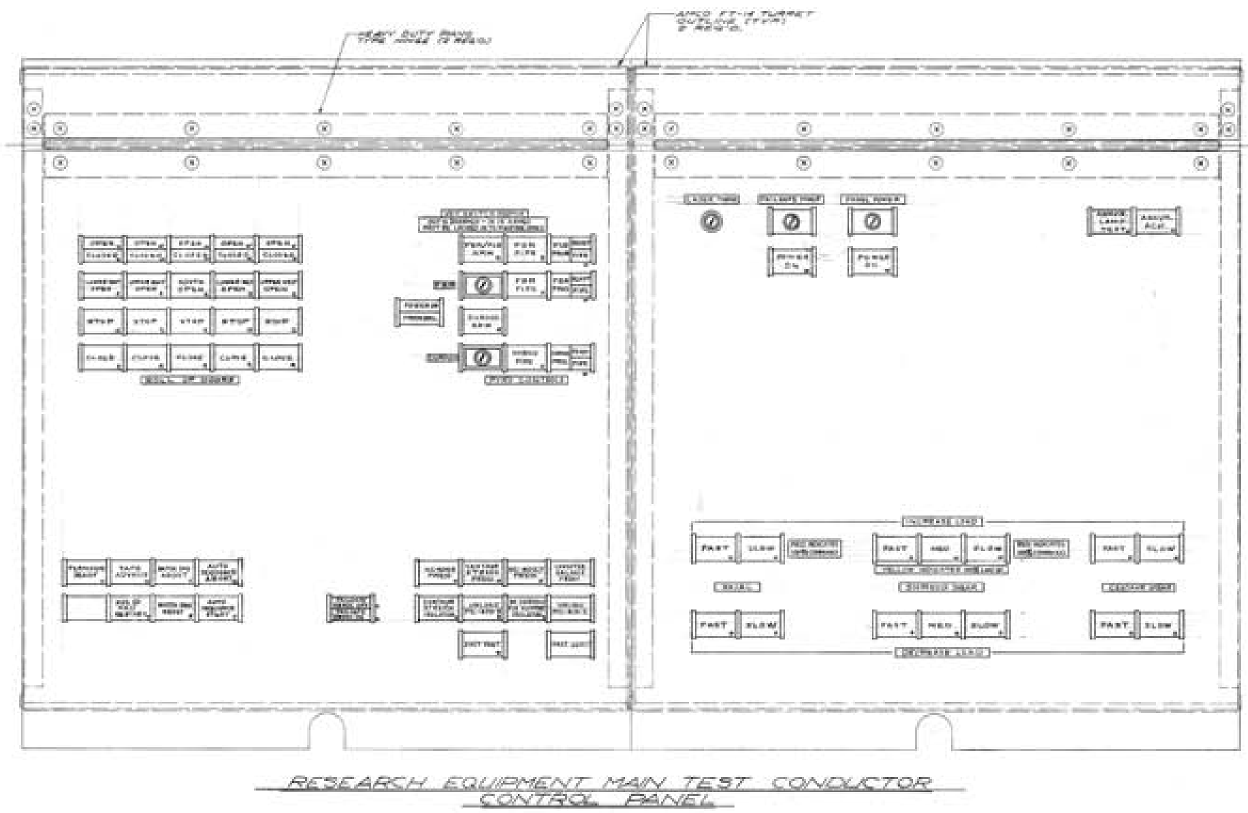

Figure 2.34.—Main B–1 control panel for the Centaur tests, 1963 (29169 PF 01 C, NASA Glenn).

2.5.2 Titan III-Centaur-Viking Tests (B–3)

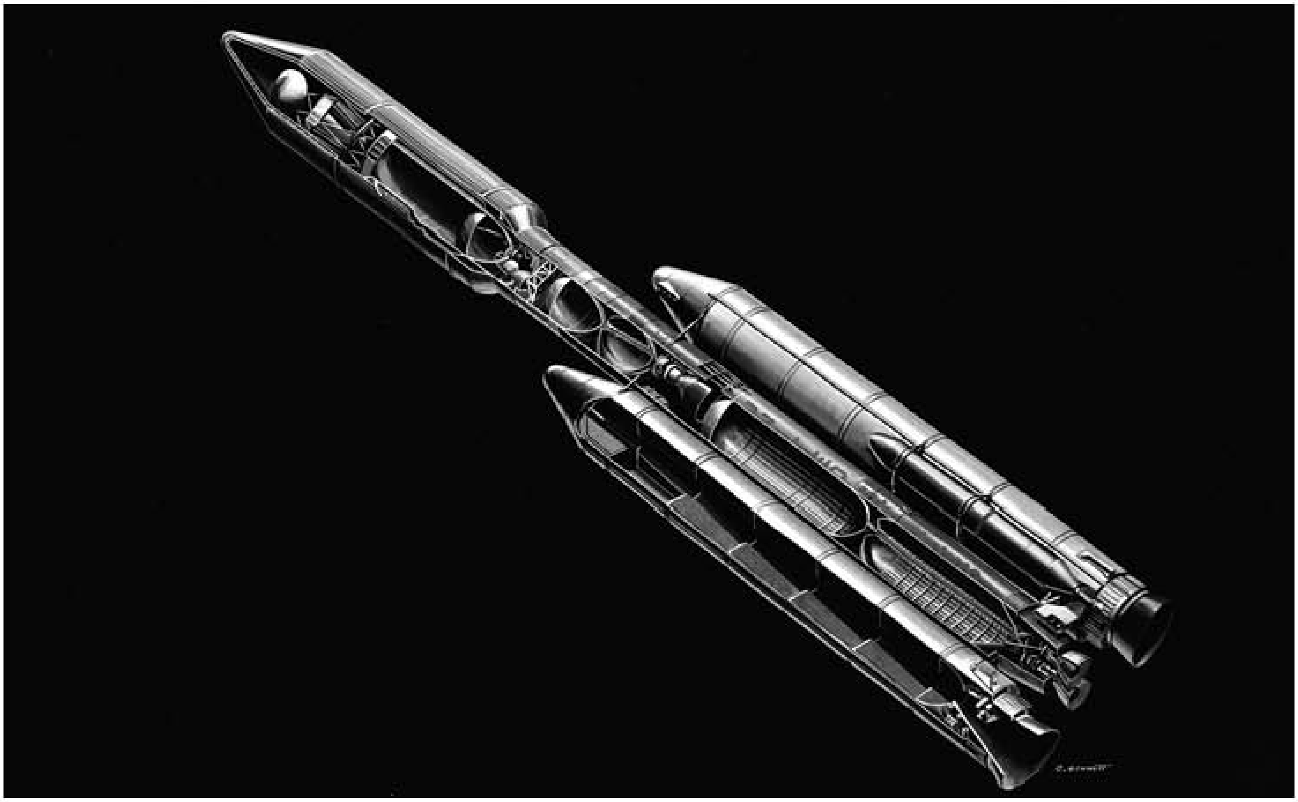

Figure 2.35.—Cutaway drawing of Titan III-Centaur-Viking spacecraft. The shroud envelops the upper third of the rocket, 1972 (C–1972–00483).

In the mid-1960s the Atlas-Centaur launch vehicle had proven itself to be a reliable and powerful tool for launching heavy satellites and spacecraft into orbit. Simultaneously, NASA engineers were planning a new and even more ambitious mission—sending two rover vehicles to the surface of Mars. The $1 billion Viking Program was vital to NASA's future. A failure would not only jeopardize future planetary missions but the Agency itself (Ref. 102).

The Viking rover was the heaviest payload that anyone had ever attempted to launch into space and was over three times the weight of the previous heaviest Atlas-Centaur payload. NASA engineers sought a more powerful booster to mate with the Centaur for the mission. The answer was the Lockheed Martin Titan booster that was originally developed in the mid-1950s to launch the Air Force's nuclear missiles. The Titan III version was developed in 1962 specifically to launch military satellites. NASA Lewis engineers had the difficult task of integrating the Titan with the Centaur as well as the Vikings with the Centaur.

General Dynamics had also been in the process of introducing a new Centaur model—the D–1T for Titan. The D–IT was similar to the D–1A recently designed for Atlas. It was 23 ft long, 10 ft in diameter, and weighed 39,000 lb. It had an improved electrical system and a slightly more powerful computer system. The biggest change for the D–1T was a completely new shroud designed by Lockheed, called the Centaur Standard Shroud (CSS). The shroud was 58 ft tall and 14 ft in diameter, making it 4 ft larger in diameter than the Titan booster. This gave the 160-ft-tall

Titan-Centaur stack its unique shape (Ref. 102). The increased size of the new shroud would impact the structural loading of the Centaur. Consequently, a longer shroud was used that would envelop both the payload and the Centaur second-stage, thus providing additional support. The shroud would also provide insulation for the liquid-hydrogen tank. As the vehicle entered space, a pyrotechnic cutting system would release a series of latches that joined the two halves (Ref. 103).

The shroud is an important component of any launch vehicle mission. The conical two-piece covering encapsulates the payload to protect it against adverse conditions and improves the launch vehicle's aerodynamics as it passes through the atmosphere. Once the vehicle is at the edge of space, the shroud is jettisoned. Even a minor error in the jettison system could result in a launch failure. Lockheed was looking to test the new shroud's jettison system before the launch. The shroud, its insulation, the Centaur ground-hold purge system, and the hydrogen tank venting system would all be studied in B–3 (Ref. 103).

Although it was a new field for B–3, NASA Lewis had a good deal of experience in shroud testing. The vacuum chamber in the Space Power Chambers (SPC) at Lewis's Cleveland campus had been used to verify the shrouds for Atlas-Centaur-4 and -6 Surveyor missions in 1964 and 1965. The SPC's high-altitude chamber had been used for an Atlas-Agena shroud for the Orbiting Astronomical Observatory (OAO)–1 mission in 1965. An Agena shroud was then modified to fit on a Centaur and tested in SPC for the OAO–2 mission in 1968. After a shroud mishap caused the 1970 OAO–B mission to fail, the SPC was used for the accident investigation and to qualify the new design for the OAO–C mission in 1972.

The CSS was 18 ft longer than the OAO shroud and too large for the vacuum chamber in the SPC. In July 1970, Plum Brook management agreed to support the CSS tests in its B–3 test stand and new Space Power Facility. Jack Humphrey, who was a veteran of the earlier Centaur shroud tests, was the Launch Vehicle Division researcher, and Bill Klein oversaw the Plum Brook operations. Setup work began at B–3 in January 1971. The B–1 and B–3 test stands had sat idle from June 1969 through December 1970. This was largely due to the focus on the initial Centaur boost pump tests being run in the new B–2 facility.

There were three series of CSS tests planned for B–3. The first involved structural load tests to determine the ultimate flight loads on two axes, establish the Centaur load sharing, and combine spacecraft loads with CSS. The next series would be run at cryogenic temperatures. These included heat transfer to determine propellant boiloff during launch holds; verification of the vent system capacity; and unlatch tests to ensure separation and to determine separation loads and clearances. The final series included jettison tests run both at sea level and altitude. These would determine structural flexing, hinge release behavior, and trajectory (Ref. 104).

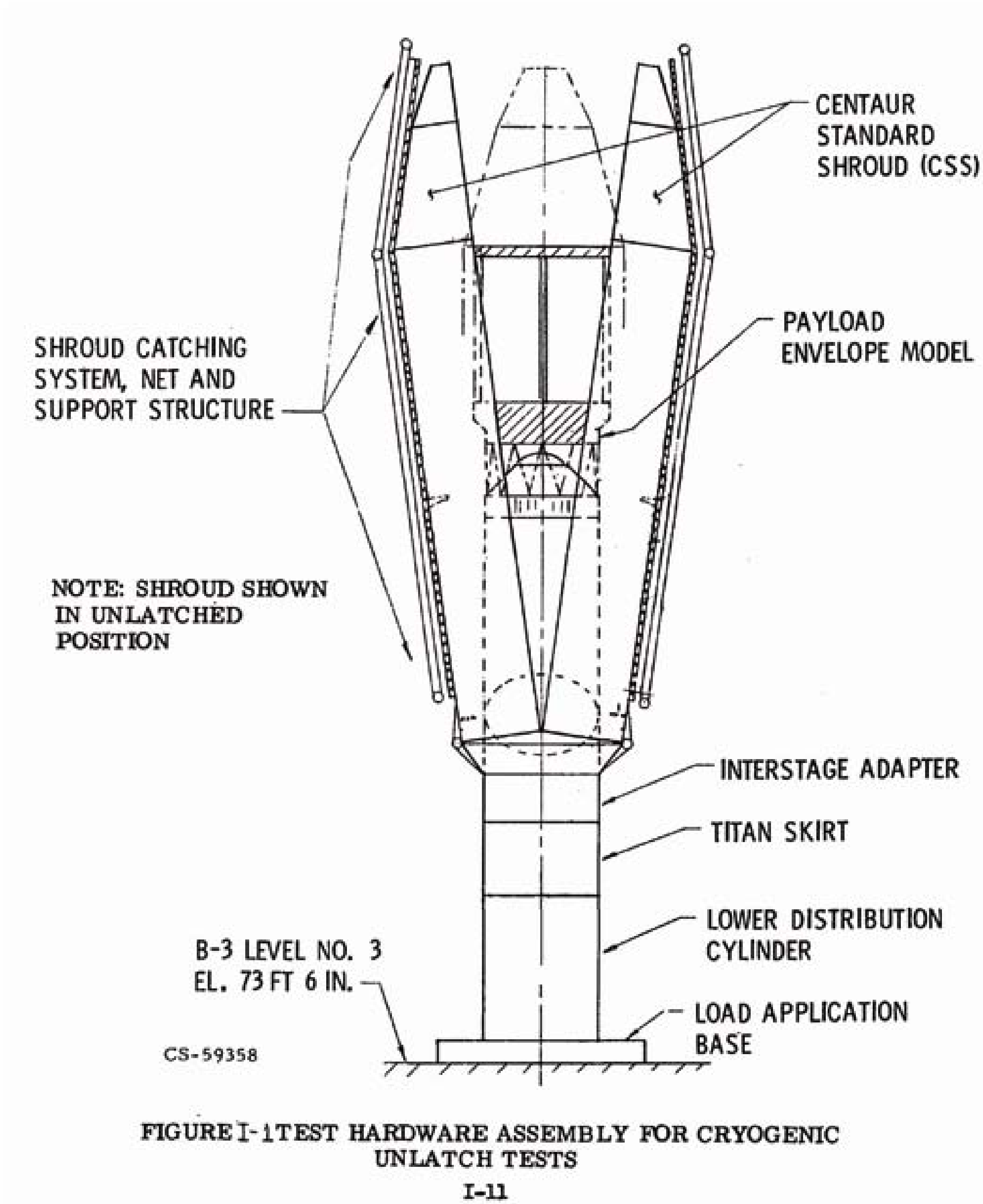

Figure 2.36.—Setup for Centaur Standard Shroud (CSS) unlatch tests in the B–3 test stand, 1973 (CS–59358, NASA Glenn).

The test equipment included the CSS shroud, explosives, and hardware; a Centaur tank and systems; a Centaur interstage adapter, Titan skirt, and Viking payload model. The shroud was designed so that most of the stress was carried by the actual shell and not the supports. The payload section was 31 ft long and included the stainless steel nose cone. There were two conical magnesium halves, two cylindrical aluminum halves, and an aluminum equipment section that permitted access to the payload. The cylindrical section that surrounded the Centaur tank had fiberglass panels inside to insulate the tank. This was a critical design element. The insulated portion of the shroud had to keep the Centaur from freezing during 2-hour prelaunch tanking of the cryogenic liquid hydrogen (Ref. 105). The shroud was jettisoned when a series of noncontaminating pyrotechnics separated all the joints along the splitline. The shroud halves were then pushed away by eight springs at the base (Ref. 103).

