HISTORIC AMERICAN ENGINEERING RECORD

GLENN RESEARCH CENTER, PROPULSION SYSTEMS LABORATORY NO. 1 AND 2

HAER OH-136

Location:	National Aeronautics and Space Administration (NASA)	
	John H. Glenn Research Center	
	21000 Brookpark Road	
	Cuyahoga Country, Cleveland, Ohio	
	The Propulsion Systems Laboratory (PSL) No. 1 and 2 facility was located on a rectangular northwestward-facing flat plot near the center of the NASA Glenn Research Center. It was bordered by Walcott Road on the northwest, Moffett Road on the east, and Westover Road on the west.	
UTM Coordinates:	Longitude: -81.8656	
	Latitude: 41.4145	
Present Owner:	NASA Glenn Research Center.	
	NASA Glenn began operation in 1942 as the National Advisory Committee for Aeronautics (NACA) Aircraft Engine Research Laboratory (AERL). In 1947 it was renamed the NACA Flight Propulsion Laboratory. In September 1948, following the death of the NACA's Director of Aeronautics, George Lewis, the name was changed to the NACA Lewis Flight Propulsion Laboratory. On October 1, 1958, the lab was incorporated into the new NASA space agency, and it was renamed the NASA Lewis Research Center. Following John Glenn's flight on the space shuttle, the center name was changed again on March 1, 1999, to the NASA Glenn Research Center.	
Present Use:	PSL No. 1 and 2 was demolished in 2009. After the test facility's closure in 1979 and before 2009, the Shop and Access Building (Bldg. 65/66) was used as office space. The Equipment Building (Bldg. 64) continues to operate in support of PSL No. 3 and 4. The Operations Building (Bldg. 60) continues to serve as an office building.	
Significance:	PSL's two chambers, referred to as PSL No. 1 and PSL No. 2, could simulate the internal airflow conditions experienced by the Nation's most powerful engines over a full range of power and altitude levels. This allowed researchers to analyze the engine's thrust, fuel consumption, airflow limits, combustion blowout levels, acceleration, starting	

characteristics, and an array of other parameters. The range of PSL's studies was later expanded to include noise reduction, flutter, inlet distortions, and engine controls. The PSL was used to study the performance of a variety of rocket engines in the 1960s.

PSL No. 1 and 2 served as a major component of NASA Glenn's advanced propulsion legacy that began in 1942 and continues today. The facility was a technological combination of the static-sea-level test stands and the complex AWT, which re-created actual flight conditions on a larger scale.

PSL's significance lies in the size and power of the engines it tested. When it became operational in 1952, the PSL was the Nation's only facility that could operate these large full-size engine systems in controlled altitude conditions. The ability to control the test environment was imperative in the advancement of the ever-increasing and complex turbojet systems. Today, PSL's successor, PSL No. 3 and 4, is NASA's only facility with this capability.

PSL's two 14'-0"-diameter, 24'-0"-long chambers were first used to study the increasingly powerful jet engines of the early 1950s and the ramjets for missile programs such as Navaho and Bomarc. With the advent of the space program in the late 1950s, the facility was used to study complex rocket engines, including the Pratt & Whitney RL–10 that was used to power the Centaur rocket and Saturn I upper stages. In the mid-1960s, the PSL returned its focus to jet engines, which continued to grow in size and performance. It was a vital tool in studying complex problems such as inlet distortion and flutter and contributed to NASA's fly-by-wire research.

The PSL served as a key component in NASA Glenn's sixty-five-year history of altitude testing of engines and was proven to be a robust test facility that could keep pace with the relentless advance of aerospace technology over the decades. The original chambers were versatile enough to study emerging propulsion systems such as the turbojet, ramjet, chemical rocket, and turbofan engines, and the PSL's work on the RL–10 rocket engine was essential to the success of the Centaur Program.

- Historian: Robert S. Arrighi Wyle Information Systems, Inc. NASA Glenn History Program Cleveland, Ohio 44135 January 2015
- Project Information: In 2005, NASA Glenn proposed to remove the original two PSL test chambers and the Shop and Access Building. The Equipment Building

(currently known as the Central Air Equipment Building) and PSL No. 3 and 4 remain in operation. Although the PSL No. 1 and 2 test chambers had been idle since 1979, this facility had had a rich history and had played an important role in NASA and aerospace history. For this reason, NASA Glenn decided to document the facility as thoroughly as possible before its demolition and to share the information with the public and within the Agency.

This report was part of a wider effort to document PSL No. 1 and 2 prior to its demolition. Documentation formally began in May 2005 after Statement of Work 6.31 for the NASA Glenn History Program was finalized. The project included the gathering of records, images, films, and oral histories; and researching the facility, its tests, and significance. The resulting information was disseminated via a book ("Pursuit of Power: The Propulsion Systems Laboratory No. 1 and 2),"¹ a website (http://pslhistory.grc.nasa.gov/),² an exhibit display, and this report.

Robert Arrighi created this report. Nancy O'Bryan edited the report, Lorie Passe worked on the layout, and Lori Feher edited the references. Marvin Smith created the accompanying photographic prints. Quentin Schwinn, Bridget Caswell, and Mark Grills photographed the facility prior to and during its demolition and scanned historic negatives.

¹ Robert A. Arrighi, "Pursuit of Power: The Propulsion Systems Laboratory No. 1 and 2" (Washington, DC: NASA/SP—2012-4548, 2012), accessed January 8, 2215. <u>http://ntrs.nasa.gov/</u>

² "NASA Propulsion Systems Laboratory (PSL) No. 1 and 2," NASA Glenn Research Center Historic Facilities, accessed January 8, 2015. <u>http://pslhistory.grc.nasa.gov/</u>

Contents

0 Ger and	neral Information—Overview of the Propulsion Systems Laboratory N	o. 1
1 1	General Description and Photographs	
1.1	Location Maps and Aerial View	
1.2	Topography	
1.5 1 A	Original Plans	
I. 4 Hie	tory	0
2 1	Uistoriaal Contaxt	יייייייייייייייייייייייייייייייי
2.1	2.1.1 Glenn Propulsion Eacilities	77
	2.1.2 NACA Turbojet Studies	/
	2.1.2 NACA Turbojet Studies	۵۵ ۵
	2.1.4 NACA Lowis Pocket Engine Studios	
	2.1.5 NASA Lewis Turbaiat and Turbafan Studios	
	2.1.5 NASA Lewis Turbojet and Turboran Studies	
<u> </u>	2.1.0 Engine History Summary	
2.2	PSL No. 1 and 2 Physical History	
	2.2.1 PSL No. 1 and 2 Construction Data Sheet	
	2.2.2 PSL Original Construction and Startup	
• •	2.2.3 PSL Alterations	
2.3	Research History	
	2.3.1 PSL Ramjet and Turbojet Testing	
2 2	2.3.2 Rocket Engine Testing	
	2.3.3 PSL No. 1 and 2 Turbofan and Turbojet Testing	
2.4	Closure of PSL No. 1 and 2	
Arc	chitectural Information	
3.1	PSL Overview	
3.2	Test Area	
	3.2.1 Test Chambers	
	3.2.2 Control Room	
	3.2.3 Instrumentation	
3.3	Combustion Air System	
	3.3.1 Compressors	
	3.3.2 Temperature-Adjusting Equipment	
3.4	Exhaust System	
	3.4.1 Exhausters	
	342 Air Coolers	36
	3 4 3 Cooling Water	37
Sun	nort Buildings	37
4 1	Overview	37
4.1	Shop and Access Building	38
<i>ч.2</i>	A 2.1 Ground Floor	
	12.1 Oround 11001	
12	T.2.2 Ivialit 11001	
4.3	4.2.1 Exterior of Equipment Duilding	
	4.5.1 Exterior of Equipment Duilding	
	4.5.2 Interior of Equipment Building	

GLENN RESEARCH CENTER, PROPULSION SYSTEMS LABORATORY NO. 1 AND 2 HAER OH-136 Page 5

4.4 PSL Operations Building	40
5.0 Demolition	
6.0 Index of Propulsion Systems Laboratory No. 1 and 2 Photographs	
Bibliography	52
Appendix A—Acronyms	
Appendix B—Figures and Images	59

1.0 General Information—Overview of the Propulsion Systems Laboratory No. 1 and 2

1.1 General Description and Photographs

Figure 1 describes the PSL No. 1 and 2. Figure 2 is an aerial photograph of the facility in 1956, Figure 3 shows the NACA Lewis campus from the east in 1953, and Figure 4 is an isometric drawing of PSL No. 1 and 2 in 2009.

1.2 Location Maps and Aerial View

Figure 5 is a map showing PSL No. 1 and 2's location on the NASA Glenn's Lewis Field campus and within Ohio and Cuyahoga County, and Figure 6 is an aerial photograph with PSL at the center of the NACA Lewis campus.

1.3 Topography

The PSL was located near the center of NASA Glenn in Cleveland, Ohio. The NACA had acquired 200 acres from the Cleveland Municipal Airport in late 1940 to construct an engine research laboratory (the current location of NASA Glenn's Lewis Field campus). The site had previously been used by the airport for parking and grandstands for the annual National Air Races. The airport borders Glenn on the southeast. The rest of the border loosely follows the Rocky River, which bows to the northwest around the main campus. The river valley is densely forested, but the main portion of the property is flat and featureless.

The PSL complex faced northwest onto Walcott Road. Moffett Road ran along the east and Westover Road to the west of the facility. The Shop and Access Building was in front with the Equipment Building behind, and later PSL No. 3 and 4 were built behind that.

The nearby area contained several other laboratory buildings, including the 8- by 6-Foot Supersonic Wind Tunnel to the west, the Chemistry Building to the east, and the PSL Operations Building to the northwest.

1.4 Original Plans

PSL No. 1 and 2 was constructed between 1949 and 1952 to test full-scale airbreathing propulsion systems. The PSL was the NACA's most powerful facility for testing full-scale engines at simulated flight altitudes. The original PSL chambers, referred to as PSL No. 1 and 2, were a technological combination of basic static sea-level test stands and the complex Altitude Wind Tunnel (AWT), which re-created actual flight conditions on a larger scale. PSL's significance lies in the size and power of the engines it tested. When it became operational in 1952, the PSL was the Nation's only facility that could run contemporary full-size engine systems in controlled altitude conditions. The ability to control the test environment was important in the advancement of the ever-increasing and complex turbojet systems. During its twenty-seven years of operation, PSL's two test chambers were used to study a variety of turbojet, ramjet, rocket, and turbofan engines.

The PSL included two altitude chambers, a modern control room, a combustion air supply system, an exhauster system, and a cooling water system (Fig. 7). The two 14'-0"-diameter, 24'-0"-long test chambers were located in the Shop and Access Building (Fig. 8). The complex included a

number of support buildings, the largest of which was the Equipment Building. The Equipment Building, which was directly behind the Shop and Access Building, housed the large compressor and exhauster systems used to simulate altitudes in the test chambers.

PSL's air-handling system was linked to the NACA's Cleveland laboratory's central air system, which allowed it to augment the compressors in other test facilities. Originally, PSL No. 1 and 2 could be used to test engines with up to 15,000 pounds (lb) of thrust at simulated altitudes of 50,000'. These capacities were continually increased throughout the facility's lifespan.

The PSL complex included the Shop and Access Building (Bldg. 66/65), the Equipment Building (Bldg. 64), two primary coolers (Bldg. 67) (Fig. 9), a secondary cooler (Bldg. 68), the Support Service Building (Bldg. 73), the Fuels Storage Building (Bldg. 96), a Desiccant Air Dryer (Bldg. 95), heating equipment (Bldg. 76), a cooling tower, and a substation. In 1972 the two larger test chambers, PSL No. 3 and 4, were added in a separate structure (Bldg. 125) behind the Equipment Building.

2.0 History

2.1 Historical Context

As its name implies, PSL No. 1 and 2 was used to study propulsion and engine systems. Unique and powerful engine test facilities have been one of NASA Glenn's hallmarks since its inception as the NACA AERL in 1942, and NASA Glenn remains an important leader in aerospace propulsion after nearly seventy-five years of research.

2.1.1 Glenn Propulsion Facilities

The NASA AERL began operations in 1942. The NACA, which was established in 1915, had largely ignored aircraft engines during the first twenty years of its existence. Most of its engine studies were carried out by the National Bureau of Standards. It was the realization of Germany's propulsion advancements in the 1930s that prodded the NACA to create two new research labs— the Ames Aeronautical Laboratory and the AERL. Ames, located at Moffett Field, California, was designed to investigate high-speed flight. The AERL, in Cleveland, Ohio, was created to study aircraft propulsion systems and had the unique ability to test full-scale engines in simulated altitude conditions.

In May 1942 the Engine Propeller Research Building, or Prop House, was the first major facility to come online at the AERL. The Prop House contained four 24'-0"-diameter test cells that could run 4000-horsepower (hp) piston engines in ambient conditions. The facility was well suited for the large reciprocating engines of the day, but it was largely outdated by the end of World War II.

The AWT, which was completed in early 1944, was a much more complex and valuable facility. The AWT could run the same size engines as the Prop House, but it operated them at speeds up to 500 miles per hour in conditions that simulated altitudes up to 50,000'. The AWT was the Nation's only wind tunnel capable of studying full-scale engines under realistic flight conditions. It was designed for piston engines but was robust enough to also test the new jet engines. Over the next ten years, the AWT played a significant role in the development of the first U.S. jet engines as well as technologies such as the afterburner and variable-area nozzle.

The AERL performed an immense amount of work on the development of the early jet engines during World War II and on the development of their successors in the immediate aftermath. At the request of the military and engine manufacturers, the AWT was used to analyze almost every turbojet design of the period.

The AWT was so successful that its schedule was backed up for months on end. AERL management decided to quickly build two static engine test stands in the Engine Research Building. This Four Burner Area could also run full-size engines at simulated altitudes up to 50,000' (see Fig. 10). The air was ducted directly to the engine inlet, and the exhaust was expelled into a pipe. The Four Burner Area began operating in 1947.

During the late 1940s and early 1950s, the jet engine rapidly grew in power and size. NACA engineers realized almost immediately that a new, more powerful test facility would soon be needed. Plans were made to construct a facility similar in design to the Four Burner Area, but larger in size and with more powerful altitude simulation capabilities. The new PSL was designed specifically to handle the larger jet engines of the 1950s and 1960s.

2.1.2 NACA Turbojet Studies

The U.S. armed forces made the decision early on to fight World War II with existing aircraft technology and not to lose time developing experimental concepts. The Nation had several powerful reciprocating engines that were used on a variety of military aircraft. The NACA was given the job of improving these aircraft. The AERL's initial wartime efforts focused on propulsion problems such as engine knock, turbosupercharger performance, and engine cooling. The Prop House tested Wright Aeronautical's R–2600 and R–3350 engines, which were used extensively by the military during the war.