The tests were scheduled to be run from July to October 1972, but delays in designing the catch-net system not only postponed the tests but also began to threaten to impact the launch date. In September 1972, engineers from NASA Lewis's Cleveland campus decided to redesign the system. Hydraulic proof tests were run in January 1973. The new catch-net system was installed immediately afterward. The half-scale model of the CSS shroud was lifted into B–3 on March 3. The catch-net system tests began on March 9, and a half-speed run was performed on March 10. As the test ended, an operator mistakenly brought the shroud back to its upright position too quickly. This resulted in the breaking of two support columns in the shroud half. These shroud supports were quickly repaired, and the final runs were successfully completed on March 15, 1972. The model was removed from the test stand on March 24. The Cleveland researchers were satisfied with the tests and the catch-net system. They decided to cancel future cryo-unlatch tests (Ref. 106).

Several hinge load test runs were conducted in June. Work began in July preparing B–3 for a series of shroud leak tests to ensure that it would maintain its seal during a launch. The first jettison test was run at 11:57 p.m. on September 28. The test revealed three significant problems: the liquid-hydrogen vent sleeve cracked and leaked hydrogen; the shroud superzip ordnance containment tube ruptured, which could have damaged the payload; and the shroud could not be properly pressurized with liquid hydrogen in the Centaur tanks. Difficulties continued during November and December (Ref. 107). On February 7, 1973, the unlatch system was finally tested successfully. This was the last separation test in B–3.

Figure 2.37.—Half of a Titan-Centaur shroud is lifted into B–3. The Centaur can be seen near the top of the photograph, 1973 (C–1973–01376, NASA Glenn).

After 2 months of modifying the test stand, researchers initiated a series of CSS structural load tests in April 1973. The initial tests demonstrated that the shroud deflected 50-percent more than expected. The effect of these loads on the Centaur tank, the vent fin disconnect motion, payload clearance, and design of the forward seal then had to be determined. Struts were added for two ensuing tests to obtain information for redesigning the struts (Ref. 108).

B–3 had a heavy run schedule during June and July. A seal that had come loose during the tests was redesigned by General Dynamics and retested. Four tests were run on June 14 and 15, 1973: (1) launch transient loading, (2) limit loading on the strut system, (3) separation, and (4) payload branch spring rate without struts. There was also a boiloff test that demonstrated that the insulation system was sound. Several limit load and bearing separation tests were run on June 28, and two structural tests were run on July 2 to complete the program (Ref. 109).

The next phase, the heated jettison tests, would be run in the Space Power Facility. The shroud and equipment were removed from B–3 during the next 2 weeks. On July 13, the Centaur was removed from the test stand and stored. After cleaning up the facility and inventorying the equipment, the Plum Brook crew was reassigned to HTF and the Cryogenic Propellant Tank Facility (K Site). A skeleton crew remained to prepare B–3 for CSS engineering evaluation tests (Ref. 110). Plum Brook personnel met with the Titan Centaur office during August and September to discuss parameters for the engineering tests. The researchers and engineers decided that the last series of tests would be pared down. Planning and weekly meetings continued through November, but there was virtually no activity at B–3 during the fall (Ref. 111).

In January 1974 the system proof tests began. Calibration for the twang tests was completed, and the liquid-level system neared completion (Ref. 112). "Twang" is the movement of the launch stack when the engines are fired but the stack is still tethered to the launch pad. Preparations continued throughout February and March, with the shroud and equipment being stacked up in May. The twang tests were run on April 8 and 9. The results corroborated the CSS dynamic computer model. Stackup for the structural tests began almost immediately and was complete by the end of April (Ref. 113).

The engineering evaluation structural test series was run in early May with cryogenic runs on May 10 and 15. These tests were conducted in atmospheric conditions with liquid nitrogen in Centaur's oxidizer tank simulating cold temperatures. The series was successful, and the strength envelope for the shroud was defined. The shroud and associated components were removed from the stand and boxed up soon afterward (Ref. 114).

The shroud was then transported to the Space Power Facility where it would be jettisoned in altitude conditions to verify its performance. Shroud insulation tests resulted in a redesign of the insulation system (Ref. 4).

The first Titan III-Centaur proof flight failed on February 12, 1974, when the Centaur's RL–10 engines failed to start. The new shroud, which had not been flown previously, had jettisoned properly. A large group of NASA Lewis employees watching the launch were despondent. It was carrying a rare Lewis-developed experiment called Space Plasma High-Voltage Interaction Experiment (SPHINX) (Ref. 115). Despite an intensive investigation, Lewis engineers could not precisely identify the cause of the accident. It was clear that something had malfunctioned in the boost pumps, but even after tests in B–2, the exact problem could not be determined for several years (Ref. 102).

In March 1975 Titan III-Centaur proved itself with the successful launch of the German Helios satellite. All components functioned properly, and the mission was a success. The fact that the launch vehicle did not have any problems was a huge boost for the Viking program. After delays caused by two separate problems on the launch pad, the first of the two Viking spacecraft was launched on August 20, 1975. The second Viking was successfully launched on September 9. Each spacecraft took over 300 days to reach Mars. Both the orbiters and landers functioned successfully. Viking 1 and 2 operated on the Martian surface until November 1982 and April 1980, respectively (Ref. 102). The Titan III-Centaur rocket would have a relatively short career. It was utilized only three more times: by another Helios spacecraft and by a pair of Voyager spacecraft that are still exploring the edges of the universe today.

2.6 Closure of Plum Brook Station

NASA's budget had been steadily declining since its peak in 1965, and the Nixon Administration was concentrating on reducing Federal expenditures. There was intense debate in Washington from 1969 to 1972 on two costly NASA programs—the space shuttle and NERVA. There were disparate views on whether the shuttle was needed and if so, how it should be designed. Simultaneously, NERVA's anticipated missions to Mars slipped indefinitely into the future. Earlier budget cuts had meant that the program had not yet produced a flyable nuclear engine. Again, there was much political discussion over the future of the program (Ref. 116).

A second flight-type NERVA engine, the XE, was tested in June 1969. It was the followup to the 1966 NRX test except that entire engine was in its true flight configuration. Again the tests proved successful (Ref. 57). Despite the XE success and strong Congressional support, funding for NERVA was significantly reduced by President Nixon for fiscal year 1972. In an effort to save some portion of the program, NERVA was redesigned in 1971 as a smaller nuclear engine that could be carried on the shuttle. Debate continued within NASA and the Government over the need for NERVA. Key Congressmen threatened to retract support for the shuttle if NERVA was dropped. When the shuttle was officially approved by the President in January 1972, NERVA was left in a precarious position (Ref. 13). NASA Lewis was also in a precarious position. It had lost 700 positions in 1971 alone and would not have much involvement with the shuttle program (Ref. 117).

Although NASA Administrator James Fletcher seems to have already decided that NERVA would be dropped soon, he publicly stated his continued support for the smaller NERVA engine program. Engineers at Los Alamos had spent most of 1972 working on the smaller version, but NASA Lewis had done little. When Fletcher submitted his fiscal year 1973 budget request in September 1972, NERVA was omitted in order to stay within NASA's budget limit. All nuclear propulsion and power programs would be terminated. The AEC, SNPO, and Lewis had not been given any indication of the cancellation until the budget was officially announced on January 5, 1973 (Ref. 13). It was 1 year to the day after the approval of the shuttle and just 17 days after the splashdown of the final Apollo mission.

That morning, NASA Lewis Center Director Bruce Lundin drove out to Plum Brook and announced to a full cafeteria that Plum Brook Station would be closed down. The reactor would be first, and the other facilities would be closed by fiscal year 1974. Over the next 18 months, the staff was reduced from 600 to 54 and to a half dozen by the mid-1970s. In addition, Lewis's main campus would lose several hundred employees to early retirements and layoffs (Refs. 46 and 118). The reactor was mothballed by June 30, 1973, and the Rocket Systems Area by June 30, 1974. The Space Power Facility continued until October 1975 (Refs. 4 and 26).

Elyria Chronicle-Telegram, January 6, 1973

NASA slashes Plum Brook

By DAVE RUSS

More than 600 jobs will be eliminated as the federal government curtails activities at the Lewis Research Center in Cleveland and phases out the Plum Brook facility in Erie County near Sandusky in the next year-and-a-half.

As part of a nationwide program to decrease spending on space programs, the National Aeronautics and Space Administration (NASA) announced the cutbacks yesterday.

Officials had no exact figures on the number of Lorain countians affected by the surprise announcement, but many work at the two space facilities.

THE $70 MILLION Plum Brook station, which employs 461, provides an annual contribution of approximately $12 million to the Sandusky area economy.

This is made up of salaries, support contracts and procurement activities, according to Hugh Harris, NASA public information officer in Cleveland.

Only a handful of caretakers and security personnel will work at the 8,000-acre Plum Brook facility, located on Sandusky's southern border when the phase-out is completed by June 30, 1974.

The government will attempt to aid all employees affected by the cutback, Harris said. Some will receive early retirement, others transfers, and some a form of severance pay.

AT LEWIS, located at Brookpark and Grayton roads on Cleveland's west side, the curtailment will deal mainly with the programs involving nuclear propulsion and power programs.

The reduction of about 600 jobs at both facilities is "in addition to a planned reduction of about 90 at both plants," Harris said.

The first employees to leave Plum Brook will be about 180 who were involved with the nuclear programs.

A NUCLEAR reactor, which cost $15 million, will be shut down by June 30 this year, Harris said.

"In research and technology, work on nuclear propulsion will be discontinued and work on nuclear power will be sharply curtailed," NASA said.

Plum Brook has been the principal NASA installation involved with testing nuclear power.

NASA said near-term projects that will not be affected by the cutback include the Skylab experimental space station, the space shuttle, the Apollo-Soyuz test project, Viking, and the Mariner-Jupiter Saturn mission.

AT PLUM BROOK the nuclear reactor test facility was first used in 1961.

Also at the site is a $4.4 million space power facility that simulates altitude conditions for tests of spacecraft and spacecraft components. It began operations last year.

A $12 million space propulsion research facility opened in 1969 is a vacuum chamber that has the capability of handling firings of full-scale rockets.

All Plum Brook radioactive material that is moveable will be relocated, but parts of the reactor itself are immovable and will remain.

COMPONENTS not moved to the Cleveland facility will be placed in an equipment pool and used as needed, NASA said.

"The land is being placed in standby with the assumption operations will be resumed sometime in the future," the spokesman said.

The NASA cutbacks will trim $200 million from the space agency's $3.4 billion budget for fiscal 1973. Spending cuts are expected to continue through fiscal 1974.

The caretaker and security crew that will remain at Plum Brook will be accompanied by numerous deer that roam the 8,000-acre reservation.

Negotiations between NASA and the Department of the Interior are now underway to provide for their care.

NASA'S Plum Brook facility in Sandusky will be closed by the end of June next year. The deactivation is part of a NASA budget cut that will eliminate or sharply curtail several long-term programs.

Figure 2.38.—Headline from local newspaper following NASA's announcement that it would close Plum Brook, January 6, 1973 (Elyria Chronicle-Telegram).

Continental Aircraft Engine (Teledyne) in nearby Toledo, Ohio, was interested in using B–3 or B–1 as a vertical-takeoff-and-landing engine test stand. NASA felt that this would change the nature of the facility and not fully optimize its capabilities. NASA suggested using it to test turbopump systems for the electric power industry, fluidized bed combustor or turbine research, coal gasification, or fuel oil cracking. Pratt & Whitney and the Air Force suggested that B–1 be used for high-powered laser work (Ref. 4).

The standby care of B–1 and B–3 is described in Sections 2.2.3 and 2.3.3, respectively. Sometime prior to 1979 NASA decided not to keep all the facilities in standby condition. Those not preserved were cannibalized for research and test equipment, but the overall structure and systems remained in place.

3.0 Architectural Information

3.1 B–1 Test Stand

The B–1 test stand could be used to test engines up to 6000 lb of thrust for 6 minutes, but with minor modifications, this capacity could have been increased fivefold. It included a 13-ft-diameter, 30-ft-long chamber for testing engines in a space environment and a steel carriage for cold-flow tests (Ref. 4). B–1 had cryogenic propellant run tanks, exhaust gas scrubbers, and large gaseous and cryogenic storage trailers. A two-stage steam ejector provided vacuum pumping. The facility also was tied into Plum Brook’s data-acquisition system (Ref. 4).

The tower faced two rectangular retention basins to the southwest. Two steam accumulators and a steam ejector stack were linked to the southeast wall of the stand. The Shop Building was a single-story structure adjacent to the northwest wall of the stand. A rectangular single-story Pump House and a smaller Valve House stood between the stand and the large retention basins. A water tower was to the west of the basins. Also in 1965 a railroad spur was added to the facility to provide better access for additional liquid hydrogen supplies (Ref. 61).

Figure 3.1.—B–1 test stand with steam accumulators (left) and exhaust stack (right), 1961 (P62–01859, NASA Glenn).

3.1.1 B–1 Structure

The B–1 test stand was a 135-ft-tall vertical tower that was enclosed above the 68-ft level and had an enclosed elevator shaft extending to the ground in the west corner. Initially each of the walls in the upper section had three sets of 12-paned windows and a narrow vent window aligned vertically. By 1964, however, rollup doors replaced the windows on the southeast, southwest, and northwest walls. The doors provided ventilation in the event of a hydrogen leak. The walls and roof were corrugated galvanized steel. A ridge vent ran along the peak of the roof. The stand was elevated on steel trestles.

Figure 3.2.—B–1 trailer storage (left) and shop area (right), 1962 (P62–01531, NASA Glenn).

Ground level: The base of the test stand was 34.17 ft across and 42 ft deep. The majority of this space was an open area above a 9-in.-thick concrete slab. The 8.5 ft along the northwest end was enclosed, however. The western 17-ft area adjacent to the shop area had a stairwell and an elevator shaft that both terminated at the test section on the 68-ft level. The original 500-lb elevator was replaced with a 3000-lb version in 1965 (Ref. 61). The northern end had an equipment room. Double doorways opened into both the shop area and the base of the test stand (Ref. 119).

Shop area: The shop area was located on the ground floor adjacent to the northwest side of the test stand. It was 27.25 in. deep, 40.5 ft wide, and approximately 11 ft tall with a slightly sloping V-beam aluminum roof. The walls were 1-ft thick concrete. The exterior was covered in corrugated galvanized steel. The north wall had a double doorway and a four-paned window. The west wall had two adjacent nine-paned windows, a single door, and a third nine-paned window. A monorail crane ran across the interior ceiling. The north corner of the interior had a restroom and an emergency shower area. The east corner had a 11.75-ft-deep by 17-ft-wide instrument terminal room with an entrance and two electrical panels on its north wall (Ref. 119).

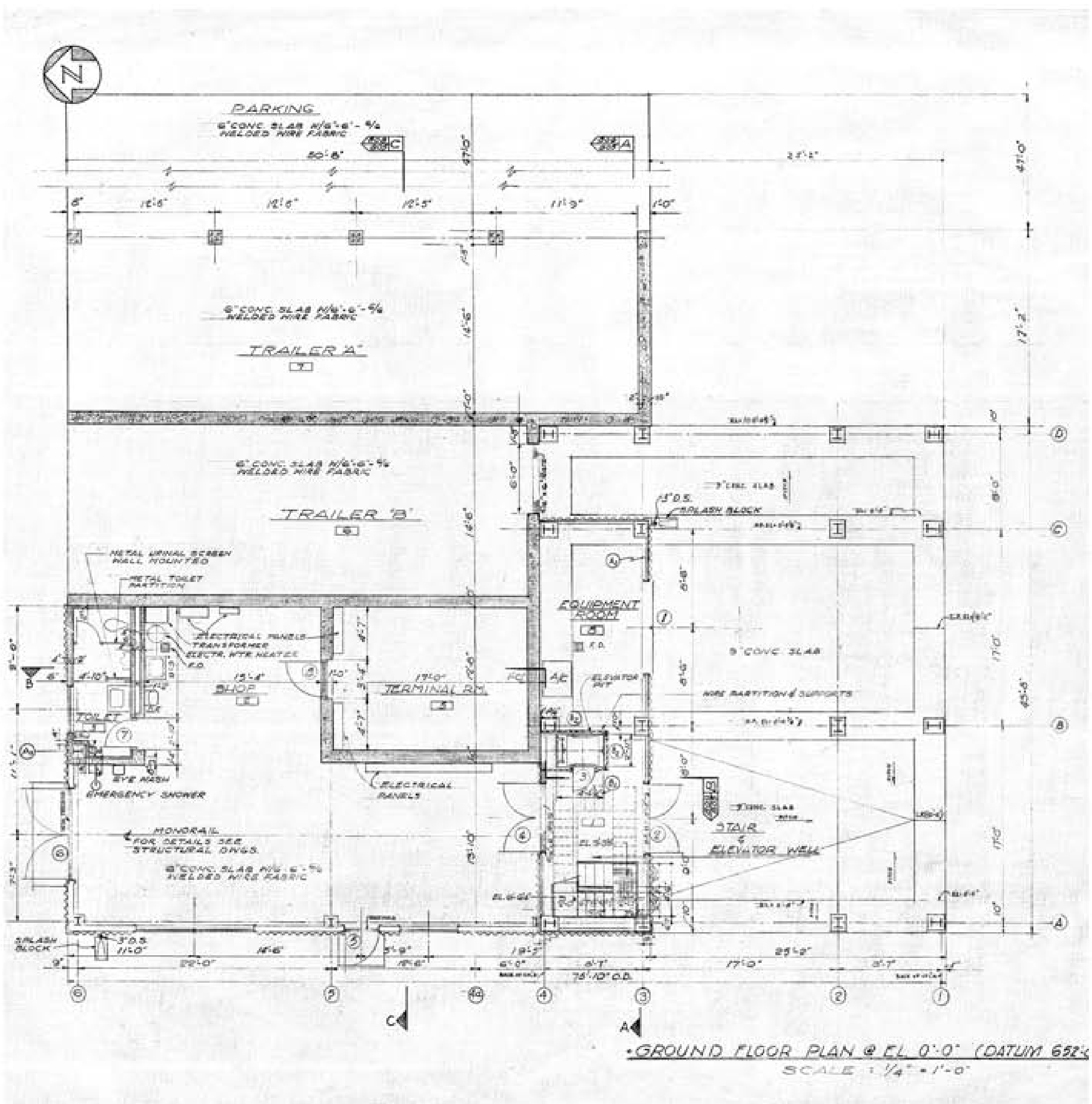

Figure 3.3.—Architectural drawing of B–1 ground floor, shop area, and trailer storage, 1960 (PF–20451, NASA Glenn).

Trailer storage: Adjacent to the northeast wall of the shop area was a concrete shelter with two bays for mobile liquid-hydrogen tank parking. The butterfly roof was 20 ft high on the sides and sloped to the 18-ft level at the center wall separating the two bays. The two 36.33-ft-wide, 14.5-ft-deep bays had entrances at the northwest and a south wall that abutted the bottom of the test stand. In order to provide adequate ventilation for the fuel trailers, the sides of the structure were not walled in but merely supported by columns (Ref. 119).

42-ft 2-in. level: The test stand's first access level contained only a 5.5-ft-wide by 25-ft-long steel-grated platform along the northwest side near the northern corner. The rest of the area except the stairwell and elevator shaft was open.

55-ft 1-in. level: The first large access level had 5.5-ft-wide steel grating along the northwest, northeast, and southeast sides of the stand, a total length of 67 ft. The center remained open to provide access to the diffuser.

68-ft level: This was the main test area and the first level that was completely enclosed. The area was divided into three sections arranged southwest to northeast. The first was 17 ft deep and had an elevator shaft and stairwell to the west, a square 16- by 16-ft removable operating floor, and an 11.83-ft-wide open area. The next section in the center of the level had steel-plate and steel-grated floor areas. At the center was a 15.5-ft-diameter circular opening into which the engine and test equipment were installed. The third section was a steel-grated platform along the northeast wall (Ref. 120). On this level, the engine and nozzle being tested were mounted with the turbopump above.

84.75-ft level: The level above the test section allowed access to the turbopump assembly. The majority of this level was covered in steel plate. Near the center was the turbopump and propellant feed assembly linking the 18-ft-tall liquid-hydrogen propellant tank on the level above and the engine on the level below. The pump drew the propellant down into an unfueled reactor that included an exhaust nozzle (Ref. 61). Initially a ladder, and later a staircase, connected the three levels.

93 ft 10 in. level: At this level there was a 3.5-ft-wide catwalk along the southeastern wall with a ladder leading down to the test section level. This provided access to the bottom of the 18-ft-tall liquid-hydrogen tank, which was suspended above. A crane rail ran across the stand at the 105-ft level. It could reach down to the test section (Ref. 120 to 123).

98.25-ft level: An approximately 18-ft-tall liquid-hydrogen tank sat on the 98.24-ft level. A venting system, vacuum lines, and tanking system at the 117.5-ft level entered the top of the tank. The vent exited the roof of the test stand. The liquid-hydrogen, gaseous-hydrogen, and liquid-nitrogen supply lines and a helium purge line ran down the length of the northwest side of the stand. A vacuum pump was located at the base of the tank at this level (Ref. 123).

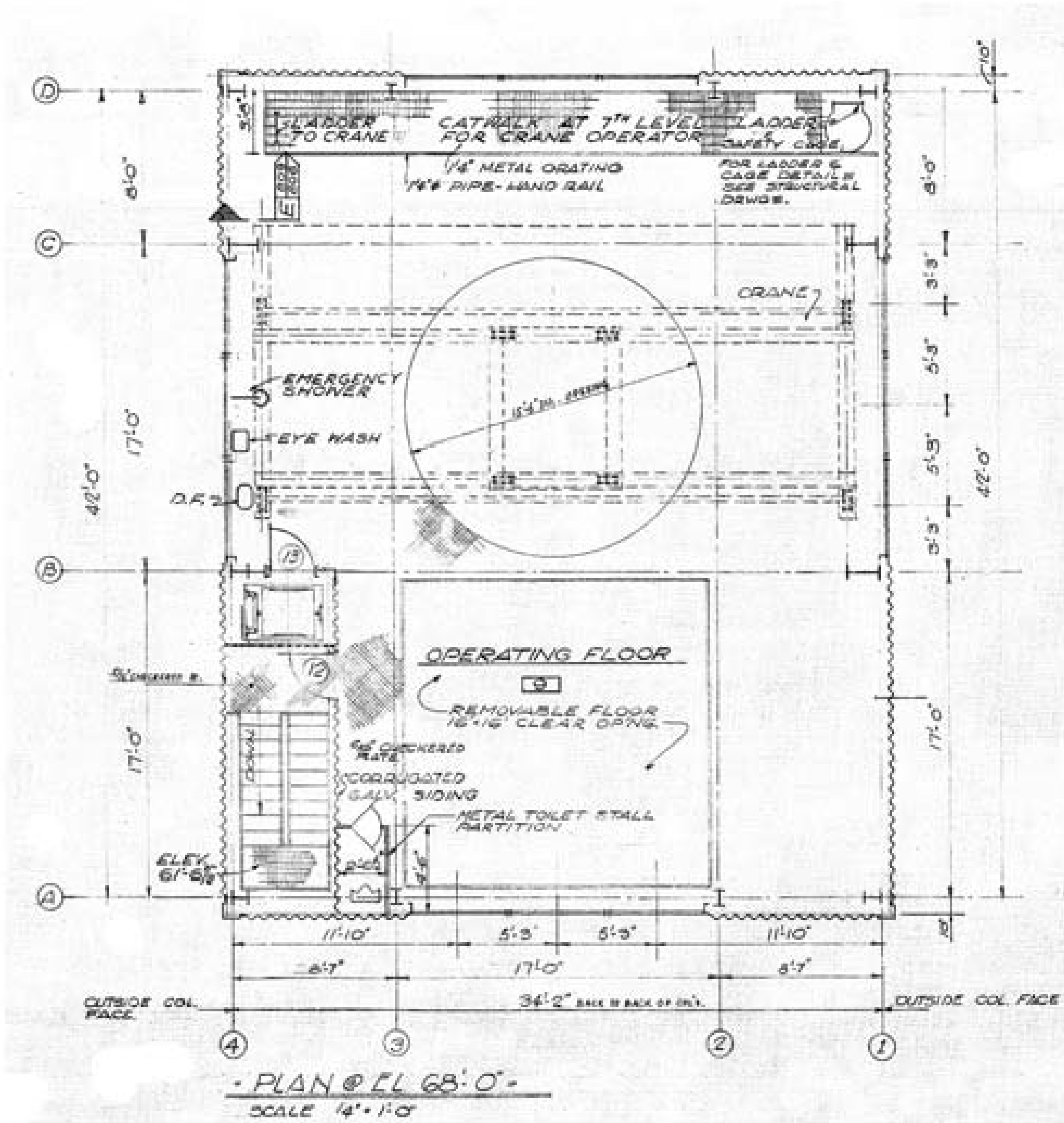

Figure 3.4.—Floor plan for the 68-ft level of the B–1 test stand, 1960 (PF–20452, NASA Glenn).

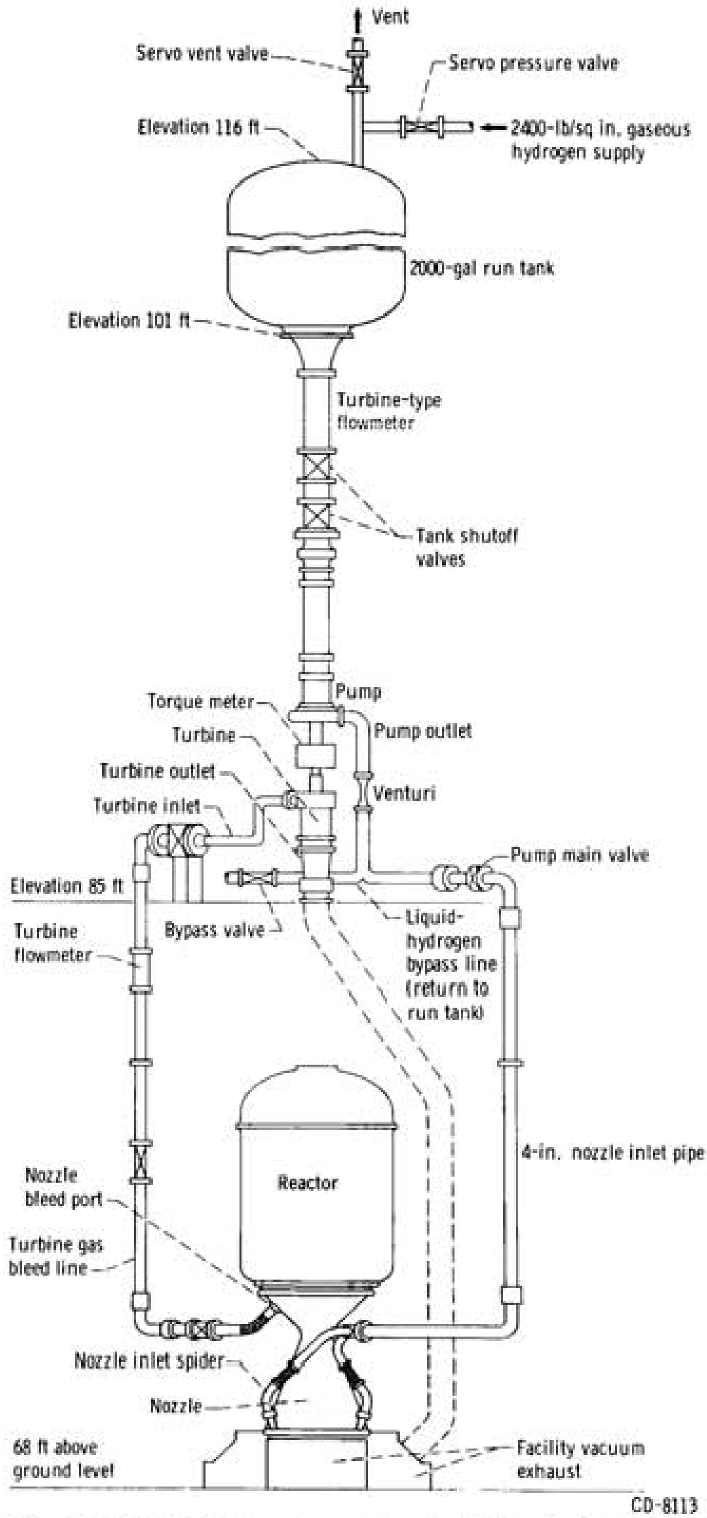

Figure 2. - Schematic of simulated nuclear rocket experimental test setup in B-1 facility.

Figure 3.5.—B–1 Nuclear Engine for Rocket Vehicle Application (NERVA) propellant feed system setup, 1966 (NASA TM X–1213, Fig. 2; CD–8113, NASA Glenn).

3.1.2 Nuclear Engine for Rocket Vehicle Application (NERVA) Test Assembly and Installation (B–1)

The 2000-gal stainless steel liquid-hydrogen propellant tank for the NERVA tests at B–1 was 15 ft long and 5 ft in diameter. The tank was insulated with 4 in. of polyurethane insulation. There were 10 ports in the top of the tank for the liquid-hydrogen level probe, hydrogen fill and pressurization lines, return line, purge and burst disc connections. The bottom of the tank had a single outlet for a liquid antiswirl vane assembly and filter through which the liquid-hydrogen flowed. The hydrogen then passed through straightening vanes and entered the 4-in. flowmeter (Ref. 61).

The Mark IX turbopump contained a pump, a torquemeter, and a turbine mounted vertically on a tripod-like frame. Spline gear couplings transferred the power from the turbine through the torquemeter and into the pump. The pump was specifically designed for liquid hydrogen. It consisted of an axial entrance mixed-flow axial-discharge inducer stage, six identical high-pressure axial-flow stages, and a single-outlet collecting volute. The torquemeter contained a calibrated torque shaft with a 60-tooth rotor and a fitted drive shaft at each end, two magnetic pickups, and two oil-lubricated bearings. The six-stage pressure-compound axial-flow turbine was designed to produce 15,000 hp with hydrogen and oxygen byproducts. The fluid entered through a collecting scroll and was expelled through an axial core diffuser (Ref. 61).

The reactor for the B–1 tests was similar to a Kiwi-B1B model, but some specifications were simplified to reduce the manufacturing costs. The fuel element cooling passages were made a uniform size, left uncoated, and not filled with uranium. Aluminum replaced beryllium for the reflector, and the control rods and poison plates were also aluminum. In addition, viewing ports were installed for high-speed cameras. An array of pressure and temperature instrumentation was installed by Plum Brook personnel prior to the tests (Ref. 61).

The reactor was assembled at NASA Lewis's Cleveland campus and shipped to Plum Brook on a trailer equipped with an engine generator and instrument housing. Accelerometers were used to monitor the reactor loads on three axes during the trip. Teflon shims were inserted between the modules, and a rubber shock pad was placed under the assembly. The tire pressure on the trailer was also reduced, and speeds were kept between 10 and 30 mph (Ref. 61).

At Plum Brook the reactor was placed in a "turnover" stand that allowed the nozzle to be pointed at the ground. The reactor was then lifted in B–1. The reactor was inspected and checked out with no problems. Shims were inserted to reduce vibrations that might damage the core (Ref. 61).

Figure 3.6.—Kiwi-B reactor is placed in a turnover stand so that its nozzle can be pointed at the ground, 1963 (P63–01357, NASA Glenn).