New engine technologies were emerging in Europe, however. The Germans had three types of turbojets, two rockets, and a pulse-jet aircraft in operation during the war.³ Despite its avowed mission, the AERL soon became involved in new types of propulsion that emerged during the war—the turbojet, ramjet, and rocket. Between late 1943 and the end of the war in August 1945, the AERL studied both centrifugal and axial-flow compressor jet engines, pulse-jet and steady-flow types of ramjets, and small rockets. Work on all of these systems would be expanded after the war.

The military selected General Electric's West Lynn facility in 1941 to secretly replicate the centrifugal turbojet engine designed by British engineer Frank Whittle. General Electric's first attempt, the I–A, was fraught with problems. The design was improved somewhat with the subsequent I–16 engine. The 1600-hp engines were incorporated into an existing Bell airframe, and in October 1942 the Airacomet was secretly test flown in the California desert. The aircraft's performance was limited, however, and the Army Air Corps' Colonel Donald Keirn asked the NACA to study the engines in the AWT.

The General Electric I-16 engines were studied exhaustively during spring 1944. Tests of the modified version showed that the improved distribution of airflow increased the I-16's

³ Sterling Michael Pavelec, "The Jet Race and the Second World War" (Westport, Connecticut: Praeger Security International, 2007).

performance by 25 percent. The Airacomet never overcame some of its inherent design problems, but the I–16 engine's next reincarnation as the I–40 in 1943 was a dependable 4000-lb-thrust engine. The I–40 was incorporated into the Lockheed Shooting Star airframe and successfully flown in June 1944. NACA researchers studied the aircraft in the AWT in early 1945. The Shooting Star became the United States' first successful jet aircraft and the first U.S. aircraft to reach 500 miles per hour.

The future of jet engines, however, lay in the axial-flow compressor design. Axial-flow compressors employed compressor stages in a row on a turbine instead of using a single large centrifugal compressor. Additional stages could be added to increase performance. In October 1942 Westinghouse Electric became the first company to begin work on an American-designed turbojet engine. The company's original 19A led directly to the 19B and 19XB. The 19A became the first and only U.S. axial-flow engine to be flight tested during the war.

In 1943 the military asked General Electric to develop an axial-flow jet engine; this became the TG–180. The military understood that the TG–180 would not be ready during World War II but recognized the axial-flow compressor's long-term potential. Although the TG–180 (also known as the J35) was not the breakthrough engine that the military had hoped for, it did lead to a string of successful General Electric axial-flow compressor engines in the 1940s and 1950s.

The AERL reorganized immediately after the war to better investigate turbojets, ramjets, and rockets. The four research divisions were the Fuels and Thermodynamics Division, the Compressor and Turbine Division, the Engine Performance and Materials Division, and the Wind Tunnels and Flight Division. The NACA's researchers were able to create a succession of advancements on the turbojet engines that resulted in a tremendous surge in thrust capabilities in the late 1940s and early 1950s.

Researchers studied individual engine components, small-scale models, and full-scale engines. After 1947, the full-scale testing was performed in the AWT, in the Four Burner Area, and during flight underneath research aircraft.

During the late 1940s General Electric and Westinghouse were producing second- and thirdgeneration versions of their axial-flow turbojets as Pratt & Whitney and Wright Aeronautical began to design their first jet engines. NACA's Cleveland laboratory began studying British turbojets such as the Nene. The study and improvement of the axial-flow engine from 1945 to 1949 was the AWT's most enduring contribution to the aerospace field (see Fig. 11). The improvements developed in the 1940s would manifest themselves with drastic increases in engine performance and thrust in the early 1950s. Realizing that its facilities would soon be outpaced by the technology, in 1947 the NACA began planning for the PSL.

2.1.3 NACA Ramjet Development

The Cold War commenced almost immediately after World War II. The Soviet Union and the United States raced to integrate German technology into their military, particularly the long-range rocket or missile. The United States pursued both rockets and airbreathing engines for its nascent missile efforts. The V–1 missile was powered by an airbreathing pulse-jet engine, whereas the V–

2 missile was rocket-powered. Ramjets, however, were the most widely considered type of airbreathing engine for missile applications.

Ramjet engines are continually burning engines that have theoretical efficiencies far superior to other types of propulsion systems. Ramjets ingest and compress air as they moved through the atmosphere and have no moving components. The diffuser at the inlet slow the airflow to increase its pressure. Fuel is sprayed into this pressurized air and ignited by the flameholder. The expanding hot air is expelled through the exhaust nozzle as thrust.⁴ A ramjet's thrust intensifies exponentially as the engine's velocity increases. Ramjets, however, have to rely on some type of booster to attain the high velocities at which they are so efficient.

NACA's Cleveland laboratory initiated an extensive effort to understand and perfect ramjet propulsion systems for high-speed aircraft and missile applications. Although the ramjet concept dates back to the 1910s, the required boosters were not available until World War II. The German V–1 buzz bomb was the first operational ramjet missile.⁵

The Cleveland lab's analysis of ramjets involved aerodynamic studies in its small supersonic wind tunnels, flight testing on research aircraft, and full-scale engine testing in the AWT, Four Burner Area, and PSL No. 1 and 2. The program analyzed the entire propulsion system and individual components such as the flameholder. The flameholder was a grate-like device designed to maintain a constant flame to ignite the fuel-injected airflow.

The lab's engineers commenced their efforts by designing a 20"-diameter ramjet in order to study basic ramjet concepts. The engine was analyzed briefly in the AWT in 1945 and 1946. Other researchers were simultaneously studying a small-scale version in the AERL's new 18" x 18" supersonic wind tunnel. Beginning in October 1946, the ramjet underwent a series of flight tests underneath the AERL's B–29 Superfortress to demonstrate that it could operate at high altitudes and reliably compress the supersonic airflow (see Fig. 12). The researchers compared the data from both sets of tests and concluded that flight-worthy ramjets were indeed possible.⁶

Project Bumblebee was an effort by the Navy to develop a 16"-diameter ramjet-powered interceptor missile. The development, led by Johns Hopkins University, was steady but slow. In 1947 the Cleveland lab was called on to investigate different flameholder designs for the Bumblebee ramjet in its AWT. In the 1950s, Lewis's researchers studied the design further in their large supersonic wind tunnels. In 1958 the Bumblebee ramjet finally manifested itself as the Talos missile.⁷

⁴ John Disher and Leonard Rabb, "Flight Tests of Full-Scale Ramjet Engines" (Cleveland, Ohio: NASA Glenn History Office Collection, Inspections Collection, 1954).

⁵ "Ramjets: Some Experimental Applications," Flight, February 3, 1949.

⁶ NACA: "Thirty-second Annual Report of the National Advisory Committee for Aeronautics" (Washington, DC: Government Printing Office, 1946), 26.

⁷ W.H. Sterbentz and T.J. Nussdorfer, "Investigation of Performance of Bumblebee 18-Inch Ramjet With a Can-Type Flameholder" (Washington, DC: NACA RM–E8E21, 1948), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

The lab's initial Bumblebee studies coincided with the Air Material Command's 1947 request that the laboratory systematically study the fundamentals of the subsonic and supersonic ramjets.⁸ The studies focused on a series of NACA-designed 16"-diameter ramjets that were similar in size to the Bumblebee engines but included other designs. The program involved inlet and nozzle analysis in the small supersonic tunnels, combustion studies in the AWT, aerodynamic analysis in the 8-by 6-Foot Supersonic Wind Tunnel, and flight tests on the lab's research aircraft.

In 1947 the Cleveland laboratory's management outlined the extensive two-phase test program in which five types of fixed-geometry ramjet engines were to be launched by research aircraft near Wallops Island. The ramjets had a diameter of 16" and were 16'-0" long.⁹ Lewis's ramjet missiles were affixed underneath the research aircraft, most frequently an F–82 Twin Mustang, and flown at altitudes up to 35,000'. The program began in 1948 and lasted several years. Later in the series, the researchers affixed rocket boosters to the ramjets to increase their speeds. The program yielded valuable design and aerodynamics information. By the 1950s, the lab's researchers had increased ramjet engine performance, speed, range, and fuel efficiency.¹⁰ The inlet diffuser studies foreshadowed the missile aerodynamics studies of the late 1950s.

By the time that the PSL began operating in 1952, the Korean War was underway, adding an increased urgency to the research. The military was now asking the lab to test ramjets for specific missile programs. The new PSL facility was powerful enough to study full-scale ramjet engines for Navaho cruise missile and the Bomarc interceptor missile programs.

2.1.4 NACA Lewis Rocket Engine Studies

The NACA's Cleveland laboratory had been involved in small rocket and propellant research since 1945, but the NACA leadership was wary of involving itself too deeply since ballistics traditionally fell under the military's purview. A group of fuels researchers at the lab refocused their efforts after World War II in order to explore high-energy propellants, combustion, and cooling. On the organization chart, this group appeared as the High Pressure Combustion Section in the Fuels and Lubricants Division.

A group of small test cells, referred to as the Lewis Rocket Lab, was built in a remote corner of the Cleveland laboratory to carry out their investigations. The Rocket Lab was a collection of ten one-story cinderblock test cells located behind earthen barriers at the western edge of the campus. The rocket engines tested there were comparatively small, but could be used to study different configurations, combustion performance, and injectors and nozzle design. Usually, the rockets were mounted and fired horizontally.

The rocket group was elevated on the organizational chart in 1949 and renamed the Rocket Research Branch. The NACA began easing its restrictions on rocket studies and created a Subcommittee on Rocket Engines to oversee the Agency's rocket research. At the Cleveland lab

⁸ Jesse Hall, memorandum to Carlton Kemper, "Cleveland Laboratory Test Program for Investigating Ramjet Engines in Free Flight," August 18, 1947.

⁹ Hall, memo to Carlton Kemper.

¹⁰ Disher and Rabb, "Flight Tests of Full-Scale Ramjet Engines."

(now NACA Lewis), a new larger test facility, the Rocket Engine Test Facility, was approved in 1952 and became operational in 1957.

Following the 1949 reorganization of the research divisions, the rocket group began working with high-energy propellants such as diborane, pentaborane, and hydrogen. The lightweight fuels offered high levels of energy but were difficult to handle and required large tanks. In late 1954, Lewis researchers studied the combustion characteristics of gaseous hydrogen in a turbojet combustor. Despite poor mixing of the fuel and air, it was found that the hydrogen yielded more than a 90-percent efficiency. Liquid hydrogen became the focus of Lewis researchers for the next fifteen years.

NACA Lewis hosted an Inspection in October 1957 where representatives from the military, aeronautical industry, universities, and the press were invited to be briefed on the NACA's latest research efforts and to tour Lewis's test facilities. During the rehearsals for the Inspection, NACA Executive Secretary John Victory is said to have heard one of the researchers mention outer space in his presentation. Victory ordered the remark removed so as not give the perception to the visiting dignitaries that the NACA was spending too many of its resources on nonaeronautical pursuits. The launch of Sputnik I by the Soviet Union days before the event changed everything. The dignitaries wanted to hear about the NACA's rocket work and its space ambitions. The original talks were given, and Lewis demonstrated its high-energy propellant accomplishments.

PSL No. 1 and 2 quickly switched from ramjets and turbojets to small Lewis-designed rocket engines. The newly formed Propulsion Systems Division took over most of the PSL research. Initially the researchers utilized small rocket engines built in-house to test different propellant mixtures as well as different nozzles, turbopumps, and other components.

The Sputnik launch created a new urgency for rocket research at Lewis and across the Nation. NASA was officially established on October 1, 1958. As the coordinated national space program began to formulate, Lewis researchers were forced to alter their studies to address the immediate propulsion needs of NASA's space program.¹¹ To expedite the initial Mercury launches, existing military missiles were used to launch the spacecraft. The larger Apollo vehicles required much more powerful multistage launch vehicles, however. NASA Lewis work with liquid hydrogen would be a key element of these vehicles.

The Saturn Vehicle Team, informally termed the "Silverstein Committee," was created in late 1959 to select upper stages for the Saturn rocket. The team, which was led by Lewis veterans, was able persuade Werner von Braun to use liquid hydrogen the Saturn stages.

In 1955 the military had asked Pratt & Whitney to develop hydrogen engines specifically for aircraft. The program was canceled in 1958, but Pratt & Whitney decided to use the experience to develop a liquid-hydrogen rocket engine, the RL–10. Two of the 15,000-lb-thrust RL–10 engines were used to power General Dynamics's new Centaur second-stage rocket (Fig. 13). Centaur was designed to carry the Surveyor spacecraft on its mission to soft-land on the Moon. The Surveyor missions were an important precursor to Apollo landings. Centaur's first launch attempt failed

¹¹ Virginia Parker Dawson, "Engines and Innovation: Lewis Laboratory and American Propulsion Technology" (Washington, DC: NASA SP-4306, 1991), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

shortly after liftoff in May 1962. After much debate, the Centaur Program was transferred from the NASA Marshall Space Flight Center to NASA Lewis in October 1962.

NASA Lewis was also studying general rocket system concepts in order to improve rocket engine performance while reducing size, costs, and development time for the entire industry. Lewis conducted a wide-ranging storable propellant program during late 1963 and 1964 that focused on a 9000-lb-thrust engine. Storable propellants, such as nitrogen tetroxide and hydrazine, are appealing because they do not require any special temperature- or pressure-control measures. Although this type of fuel had been studied for several years, combustion instability, ablative thrust chamber durability, and nozzle efficiency had to be investigated before storable propellants could be used for the space program.¹²

As the costs of the space program escalated in the mid-1960s, NASA became increasingly interested in solid rockets for heavier payloads. Solid rockets are significantly less complicated and expensive than chemical rockets—containing only a nozzle, the propellant, and an igniter. The rocket's shell serves as the pressure chamber.¹³ Not all payloads required the sophisticated rocket concepts originally developed for missiles. Solid rocket proponents believed that larger, "dumber" rockets could perform many of the same missions at a much lower cost.¹⁴

2.1.5 NASA Lewis Turbojet and Turbofan Studies

After nearly a decade of focusing almost exclusively on space, in 1966 NASA Lewis began tackling issues relating to the new turbofan engine, noise reduction, energy efficiency, supersonic transport, and the never-ending quest for higher performance levels with smaller and more lightweight engines. Unlike their groundbreaking engine work in the 1940s and 1950s, Lewis's new studies were not exclusively for the military but were also for the Federal Aviation Administration and the Department of Transportation.

NASA Lewis instituted an Airbreathing Engine Division in 1966 that used the Lewis's F106 aircraft, new Quiet Engine Test Stand, and 10- by 10-Foot Supersonic Wind Tunnel to study the turbofans. The new division also assumed control of all testing in PSL No. 1 and 2. Lewis's two other altitude testing facilities, the AWT and the Four Burner Area, had been taken offline permanently in the early 1960s. Lewis aeropropulsion research in the 1960s and 1970s was extremely diverse. For the sake of brevity, this document concentrates on the three primary areas that involved PSL No. 1 and 2: (1) the traditional analysis of full-scale engines for specific programs; (2) studies of issues such as flutter or inlet distortions, which can be applied to a variety of different engines; and (3) engine control systems (see Fig. 14).