Propellant feed system and nozzle: The liquid-hydrogen feed line consisted of the tank discharge to the pump inlet portion and the pump discharge to the nozzle inlet portion. The former was an 8-in.-diameter vertical pipe that ran 8.5 ft and had 4 in. of insulation on the exterior. It narrowed to 4 in. in diameter to pass through a flowmeter. A filter and straightening section started just above the flowmeter and extended into the tank. The section from the flowmeter into the pump diameter returned to 8 in. and incorporated two shutoff valves. Approximately 18 ft downstream from the main flow-control valve, the propellant line was divided equally into three 2-3/8-in.-diameter ducts that fed the nozzle inlet manifold (Ref. 61).

A 58-in.-long regeneratively cooled tubular wall RN–2 nozzle was used for the NERVA tests. Its contraction ratio was 17.3:1, and it narrowed from 36.25 in. at the reactor to 8.72 in. at the throat. The expansion ratio was 12:1, and it expanded from 8.72 in. at the throat to 30.21 at the exit. The nozzle wall consisted of 180 tubes through which liquid hydrogen passed before entering the reactor. The liquid hydrogen cooled the nozzle, the attachment flange, and bolts. Small repairs were made to the nozzle for the tests. In addition, a camera and light port and a port for bleeding turbine gas were added. Both high- and low-speed cameras were used for the tests (Ref. 61).

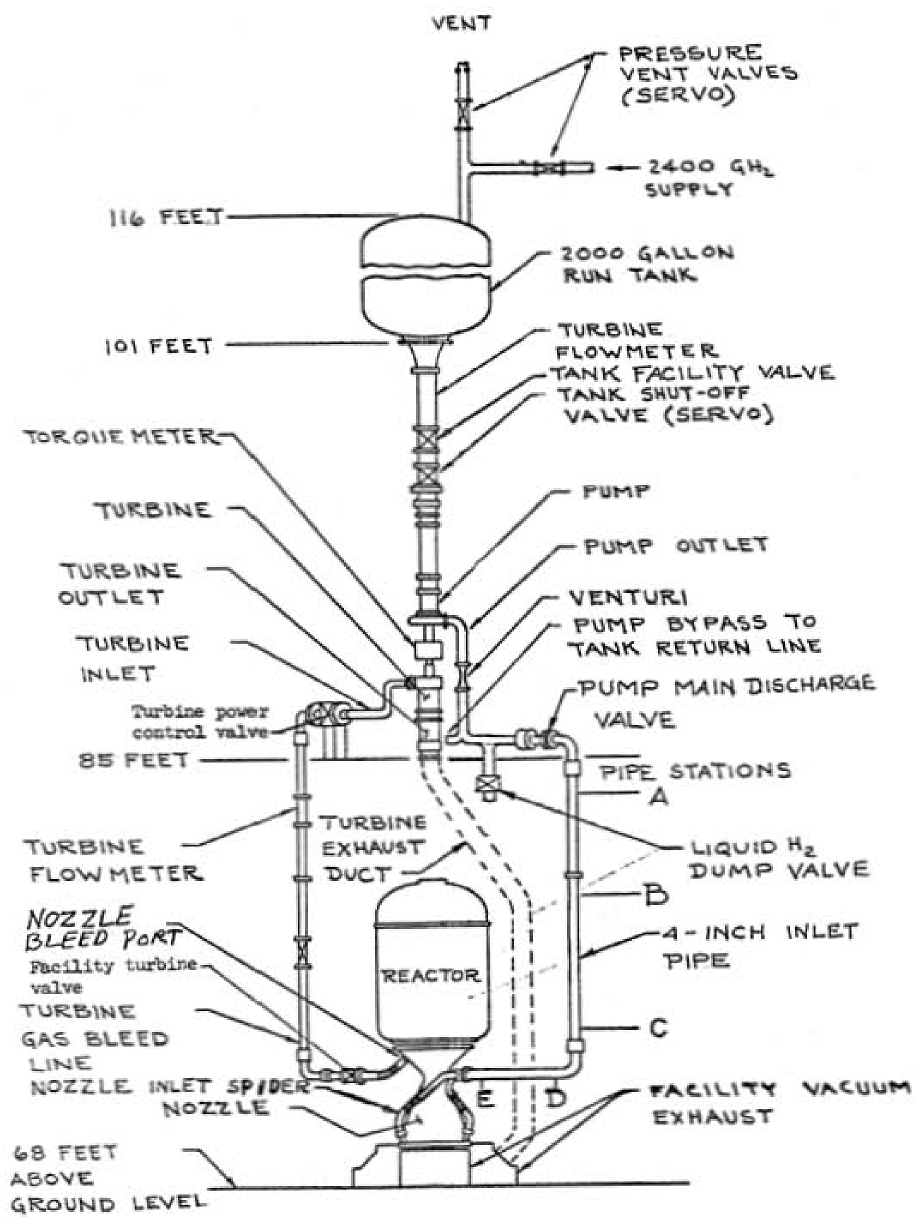

Figure 3.7.—Reactor and turbopump assembly for Nuclear Engine for Rocket Vehicle Application (NERVA) tests, 1964 (NASA TM X–52204, Fig. 2, NASA Glenn).

Test procedures: The NERVA tests at B–1 usually required a 2-day countdown that involved 25 engineers, mechanics, and technicians. It took nearly 2 days for the B–1 Boiler House to fill the steam accumulators. The process included moving the nitrogen and hydrogen trailers into the dock, calibrating and verifying all the instrumentation, checking the support systems, and sequencing the run programmer equipment. The liquid-hydrogen lines and exhaust duct were cleared and inerted, and the data system’s final electrical calibration signal was taken. Then the pump and feedline were chilled (Ref. 61).

During the actual tests, there were between 8 and 10 people in the B–1 control room. The controls engineer sequenced the events for the test and made sure that the valves and pumps were operating. An instrumentation engineer verified that all of the preinstalled sensing equipment was functioning. A data engineer communicated with the H Control and Data Building to make sure that they were receiving the test data, and an electrical technician monitored the data recorders and other electronics. The operating engineer actually ran the test. In addition to this Plum Brook staff, there were usually three or four researchers from NASA Lewis's Cleveland campus in the B–1 control room (Ref. 124).

At this point the steam ejector system was initiated. The operators would wait for the exhaust duct to eject 2 psi, then allow the test program timers to commence the test. The tests usually lasted under 1 minute. Afterward, any lingering hydrogen was removed and the facility was secured (Ref. 61).

A single 400-second test run using liquid hydrogen generally required about 16 hours of preparation and cleanup. Two shifts were employed. The instrumentation was checked out in the morning, then the liquid-hydrogen lines were purged and the controls were set up. The liquid nitrogen was loaded, data equipment were turned on, and the area was cleared of personnel. The countdown of checks was begun in the evening; then the test was run (Ref. 124).

3.2 B–3 Test Stand

B–3 was used to study tanking and flow systems for complete rocket systems at simulated altitudes. The rocket's combustion chamber was pressurized to simulate an actual launch, but the engines were not fired. Researchers could study the effect of combustion chamber pressure on flow dynamics (Ref. 5).

3.2.1 B–3 Structure

The 210-ft-high tower, which had a 50- by 50-ft square base, was the tallest structure at Plum Brook. The upper section was 32 by 27.5 ft. It was enclosed above the 74-ft level. The stand faced south and had removable corrugated metal walls on three sides. The floors could be moved to assist in mounting in the upper section (Ref. 125).

The tower had three floors (at 73.5, 94.5, and 115.5 ft), access platforms, stairways, and walkways. It also had three partial floors (at 42, 126, and 147 ft). A shop and other service areas were at the tower base, which was reinforced concrete. A 65-ton crane was installed at the 176-ft level to load the test articles inside. This double-girder crane spanned 28 ft and could travel outside the test stand to access the railroad line adjacent to the facility and to reach the main test area at 74 ft. The main working levels of the test stand were accessible by a 3-ton elevator (Ref. 126), and roll doors were included on three sides for ventilation (Ref. 127). The 110-ft-tall rolling doors were cited as the largest ever built (Ref. 49).

Shop area and equipment rooms: The first floor had a shop area, a mechanical equipment room, a tool crib, a manifold-purge control room, forward instrument room, and restrooms. The shop area and mechanical equipment room were in a 30-ft-wide, 65-ft-long, and 21-ft-tall structure adjacent to the east side of the test stand. It was covered in corrugated metal and had a shed roof. The mechanical equipment room occupied the 14.17 ft at the south end of the structure. Double doors in its north and west walls provided access to the shop area and to the rear of the test stand, respectively. The shop area had a large truck entrance, a pedestrian entrance, and two pairs of nine-paned windows on the east wall. There was also a single doorway on the north wall and another truck door leading to the test stand on the west wall (Ref. 128).

Forward instrument room: The 24.33- by 12.5-ft forward instrument room was adjacent to the north side of the test stand. A 6-ft wind entranceway was adjacent to the west wall of this room. It could be accessed through a doorway between the two rooms or from the entrance at its north end. The hall led to the area beneath the test stand.

Controls Room and base of the test stand: The actual base of the test stand was a 50- by 50-ft square. The southern 28.5 ft were unenclosed. The 5-ft-diameter altitude exhaust pipe entered this area along the ground from the west, and then at the center of the test stand, it ran upward to the test section. The northern 21.5 ft of the base was an enclosed structure, with the forward instrument room adjacent to the north and the shop area adjacent to the east. Along the southern length of this enclosure was a 10-ft-wide passageway leading from the shop at the east to the north-south passageway at the other end. A stairwell near the west end of the passage rose the entire length of the stand. A 10-ft doorway opened up into the open space beneath the stand, and an elevator entrance and corridor leading north to the forward instrument room were off the north side of the hall. To the north of the hall was a locker room, the north-south hallway, the elevator shaft, and the Controls Room. The Controls Room was 20 by 15.75 ft (Ref. 128).

Elevator, stairwell, and cable chase: The 8.75- by 8.75-ft elevator shaft ran up the center of the north wall of the stand. The entire north wall was enclosed for the entire height of the stand. There was an elevator machine room at the top level (Ref. 129). A 17- by 15.75-ft area in the northwest corner was used to run cables from the control room on the ground floor up to the test section. The stairwell from the ground level to the top of the stand was at the northeast corner. A pipe chase was located between the elevator and the stairs. The elevator, stairwell, and cable chase were enclosed (Ref. 130).

42-ft level: At this level a 4.5-ft steel-grated balcony ran the length of the north wall to provide to access to panels on the cable chase (Ref. 130).

73.5-, 94.5-, and 115.5-ft levels: These were the main working levels. An overhang extended from the front of the tower that could be enclosed from the 75.5-ft level to the top. At the base was a garage. The first level to be entirely closed by walls and roll-down doors was at 73.5 ft. This level also had removable steel-plate flooring, the center of which could be opened to various sizes. The stairwell, elevator, and chases were along the north wall. Railings ran across the openings. The 73.5- and 94.5-ft levels were identical, but the 115.5-ft level had a steel-plate floor with a square 14.5- by 14-5-ft opening in the center. The cable and pipe chases terminated at this level (Ref. 131).

The test area began at the 74-ft level and extended to the crane bottom at 176 ft. There was a 24- by 36-ft open area inside the test stand. Hydrogen was pumped into the test stand at

800 gal/min through a 3-in.-diameter vacuum line. Three 4500-gal trailer tanks were used to supply liquid nitrogen (Ref. 103).

126- and 147-ft levels: There was a 5.25-ft steel-grated platform along the north edge, and steel-grated platforms replaced the cable and pipe chases on either side of the elevator. The remainder of the space was open. The 126- and 147-ft levels were identical in design (Ref. 131). The 46,000-gal (18-ft-tall) propellant tank was in the middle.

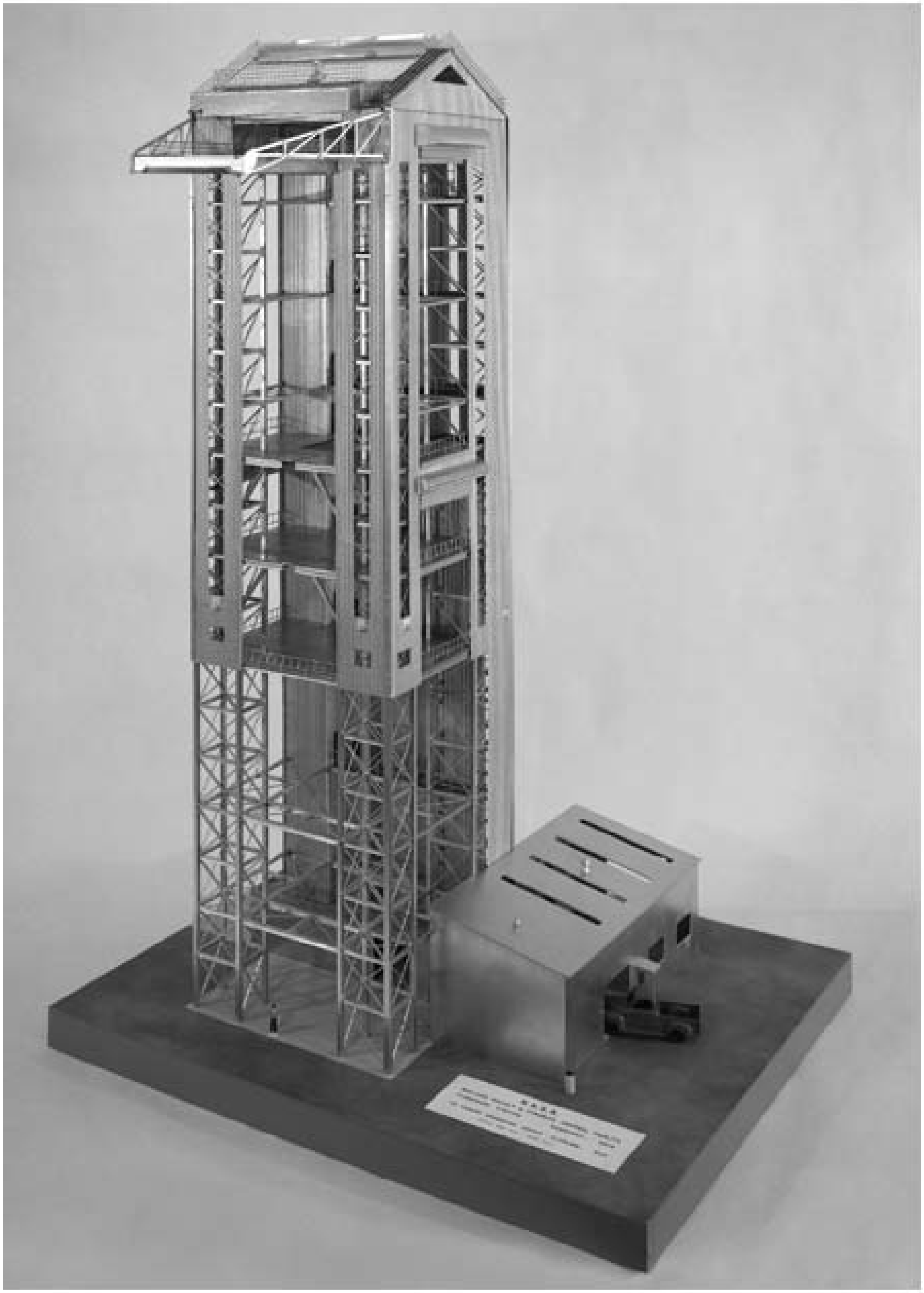

Figure 3.8.—Model of the B–3 test stand (viewed from the southeast), 1963
(C–1963–64249, NASA Glenn).