The Nation's early jet engines were sturdy pieces of equipment that were relatively impervious to the effects of airflow distortions. Axial-flow compressor engines grew in power and sophistication

¹² Carl Auckerman and Arthur Trout, "Experimental Rocket Performance of Apollo Storable Propellants in Engines With Large Area Ratio Nozzles" (Cleveland, Ohio: NASA TN D–3566, 1966), accessed January 8, 2015. http://ntrs.nasa.gov/

¹³ "Advanced Chemical Rockets: Presented at 1966 Inspection of the Lewis Research Center. October 4, 1966" (Cleveland, Ohio: NASA Glenn History Collection, Inspections Collection, 1966).

¹⁴ Lionel Johns, Ray Williamson, and Richard DalBello, "Big Dumb Boosters: A Low-Cost Space Transportation Option?" AN OTA Background Paper, February 1989 (paper presented at the Workshop on Low-Technology, Low-Cost Space Transportation Options, December 1, 1987).

during the 1950s and 1960s, increasing the number of compressor stages and incorporating dualspool configurations. These complex powerplants brought with them a new set of operating problems, including flutter—the self-induced vibration of the compressor stator blades due to irregular airflow or distortions. The vibrations could weaken or damage the stators, which would eventually inhibit the engine's performance. In order to improve performance, the stator blades were made thinner and thinner. This improved performance in normal conditions but often stalled the engine from flutter during abnormal conditions.

NASA Lewis also spent a good deal of time in the 1960s and 1970s investigating the effects of airflow distortions on engine inlets and compressors. The design and performance of aircraft engines and inlets continually evolved to meet escalating expectations. The constant battle to increase thrust while decreasing overall weight created additional stress on jet engine components, particularly compressors. As speed and maneuverability were enhanced, the strain on the engines and inlets grew, primarily as a result of lower Reynolds numbers and inlet flow distortions. These distortions are produced by shifts in either pressure or temperature—usually by strong winds, high angles of attack, aircraft wakes, or boundary layer interactions. The thorny combination of lower Reynolds numbers and inlet flow distortions distortions reduced compressor stability and led to increased stall margins.¹⁵

In the mid-1970s, NASA Lewis and the U.S. Air Force collaborated on two extensive programs that studied a variety of design problems on full-scale engines. The first, the Full-Scale Engine Research (FSER) program, utilized surplus U.S. Air Force engines as testbeds for a variety of research purposes, including flutter, inlet distortion, and electronic controls. The goal was to produce technological achievements, not to resolve hardware problems on specific engines. The data were aggregated so that they could be used for future engine development efforts.¹⁶ The second program, the Aeroelasticity of Turbine Engines, included several projects aimed at improving compressor blade design and analysis. A better understanding of flutter was expected to lead to flutter-proof engine designs and to prevent development delays and added costs.¹⁷ The Aeroelasticity of Turbine Engines program used computer simulations to create analytical models but required full-scale engine testing to validate the codes.

2.1.6 Engine History Summary

Since the inception of turbojets in the 1940s, engineers have been simultaneously advancing both engine performance and control. Engine control systems determine the fuel required to produce the specific levels of desired thrust. The thrust must be available despite the presence of turbulence or other abnormal flight conditions. Veteran Lewis control system researchers Sanjay Garg and Link Jaw identified four phases of control system development: the inception during the 1940s, an expansion in the 1950s and 1960s, the use of electronics in the 1970s and 1980s, and a final

¹⁵ John McAulay and Mahmood Abdelwahab, "Experimental Evaluation of a TF–30–P–3 Turbofan Engine in an Altitude Facility: Afterburner Performance and Engine-Afterburner Operating Limits" (Cleveland, Ohio: NASA TN D–6839, 1972), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

¹⁶ W.J. Deskin and H.G. Hurrell, "Summary of NASA/Air Force Full Scale Engine Research Using the F100 Engine" (Reston, Virginia: AIAA 79–1308, 1979).

¹⁷ "The Fan-Compressor Flutter Team," Lewis News, February 3, 1978.

integration in the 1990s.¹⁸ The larger turbojets and turbofans of the 1960s led to advances in the control systems. Aircraft engines traditionally used fixed-geometry components with variable fuel flow and nozzle areas. The new engines implemented variable-shape compressor and fan blades. In addition, digital control technology developed for the Apollo Program was slowly taken on for aircraft propulsion. The new "fly-by-wire" electronic controls were lighter and more reliable, and they allowed greater design flexibility.

¹⁸ Link Jaw and Sanjay Garg, "Propulsion Control Technology Development in the United States" (Cleveland, Ohio: NASA/TM—2005-213978, 2005), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

2.2 PSL No. 1 and 2 Physical History

2.2.1 PSL No. 1 and 2 Construction Data Sheet

Dates of Construction: 1949 to 1952

Construction began in late summer 1949 with the installation of an overhead exhaust pipe connecting the PSL to the AWT and Engine Research Building. Excavations for the PSL began in September. In spring 1950, the facility's supports were erected and the two large exhaust gas coolers were installed. Construction of the Access Building began with the large test section pieces arriving in early 1951. Construction of the Equipment Building also began in early 1951. The exhausters and compressors were added in spring 1952, and the facility was completed in September 1952—three years after construction began (see Fig. 15).

- Engineers: PSL No. 1 and 2 was designed by NACA Lewis engineers including Eugene Wasielewski, Benjamin Pinkel, Dan Williams, Bruce Lundin, and Achille Gelalles. Certain components and subsystems were designed by external firms.¹⁹
- Contractors: Burns and Roe Company worked closely with the NACA engineers to create the master drawings from these specifications. The Sam W. Emerson Company, which had built many of the Cleveland lab's buildings in the early 1940s, was selected to perform much of the basic construction work. The compressors were designed by the Elliott Company, the exhausters by Roots-Connersville Corporation, the primary and secondary coolers by Ross Heater Company, and the two altitude chambers by Treadwell Construction.^{20,21}
- Owners: The NASA Glenn Research Center.
- Original Cost: Estimated at \$11,830,000²²

¹⁹ Edward R. Sharp, "Appointment of Propulsion Sciences Laboratory Project Engineer. March 17, 1948" (Cleveland, Ohio: NASA Glenn History Collection, Directors Collection, 1948).

²⁰ Burns and Roe, Inc., "Progress Report No. 22 for Propulsion Science Lab Phase I Part II. October 6, 1949" (Cleveland, Ohio: NASA Glenn History Collection, Test Facilities Collection, 1949).

²¹ "Progress Report No. 20 for Propulsion Science Lab Phase I Part II. Sept. 8, 1949" (Cleveland, Ohio: NASA Glenn History Collection, Test Facilities Collection, 1949).

²² Burns and Roe, Inc., "Estimated Cost of Propulsion Science Laboratory as of November 20, 1950" (Cleveland, Ohio: NASA Glenn History Collection, Test Facilities Collection, 1950).

2.2.2 PSL Original Construction and Startup

In 1947 NACA Lewis engineers began planning a new facility that combined the altitude test cell concept of the Four Burner Area with the massive infrastructure of the AWT. The new facility, the PSL, would be part of a comprehensive plan to improve the altitude testing capabilities across the laboratory. The exhaust, refrigeration, and combustion air systems from all the major test facilities would be linked. In this way, the facilities could complement the capabilities each other. Within five months, veteran engineer Eugene Wasielewski converted the recommendations of Lewis' Research Facilities Panel into design specifications. The Cleveland-area Burns and Roe Company worked closely with the NACA engineers to create the master drawings from these specifications.

The PSL was composed of three major components: a combustion air system, an altitude exhaust system, and the test chambers equipment. The overall concept of the PSL was relatively simple, but the integration of the massive systems and achieving the designed performance levels was complicated. The facility consisted of two test chambers, exhaust gas coolers, exhausters, and compressors. It also included a compressed air system that supplied combustion air, an altitude exhaust gas system, research equipment installations, a cooling water system, an electrical power system, as well as basic utilities, an intercommunication system, control rooms, roads, and a fire protection system. The equipment was contained in the Shop and Access Building, Equipment Building, a cooling tower, a pump house, and an office building.

The PSL was projected to cost \$11,830,000, which included almost \$3 million for the exhaust system. The plan was to build the facility in two phases. The second, more powerful phase was added shortly after the facility became operational. The Sam W. Emerson Company, which had built many of the lab's buildings in the early 1940s, was selected to perform much of the basic construction work. The compressors were designed by the Elliott Company, the exhausters by Roots-Connersville Corporation, the primary and secondary coolers by Ross Heater Company, and the two altitude chambers by Treadwell Construction.^{23,24}

Construction began in late summer 1949 with the installation of an overhead exhaust pipe connecting the PSL to the AWT and the Engine Research Building. Excavations for the PSL began in September. In spring 1950, the facility's supports were erected and the two large exhaust gas coolers were installed (Figs 16–17). Work on the Access Building then began with the large test section pieces arriving in early 1951 (Fig. 18). Construction of the Equipment Building began in earnest in early 1951 (Fig. 19). By summer 1951, the Access Building structure was nearly complete. The intercooler and air heaters were installed in August, and the exhausters and compressors were added in spring 1952.

Calibration of the exhaust, compressor, and other systems took place throughout spring and summer 1952. The airflow and altitude limits had to be determined before any actual tests were run. The facility was completed in September 1952—three years after construction began.

²³ Burns and Roe, Inc., "Progress Report No. 22."

²⁴ "Progress Report No. 20 for Propulsion Science Lab."

2.2.3 PSL Alterations

A two-phase approach was implemented to expedite PSL's construction. The first phase sought to have the facility operating by January 1, 1951, in order to test existing engines. Later, the second phase would upgrade the facility's capabilities to accommodate the larger engines of the future. All elements of the design had to be adaptable to this future expansion.²⁵

The \$10,000 Phase I included the combustion air supply, altitude exhaust, and process water systems.²⁶ The PSL was designed to simulate altitudes of 50,000' and handle engines of up to 15,000 lb of sea-level thrust, which was more thrust than produced by any engines available in 1948.²⁷ Phase II would increase the combustion air capability to simulate 80,000' altitude and would add a refrigeration system. Funds for this phase were approved in July 1952.²⁸

By the late 1950s, Pratt & Whitney, Wright Aeronautical, and the U.S. Air Force had begun building their own propulsion labs and altitude facilities. The PSL remained a vital resource by continually upgrading its two chambers, control room, and air-handling system.

In 1955 a fourth line of exhausters was added. The total inlet volume of the four-stage exhausters was 1.65 million cubic feet per minute. The exhausters were continually improved and upgraded over the years, and remain in operation today.²⁹

The installation of a pebble bed heater in PSL No. 2 in the late-1950s permitted hypersonic studies (Fig. 20). Lewis researchers were frustrated at their inability to simulate normal atmosphere at high temperatures in their facilities. As early as 1956, Lewis engineers sought ways to increase combustion air to hypersonic temperatures.³⁰

The pebble bed heater simulated the high temperatures produced at supersonic and hypersonic speeds by creating 3500 degrees Fahrenheit (°F) airflows through a 24"-diameter test section. The heater was a cylindrical brick structure filled with 10 tons of aluminum-oxide pebbles that stood vertically beneath PSL No. 2. A gas-fired heater initially brought the bed up to proper temperature. The flame was then closed, and cool air was passed through the bed. The hot pebbles warmed the airflow as it passed through the bed. The heated air expanded through a nozzle into the test section.

²⁵ "Specifications for Furnishing Architect-Engineer Services for the Propulsion Sciences Laboratory Phase I Project No. 794, NACA Lewis Propulsion Research Laboratory, August 5, 1948" (Cleveland, Ohio: NASA Glenn History Collection, Test Facilities Collection, 1948).

²⁶ "Specifications for Furnishing Architect-Engineer Services."

²⁷ Carlton Kemper, et al.: "Memorandum for Director, Report of the Special Panel Appointed to Study General Requirements of the Propulsion Sciences Laboratory. March 18, 1948" (Cleveland, Ohio: NASA Glenn History Collection, Facilities Collection, 1948).

²⁸ C.S. Moore, Appendix A, "Proposal for Propulsion Sciences Laboratory" (Cleveland, Ohio: NASA Glenn History Collection, Directors Collection, March 26, 1948).

²⁹ "Major Research Facilities of the Lewis Flight Propulsion Laboratory, NACA Cleveland, Ohio, Wind Tunnels— Propulsion Systems Laboratory. July 17, 1956" (Cleveland, Ohio: NASA Glenn History Collection, Facilities Collection, 1956).

³⁰ M.J. Krasnican, et al.: "Propulsion Research for Hypersonic and Space Flight. NACA Lewis Flight Propulsion Laboratory Inspection, October 7–10, 1957" (Cleveland, Ohio: NASA Glenn History Collection, Inspections Collection, 1957).

This resulted in a small hypersonic wind tunnel inside the PSL chamber.³¹ The small tunnel could test 16"-diameter ramjet engines for 3 to 5 minutes to study cooling and dissociation.³²

Other PSL modifications in the 1960s included the addition of cryogenic fuel pumping capabilities and an upgrade of the control room. PSL's liquid hydrogen and liquid oxygen were stored in temperature-controlled tanks outside the Access Building. Nitrogen, which was used to move the propellants through the lines, was trucked into the site.

The control room was frequently updated, and the control panels were rearranged periodically. The manometers were replaced with electronic units by the early 1960s. A number of television consoles were installed so that the test engineers could view the engine in the chamber during the test. Temporary data-recording equipment was installed for certain tests and later removed.

As the engines being tested in the PSL increased in size, the primary cooler became damaged by the higher temperature exhaust flows. A flamespreader was installed in the late 1960s to slow the flow of hot gases at the cooler inlet by spreading the exhaust over a larger area. This increased the cooler's heat transfer capabilities and prevented damage to the cooler tubing.³³

2.3 Research History

After 3 years of construction, the PSL No. 1 and 2 facility began operating in October 1952. The new facility became NACA Lewis's most important propulsion research tool. There were three distinct eras during PSL No. 1 and 2's operating years, each with its own group of researchers: Lewis's Engine Research Division managed the ramjet and turbojet period of the 1950s, the Chemical Rocket Division conducted most of PSL's research in the 1960s, and the Airbreathing Engines Division assumed control for the turbofan and supersonic inlet studies of the late 1960s and 1970s.

2.3.1 PSL Ramjet and Turbojet Testing

NACA's Cleveland laboratory had studied general ramjet concepts since 1945 and performed simulated altitude testing of the Navy's Project Bumblebee ramjet in the AWT. As the PSL began preparations to begin operation in 1952, however, the military requested that NACA Lewis test the Curtiss-Wright XRJ47 ramjet engine for use on the North American Aviation Navaho missile. The 48"-diameter engine was the most powerful powerplant available.