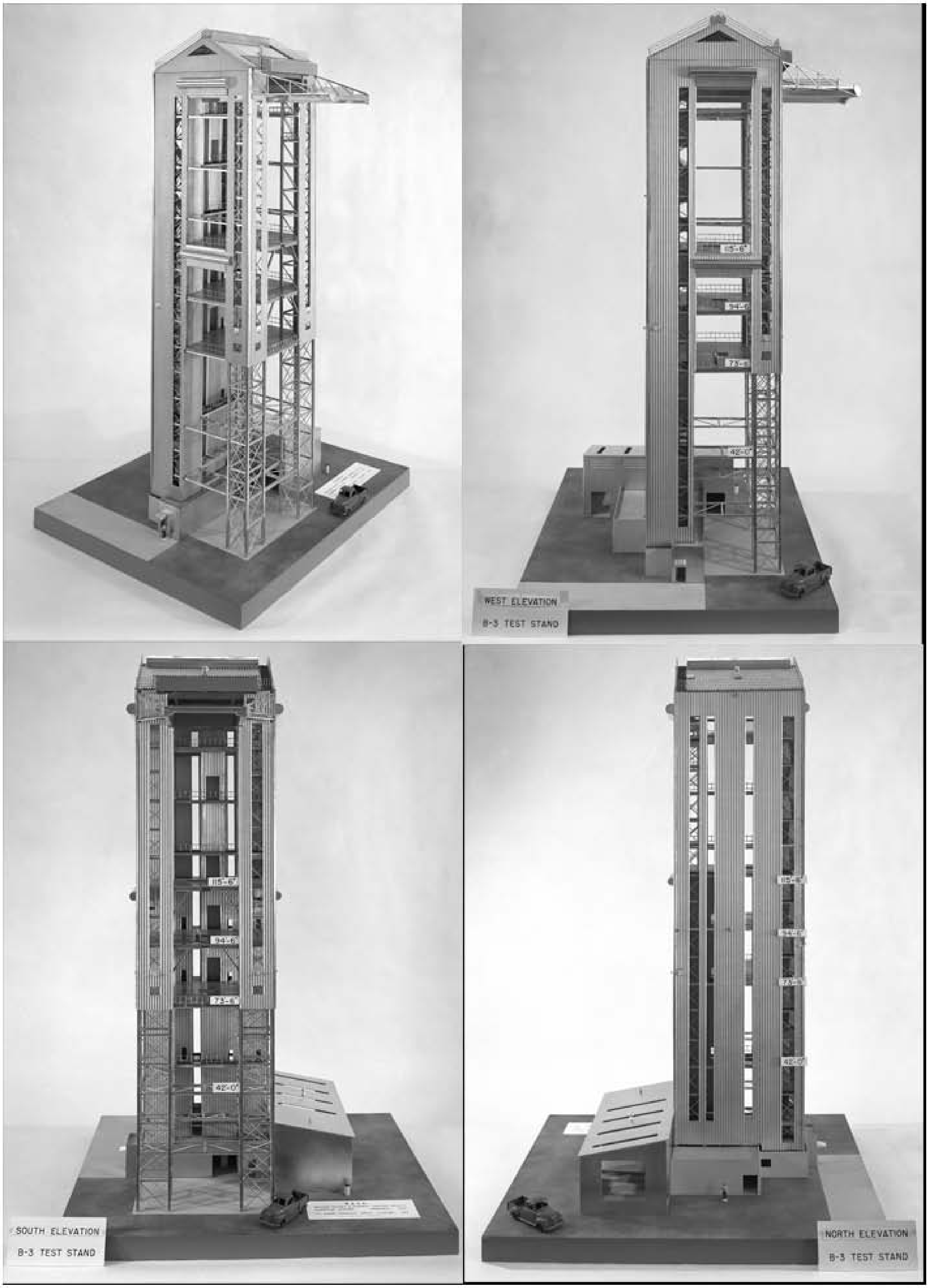

Figure 3.9.—Model of the B–3 test stand (clockwise viewed from the southwest, west, north, and south), 1963 (C–1963–64248, C–1963–64253, C–1963–64252, C–1963–64250, NASA Glenn).

3.2.2 Centaur Standard Shroud Test Setup (B–3)

Catch nets: A catch net was needed to receive the jettisoned half of the shroud during the separation tests. The nets were constructed from 1-in. nylon straps spaced approximately 10 in. apart. A 6-in.-diameter aluminum pipe supported each side of the net, and disk brakes absorbed the energy during the jettison (Ref. 126).

Test sequence: The first step in the jettison tests was to load the explosives used to separate the fairing halves. Next the system was purged first with gaseous nitrogen then with gaseous helium. The explosives were then set, the stand evacuated, and the liquid-nitrogen and liquid-hydrogen propellants were loaded into Centaur's tanks. The rocket was then allowed to chill to thermal equilibrium, and heat transfer, or boiloff, tests were run to determine the tank heating rate prior to launch. The propellant tanks were then emptied. Explosives were fired to separate the forward bearing struts and the forward seal. The shroud's two halves were then jettisoned into catch nets. For two runs, a secondary jettison system was fired while the shroud was in the catch nets. The facility was then cleaned up, the hardware was inspected, and the shroud was removed for repairs. Refurbishing and reinstalling the shroud usually required 6 to 7 weeks.

Shroud: It was necessary to have a space between the shroud and the propellant tank. This was accomplished with a forward circumferential seal, an aft circumferential seal, two forward split-line seals, and two aft split-line seals. The circumferential seals allowed the area between the shroud and the tank to be purged with helium during the tanking. The other enclosed areas were purged with nitrogen. The seals kept the helium from entering the nitrogen spaces.

Test procedures: The CSS test runs generally required about 12 hours of preparation and cleanup to run. The instrumentation was inspected, liquid nitrogen and other systems were checked out, and data-recording equipment was activated. There were about 15 to 18 people in the B–3 control room during the tests. This included several representatives from the shroud manufacturer, Lockheed Corporation.

3.3 Altitude Exhaust System

Figure 3.10.—Boiler Building (viewed from the northeast), 1964 (C–1964–72617, NASA Glenn).

B–1 could test turbopump performance in conditions that matched the altitudes of space. A large steam-powered altitude exhaust system reduced the pressure at the exhaust nozzle exit to 0.5 psi for up to 4 minutes. The system included boilers, accumulators, valves, and ejectors (Ref. 61). A smaller boiler building (the B–3 Boiler House) was added for the B–3 test stand. B–3 (and later B–2) also were linked to the original steam system.

3.3.1 Boiler Houses

The Boiler House (Bldg. 5221), located approximately 1000 ft west from B–1 was originally built for the Ordnance Works in the early 1940s. The building contained four Babcock and Wilcox boilers that were similar to those used on World War II era battleships (Ref. 118). Each could discharge 28,000 lb/hr of 500-psig[4] saturated steam. Of that, 25,000 lb/hr were used to charge the accumulators while the remaining 3000 lb preheated the supply water and fuel oil and drove the turbines used by water pumps. The length of operation of the boilers was hampered only by the amount of oil and the domestic water supply (Ref. 61). An air dryer, after cooler, and air compressor were located in the northwest corner. A condensate reservoir tank, chemical feed pumps, and a tank were located along the north wall. In the northeast corner was an auxiliary

[4]Pounds per square inch gauge.

boiler with its own 12-in. stack. Two feedwater pumps were between the boilers near the center of the room (Ref. 132).

The B–1 Boiler House was a rectangular structure running north and south with a large water storage tank on its roof, a smaller deaerator tank on top of that, and two large stacks, one for each pair of boilers, rising through the roof. At the east end was shedlike structure perpendicular and adjacent to the main building. It looked like several small structures had been thrown together. The boilers extended out from the east and west walls. There were a doorway and window in the north wall, a doorway on the east wall, and two doors on the south wall. In addition to the main stacks, there were several smaller vents through the roof (Ref. 132). A cylindrical blowdown drum and a liquid-level standpipe stood vertically outside the north end. There were stairways and platforms to access the water tank (Ref. 133).

A 54-in.-diameter vacuum line was extended to B–3 so that it could use the B–1 ejector system. The run time for the B–1 ejector system was increased to 450 seconds and would allow for a 880-second run time at B–2 (single ejector) and a 270-second run time at HTF in later years (Ref. 118). The B–1 steam system was rehabilitated in the early 1990s for B–2 testing.

A second boiler building (the B–3 Boiler House) was added during the construction of the new B–3 test stand. This 22.25- by 20-ft single-story structure sat approximately 150 ft to the northwest of B–3. It had a gabled roof, insulated metal siding, and two stacks. The entrance was a double set of doors on the south wall, and there was a six-paned window on both the east and west wall (Ref. 134).

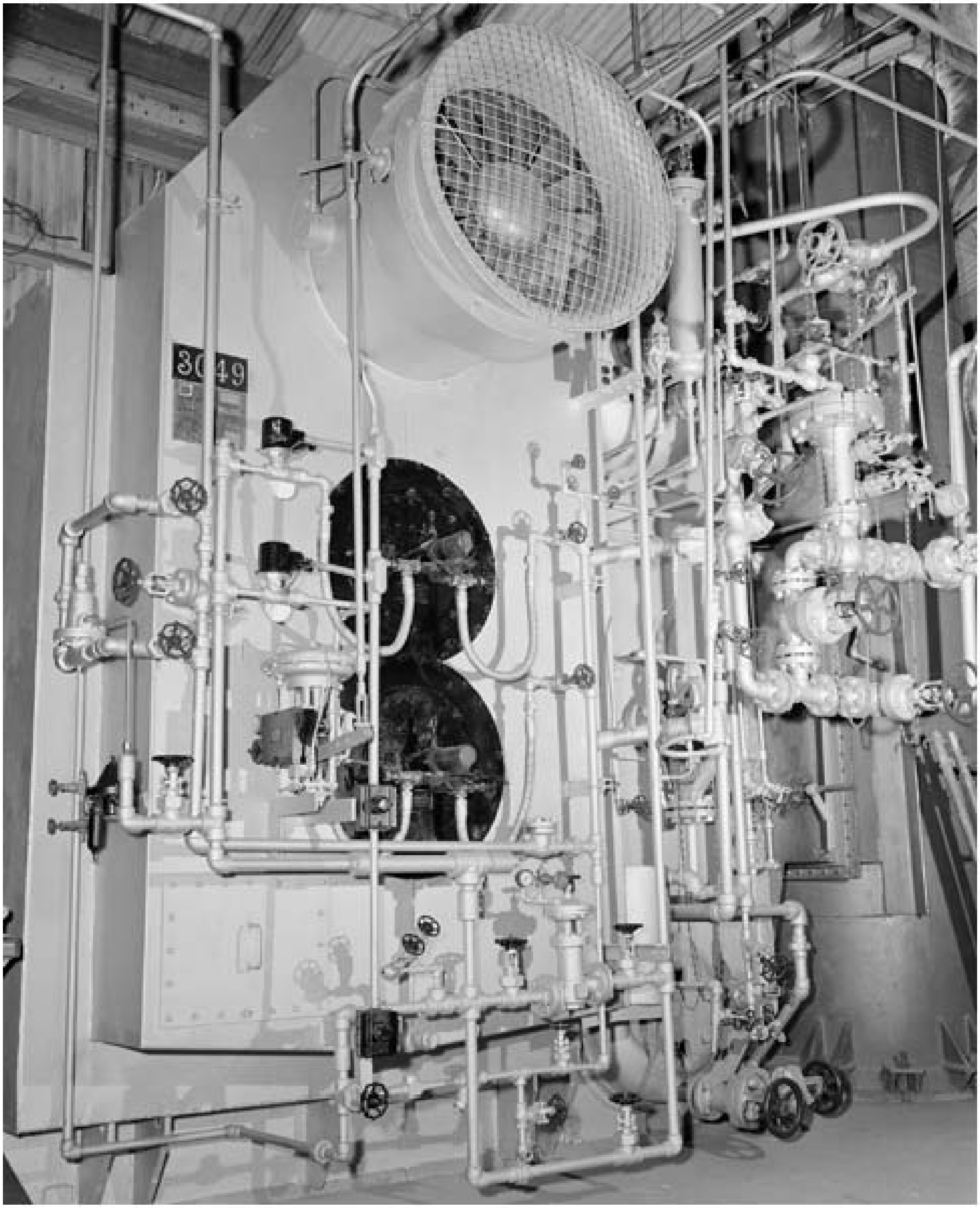

Figure 3.11.—Boiler in the B–1 Boiler House, 1962 (P62–01036, NASA Glenn).

Figure 3.12.—Rectangular Pump and Shop Building (right), freshwater basin (top left), and waste-water basin (foreground), 1962 (P62–01525, NASA Glenn).

3.3.2 Pump and Shop Building

The B–1 test stand was originally designed to hot-fire rocket engines, but it was never used in this capacity. The Pump and Shop Building and the two rectangular basins were intended to cool the rocket exhaust, but were never utilized (Ref. 124). The 142- by 300-ft basin to the west supplied freshwater, and the 136- by 200-ft one to the east was used for waste water. Four-foot-deep gated channels extended from the top of the basins. A 23-ft-wide, 160-ft-long dike ran from near the northwest corner of the freshwater basin (Ref. 1).

The Pump and Shop Building was a 32- by 101.5-ft rectangular structure at the eastern edge of the freshwater basin. It was 11.75 ft tall with a gabled roof. The walls were concrete block with steel siding. The first floor was mostly open. The west wall had five 9-paned windows. The east wall had four windows and two double-door entrances. An interior wall created a 20- by 32-ft room at the southern end, and there was a doorway between the two rooms. A monorail crane track ran the length of the larger room. A small restroom was located in the northeast corner, and a boiler was located along the north wall. A set of stairs near the center of the room led to the basement (Ref. 135).

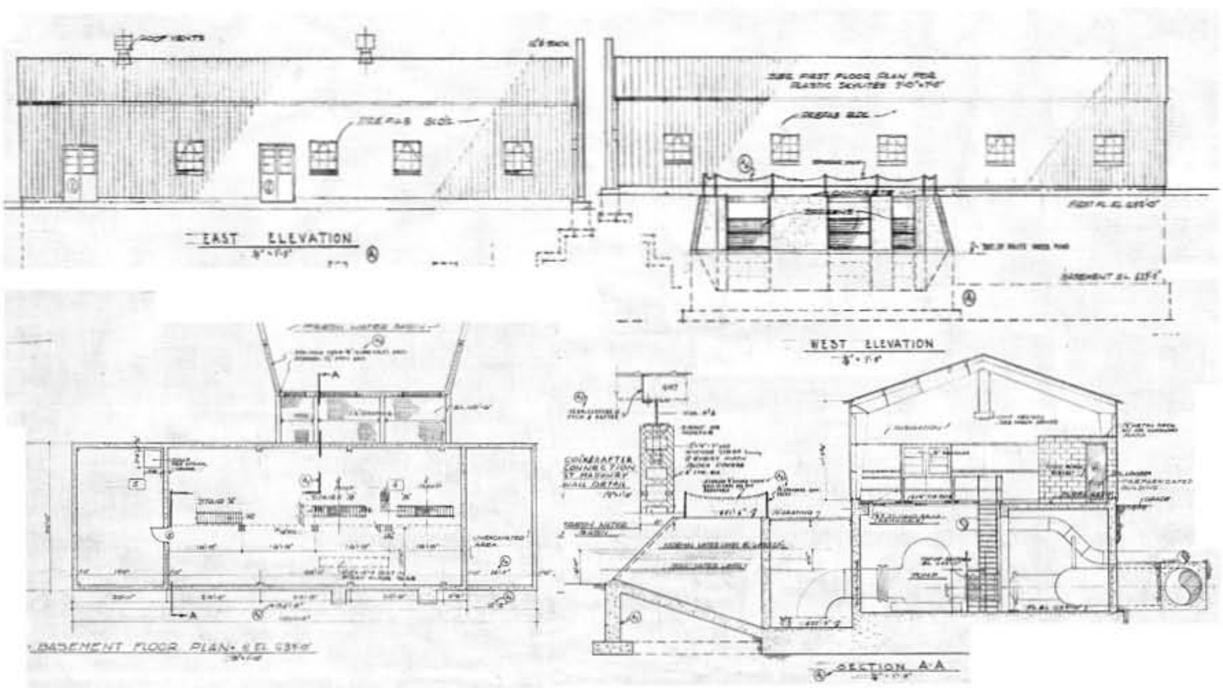

Figure 3.13.—Pump and Shop Building elevations and floor plans, 1962 (PF–20468, NASA Glenn).

Most of the pumping equipment was located in the basement. The layout was identical to the first floor, with the southern 20 ft separated by a wall. This area contained a sump pump, a waste-water circulating pump, a gas compressor, and a dry lime feeder. A 14.5-ft section at the north end of the basement was unexcavated. The two large pumps were located near the west wall close to the center of the building. Each was accessible by a fixed steel ladder from the first floor (Ref. 135).

Water from the basin entered the structure through gates in three concrete bays. Two 3500-gal/min pumps were located in the southern half of the basement. Their 12-in.-diameter intake lines were tied to a single inlet bay, and they pumped the water through a single 18-in.-diameter pipe to the test equipment. Two larger 33,000-gal/min pumps were located in the northern half of the basement. Each of these had its own 42-in.-diameter intake line and bay. The exit lines merged into a 54-in.-diameter pipe. The 54- and 18-in. pipes were enclosed in a concrete encasement as they exited the Pump House. The pipes immediately turned to the east and traveled to the steam ejector (Ref. 136).

3.3.3 Accumulators, Ejectors, and Valve House

Three steam accumulators made of 2.18-in. steel plate were located off the south corner of the test stand. They were 53.5 ft long with a 12-ft outside diameter and had a 3-in. layer of insulation on the interior. These large accumulators could store 42,000 gal of steam and hot water (Ref. 61). The three accumulators were connected by single steam line. Two more 50,000-gal steam accumulators and a third control valve were added to the steam system around 1968. This increased the total available steam for the ejector systems to 160,000 lb-mass (Ref. 118).

Figure 3.14.—B–1 test stand with steam accumulators (left), Valve House (center), and steam ejector (right), 1961 (P62–01859, NASA Glenn).

The steam stored in the accumulators was used to operate two large Elliot steam ejectors located outside B–1's southeast wall. The ejectors used a pressure regulating system in the nearby Valve House to reduce the pressure at the exhaust duct to simulate the altitudes of space. The throat area of the first-stage ejector was 34.5 in.^{2} and that of the second larger ejector was 134.5 in. The pumping capacities of these ejectors were 10, 20, 30, and 48 lb of gaseous hydrogen with exhaust nozzle exit pressures of 1.5, 4, 8, and 14.7 psi, respectively. The system could evacuate the 30,000 ft^3 of duct to 0.5 psi in approximately 45 seconds (Ref. 61).

Figure 3.15.—Interior of one of the steam accumulator tanks, 1963 (P63–01451, NASA Glenn).

At maximum boiler capacity, the steam system required 2 days to furnish approximately a total 100,000 lbm of steam to the ejector system at B–1, which could support ejector operation at B–1 for approximately 6 minutes. The control system from the General Regulator Company in New Jersey regulated the steam flow to the approximately 150 psi needed to operate the B–1 ejector system, this mechanical control system was modified and upgraded to an electronic control around 1964 (Ref. 118).

The Valve House was a 20- by 32-ft single-story structure with metal siding and a gabled roof. It was located between the accumulators and the ejectors. There were two 9-paned windows on both the northwest and southeast walls and a doorway on the southeast wall. Three lines from the accumulators entered the northwest wall of the Valve House and connected to a 14-ft-long tank. A 16-in.-diameter pipe exited the tank and building and connected with the steam ejectors. A second 30-in.-diameter line was added around 1964 (Ref. 137).

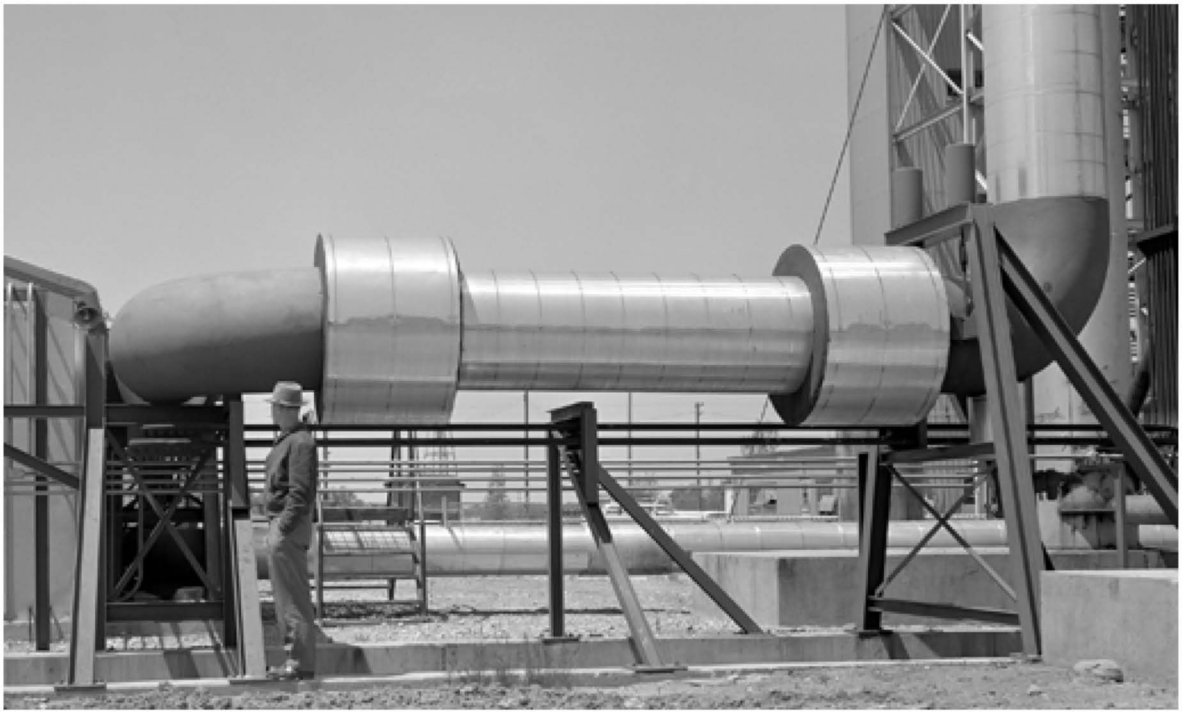

Figure 3.16.—Exhaust pipe passing behind the Valve House, 1963 (P63–01460, NASA Glenn).

Another ejector, referred to as the zero-flow ejector, used the liquid hydrogen’s kinetic energy and the two Elliot ejectors to minimize the back pressure from the engine exhaust by keeping full flow through the engine nozzle for the majority of the test run. The contraction area ratio of the zero-flow ejector was 1.6, the diffuser inlet diameter was 32.5 in.; and the contraction angle was 6°. The length of the second throat was six times the diameter, and the subsonic diffuser expansion angle was 15° (Ref. 61).

Figure 3.17.—Steam ejector exhaust stack venting, 1963 (P63–01163, NASA Glenn).

Since the rocket engine was not fired during the tests, the liquid hydrogen pumped through the engine had to be displosed of. It flowed down through the exhaust duct and mixed with the steam at the ejector. This explosive mix was burned off in the ejector stack and vented into the atmosphere. B–3 used 40,000 gal of liquid hydrogen for a single 400-second run. A separate ejector stack was built 600 ft from the stand to burn off the propellant (Ref. 124).

3.4 Fuel and Gas Supply

A number of ground-level semitrailers, fixed gas storage bottles, and mobile liquid dewars were used to store the gaseous and cryogenic materials for the B–1 and B–3 test stands. The cryogenics were mostly used to fuel the rocket engines, and the gases were used for pressurization and inerting.

3.4.1 Cryogenic Fuel Systems

The cryogenic liquid hydrogen and liquid nitrogen were used to fuel the Centaur and NERVA engines during many of the tests. The hydrogen system was used to fuel the reactor during the test. The hydrogen was pumped through a vacuum-jacketed line to the top of B–1 where it was pumped through the engine during the test run (Ref. 61). Initially B–1 used two trailer truck tanks and 100,000 ft^3 of permanent storage to supply each test run with the cryogenic fuels. An external pump was used to transfer the fuels to the top of the test stand (Ref. 61).

A 200,000-gal dewar, the world’s largest liquid-hydrogen dewar at the time, was installed at the B Complex by the Chicago Bridge and Iron Company in 1963 (Ref. 138). In comparison, Los Alamos had only a 100,000-gal tank at its Jackass Flats test site where the actual NERVA reactors were tested. Cape Canaveral would subsequently have two larger dewars. Plum Brook’s $382,000 dewar was 37 ft in diameter and had a volume of 26,800 ft^3 (Ref. 139).

The dewar was located approximately 300 ft northeast of B–1 and an equal distance northwest of B–3. Vacuum-jacketed lines could supply 800 gal/min to the stands. The dewar had a 12-ft-high control building (Bldg. 5335) that received its own upgrade in 1966. The dewar was used not only for B–3 tests but also as a general liquid-hydrogen storage facility for other Plum Brook test facilities.

Four 4500-gal tanker trailers supplied the liquid nitrogen for B–3. They connected to a manifold at the test stand’s base. A 2.5-in.-diameter insulated copper line carried the liquid to the upper levels of the test stand (Ref. 126).

Twelve flares were installed at the exit of B–1’s second ejector to burn off any remaining or excess hydrogen in the exhaust section. The flares were ignited when technicians in the Valve House lit the natural gas in a tube leading to the flares (Ref. 61). A similar stack was located 315 ft southeast of B–3. A natural-gas flare at the top was used to dispense up to 200 lb of hydrogen/sec (Ref. 126).

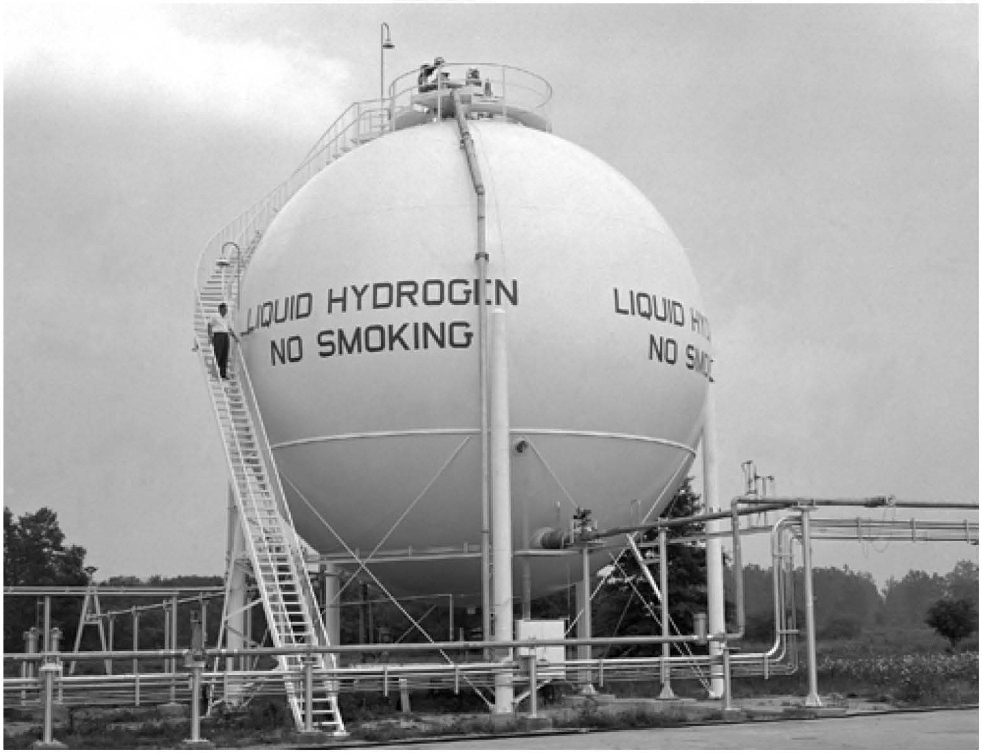

Figure 3.18.—Liquid-hydrogen dewar at the B Complex, 1965 (P65–02438, NASA Glenn).

Figure 3.19.—Three-inch-diameter vacuum-jacketed liquid-hydrogen line from the dewar to B–3, 1965 (P65–02645, NASA Glenn).

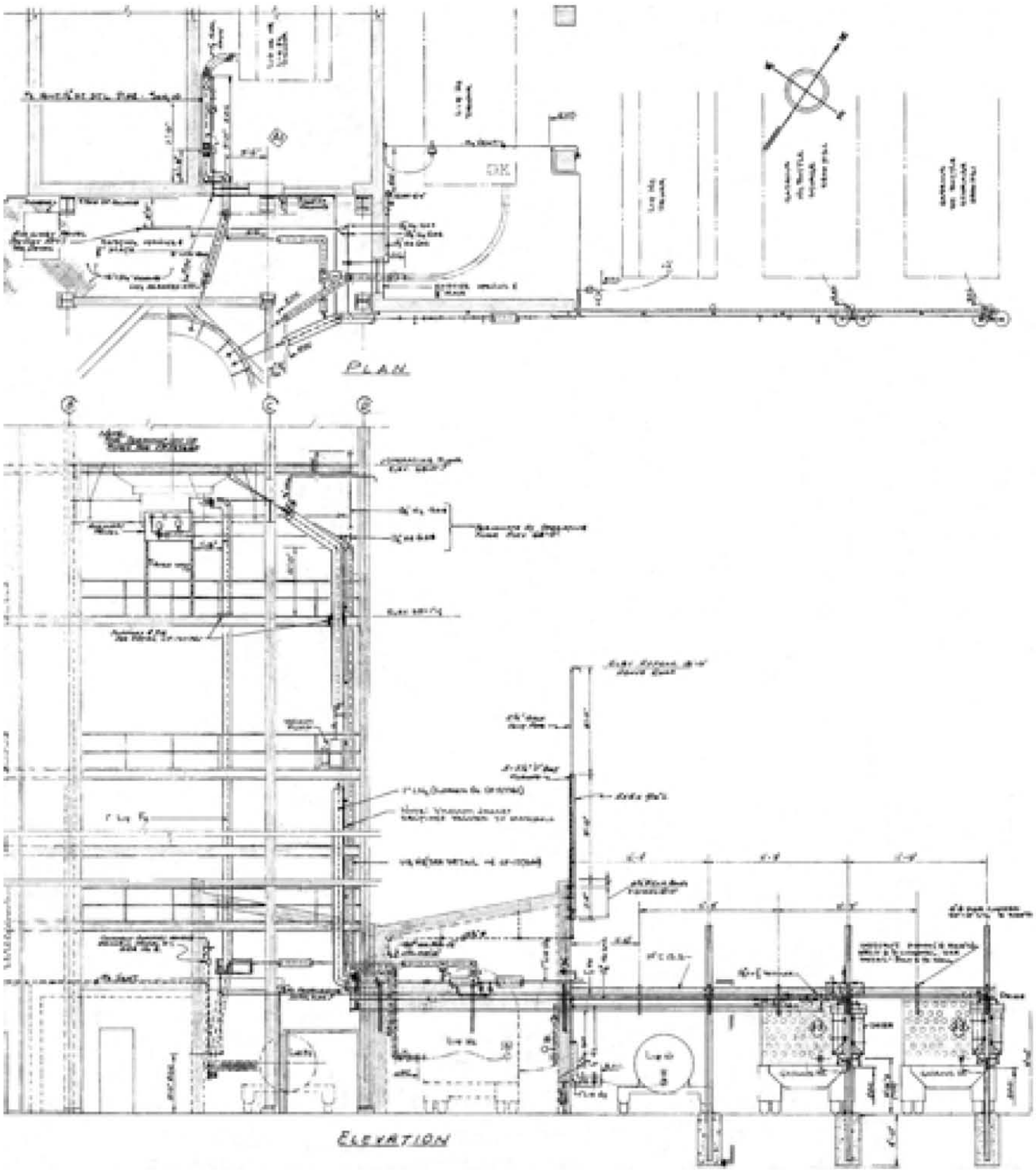

Figure 3.20.—B–1 liquid-propellant feed system drawing, 1960 (PF–20212, NASA Glenn).