The Navaho was a winged missile that was intended to travel up to 3000 miles (mi) carrying a nuclear warhead. It was launched using rocket booster engines that were ejected after the missile's ramjet engines were ignited. Its unique navigation system was designed to permit the missile to return to its base and land. There were three phases to the Navaho program: the 500-mi X–10 test vehicle powered by two Westinghouse J40 turbojets; the 1500-mi G–26, or Navaho II, with by

³¹ Krasnican et al., "Propulsion Research." 4.

³² "Hypersonic Tunnel Facilities. Sept. 23, 1957" (Cleveland, Ohio: Glenn History Program, Director's Collection, 1957).

³³ James DeRaimo, "Flame Spreader for Cell #2 at PSL. Aug. 12, 1968" (Cleveland, Ohio: NASA Glenn History Collection, Facilities Collection, 1968).

two Wright XRJ47–W–5 ramjets; and the final 68'-0"-long, 3000-mi range G–38 with two more-powerful XRJ47–W–7 ramjets.³⁴

North American contracted Curtiss-Wright's Wright Aeronautical Division in October 1950 to create the two powerful XRJ47 ramjets for the missile. Not only were the engines among the largest ever attempted, but they were initially fraught with problems. Because Wright did not have a facility large enough to test the 48"-diameter engines, in 1951 the military solicited the assistance of NACA Lewis and its brand new PSL facility.

NACA Lewis's Engine Research Division's massive, multifaceted XRJ47 test program in PSL No. 2 formally began in October and lasted five years. The studies addressed specific XRJ47 performance issues, general ramjet concerns, and the advantages of different fuel types. The engine was tested in conditions that simulated the high-altitude cruising portion of its flight using both direct-connect and free-jet setups. The focus was on different elements of the combustion process. In addition, the engine's performance was studied with the experimental pentaborane fuel as part of the larger Project Zip.

The engine was run at Mach 2.75 and simulated altitudes between 58,000' and 73,000'. Lewis researchers studied engine ignition, the exterior shell of the burner, fuel flow control, different flameholder configurations, and overall engine performance. They also were interested in studying elements that affected the control of the ramjet, including diffuser shock movement and the recovery control performance range. The researchers analyzed performance using three combustor lengths and four fuel-distribution systems.³⁵

While these studies were being conducted in the PSL, an early turbojet-powered version of the missile was successfully launched numerous times. The second phase of the Navaho Program, which used the ramjets, began launching in late 1956. It took twelve launch attempts to get four of the missiles into the air, and those four performed marginally at best. The program was canceled in July 1957, but its legacy lived on in other programs such as the Redstone, Thor, and Atlas rocket systems.

Bomarc was a long-range interceptor missile for the U.S. Air Force that underwent a protracted development in the 1950s. The missile was launched vertically using a rocket engine, but its flight was powered by two Marquardt RJ43 ramjets. The Bomarc was the first U.S. long-range interceptor missile for combating Soviet bombers. In 1949 the Air Force contracted with Boeing to research the possibility of a supersonic anti-aircraft missile. The University of Michigan Aeronautical Research Center was soon brought in as a partner, and the project was named Bomarc. Development officially began in January 1951, and the first test flight was on September 10, 1952, just as the PSL was being completed.³⁶

NACA Lewis's Engine Research Division took on a broad study of the 28"-diameter RJ43's altitude performance in both PSL No. 2 and the Four Burner Area throughout 1954 and 1955 (see

³⁴ James N. Gibson, "The Navajo Missile Project" (Atglen, Pennsylvania: Schiffer Publishing Ltd., 1996).

³⁵ Arrighi, "Pursuit of Power."

³⁶ Michael Lombardi, "Reach for the Sky: How the Bomarc Missile Set the Stage for Boeing to Demonstrate Its Talent in Systems Integration," Boeing Frontiers, June 2, 2007.

Fig. 21). The studies covered a variety of performance issues including the system's dynamics response and the pneumatic shock-positioning control unit. The PSL test data were then turned over to Marquardt to verify their design.

The missile's lengthy development was hampered by budget constraints and political issues. Only ten Bomarc sites were established when deployment was finally completed in 1962. The program was canceled by Congress in 1970, and the last missile was retired two years later. Boeing researchers emerged from their first missile program as experts in large-scale systems integration.³⁷

The PSL No. 1 test chamber was used exclusively for turbojets throughout most of the 1950s. The first investigation involved a General Electric J73–GE–1A (Fig. 22). The twelve-stage J73 was a successor to the company's successful J47. The J73s were used primarily on the U.S. Air Force's F–86H Sabre jet fighters. During 1952 and 1953, Lewis researchers subjected the J73 to 44 runs in PSL No. 1 and created performance curves showing the optimal range for combustion and compressor efficiency.³⁸ Others Lewis researchers examined the range of combustion and compressor efficiency using a 10-percent larger turbine nozzle to avoid compressor surge.³⁹ In September 1954, not long after the PSL tests, the Sabre with its J73 engine set a new world's speed record at the National Aircraft Show in Dayton. The performance of a YJ73–GE–3 version was then studied over almost 200 runs in the PSL. Problems with the aircraft design and General Electric's production of the engine resulted in the cancellation of the Sabre program.

General Electric's next-generation turbojet was the J79. The engine's variable stator vanes permitted J79-powered fighter jets to reach twice the speed of sound. The U.S. Air Force requested that NACA Lewis improve afterburner performance on the engine. Afterburner configurations for the prototype XJ79–GE–1 were tested in PSL No. 1 during 1957. Basic modifications to the flameholder and fuel system increased the combustion efficiency and reduced the pressure drop.⁴⁰ The seventeen-stage compressor engine was used extensively in the Vietnam War on the F–4 Phantom, F–104 Starfighter, and B–58 Hustler.

In 1957 Lewis researchers also had a chance to test a rare Canadian jet engine, the Iroquois PS.13, in PSL No. 1. The Avro Canada Company had begun designing its CF–105 Arrow jet fighter in the mid-1950s, and the aircraft was powered by PS.13 engines that also were developed by Avro. These engines were more powerful than any contemporary U.S. jet engine and were lightweight and fuel efficient.

The Iroquois engine was ground tested thousands of times in a variety of facilities between its first run (in December 1954) and 1958, including PSL No. 1.⁴¹ The PSL studies determined the

³⁷ Lombardi, "Reach for the Sky."

³⁸ Carl E. Campbell and Conrad, E. William, "Altitude Performance Characteristics of the J73–GE–1A Turbojet Engine" (Cleveland, Ohio: NACA RM–E53I25, 1954), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

³⁹ Carl E. Campbell and Adam Sobolewski, "Altitude-Chamber Investigation of J73–GE–1A Turbojet Engine Component Performance" (Cleveland, Ohio: NACA RM–E53I08, 1954), accessed January 8, 2015. http://ntrs.nasa.gov/

 ⁴⁰ Harry E. Bloomer and Carl E. Campbell, "Experimental Investigation of Several Afterburner Configurations on a J79 Turbojet Engine" (Cleveland, Ohio: NACA RM–E57I18, 1957), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>
⁴¹ "Aero Engines 1959," Flight, March 20, 1959, 396.

Iroquois's windmilling and ignition characteristics at high altitude (Fig. 23). The tests were run over a wide range of speeds and altitudes with variations in exhaust-nozzle area. After operating for 64 minutes, the engine was reignited at altitudes up to the 63,000' limit of the facility. The researchers found that decreasing the nozzle area reduced windmilling.⁴²

The manufacturer modified two engines by adding a set of variable guide vanes at the highpressure compressor inlet and minor alterations to the compressor. Lewis researchers studied the operating limits of the original engine in the PSL to better understand the problem. They then studied the two modified engines. They found that severe radial flow distortions at the compressor inlet reduced the high-pressure compressor stall limit. Various modifications were studied that reduced the occurrence of stall, but they did not totally eradicate the problem.⁴³

The Arrow made its flight debut in March 1958, but the program was canceled in 1959. The transition of U.S. and Soviet Union weaponry to ballistic missiles had rendered the Avro Arrow prematurely obsolete. The Iroquois testing took place as the NACA was transitioning into space-related projects and research. It was the final airbreathing engine tested in the PSL for nine years.

2.3.2 Rocket Engine Testing

Between 1958 and 1960, NASA Lewis refocused its efforts almost completely on the space program. Although designed for airbreathing engines, PSL's two test chambers were quickly converted into rocket cells. The pebble bed heater was added to PSL No. 2 to permit hypersonic testing, and a thrust rig was built in PSL No. 2 to complement the pebble bed heater. Researchers used the rig to study nozzle configurations for thrust-vectoring tests in 1961.^{44,45}

The initial rocket testing at the PSL between 1957 and 1961 involved a number of small rockets and rocket components built by Lewis's fabrication and machine shops. These included rockets fueled by hydrogen peroxide and by isentropic or storable propellants (Fig. 24). The first studies were on a water-cooled engine fueled by JP–4 and oxygen.⁴⁶

The most significant testing performed in the PSL during the 1960s involved the Pratt & Whitney RL–10. The 15,000-lb-thrust engine was the first to use liquid hydrogen and liquid oxygen as its propellant and oxidizer. Lewis's research with liquid hydrogen in 1950s spurred Pratt & Whitney to utilize this combination when designing the engine in 1959. The RL–10s were also unique in their ability to restart themselves in space. The Centaur second-stage rocket, which was propelled by two of the RL–10 engines, was under the supervision of NASA Marshall. The Saturn I, a precursor to the Saturn V that was used for Apollo, also used the RL–10s for its upper stages in the early 1960s. Six RL–10s powered the Saturn-IV second stage and two RL–10s powered the Saturn-V third stage.

⁴² Daniel Peters and John McAulay, "Some Altitude Operational Characteristics of a Prototype Iroquois Turbojet Engine" (Cleveland, Ohio: NACA RM–SE58F17, 1958), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

 ⁴³ John McAulay and Donald Groesbaeck, "Investigation of a Prototype Iroquois Turbojet Engine in an Altitude Test Chamber" (Cleveland, Ohio: NACA RM–SE58E26, 1958), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>
⁴⁴ "Hypersonic Tunnel Facilities."

⁴⁵ "Propulsion Systems Division, Data Tabulation, Altitude Chambers, PSL–1" (Cleveland, Ohio: NASA Glenn History Collection, Facilities Collection, 1961).

⁴⁶ "Propulsion Systems Division, Data Tabulation."

NASA Headquarters assigned NASA Lewis the responsibility for investigating the RL–10 problems because of Lewis's long history of liquid-hydrogen development. Lewis began a series of tests to study the RL–10 in March 1960 (Fig. 25). During their tests, Pratt & Whitney researchers destroyed two RL–10s before the PSL test program began in early 1961.⁴⁷

The PSL was used to throttle the engine to produce different thrust levels and to gimbal, or steer, the engine as it would during a mission in simulated altitude conditions. During the tests, the area around the PSL was evacuated and the researchers and technicians were locked in the unpressurized control room because of the explosive nature of the liquid hydrogen.

The research led to another key improvement of the RL–10 in the PSL—the resolution of the lowfrequency combustion instability in the fuel system, or chugging. In most rocket engine combustion chambers, the pressure, temperature, and flows are in constant flux. The engine is considered to be operating normally if the fluctuations remain random and within certain limits. Lewis researchers used high-speed photography to study and define the RL–10's combustion instability by throttling the engine under the simulated flight conditions. They found that the injection of a small stream of helium gas into the liquid-oxygen tank immediately stabilized the system.⁴⁸

The low-frequency oscillations at low thrust levels were a little more difficult to resolve. Ultimately, the researchers determined that the abrupt change in the propellant's density as its temperature increased in the cooling jacket caused the instability. They combated this by injecting gaseous helium or hydrogen just upstream from the cooling jacket.⁴⁹

Next, the researchers decided to try to cool the pump with helium and wait to flow the hydrogen into the engine until it was time to ignite.⁵⁰ In addition, insulation was installed to keep the system cold until the upper stage was ignited. Chilling the system with helium before launch was first demonstrated in the PSL on an RL–10. This precooling was one of Lewis' most important modifications to Centaur and is still used today.⁵¹

Centaur's first launch failed shortly after liftoff on May 8, 1962, because of an insulation panel malfunction, and NASA Marshall advocated the cancellation of the program. Instead, in October 1962, NASA decided to transfer the Centaur program to NASA Lewis because of its recent success with the RL–10 in the PSL.

The Surveyor spacecraft, launched by Centaur and its RL–10s, made the first soft landing on the Moon on June 2, 1966. Although it was designed solely for the Surveyor missions to explore the

⁴⁷ R.F. Holsten, "Centaur Propulsion Systems Testing Volume I, December 7, 1962" (East Hartford, Connecticut: Pratt & Whitney FR-431, 1962).

⁴⁸ William E. Conrad, Ned P. Hannum, and Harry E. Bloomer, "Photographic Study of Liquid-Oxygen Boiling and Gas Injection in the Injector of a Chugging Rocket Engine" (Cleveland, Ohio: NASA TM X–948, 1964), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

⁴⁹ Conrad, "Photographic Study of Liquid-Oxygen Boiling."

⁵⁰ John Kobak, Interview. September 1, 2009 (NASA Glenn History Collection, Oral History Collection, 2009).

⁵¹ "1962–1972: The First Decade of Centaur." Lewis News, October 20, 1972.

Moon's surface, Centaur went on to perform scores of missions: Pioneer, Viking, the Lunar Orbiter, Orbiting Astronomical Observatories (OAOs), Cassini, and many others.

NASA Lewis's Chemical Rocket Division was created in 1963 and took over all testing in the PSL. Over the next three years, the group studied various rocket engines that employed storable propellants—fuels that can be stored in a tank without any special pressure or temperature control measures. NASA officials intended to use storable propellants for the Apollo Command Service Module. NASA had been studying the problems of combustion instability and thrust chamber durability for several years, but the important testing of the overall engine and nozzle efficiency remained a problem because of the lack of altitude chambers. NASA Lewis undertook this task in PSL No. 2 in late 1963 and 1964.⁵²

Researchers sought to determine the impulse value of the storable propellant mix, and to classify the internal engine performance, improve that performance, and compare the results with analytical tools. A special setup was installed in the chamber that included a calibration stand and a device to measure the thrust load (see Fig. 26). Both cylindrical and conical combustion chambers were examined with the conical large-area-ratio nozzles. In addition, two contour nozzles were tested, one based on the Apollo Service Module Propulsion System and the other on the U.S. Air Force's Titan transtage engine. Three types of injectors were investigated, including a Lewis-designed model with 98-percent efficiency. The researchers determined that combustion instability did not affect the nozzle performance. Although much valuable information was obtained during the tests, attempts to improve the engine performance were not successful.⁵³

In June 1963 Aerojet began developing a 260"-diameter engine for the U.S. Air Force at its specially constructed test facility in the Florida Everglades. In March 1965 NASA assigned Lewis the responsibility for a feasibility study of Aerojet's 3.25-million-lb-thrust rocket. The massive rocket had 260"-diameter nozzles and contained 1.6 million lb of storable solid propellant.⁵⁴

Because of the lack of existing data, Aerojet struggled with the steering system for the motor's aft end. Aerojet systematically created these data as well as an analytical model to predict the ignition motor pressure levels.⁵⁵ Shortly thereafter, Lewis researchers performed a series of small-scale model tests of the engine in the PSL (see Fig. 27). They decided that the best way to improve the aft thrust vector control was to have a gimballing nozzle. The new design relied on a bearing that sat directly in the nozzle's smallest diameter area, and the nozzle was inserted further into the actual engine. The new hot gas flow patterns raised concern about the nozzle's structural integrity, particularly in the high-velocity annular region.