3.4.2 Inerting Gases

Gaseous nitrogen was used to purge the liquid-nitrogen lines and electrical equipment after each test run and to pressurize the shroud payload area and valve operators. B–1 included a large nitrogen system to purge the exhaust duct, a vent stack, a pump, a reactor, and a terminal. A single helium trailer was used for each test run to purge the test equipment and keep the reactor and observation windows free of frost (Ref. 61). At B–3, two 780,000-ft^3 railroad car nitrogen tanks and four 70,000-ft^3 trailer helium tanks were used for each test. A gaseous nitrogen bottle farm was a backup for the valve operators. A similar setup was used for gaseous helium. The helium was used to pressurize the shroud tank section and to inert the liquid-hydrogen lines. A single-stage vacuum pump inerted the liquid-hydrogen transfer and dump lines. It could reduce the pressure to less than 1 torr (Ref. 126).

Hydraulic servovalves were used to maintain tank pressure and flow through the test equipment. The two redundant systems could pump 20 gal/min. There was also an oil lubrication system for the test engine. An educator system and diffusion pump were used to rapidly pump down the interior of the tank and fuel lines. By pumping down the empty system and returning it to atmospheric pressure several times, remaining hydrogen would be purged from the tank, making it ready for its next test (Ref. 61).

Figure 3.21.—Nitrogen trailers discharging cryogenic liquid nitrogen at the B Complex, 1963 (P63–01627, Plum Brook).

3.5 Control and Data Acquisition

Over 400 sensors were installed in the test stands. Data from each were sent to the B Control and Data Building to be digitized. Then the data were relayed to the H Control and Data Building to be saved to magnetic tape. Finally, those tapes were shipped to NASA Lewis's Cleveland campus for analysis of the data.

3.5.1 B Control and Data Building

The B Control and Data Building was constructed in 1960 to remotely control the operation of the B–1 test stand. By January 1963 plans were made to greatly expand the facility to include the B–3 and HTF control rooms. Later when B–2 began operating, its control room was also added. The reinforced-concrete B Control and Data Building was located approximately 2300 ft southwest of B–1, and 2600 ft west of B–3. The distance protected the staff from possible explosions at the test site (Ref. 61). Electrical lines and cables connected the building to the test site. Instrumentation signals were sent to patchboards and relays via land lines to the control room at the test stand.

The B–1 control room was an L-shaped room that was separated off the eastern corner of the facility. It had two rows of panels running parallel to one another and a third set of panels perpendicular to the right. Two operators ran the test from the main facility control panels, which controlled the liquid-hydrogen tank feed, liquid-hydrogen chilldown, the ejectors, and the purge system. The operators also were responsible for monitoring the annunicator board and television console. The annunciator system watched for leaks or other safety issues. It issued warnings to the operators and could also shut down the test run. Event recorders tracked the opening and closing of each valve on the test equipment (Ref. 61).

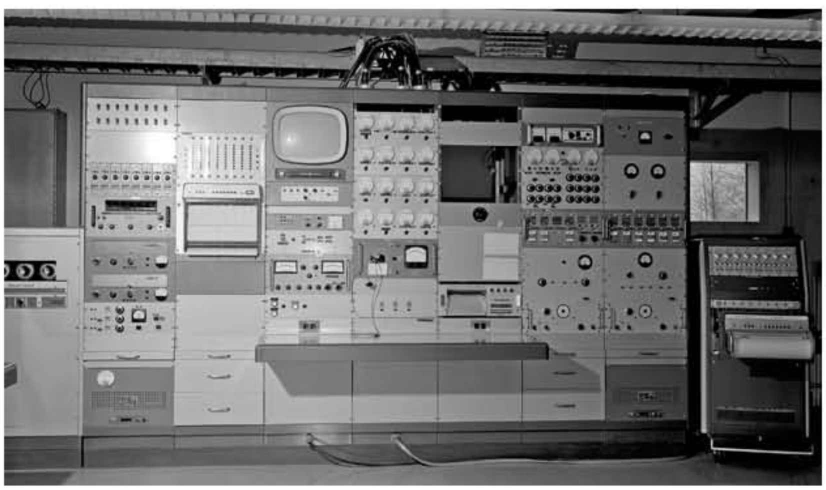

Figure 3.22.—Servocontrol panels in the B–1 control room where operations personnel were stationed. This set of panels was perpendicular to the main control panels, 1964 (P–1964–1273, NASA Glenn).

To the left of the main facility panels were the controls for the carbon dioxide and hydrogen detection systems, the steam system, and the nitrogen-altitude-exhaust purge system. Two technicians staffed this station (Ref. 61). At a right angle to the right of the main control panels were servocontrol panels that were used to program the test runs. This station required three technicians to monitor the pumps, servocontrollers, amplifiers, servocontrol programmer, and overspeed indicators (Ref. 61).

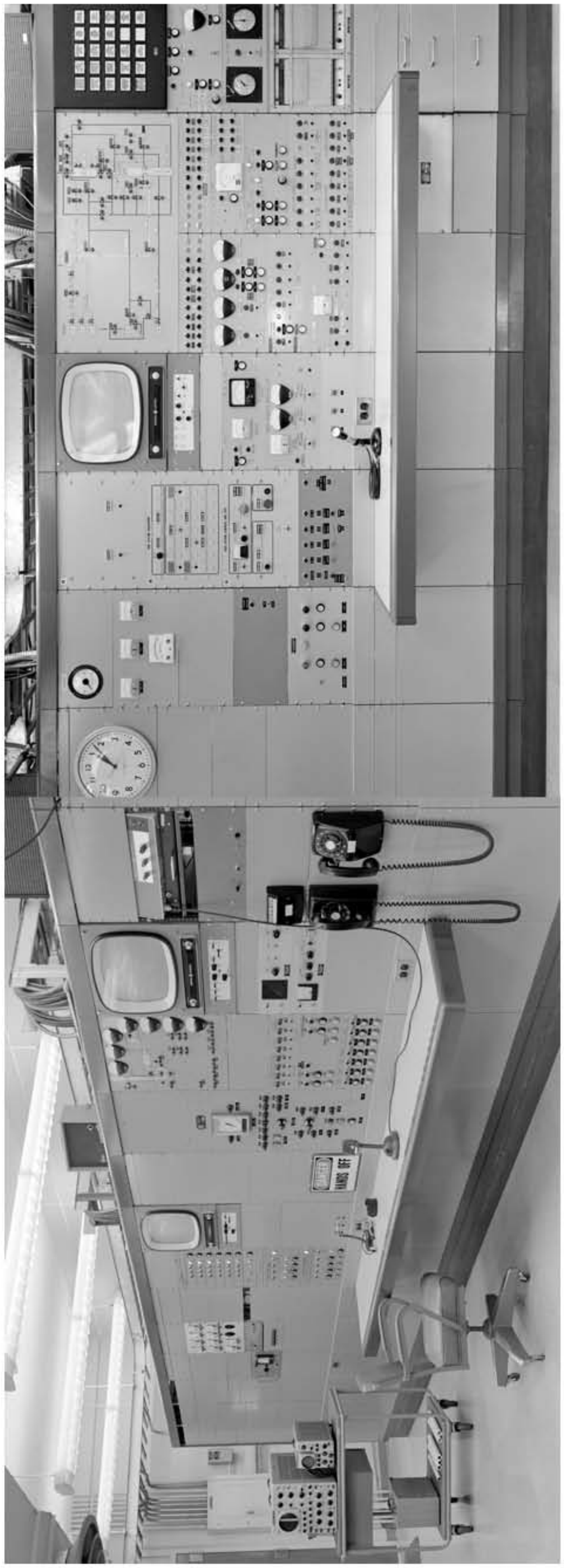

Figure 3.23.—Main B–1 control panels. Left to right: area warning system, motion picture control, main control panels, and event recorders, 1964 (P–1964–1272, NASA Glenn).

Figure 3.24.—Row of amplifiers and chart records (seen from both ends of the row) that ran parallel to the main control panels. The set of servocontrol panels is at the far end of the row, 1964 (P–1964–1274 and P–1964–1270, NASA Glenn).

3.5.2 Expansion of the B Control and Data Building

In 1963 the B Control and Data Building was significantly expanded to provide control rooms for HTF and B–3, which were just being constructed. The new 87- by 107-ft by 11.67-ft-tall section was connected to the northwest corner of the existing facility (Ref. 140). The new area included a 59- by 68-ft area that served as the control rooms for HTF and B–3. The walkway through the room connected to double doors on the north and south walls. There was another door on the west wall that led to the Data Acquisition Instrumentation Room. That room occupied the 68- by 36-ft area at the west end of the new addition. Along the south wall were (from west to east) a 26- by 16-ft instrument room, a 21- by 16-ft office, a small restroom, and a 25.02- by 21-ft equipment room. All the new rooms were accessed by an 8-ft-wide corridor that ran west to east through the new section to the front entrance (Ref. 141).

In addition an 11.83- by 14.08-ft turretlike observation tower was built. The walls were 1-ft-thick reinforced concrete. The hexagonal room extended 5.83 ft above the new entrance where the old and new sections joined. It had three 28- by 22-in. glass windows that faced the test stands, a door on the south wall that exited to the roof, and a stairwell that descended through the floor to the first level of the building (Ref. 141). The windows were 2.5-in.-thick multiplate glass set in a 0.25-in. compressed “lasto-meric” adhesive sealing compound (Ref. 142).

The B Control and Data Building was a single-floor structure with a concrete observation tower rising above to view the test sites. Eventually, it would occupy 11,508 ft^2 and contain 14 rooms, including five control rooms, the Terminal and Instrument Repair Room, an office, equipment storage, and a utility and observation room (Ref. 26). It contained four separate control rooms that operated B–1, B–2, B–3, and HTF. The data-transmission cables ran from the test stands to control cabinets in the B Control and Data Building. From there, they were routed to panels in the applicable control room (Ref. 61).

B Control and Data Building’s reinforced-concrete walls were divided into approximately 6.33-ft sections with concrete flutes dividing them. The original structure was 37.66 by 67.16 ft and 12.5 ft tall. The B–1 control room (which had small windows on its east and south walls (Ref. 143)) occupied an L-shaped area and dominated the structure. In addition, there was the 14.5- by 28.5-ft Terminal and Instrument Repair Room, a 16- by 25.5-ft utility room, a restroom, and an 8- by 20-ft vestibule in between. The main entrance was into the vestibule on the east wall. There were interior doorways into all the other rooms from the vestibule. There was another entrance into the repair room on the west wall.

Instead of being downgraded like B–1 and B–3, the B Control and Data Building was upgraded in the 1982 review to Readiness Category 1. It was reactivated in the late 1980s for B–2 and HTF testing. In the mid-2000s the B–2 control room was modernized as part of an overall modernization of B–2.

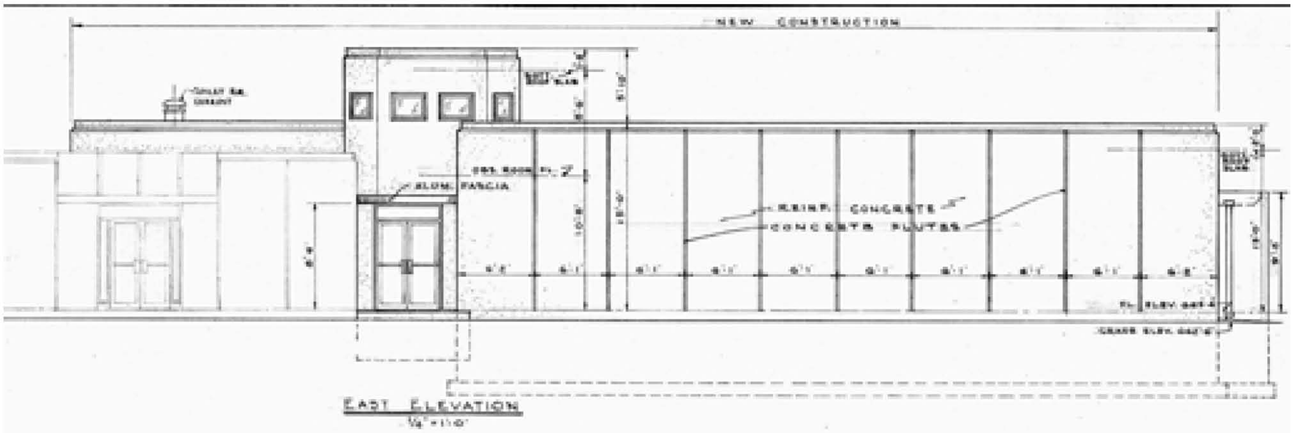

Figure 3.25.—Elevation of the new addition to the B Control and Data Building showing the observation tower, 1963 (PF–24404, NASA Glenn).

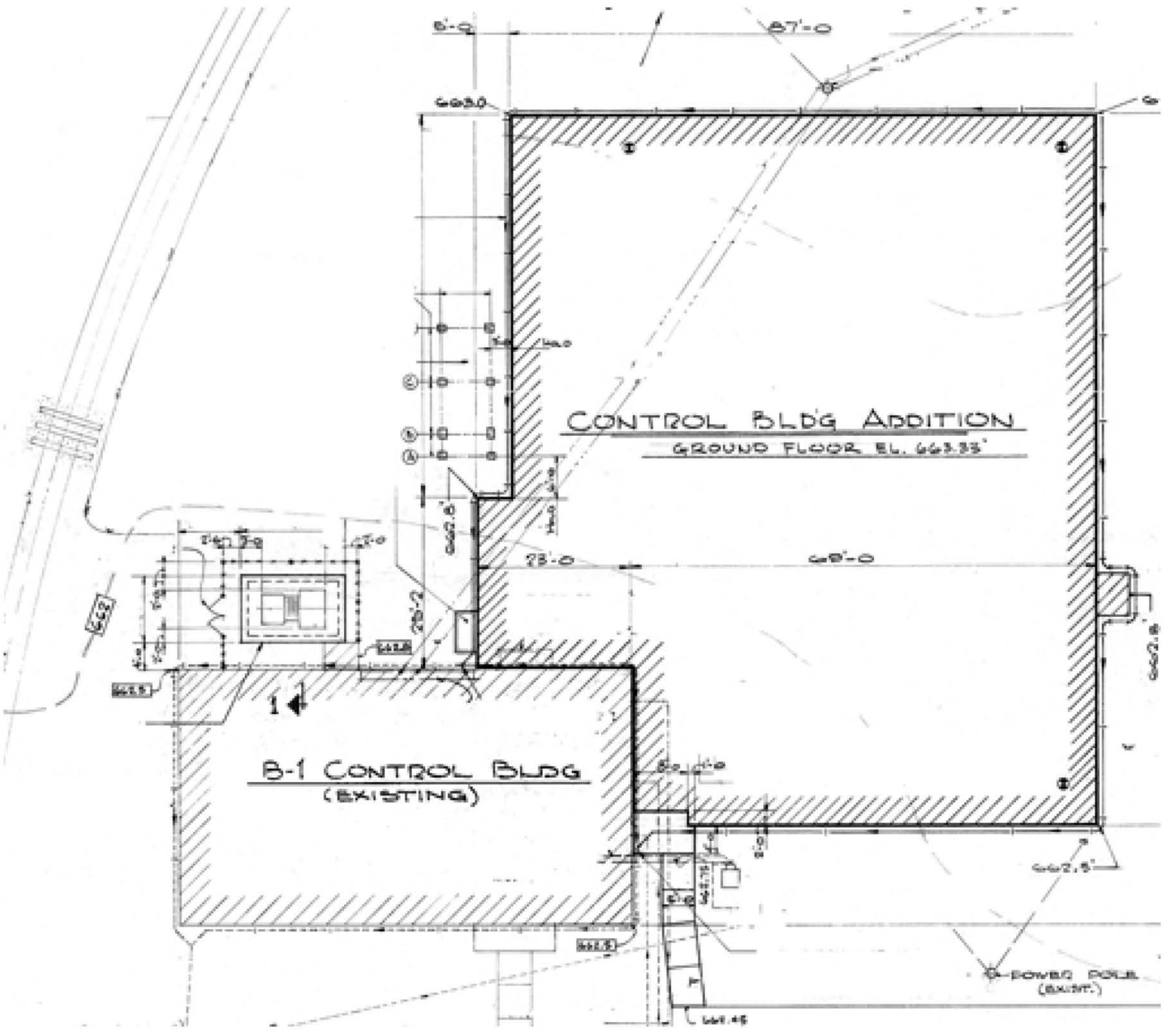

Figure 3.26.—B Control and Data Building layout showing the original B–1 control room (lower left) and the new addition for the B–3, B–2, and the Hypersonic Tunnel Facility (HTF) control rooms, 1963 (PF–24402, NASA Glenn).