During summer 1966, NASA Lewis used a 0.07-scale model of the engine in the PSL at altitude conditions with compressed airflow to study the velocity and direction of the annular channel flow. High-speed color motion pictures helped researchers determine the causes of the flow. After several attempts, Lewis was able to modify the model so that the nozzle's integrity was bolstered

⁵² Auckerman and Trout, "Experimental Rocket Performance."

⁵³ Auckerman and Trout, "Experimental Rocket Performance."

⁵⁴ "260-Inch Diameter Motor Feasibility Demonstration Program" (Sacramento, California: Aerojet General Corporation, 1966).

⁵⁵ Carl Ciepluch, "Status of the 260-Inch Diameter Solid Rocket Motor Program" (Cleveland, Ohio: NASA TM X– 52275, 1967), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

by increased insulation, and the annular airflow was lower than in the pregimballed design. This configuration was verified during ambient conditions inside the former AWT tunnel.^{56,57}

By 1966 two half-scale versions of the motors had been fired at an Aerojet facility in Florida generating 1.6 million lb of thrust. The 2.67 million lb of thrust generated by a third engine test was the largest amount of thrust ever produced by any type of rocket.⁵⁸ A full-scale test without gimballing was scheduled for mid-1967.⁵⁹

The program successfully ended in 1967, and several new cost-saving technologies were demonstrated. NASA Lewis continued with other solid rocket activities to further reduce launch costs, investigate problem areas, and improve reliability. Like other space technologies that had no immediate application, however, the 260" rocket program was canceled as NASA's budgets dried up in the late 1960s.⁶⁰

2.3.3 PSL No. 1 and 2 Turbofan and Turbojet Testing

The 1960s and 1970s were among the busiest years for PSL No. 1 and 2. After nearly a decade of concentrating on rockets, NASA Lewis began returning to aircraft propulsion in 1966. The use of full-scale engine models was crucial to the understanding of system integration, the perfection of technologies, and the determination of which technologies to pursue. NASA Lewis's full-scale engine programs vetted new propulsion technologies. The PSL was NASA's only facility capable of testing these full-scale engines in simulated flight conditions.

Boeing led the Nation's effort in the late-1960s to develop a supersonic transport aircraft powered by four massive 65,000-lb-thrust GE4 turbojets. Engine noise levels and the amount of fuel required to reach supersonic speeds were two of the larger problems besetting the program. In order to provide a better general understanding of these issues, from 1967 to 1977 Lewis undertook extensive studies to reduce drag and noise. The programs focused on the inlets and nozzles for advanced propulsion systems.

In order to test different noise-reducing components, nozzles, and compressor designs, Lewis engineers first had to be able to determine the baseline performance characteristics of an engine. General Electric's J85–13 engine was selected for this calibration study. The J85 was a relatively slow and lightweight, but efficient engine, developed in the late 1950s. It was used extensively by Lewis's Airbreathing Engine Division in the late 1960s and early 1970s.

Different nozzle configurations were first explored in Lewis's two large supersonic wind tunnels. Because the tunnels' size limitations precluded complete engine testing, a full-scale version was then checked out in the PSL. Afterward, the modified engine was flown at transonic and supersonic

⁵⁶ Reino Salmi and James Pelouch, Jr., "Investigation of a Submerged Nozzle for Solid Rockets" (Cleveland, Ohio: NASA TM X–52285, 1967), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

⁵⁷ Reino Salmi and Pelouch, James, Jr., "1/14.2-Scale Investigation of Submerged Nozzle for SL–3 260-Inch Solid Rocket" (Cleveland, Ohio: NASA Lewis Research Center, 1968).

^{58 &}quot;Advanced Chemical Rockets."

⁵⁹ Salmi and Pelouch, "Investigation of a Submerged Nozzle."

⁶⁰ J.D. Hunley, "The Development of Propulsion Technology for U.S. Space-Launch Vehicles, 1926–1991" (College Station, Texas: Texas A&M University Press, 2007), 270.

speeds on the F–106B. The mounting of the research engines under the F–106B's delta wings provided researchers with a subscale facsimile of the Supersonic Transport (SST).⁶¹

Congress canceled the SST program in October 1971 as the public became increasingly wary of its noise, sonic booms, and possible ozone depletion over U.S. territory. Although Lewis's SST noise-reduction efforts were disappointing overall, researchers did make abatement strides by using the plug nozzle and relocating the engine underneath the wing.⁶²

Another general engine examination involved the Lewis-designed Low Cost Engine. There was an emphasis in the early 1970s on smaller, less expensive jet engines. One of the new initiatives emerging from Lewis in the late 1960s was a small 650-lb-thrust low-cost jet engine. Jet engines had proven themselves on military and large transport aircraft, but cost precluded their use on small general aviation aircraft. To fill this niche, Lewis undertook a multiyear effort to develop a 75-percent less expensive engine that would create less pollution and use less fuel.⁶³

The U.S. Navy became interested in using the technology as a possible alternative to the rockets that powered their expendable drone aircraft. The Navy began cosponsoring the program in 1970, and Lewis altered the engine design to meet their specifications. In 1973 the Low Cost Engine had its first realistic analysis in PSL No. 2. It was installed in the altitude chamber with a direct-connect setup and successfully operated at speeds up to Mach 1.24 and simulated altitudes of 30,000'. The engine was restarted several times at altitude and demonstrated the ability to perform continuously for one hour.⁶⁴ NASA released the \$3,000 engine to private industry in the hope that design elements would be incorporated in future projects and reduce the overall cost of small jet aircraft.⁶⁵

A new generation of high-altitude, unmanned reconnaissance aircraft was instituted in 1971 to penetrate Chinese territory. Teledyne Ryan's Compass Cope was similar in design to Lockheed's U-2, but it would be deployed on missions too dangerous to send a pilot.⁶⁶

Garrett Corporation had produced two versions of the ATF3 jet engine specifically for the Cope vehicle, SN 16 and SN 17. The U.S. Air Force requested the use of NASA Lewis's PSL facility from 1971 to 1973 to compare the two engines in altitude conditions (see Fig. 28). The 4050-lb-thrust SN 16 was installed in PSL No. 1 and run at a pressure-simulated 60,000' in January 1973. The engine performed well at that altitude, but the engineers found that the engine would stall when the power was reduced.⁶⁷

Modifications were made to the turbine nozzle, inlet guide vanes, fuel control schedules, and inlet compressor bleed system. The updated SN 16 was successfully retested at altitudes throughout the

⁶¹ Fred Wilcox, "F106B Retirement, Comments on Its Tour of Duty at Lewis. May 17, 1991" (Cleveland, Ohio: NASA Glenn History Collection, Facilities Collection, 1991).

⁶² Wilcox, "F106B Retirement."

 ⁶³ Robert Dengler and Lawrence Macioce, "Small, Low-Cost, Expendable Turbojet Engine—II Performance Characteristics" (Cleveland, Ohio: NASA TM X–3463, 1976), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>
⁶⁴ "Center Tests Small Low Cost Jet Engine," Lewis News, March 24, 1972.

⁶⁵ "Center Tests Small Low Cost Jet Engine,"

⁶⁶ Bill Yenne, "Attack of the Drones: A History of Unmanned Aerial Combat," Zenith Press, 2004.

⁶⁷ Jerry Steele, email to Robert Arrighi, "Altitude Testing," May 23, 2011.

flight envelope.⁶⁸ The SN 17 engine was then analyzed. It not only easily covered the proposed flight envelope, but the engineers were able utilize the SN 17's Electronic Engine Control. It was the first complete locked-throttle climb of any turbofan.⁶⁹

Both ATF3 engines had demonstrated the ability to cover the Compass Cope's flight envelope and had outperformed the TFE 731. In the end, the SN 16 ATF3 was chosen over the SN 17 because there was enough existing hardware to create three of the engines.⁷⁰ The Cope program was canceled in July 1977.⁷¹ The TFE 731, which had become the dominant engine in the midsized business jet market between 1973 and 1977, had almost no competition in its size and power. In addition, its low noise levels and fuel efficiency coincided perfectly with the times.⁷²

Engineers at the NASA Ames Research Center, NASA Dryden Flight Research Center, and Rockwell International devised two subscale Highly Maneuverable Aircraft Technology (HiMAT) vehicles in the mid-1970s as safe post-wind-tunnel-test vehicles. The HiMAT vehicles would be used to study the behavior of fighter aircraft in the transonic realm to expedite the transition from the design phase to flight testing. These unpiloted vehicles could use new design concepts that might be too risky for a piloted vehicle.⁷³ The HiMAT was fairly small and launched at 45,000' from underneath a B–52. The GE 5,000-lb-thrust J85–21 turbojet provided the HiMAT propulsion.

Researchers worried that distortion from the J85–21's short turning inlet would stall or hinder the HiMAT's performance. In late 1977 Lewis's Leo Burkardt and the U.S. Air Force's George Bobula studied the engine in PSL No. 2. They charted the inlet quality for various combinations of five screens.⁷⁴ The two HiMAT aircraft performed eleven hours of flying over the course of twenty-six missions from mid-1979 to January 1983 at Dryden and Ames.⁷⁵

The PSL test chambers were also used to conduct basic research on general engine operating phenomena. The initial topic was inlet distortion. In 1968 Lewis undertook a wide-ranging, long-term study of airflow distortion. The goal was to collect a large amount of data and combine it in analytical models. The 10- by 10-Foot Supersonic Wind Tunnel was used to study the compatibility and control of different inlets and engines under simulated flight conditions at the compressor. The PSL was more suitable for simulating the conditions at the engine inlet.⁷⁶ The

⁶⁸ Steele, email to Robert Arrighi.

⁶⁹ John C. Evans, "Teledyne-Ryan Compass Cope YQM–98A R-Tern," The Garrett AiResearch ATF3 Online Museum, 2011, accessed January 8, 2015. <u>http://www.atf3.org/ATF3_Online_Museum.html</u>

⁷⁰ Steele, email to Robert Arrighi.

⁷¹ Yenne, "Attack of the Drones."

⁷² Richard Leyes and William Fleming, "The History of North American Small Gas Turbine Aircraft Engines" (Reston, Virginia: AIAA and Washington, DC: Smithsonian Institution, 1999).

⁷³ Dwain A. Deets, V. Michael DeAngelis, and David Lux: "HiMAT Flight Program: Test Results and Program Assessment Overview" (Edwards, California: NASA TM–86725, 1988), accessed January 8, 2015. http://ntrs.nasa.gov/

⁷⁴ George Bobula and Leo Burkardt, "Effects of Steady-State Pressure Distortion on the Stall Margin of a J85–21 Turbojet Engine" (Cleveland, Ohio: NASA TM–79123, 1979). <u>http://ntrs.nasa.gov/</u>

⁷⁵ Robert Kempel and Michael Earls, "Flight Control Systems Development and Flight Test Experience With the HiMAT Research Vehicles" (Cleveland, Ohio: NASA TP–2822, 1988), accessed January 8, 2015. http://ntrs.nasa.gov/

⁷⁶ Ross Willoh, et al., "Engine Systems Technology. Aeronautical Propulsion" (Cleveland, Ohio: NASA SP–381, 1954), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

General Electric J85–13 turbojet and the Pratt & Whitney TF30 turbofan were used for the PSL studies.

NASA Lewis researchers conducted a number of tests with TF30–P–1 and TF–30–P–2 engines in PSL No. 1 to examine this phenomenon. Initially screens and other devices were used to create the distortions, but the researchers found that using nozzles to inject air into the stream was the most effective and cost-efficient way to simulate the distortions. Using this method, engineers in the PSL were able map the engine's likeliness to stall from various pulses or distortions. It was found that the duration of a stall-inducing pulse was the inverse of its amplitude.⁷⁷ The PSL tests established that the increased speeds and altitudes produced inlet flow distortions that, along with decreased Reynolds numbers, reduced the stability of the engine's compressor. In addition, afterburner performance decreased as altitude increased.⁷⁸

During summer 1969, a gaseous hydrogen burner was set up in front of both TF30–P–1 and TF30– P–3 to create temperature disturbances. The individual sections of the burner were controlled independently to produce a number of different distortion patterns. The researchers discovered that inlet temperature distortion had a significant effect on engine stability.⁷⁹

The distortion research provided a better understanding of the effect of transient distortions on engine behavior.⁸⁰ The PSL studies were performed in parallel with Lewis's computer modeling efforts. The engine tests were used to refine the virtual models, which the flow specialists used to develop strategies for combating inlet distortion. One technique involved carving slots or grooves in the compressor casing to guide the compressor blade tips. This was referred to as "treatments."⁸¹ Lewis researchers who studied various casing treatments on single-stage compressors found that treatments increased flow range, distortion tolerance, and operating envelope.

In late 1973 and in 1974 Leon Wenzel led researchers who examined the treatment types, the optimal combination of compressor stages to treat, and possible decreases in efficiency in PSL No. 2. Each of the engine's eight compressor stages was instrumented individually to provide undistorted inlet conditions.^{82,83} Research into the use of treatments has continued over the years, and they have been incorporated into some engine designs with some degree of success.

In the mid-1970s, NASA Lewis and the U.S. Air Force collaborated on two broad programs that studied a variety of design problems on full-scale engines. The first, the FSER program utilized surplus Air Force engines as testbeds for a variety of research purposes, including flutter, inlet distortion, and electronic controls. In the late 1970s, engineers from the Airbreathing Engines

⁷⁸ McAulay and Abdelwahab, "Experimental Evaluation."

⁷⁷ Leon Wenzel, "Experimental Investigation of the Effects of Pulse Pressure Distortions Imposed on the Inlet of a Turbofan" (Cleveland, Ohio: NASA TM X–1928, 1969), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u> ⁷⁸ McAulay and Abdalwabab, "Experimental Evaluation"

⁷⁹ Thomas Biesiadny, et al., "Summary of Investigations of Engine Response to Distorted Inlet Conditions" (Cleveland, Ohio: NASA TM–87317, 1986), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

⁸⁰ "Lewis Recounts Year's Progress, Looks Ahead," Lewis News, January 15, 1971.

⁸¹ Edward Milner and Leon Wenzel, "Performance of a J85–13 Compressor With Clean and Distorted Inlet Flow" (Cleveland, Ohio: NASA TM X–3304, 1975), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

⁸² Leon Wenzel, to the Record, "Tip-Treated J–85 Program. January 31, 1973" (Cleveland, Ohio: Glenn History Collection, Facilities Collection, 1973).

⁸³ J.S. Shannon, transmittal of Technical Memo No. 73–240 to Wayne Park. March 23, 1973 (Cleveland, Ohio: Glenn History Collection, Facilities Collection, 1973).

Division's Engine Research Branch studied two Air Force engines for the FSER in the PSL—the Pratt & Whitney F100 (Fig. 29) and the General Electric J85–21.

Because the Air Force began having problems with flutter in the engine in 1972, it selected the F100 for the first FSER study in the PSL. The Air Force supplied Lewis with an early prototype of the engine—a Pratt & Whitney YF100, and the flutter investigations began in fall 1974. A major component of the testing was mapping the airflow through the engines to identify flutter. The researchers purposely induced flutter as the engine neared its stall limits, used improved instrumentation and optical devices to measure flutter,⁸⁴ and then mapped the flutter envelope. Lewis researchers later analyzed the collected flutter data and offered several hypotheses to explain the phenomenon.⁸⁵ Although breakthroughs to a completely flutter-free engine did not occur, several improved design techniques were developed.⁸⁶

In early 1975, NASA obtained a General Electric J85–21 turbojet, a 5000-lb-thrust variant of the J85–13, from the Air Force for the FSER program. The engine was used for two series of investigations—internal compressor aerodynamics and mechanical instability, or flutter.⁸⁷ The researchers focused on two types of stall flutter, choke flutter, and system-mode instability. Each variation of distortion was unique, so the researchers assembled a collection of data from each type of instability.⁸⁸

NASA Lewis was involved in electronic engine control systems in the 1970s and 1980s. The work was predated by studies of a General Electric J47 in the AWT during the late 1940s. The researchers determined that fuel flow and engine speed could be calculated linearly against a constant time.⁸⁹ The dependable hydromechanical control systems of the 1940s and 1950s, however, could not keep up with the increasingly complex and powerful engines. These newer engines required more sophisticated control systems that could handle multiple parameters and additional variables while increasing the accuracy and response of the engine.⁹⁰ Digital control technology developed for the Apollo Program was slowly taken on for aircraft propulsion. The new fly-by-wire electronic controls were lighter, more reliable, and allowed greater design flexibility.⁹¹

^{84 &}quot;The Fan-Compressor Flutter Team."

⁸⁵ Deskin and Hurrell, "Summary of NASA/Air Force Full Scale Engine Research."

⁸⁶ Ad Hoc Aeronautics Assessment Committee, "NASA's Aeronautics Program: Systems Technology and Experimental Programs" (Cleveland, Ohio: NASA CR–164642, 1981), accessed January 8, 2015. http://ntrs.nasa.gov/

⁸⁷ Roger Werner, "Steady-State Performance of a J85–21 Compressor at 100 Percent of Design Speed With and Without Interstage Rake Blockage" (Cleveland, Ohio: NASA TM–81451, 1980), accessed January 8, 2015. http://ntrs.nasa.gov/

 ⁸⁸ Joseph Lubomski, "Characteristics of Aeroelastic Instabilities in Turbomachinery: NASA Full Scale Engine Test Results" (Cleveland, Ohio: NASA TM–79085, 1979), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>
⁸⁹ Jaw and Garg, "Propulsion Control Technology Development."

⁹⁰ John Szuch, et al., "F100 Multivariable Control Synthesis Program—Evaluation of a Multivariable Control Using a Real-Time Engine Simulation" (Cleveland, Ohio: NASA TP–1056, 1977), accessed January 8, 2015. http://ntrs.nasa.gov/

⁹¹ Richard Hallion, "On the Frontier: Flight Research at Dryden, 1946–1981" (Cleveland, Ohio: NASA SP–4303, 1984), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

The U.S. Air Force initiated the Integrated Propulsion Control System (IPCS) program in March 1973 to demonstrate the digital control of the engine inlet, afterburner, and nozzle. NASA Lewis developed a method to integrate the control of the inlet and engine, and NASA Dryden led the effort to flight-test the system.⁹² The IPCS went through a final test run in the PSL during spring 1975 before being successfully flight tested that summer on an F–111 Aardvark at Dryden.⁹³

The initial turbojet and turbofan engines used fixed-geometry components with fuel flow and nozzle areas as variables. The engines being developed in the 1960s and 1970s implemented a variable-shaped compressor and fan blades. These new engine types required more sophisticated control systems that could handle many parameters and additional variables while increasing the accuracy and response of the engine. Variable-geometry controls included new methods for managing the compressor stators, intake, and nozzle. One tool was the linear quadratic regulator. In 1975 the Air Force asked NASA Lewis to develop and test a multivariable control system on an F100 engine. A digital controller was devised and tested using computer simulation in 1976. Systems Control, Inc., developed the computer logic for the system, and Pratt & Whitney provided an F100 engine for full-scale testing in the PSL in mid-1977.⁹⁴ The linear quadratic regulator proved itself to be applicable to flight design digital computers, and the digital system was more accurate than traditional mechanical controls.⁹⁵

The U.S. Navy requested that Lewis develop an engine-mounted propulsion control system for fighter jets (see Fig. 30). They sought to reduce replacement costs while advancing system functionality, reliability, and performance. Full Authority Digital Engine Control (FADEC) manages every aspect of an aircraft engine for maximum efficiency, Lewis worked with Pratt & Whitney to develop a FADEC system for the FY–401 turbofan, a variation of the F100. In spring 1979 the engine and FADEC system were successfully run in PSL No. 2 at nine simulated altitudes from 7,000' to 50,000'.⁹⁶ Dryden acquired an F–15 Eagle afterward and installed a FADEC system on its F100 powerplant. The F–15 flew the first flight of a FADEC system in 1981. Because of the success of these tests, the Air Force decided to put the system into production.⁹⁷

2.4 Closure of PSL No. 1 and 2

PSL No. 1 and 2 was busier than ever in the 1970s, and NASA Lewis's aeronautics program was in full-swing when PSL No. 3 and 4 became operational in 1973. Because demand was still high for altitude testing, Lewis decided to keep PSL No. 1 and 2 operating for several more years. During this period, the four PSL cells demonstrated that they could work together in a complementary way on a single program and pursue independent studies.

In spite of this success, NASA Lewis was going through its bleakest period. There were large Reduction In Force actions in 1973 and 1974, and Lewis's budgets and staffing levels continued

 ⁹² L.O. Billig, J. Kniat, and R.D. Schmidt, "IPCS Implications for Future Supersonic Transport Aircraft" (Cleveland, Ohio: NASA N76–31135 22–01, 1976), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>
⁸³ H. W. (O. 11, D. 11, 1976), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

⁹³ Hallion, "On the Frontier."

⁹⁴ Jaw and Garg, "Propulsion Control Technology Development."

⁹⁵ "Progress Noted in Jet Engine Control Study," Lewis News, September 14, 1979.

⁹⁶ R.W. Vizzini, T.G. Lenox, and R.J. Miller, "Full Authority Digital Electronic Control Turbofan Engine

Demonstration" (Warrendale, Pennsylvania: SAE–801199, 1980). ⁹⁷ Jaw and Garg, "Propulsion Control Technology Development."

to decline throughout the decade. As PSL's most intense period of study came to an end, the future of the original test cells began to cloud.

When new Center Director Eugene McCarthy reorganized Lewis in 1978, the Airbreathing Engines Division was disbanded with some of the duties being taken up by the new Propulsion Systems Division. Lewis management decided to reduce the number of technicians and mechanics to trim operating costs. This led to the consolidation of the crews for the PSL and the two large supersonic wind tunnels.⁹⁸

Lewis could not keep all four PSL chambers and all of the other engine test rigs operating. Shutting down PSL No. 1 and 2 would free up 20 technicians to help keep the other test rigs operating.⁹⁹ PSL No. 1 and 2's final runs were for a test of a Pratt & Whitney TF–34 turbofan in 1979.

Section 5.0 describes the standby care of PSL No. 1 and 2 after its final runs. Figure 31 shows a control room panel in 2008 after it had been abandoned for years.

3.0 Architectural Information

3.1 PSL Overview

PSL No. 1 and 2 included two altitude chambers, a modern control room, a combustion air supply system, an altitude exhaust system, and a cooling water system. The facility occupied an approximately 250'-0" x 600'-0" area near the center of NACA Lewis.¹⁰⁰

The complex included a number of buildings, with the two primary structures being the Shop and Access Building and the Equipment Building (Fig. 32). In 1972 two larger test chambers, PSL No. 3 and 4, were added to the complex in a new PSL Engine Test Building.

PSL No. 1 and 2 was essential to Lewis not just because of its testing capabilities but because its power compressors and exhausters were linked to Lewis's central air system. PSL's air-handling equipment augmented the air system in the other large test facilities through a 6'-0"-diameter pipe.

3.2 Test Area

The two test chambers and control room for PSL No. 1 and 2 were contained in the Shop and Access Building. The building itself is discussed further in Section 4.2. Figure 33 is a cutaway drawing of the Shop and Access Building. The engine being tested was installed inside the test section of one of the two chambers in which pressure and temperature could be controlled to simulate altitude. Extensive instrumentation was fitted on the engine prior to the test. Once the chamber was sealed, the altitude conditions were introduced and the engine was ignited. Operators in the control room could run the engine at the various speeds and adjust the altitude conditions to the desired levels. Obtaining the desired test conditions could be a difficult process, so once they were reached, the operators would continue running as long as possible.

⁹⁸ James Connors, "Technical Services," Lewis News, January 4, 1980.

⁹⁹ "Answer Line," Lewis News, May 26, 1978.

¹⁰⁰ "Major Research Facilities."

3.2.1 Test Chambers

The two 14'-0"-diameter, 100'-0"-long altitude chambers ran parallel to one another through the second floor of the Shop and Access Building with approximately 33-percent of the chamber sunken beneath the floor. The test chambers were designed as mirror versions of each other with the 15'-0"-wide hatches opening up to the center of the room (Figs. 34 to 36). The chambers were pressurized and water-cooled with a number of access points. Although the two chambers were identical when built in 1952, each was uniquely modified over its career.

There were three areas for each chamber: the test section, inlet section, and exhaust section (Figs. 35 to 36 and Ref. 101¹⁰¹). The combustion air entered the building 16'-0" ft above ground.¹⁰² The 24'-0"-long conical inlet section contained a set of vanes that stretched across the chamber to straighten the airflow. A large, square access door provided access to the vanes (Figs. 37 to 38). For most tests, a nozzle was installed in the inlet section to duct airflow directly to the engine inlet in the test section.

The test section was 14'-0" in diameter and 24'-0" long.¹⁰³ It was separated from the rest of the chamber by a front and rear bulkhead. An engine platform inside the test section was used to both hold the engine and measure its thrust loads and drag. An overhead crane inside the Shop and Access Building was used to lower the engine onto the stand, and a large clamshell hatch sealed the test section after the engine had been installed (see Figs. 40 to 41).

The test chambers could be configured in either a direct-connect or free-jet mode (see Fig. 39). The direct-connect mode offered the simplest way of studying the internal performance of the engine: the engine was mounted on the thrust stand inside a test chamber with the airflow connected directly to the engine inlet. To test the air inlet system though, a free-jet method was required: a nozzle was used to create a supersonic jet of air that enveloped the engine inlet in supersonic altitude air. The stream was powerful, but narrow, so it did not permit the study of airflow over the complete engine. The free-jet setup was more beneficial than the direct-connect setup because the entire engine system, including the inlet duct, could be studied.

The engine's exhaust was ejected through the test section's bulkhead and into the 12'-0"-diameter, 37'-0"-long exhaust section (see Fig. 42). The air flowed through this tubular section, passed a diffuser, and then went through a transition section to the primary cooler outside the Shop and Access Building.

3.2.2 Control Room

The 34'-2" x 36'-0" control room for PSL No. 1 and 2 was located on the second floor of the Shop and Access Building between the two chambers.¹⁰⁴ The control room had separate stations for each chamber (Figs. 43 to 44). Inside the control room, operators ran the engine and worked with other

¹⁰¹ "Major Research Facilities."

¹⁰² "Existing Building 65 Elevations" (Cleveland, Ohio: NASA Glenn Research Center, January 2007), drawing CD–0065–COF00630–AD–715.

¹⁰³ "Existing Building 67 Testing Chamber Sections and Elevations" (Cleveland, Ohio: NASA Glenn Research Center, January 2007), drawing CD–0065–COF00630–AD–736.

¹⁰⁴ "Existing Building 65 Floor Plans" (Cleveland, Ohio: NASA Glenn Research Center, January 2007) drawing CD–0065–COF00630–AD–713.

technicians running the exhausters and compressors in the Equipment Building to create the proper altitude conditions inside the test chamber.

During the 1950s, cameras on fixed stands recorded the pressure measurements on banks of manometer boards in the rear of the room (Fig. 45). A console set up in the center of the room was used to monitor these manometer readings.

The control room was frequently updated and modified (see Figs. 46 to 47). By the early 1960s, the manometers had been replaced with electronic equipment. A number of television consoles were installed so that the test engineers could view the engine in the chamber during the test. Temporary data-recording equipment could be installed for certain tests and later removed, and the control panels were rearranged periodically.

Figures 48 and 49 show the remnants of the control room in 2008 after the equipment most of the equipment had been cannibalized.

3.2.3 Instrumentation

Instrumentation was installed in both the engine and the test chamber in order to obtain useful data from the tests (Figs. 50 to 51). The setup varied depending on the requirements for the specific test. It could take weeks or even months for technicians and electricians to install the multitude of thermocouples, rakes, and other required instruments.

The rakes measured the engine airflow and the general airflow through the chamber. Thermocouples measured the temperature at various locations. Chronometric tachometers measured the engine speed, and a rotameter measured the fuel flow. The majority of the pressure tubes and thermocouples were located at the engine inlet, compressor outlet, turbine outlet, and exhaust nozzle inlet.¹⁰⁵

Manometer tubes were used to record steady-state pressure measurements, and reluctance-type pressure transducers were used to gather pressure information during transient periods. The transient data were recorded on graph paper, while the steady-state data appeared in the manometers.¹⁰⁶

For some tests, each compressor stage had to have its own readings. The work was often begun in the shop area before the engine was installed in the chamber. After the test article was in the chamber, the staff could access it through the main hatch, which was a large, mechanically operated clamshell lid, or through a smaller access door in the inlet section.

The engine itself was atop a thrust stand that measured the thrust and drag. The stand was bolted to the chamber's bedplate, and the plate and engine were supported by a scale system that measured the engine's thrust.¹⁰⁷

¹⁰⁵ Campbell and Sobolewski, "Altitude-Chamber Investigation."