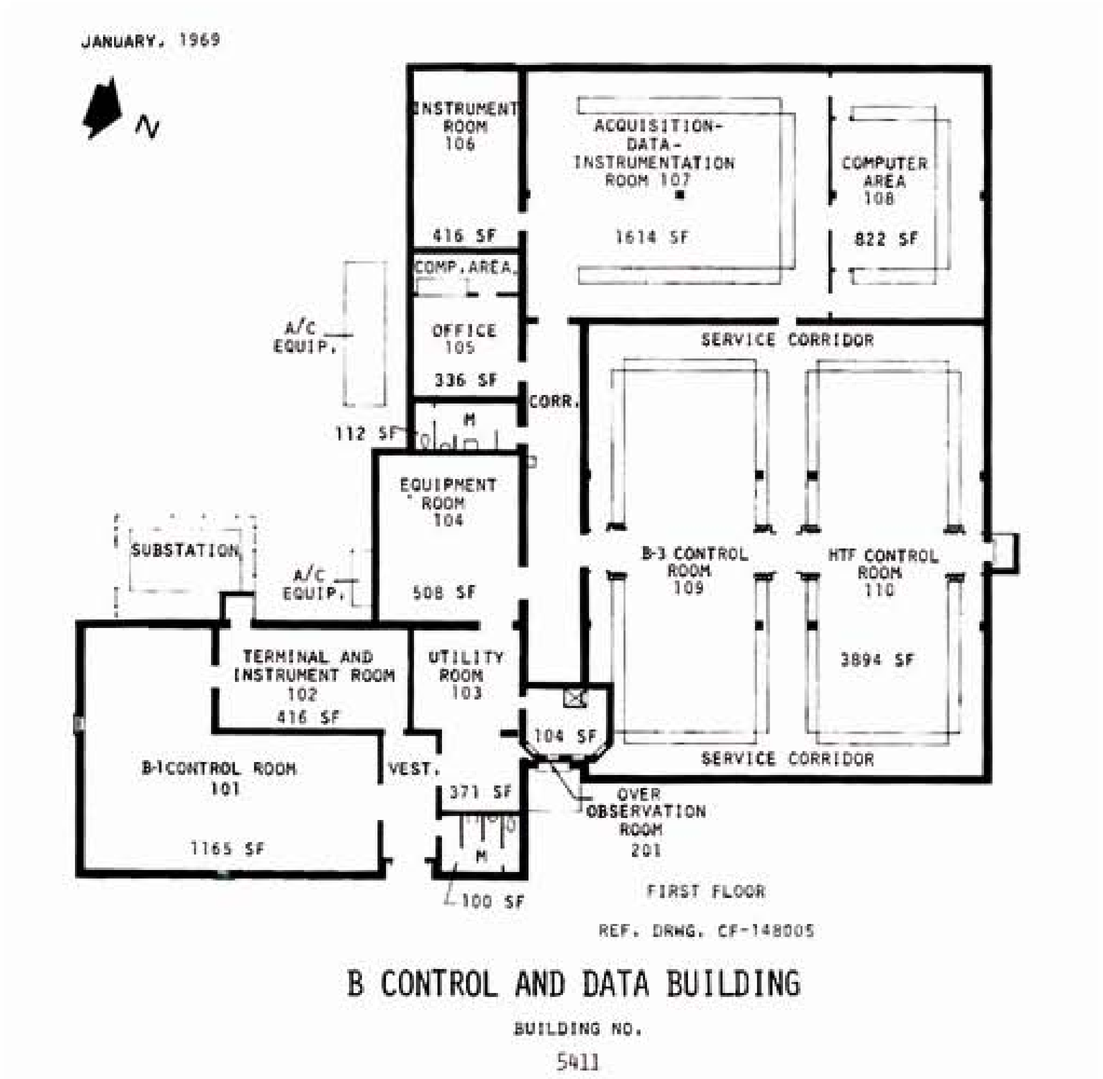

Figure 3.27.—Floor plan for the B Control and Data Building, 1962 (Plum Brook Station Plans and Structures, NASA Glenn History Collection).

Figure 3.28.—B–3 control room in the B Control and Data Building (south and west walls), 1966 (P66–01668, NASA Glenn).

Figure 3.29.—B–3 control room in the B Control and Data Building (west and north walls), 1966 (P66–01669, NASA Glenn).

Figure 3.30.—Gas and propellant control panel, 1963 (29168 PF 01 D, Plum Brook Drawing Collection).

3.5.3 Data Acquisition and Processing

The H Control and Data Building (Bldg. 5412), 5500 ft from B–1, contained all the data-acquisition equipment for all the Plum Brook facilities. There was both an analog and a digital recording system. The latter was more accurate, but the former allowed a high-frequency response. There were two digital acquisition units: a 10-kC 100-channel unit and a 4-kC 192-channel unit.[5] The analog system consisted of a 24-channel tape recorder, four 36-channel oscillographs, an 8-channel oscillograph, and voltage balance strip charts used to record facility parameters (Ref. 61).

The data-processing system was located at NASA Lewis's Cleveland campus. It included a Univac 1103 computer and an IBM 1401 input-output system. Other components included a magnetic tape system, a digital playback system, and a paper tape punch and reader. The test engineer explained the type of data needed to the computer programmer. The equipment was first calibrated, then the measured voltages were averaged to minimize the noise in the system. A great deal of effort was expended to make sure that the signals were clear. The measured voltage was converted into engineering units and printed in columns versus time, and faulty data were then removed. Then the engineering units were calculated and printed in both column and graph forms (Ref. 61).

[5]kC, kilocoulomb.

Figure 3.31.—Data-acquisition equipment for the B–3 test stand, 1967 (C–1967–00718, NASA Glenn).

At B–3, transducers were attached to various locations on the shroud, Centaur, or skirt to record data. Cables connected these sensors to boxes on the third and fourth level of the stand where they were sent to a patchboard in the forward instrument room on the ground level. The signals were multiplexed and sent through cables to the H Control and Data Building for recording on magnetic tape using the Central Recording System. The B Control and Data Building had recorders, as well, and a cathode-ray-tube (CRT) monitor that was run off minicomputers to analyze the tank pressures, temperatures, purge and vent pressures, strains, and deflection as the test was being run. The recorders in the H Control and Data Building were, however, the primary permanent documentation (Ref. 144).

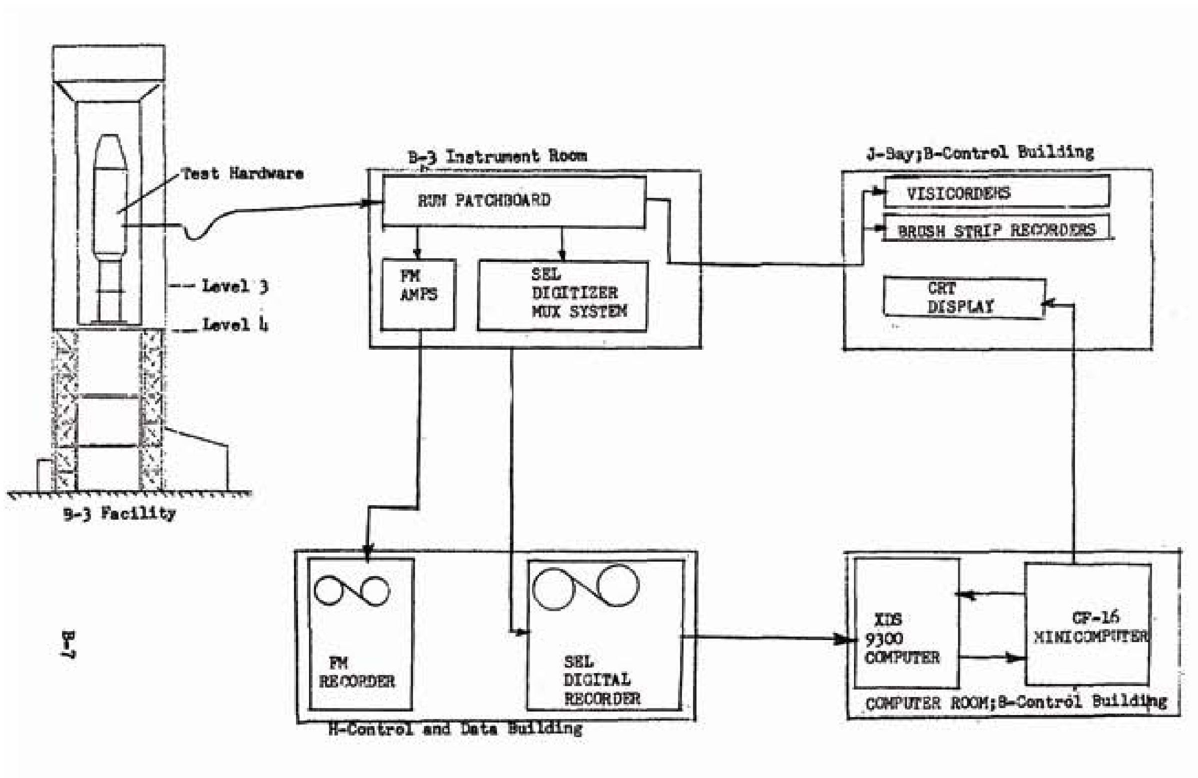

Figure B-1.-Instrumentation and data systems flow schematic for Cryogenic-Unlatch Tests - Plum Brook B-3 Facility.

Figure 3.32.—B–3 data processing, 1973 (NASA TM X–71455, Fig. B-1, NASA Glenn).

The tapes were sent to NASA Lewis's Cleveland campus to be processed by the IBM 360 computer, which transformed the signals into columns of data and plots. The columns were then microfilmed and sent out to a vendor for printing. The entire data-reduction process averaged 36 hours (Ref. 144).

4.0 Demolition

NASA Glenn Research Center's Facilities Division planned and carried out the demolition of the B–1 and B–3 test stands. The main NASA Project Team was led by Paul Kuehn. Pinnacle Construction & Development Group was hired to complete the task. They subcontracted with Brandenburg Industrial Service Company to perform the actual demolition. These companies also managed the containment and disposal of the waste materials.

All of the main systems had been disconnected in the 1970s, but the preparation of the site still required significant planning and selective demolition work. The buildings were structurally weakened at the base of each stand so that they would collapse onto their sides. On September 8, 2010, the B–1 test stand was brought down. Two weeks later, the B–3 test stand was demolished. The wreckage was scrapped, the infrastructure materials were recycled, and the site was restored by grading and planting grass.

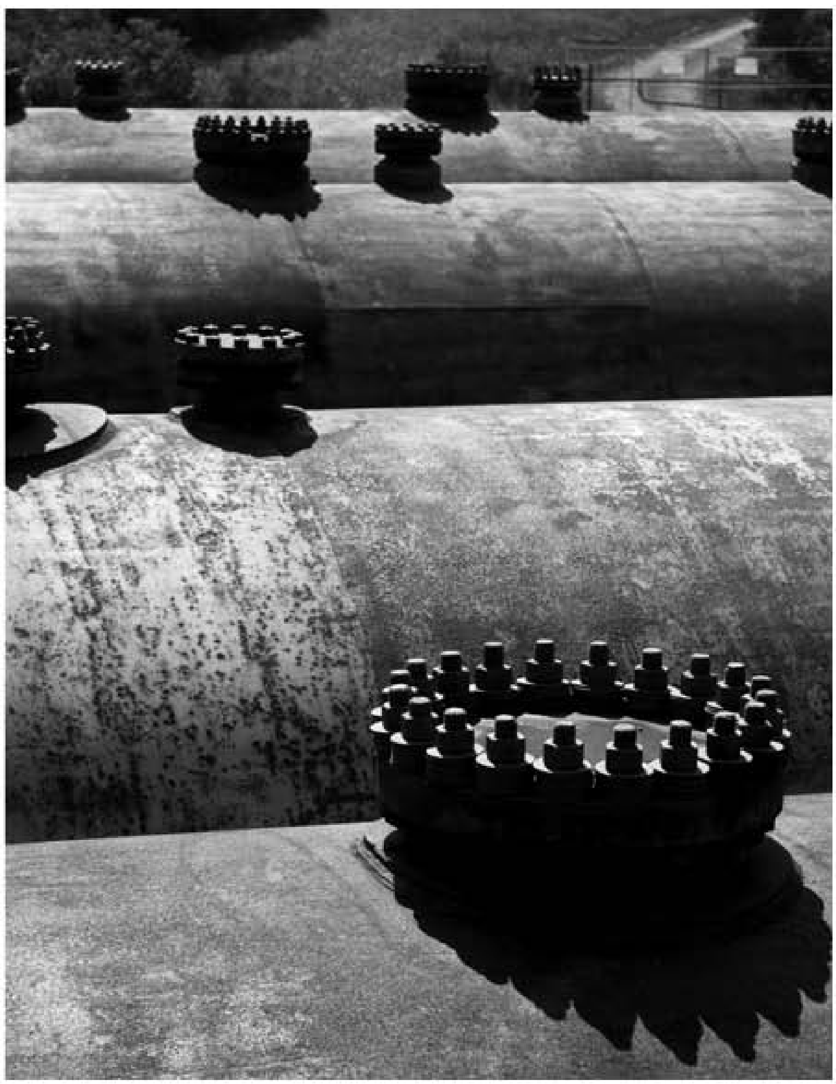

Figure 4.1.—The steam accumulators as they appeared at the time of demolition, 2010 (C–2010–04972, NASA Glenn).

Figure 4.2.—The B–1 test stand is brought down on September 8, 2010
(C–2010–04951, NASA Glenn).

Figure 4.3.—The B–1 test stand crashes into the ground, 2010 (C–2010–04969, NASA Glenn).

Figure 4.4.—The B–3 test stand is brought down on September 21, 2010
(C–2010–04998, NASA Glenn).

Figure 4.5.—The B–3 test stand crashes into the ground, 2010 (C–2010–04990, NASA Glenn).

5.0 Index of High Energy Rocket Engine Research Facility (B–1) and Nuclear Dynamics and Controls Facility (B–3) Photographs

Appendix—Acronyms

AEC	Atomic Energy Commission
AERL	Aircraft Engine Research Laboratory
B–1	High Energy Rocket Engine Research Facility (Bldg. 3111)
B–2	Space Propulsion Research Facility (Bldg. 3211)
B–3	Nuclear Rocket Dynamics and Control Facility (Bldg. 3311)
CRT	cathode ray tube
CSS	Centaur Standard Shroud
HTF	Hypersonic Tunnel Facility (Bldg. 3411)
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NERVA	Nuclear Engine for Rocket Vehicle Applications
NRX	NERVA Reactor Experiment
NRX/EST	NRX/Engine System Test
OAO	Orbiting Astronomical Observatory
P&W	Pratt & Whitney
RIFT	Reactor In Flight Test
SNPO	Space Nuclear Propulsion Office
SPC	Space Power Chambers
T–0	time zero

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