¹⁰⁶ R. Crowl, W.R. Dunbar, and C. Wentworth, "Experimental Investigation of a Marquardt Shock-Positioning Control Unit on a 28-Inch Ram-Jet Engine" (Cleveland, Ohio: NACA RM–E56E09, 1956), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

¹⁰⁷ "Major Research Facilities."

An electronic differential analyzer supplied the computation for controlling the engine. A periscope camera was set up inside one of the chambers in the 1950s, and additional cameras were set up in the 1960s so that researchers could view the tests from the control room.

Rocket tests in the 1960s captured much of the same data—engine thrust, propellant flows, engine and test chamber pressures, and engine temperatures. An automatic digital data recording system captured 4000 samples per second. The data were recorded on graphs and displayed digitally in the control room. Combustion chamber pressure data were measured by close-couple transducers and sent to an analog recording system. Strain gauge transducers on the test stand measured the thrust, flowmeters measured the propellant flow, strain gauge transducers measured the pressure, and resistors measured the temperatures.¹⁰⁸

3.3 Combustion Air System

PSL No. 1 and 2 could create high-speed airflow through the interior of the engine being tested to simulate the speeds of flight for airbreathing engines. This capability was not necessary for rocket engines, which operate in the vacuum of space. Large compressors located in the Equipment Building pushed the air through the system, heating or refrigerating equipment was used to heat or cool the air to the desired temperature, and air dryers were used remove moisture from the air. The system was linked to Lewis's central air system, which allowed it to augment the compressors in other test facilities.

3.3.1 Compressors

PSL's airflow was generated by large Elliott Company air compressors in the northwest end of the Equipment Building (Figs. 52 to 53). The compressors forced the air rapidly through the 48"-diameter pipes toward the test section. Then the air passed through heater equipment outside of the Equipment Building (Fig. 54). The air left both heaters, which were about 40'-0" tall, and joined into an elevated 48"-diameter pipe. The elevated air line traveled behind the Shop and Access Building then formed a ninety-degree angle and descended toward the ground. Before the ground level, the pipe split into two separate lines. One of the combustion air lines traveled along each side of the Shop and Access Building. At the front corners of the building, the pipes formed a forty-five-degree angle and rose up 24'-2" to the second floor level.¹⁰⁹ The pipes then entered the Shop and Access Building from the northwest and connected to the two test chambers (Figs. 55 to 56). The airflow passed through the chamber's air-straightening vanes, then a bellmouth cowl in the bulkhead, and finally through the test section and the engine.

The air compression system was continually being upgraded and modified. In 1956 there were three 16,500-hp centrifugal compressors, each capable of delivering at forty-five pounds per square inch gravimetric air at a rate of 112 pounds per second (lb/s) for a total rate of 336 lb/s. Each of these had three wheels in each of their three casings: two casings in the first stage and one

 ¹⁰⁸ John P. Wanhainen, et al., "Throttling Characteristics of a Hydrogen-Oxygen, Regeneratively-Cooled, Pump-Fed Rocket Engine" (Cleveland, Ohio: NASA TM X–1043, 1964), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>
¹⁰⁹ "Existing Process Piping for Test Chamber Plan and Elevations" (Cleveland, Ohio: NASA Glenn Research Center, January 2007), drawing CD–0065–COF00630–AD–735.

in the second stage. A separate booster compressor could provide 150-psig air at 183 lb/s. Pressureregulating valves in the test chambers kept the air supply at the desired range.¹¹⁰

3.3.2 Temperature-Adjusting Equipment

The combustion airflow in the engine might have to be either heated or refrigerated depending on the type of test being run. Ramjets and engines that operated at supersonic speeds needed to be tested in hot conditions to simulate the heat generated by their velocity. Jet engines traveling at subsonic speeds needed to be tested in cold conditions to simulate the air temperature at high altitudes.

The three gas-powered combustion air heaters were located on the exterior of the Equipment Building's northwest wall (Fig. 57). The heaters, approximately 40'-0" tall, generated the high temperatures needed for supersonic testing. The heaters ingested ambient air from the compressors inside the Equipment Building. The air flowed through vertical tubes that had been warmed by a natural gas flame as it passed upward through the heater. Each unit heated air from forty to 600 °F at 125 lb/s.¹¹¹ Later a pebble bed heater was added to the PSL No. 2 test chamber to create the extremely high temperatures found at hypersonic speeds.

The refrigeration system for the high-altitude testing was not in the original PSL construction, but it was added soon afterwards. Temperatures found at an altitude of 50,000' and speeds of Mach 0.6 to 1.5 could be re-created without the refrigeration equipment, but slower speeds required colder conditions. The refrigerated air was generated by expansion turbines located in the Equipment Building. The system could cool air by 100 °F at up to 112 lb/s as it passed through an expansion turbine.¹¹²

The air at high altitudes is very dry, so the airflow had to be dehydrated before entering the test section. At temperatures between forty and 600 °F, the two dehydrator units (see Fig. 58) could reduce the moisture in the air at 125 lb/s or 100,000 cubic feet per hour. The air flowed up through a vertical cooling tower with cascade trays. This reduced the temperature from 120 to ninety °F. The air was then cooled to forty °F by a Freon cooler. The air could be dried to one grain of moisture per pound as it passed through the dryer, which contained 190,000 lb of activated alumina. It took nine hours to dry the air and an additional six hours to reactivate the alumina.¹¹³

3.4 Exhaust System

The exhaust system served two roles: reducing the density of the air in the PSL test chambers to simulate high altitudes and removing hot gases exhausted by the engines being tested. Large exhausters in the Equipment Building provided the vacuum power, a series of cooling equipment reduced the airflow temperatures, and a water tower dissipated the heat from the cooling system water.

¹¹⁰ "Major Research Facilities."

¹¹¹ "Major Research Facilities."

¹¹² "Major Research Facilities."

¹¹³ "Major Research Facilities."

3.4.1 Exhausters

Large Roots-Connersville exhausters (Figs. 59 to 63) in the Equipment Building were used to pump the air and engine exhaust gases out of the PSL system. The original configuration could exhaust the 3500 °F gases at 100 lb/s at a simulated altitude of 50,000'. Each of the thirteen 5100-hp exhauster units contained two J33 compressor wheels that could be adapted to work in tandem or parallel to drive. The number of units used could be varied to control the power load.

In 1955 a fourth line of exhausters was added. There were three centrifugal exhausters capable of supplying air at 166 lb/s at a test chamber altitude of 50,000' or at 384 lb/s at an altitude of 32,000'. These exhausters had two first-stage castings driven by a 10,000-hp motor and one second-stage, one third-stage, and one fourth-stage casting driven by a 16,500-hp motor. The exhausters could pump 1.65 million cubic feet of inlet gas per minute at normal operating conditions, but greater amounts of gas could be removed at lower altitudes.¹¹⁴ The exhausters were continually improved over the years, including a major upgrade with the addition of PSL No. 3 and 4 in the early 1970s.

3.4.2 Air Coolers

The large engines undergoing tests in the PSL test chambers expelled extremely high-temperature exhaust that had to be cooled before it reached the Roots-Connersville exhausters in the Equipment Building. PSL No. 1 and 2 employed two primary coolers (one for each test chamber) and one secondary cooler to accomplish this task. Figure 64 is an isometric drawing depicting the airflow system through PSL No. 1 and 2, and Figure 65 is an aerial view of the cooling equipment.

The engine's exhaust exited the PSL test chamber through the 14'-0"-diameter, 37'-0"-long exhaust section of the test chamber. The air flowed through a diffuser and into the primary cooler. The diffuser consisted of two increasingly large rings with an overlaid cross and a cone at the center. The device was used to disperse the hot air as it exited the engine nozzle into the large primary cooler.

The primary cooler (Figs. 66 to 67) was approximately 40'-0" long with a 26'-0" outside diameter and an 18'-0" interior diameter. The exterior was encircled by three wheellike bands of steel and supported by a four-beam overhead support structure. Both ends of the cooler narrowed to approximately 14 ft in interior diameter. Each test chamber had its own primary cooler.

The interior of the cooler contained rows of narrow fins, or vanes, that were filled with cold water. As the 1000 to 2000 °F airflow passed between the vanes, heat was transferred from the air to the cooling water. The cooling water was cycled out of the system, carrying with it much of the exhaust heat. Each primary cooler had a smaller diameter pipe feeding to the brick chimneylike atmospheric air vent at a forty-five-degree angle (Fig. 68). This 34.5'-0"-tall, roughly 15-square-foot structure could be used to quickly vent some of the remaining high-temperature air before it was sent to the secondary cooler.¹¹⁵

¹¹⁴ "Major Research Facilities."

¹¹⁵ "Existing Muffle Building Plans, Elevations, Sections, and Details" (Cleveland, Ohio: NASA Glenn Research Center, January 2007), drawing CD–0065–COF00630–AD–739.
The airflow was pumped a short distance through the approximately 14'-0"-diameter pipe to a T, where it joined a large pipe that connected the primary coolers for each test chamber. The pipe led to another T, which directed the airflow southeast into a large secondary cooler (Fig. 69). The secondary cooler sat just off the Equipment Building's northern corner. It was similar in size to the primary coolers.

This secondary cooler, or spray cooler, cooled and scrubbed the exhaust gases from both test chambers to reduce explosion hazards. The air was then pumped through the exhausters in the Equipment Building and expelled out into the atmosphere (see Fig. 70).

3.4.3 Cooling Water

PSL No. 1 and 2's primary and secondary coolers were supplied with large quantities of cooling water by a large closed-loop water-handling system. The water was used for several purposes, including the cooling of the exhaust ducts and valves from the hot engine exhaust.

The cooling water for the primary and secondary coolers was circulated by the Circulating Water Pump House located across Walcott Road next to the Electric Propulsion Research Building, which formerly served as the Engine Propeller Research Building. The single-story cement structure contained the system's large water pumps and water-softening units. The softeners were used to prevent scale and corrosion in the pipes.

The interior of the PSL coolers contained narrow fins that were filled with cold water. As high-temperature exhaust gas passed between the vanes, heat was transferred from the air to the cooling water flowing through the vanes. The cooling water was cycled out of the system by the equipment in the pump house, carrying with it much of the exhaust heat.

The heat from the circulating water was dissipated in a 47'-0"-tall wooden cooling tower located immediately behind the pump house (Figs. 71 to 72). The cooling tower had several large pumps, three water softening units, and a settling basin. The water carrying the heat was sprayed down into the cooling tower. Ten fans in the roof exhausted the hot air out as the water was diffused into the pools at the bottom (Fig. 73). The water was then recirculated back into the system and replenished with makeup water.

4.0 Support Buildings

4.1 Overview

The PSL No. 1 and 2 complex consisted of several structures used to support the test chambers (Fig. 74). The Shop and Access Building (the former Bldg. 65/66) housed the two test chambers, the control room, and various shops and working areas. The Equipment Building (Bldg. 64) contained the exhausters, compressors, refrigeration equipment, and its own control room. Three Combustion Air Heaters (Bldg. 76) heated the combustion air before it entered the test chambers.

The primary coolers (Bldg. 67), secondary cooler (Bldg. 68), and tie-line (Bldg. 69) were used to reduce the temperature of the airflow after it exited the test chamber. The Low-Pressure Pumping Station (former Bldg. 72), High-Pressure Pumping Station (former Bldg. 73), Circulating Water Pumping Station (Bldg. 74), and Cooling Tower (Bldg. 70) supplied the facility with cooling

water. Seven tall cooling water deaerators (former Bldg. 79) removed oxygen from the water supply.

Substation U (Bldg. 75) supplied the facility with additional electrical power, and the PSL Operations Building (Bldg. 60) provided offices for researchers, engineers, and the library.

4.2 Shop and Access Building

The Shop and Access Building (see Figs. 75 to 76) was a T-shaped structure that contained the two test chambers, a control room, and several shop areas for PSL No. 1 and 2. The 41'-0"-tall, 112'-0" 10"-wide rectangular two-story shop area (Bldg. 66) was added to the 82'-8"-wide two-story Access Building (Bldg. 65) in 1956. The addition nearly doubled the size of the structure (Fig. 77). The control room was a square wing with three levels off the rear end of the rear of the Access Building.¹¹⁶ Figures 78 through 81 are drawings of the Shop and Access Building. They include elevations, floor plans, and isometric views.

The buildings were constructed with bricks but were covered in metal siding. The upper portions of the second floor of the buildings consisted primarily of large banks of multipaned windows. The shop had entrances on the northeast, northwest, and southwest walls. The Access Building had interior passage ways to both the shop and control room areas, but no exits.

4.2.1 Ground Floor

The main area of the Access Building was 82'-8" wide and 51'-0" long (see Fig. 82). The two test chambers ran through the Access Building so that their access hatches opened up on the second floor, but the lower third of the tubular chambers hung down into the first floor (see Fig. 83). A large 10'-0"-wide roll door was originally in the center of the building's front side.

A 10'-0"-wide walkway ran northwest to southeast through the center of the first floor and between the two test chambers (Figs. 84 to 85). There was a small office on either side of the walkway, and rows of control panels and equipment lined the walkway. A stairway at the left of the walkway at the rear of the main room led to the second floor. Beyond the stairway was a 36'-0"-wide, 33'-0"-long room that sat below the control room. This area contained a 32'-6" x 10'-6" locker room on the left and a 24'-8" x 10'-6" mechanical and electrical equipment room on the right.¹¹⁷

The first floor of the Shop Building (Bldg. 66, Figs. 86 to 88) was a 112'-10"-wide, 45'-2"-long room that was filled with workbenches, mechanical equipment, and electrical equipment. A 500-lb overhead crane provided service to the southern half of the room. The large combustion air lines entered the north and west corners of the room and traveled diagonally to the second floor. A 12'-0"-wide doorway was in the center of the front.¹¹⁸

¹¹⁶ "Existing Building 66 Elevations and Section" (Cleveland, Ohio: NASA Glenn Research Center, January 2007), drawing CD–0065–COF00630–AD–724.

¹¹⁷ "Existing Building 65 Ground Floor Plan" (Cleveland, Ohio: NASA Glenn Research Center, January 2007), drawing CD–0065–COF00630–AD–712.

¹¹⁸ "Existing Building 66 Floor Plans" (Cleveland, Ohio: NASA Glenn Research Center, January 2007), drawing CD–0065–COF00630–AD–723.

4.2.2 Main Floor

The second floor of the Access Building (Figs 89–92) was an 82'-8" x 51'-0" room where the two test chambers ran parallel northwest to southeast on either side of the room. The distance from the center of one chamber to the center of the other was 34'-10". The upper two thirds of the test chambers sat above the floor with several access hatches providing entry to different areas of the chambers, which are described in Section 3.2.1 (see Figs. 93 to 96). Stairways led from the floor to 6.5'-0" platforms that ran behind each of the chambers. A 14'-10" x 10'-4" well was at the front center of the building behind the roll door. A large overhead rail crane transported engines and equipment into the chambers.

The 8'-7" double doorway at the center of the southeast wall led to the 34'-1" x 36'-0" control room described in Section 3.2.2 (see Figs. 97 to 102). The controls for PSL No. 1 were in the northern corner, the controls for PSL No. 2 were in the western corner, data-recording equipment were along the southeast wall, and the main entrance was at the center of the northeast wall. A stairwell just outside the rear of the control room led to a third-floor area that was used as an Instrumentation Room.¹¹⁹

The second floor of the Shop Building was a 45'-2" x 112'-10" space that was open to the second floor of the Access Building (see Figs. 103 to 104). The area was used to prepare engines and equipment for testing in the altitude chambers. The combustion air lines rose through the floor in the room's east and south corners, formed right angles, and entered the test chambers' inlet sections in the Access Building (see Figs. 105 to 106). The upper half of the three exterior walls was composed of windows.

4.3 Equipment Building

The PSL Equipment Building, now known as the Combustion Air and Equipment Building, provided the facility's muscle: the compressors, exhausters, refrigeration equipment, and other apparatus used to condition the air for the PSL tests. Its powerful compressors and exhausters created the atmospheric conditions that made the facility so unique. The exhaust system is described in Section 3.4, and the combustion air system in Section 3.3.

4.3.1 Exterior of Equipment Building

The Equipment Building (Figs. 107 to 109) was a two-story 175'-0" x 135'-0" structure with a single floor.¹²⁰ Like the Access Building, it contained a double band of multipaned windows along the upper exterior walls. The exterior of the building was manganese spot-face modular brick that matched many of the existing structures at Lewis.

Three large heating units outside the northwest wall were connected to the compressor equipment inside the structure. A separate pipe led from the compressors to the air dryer located just beyond the heaters, which are described in Section 3.3.2.

The southwestern wall contained a truck door and double pedestrian entrance. The southwestern wall also had a rectangular brick chimney that was used to vent the system's exhausted airflow.

¹¹⁹ "Existing Building 65 Floor Plans."

¹²⁰ "Basement Floor Plan and Outside Ramp and Steps Sections and Details" (Cleveland, Ohio: NACA Lewis Research Center, February 1951), drawing CE–104748.

The exhaust line ran parallel to the northeastern side of the building and entered the structure via two below-grade portals in the northeastern side of the building. Substation J was located near the northern corner of the building.

4.3.2 Interior of Equipment Building

The Equipment Building's foundation, flooring, and footings were reinforced concrete. The main floor was designed to handle a load of 250 pounds per square foot. Areas under the exhausters and where trucks would bring in equipment were designed for higher loads. The air heaters and transformers were laid out to accommodate oil tanks if the system was ever switched over from electric to gas heaters. The Equipment Building contains one large two-story room with four lines of exhausters and three lines of compressors running northeast to southwest (see Figs. 110 to 111). Figures 112 and 113 are floor plans of the Equipment Building.

The Equipment Building control room (Figs. 114 to 115) was a narrow rectangular enclosure that was located near the center of the floor between the main compressors and exhausters. The room had double-paned acoustical windows that were positioned so that all the test equipment could be viewed. In addition, the control panels were arranged so that each machine could be seen from its operating panel. The primary equipment was started from the PSL main control room. In emergency situations, however, it could be stopped from the floor of the Equipment Building. (Figures 116 and 117 show the basement of the Equipment Building.)

4.4 PSL Operations Building

A two-story T-shaped building (Figs. 118 to 120) was built across Walcott Road from the PSL to house the researchers who used the facility. The Operations Building (Bldg. 60) was a standard NACA Lewis office building with an exterior and windows similar to those of Lewis's other brick buildings. The Operations Building was almost identical in design and appearance to the Instrument Research Lab built just a few years before in the adjacent lot.

In 1959 the Operations Building residents included the Advanced Propulsion Division, the Facilities Engineering Division, and key members of the Propulsion Systems Division. The building contained two floors and a basement, which was also used for personnel.

In the mid-1960s, NASA Lewis's library was relocated to the building. The main section of the first floor and the entire second floor still contained offices, while a large room in the rear of the first floor housed the library (Figs. 121 to 124). The rear section of the basement also was used by the library, and the main basement corridor contained equipment rooms, restrooms, and two large offices.

In 1967 the building was renamed the Library Services Building, and it housed most of the Airbreathing Engines Division and the PSL Operations Branch. This arrangement continued until 2008 when the library and aeronautics staffs were relocated so that the building could be remodeled.

5.0 Demolition

NASA Lewis's budget was cut drastically in the post-Apollo years. After large Reduction In Force actions in 1973 and 1974, the Center's budgets and staffing levels continued to decline throughout the decade. It was difficult to staff all of the Center's facilities. The crews for PSL and the two large supersonic wind tunnels were consolidated and operations cut back. Lewis could not keep all four PSL chambers and all of the other engine test rigs operating. By shutting down PSL No. 1 and 2, twenty technicians would be freed up to help keep the other test rigs operating.

The second floor of the PSL Shop and Access Building soon became an office space for engineering and maintenance staff. Temporary offices were wedged in between and perpendicular to the two altitude chambers. These offices were used until 2008. The countless pipes, access platforms, and other equipment on the outside began suffering from lack of maintenance (see Fig. 125). The Equipment Building and PSL No. 3 and 4 continued to operate and were upgraded over the years.

In 2003, for the first time in its history, NASA Headquarters allocated funds for the demolition of unused facilities and asked its centers to submit lists for consideration. NASA Glenn (which had been renamed from NASA Lewis) began reexamining its facilities and infrastructure and proposed the removal of nine buildings. Two of these, the AWT and PSL No. 1 and 2, had played significant roles in the advancement of the Nation's propulsion technology. Headquarters concurred with Glenn's decision and advocated the proposed demolition.

Reactivation of PSL No. 1 and 2 was not an option, even if chambers 3 and 4 were not keeping up with test requests. The piping and air systems would have to be recertified, the control room had been cannibalized, and the mechanical, electrical, and safety equipment were obsolete. NASA Glenn was spending \$76,000 annually to maintain an underutilized office space. NASA Headquarters agreed to the \$3.17 million proposal, and Glenn spent the next two years creating a demolition plan and soliciting bids.¹²¹

Glenn created a requirements document in September 2004 and a Statement of Work in 2005. The Ohio Historic Preservation Office was notified in May 2004, a Section 106 report was submitted in July 2006, and the report was approved in September 2007.¹²²

Design services were obtained, and demolition plans were created. Then bids to perform the work were solicited, and the contract was awarded in 2007. The demolition consisted of three phases: relocation of the utilities, lead paint and asbestos remediation, and the actual demolition of the facility. The first step was the installation of perimeter fencing around the site in spring 2008. This was followed by lead paint and asbestos abatement, including the removal of the transite walls around the Shop and Access Building and Support Service Building.

¹²¹ "Project Requirements Document for Demolition of the Propulsion Systems Laboratory Cells 1 & 2 at Glenn Research Center. Project No. 630" (Cleveland, Ohio: NASA Glenn History Collection Test Facilities Collection, May 24, 2005).

¹²² Leslie Main, "Recordation of the Glenn Research Center Propulsion Systems Laboratory No. 1 and 2, Section 106 Check Sheets" (Cleveland, Ohio: NASA Glenn History Collection, Test Facilities Collection, October 11, 2004).

The main demolition (Figs. 126 to 129) began in May 2009 with the removal of the Support Service Building and external pipes. Work ramped up quickly in June. The bulldozers tore into the Shop and Access Building and methodically ripped the two altitude tanks into pieces as the workers hosed down the dust. The interior of the massive primary coolers (Fig. 130) stood exposed for the first time in 60 years as the rubble piled up around them. The cooling vanes lay in tangled piles like an industrial haystack. By August it was all over. The coolers had been knocked down, and the debris had been loaded into trucks and hauled away. Approximately 1,000 tons of steel had been removed and recycled.¹²³ Crews had removed the concrete foundations, graded the area, and slowly transformed the site into a parking lot and grassy area.¹²⁴

The PSL No. 3 and 4 facility and the Equipment Building, since renamed the Central Air and Equipment Building, continue to operate today. The PSL remains NASA's sole facility for testing full-scale aircraft engines in simulated flight conditions (see Figs. 131 to 132).

¹²³ Main, "Recordation of the Glenn Research Center."

¹²⁴ "Project Requirements Document."

6.0 Index of Propulsion Systems Laboratory No. 1 and 2 Photographs

Figure 1.—Map of NASA Glenn Research Center's Lewis Field campus showing its	
location within Ohio and Cuyahoga County. Overview and locations of the PSL	
No. 1 and 2 facility, 2009 (OH Cuyahoga Propulsion-Systems-	
Laboratory 002).	59
Figure 2.—PSL No. 1 and 2 with its support buildings, 1956	
(OH Cuyahoga Propulsion-Systems-Laboratory 003)	60
Figure 3.—NACA Lewis Flight Propulsion Laboratory (viewed from the east), 1953	
(OH Cuyahoga Propulsion-Systems-Laboratory 004)	60
Figure 4.—Layout of PSL No. 1 and 2. The Shop and Access Building is at the front	
left, and the Equipment Building is behind to the right. Arrows indicate the	
airflow, 2009 (OH Cuyahoga Propulsion-Systems-Laboratory 005).	61
Figure 5.—Map of NASA Glenn showing PSL No. 1 and 2, 2009	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_006)	62
Figure 6.—NACA Lewis Flight Propulsion Laboratory (viewed from the north). The	
PSL was located in the center of the semicircular property, 1954	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_007)	63
Figure 7.—Drawing showing PSL No. 1 and 2, the support buildings, and PSL No. 3	
and 4, 1985 (OH_Cuyahoga_Propulsion-Systems-Laboratory_008)	63
Figure 8.—General Electric J73 turbojet installed in PSL No. 1, 1952	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_009)	64
Figure 9.—Exterior of PSL No. 1 and 2 and a primary cooler, 2008	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_010)	64
Figure 10.—One of two 10-ft-diameter altitude test chambers in the Four Burner Area,	
1956 (OH_Cuyahoga_Propulsion-Systems-Laboratory_011)	65
Figure 11.—General Electric TG–190 [or J47] being readied in the test section of the	
AWT, 1948 (OH_Cuyahoga_Propulsion-Systems-Laboratory_012).	65
Figure 12.—A 20"-diameter ramjet is test flown beneath the NACA Lewis B-29	
aircraft, 1948 (OH_Cuyahoga_Propulsion-Systems-Laboratory_013)	66
Figure 13.—Centaur second-stage rocket, which employed two RL-10 engines, in the	
General Dynamics factory, 1962 (OH_Cuyahoga_Propulsion-Systems-	
Laboratory_014).	66
Figure 14.—Chart outlining the PSL validation of computer-simulated concepts such	
as digital engine controls (OH_Cuyahoga_Propulsion-Systems-Laboratory_015)	67
Figure 15.—PSL No. 1 and 2 shortly after its construction, 1952	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_016)	67
Figure 16.—Construction of the PSL No. 1 and 2 primary cooler supports, 1950	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_017)	68

Figure 17.—Installation of the primary coolers at PSL No. 1 and 2, 1951	
(OH Cuyahoga Propulsion-Systems-Laboratory 018)	68
Figure 18.—Pieces of PSL No. 1 and 2's test chamber as they arrive at the	
construction site, 1951 (OH Cuyahoga Propulsion-Systems-Laboratory 019)	69
Figure 19.—Construction of PSL's Equipment Building, 1950	
(OH Cuyahoga Propulsion-Systems-Laboratory 020)	69
Figure 20.—Pebble bed heater nozzle in the PSL No. 2 test chamber, 1958	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_021)	70
Figure 21.—Marquardt ramjet for the Bomarc missile in PSL No. 2, 1954	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_022)	71
Figure 22.—Technicians install a General Electric J-73 in PSL No. 1, 1952	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_024)	71
Figure 23.—Researchers examine an Iroquois PS.13 turbojet in PSL No. 1, 1957	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_023)	72
Figure 24.—Installation of a hydrogen peroxide rocket engine in PSL No. 1, 1960	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_025)	73
Figure 25.—Pratt & Whitney RL-10 rocket engine in PSL No. 2, 1961	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_026)	74
Figure 26.—Apollo engine for storable propellant test in PSL No. 2, 1964	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_027)	74
Figure 27.—Solid rocket test setup in PSL No. 2, 1965 (OH_Cuyahoga_Propulsion-	
Systems-Laboratory_028)	75
Figure 28.—ATF3 SN 16 engine in the PSL for analysis for the Compass Cope	
program, 1973 (OH_Cuyahoga_Propulsion-Systems-Laboratory_029).	75
Figure 29.—Technicians work on an F100 engine in the PSL, 1978	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_030)	76
Figure 30.—Chart outlining the PSL validation of computer-simulated concepts such	
as digital engine controls, 1983 (OH_Cuyahoga_Propulsion-Systems-	
Laboratory_031).	
Figure 31.—Combustion air and exhaust system panel for PSL No. 2 in the control	
room, 2008 (OH_Cuyahoga_Propulsion-Systems-Laboratory_032).	77
Figure 32.—Floor layout of PSL No. 1 and 2's Shop and Access Building (left) and	
the Equipment Building (right) with arrows indicating the airflow, 2009	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_033)	78
Figure 33.—Cutaway of the second floor of the Shop and Access Building where the	
technical staff spent most of its time. The test chambers, control room, and tool	
crib were located in the area (OH_Cuyahoga_Propulsion-Systems-	
Laboratory_034).	79
Figure 34.—Closed main hatch on PSL No. 1 (viewed from the northwest), 2008	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_035)	79

Figure 35.—Diagram highlighting the various sections and components of each of the	
two PSL test chambers, 1954 (OH_Cuyahoga_Propulsion-Systems-	
Laboratory_035).	80
Figure 36.—Overhead view of PSL test chamber, 1956 (OH_Cuyahoga_Propulsion-	
Systems-Laboratory_037)	80
Figure 37.—Interior of PSL No. 1 inlet section. The airflow entered from the right,	
2008 (OH_Cuyahoga_Propulsion-Systems-Laboratory_038)	81
Figure 38.—Hatch open to PSL No. 1 inlet section, 2008 (OH_Cuyahoga_Propulsion-	
Systems-Laboratory_039)	81
Figure 39A and 39B.—Inlet section with air flowing left to right into large nozzle	
(view down the exhaust section with the diffuser in the background), 1954 and	
1953 (OH_Cuyahoga_Propulsion-Systems-Laboratory_040a and	
OH Cuyahoga Propulsion-Systems-Laboratory 040b).	82
Figure 40.—PSL No. 1. The air entered from the right and exited to the left. The	
overhead crane, open test section hatch, and open inlet section hatch are visible,	
1952 (OH_Cuyahoga_Propulsion-Systems-Laboratory_041)	82
Figure 41.—Rocket nozzle test setup in PSL No. 1, 1964 (OH_Cuyahoga_Propulsion-	
Systems-Laboratory_039)	83
Figure 42.—Side of PSL No. 2 (viewed from the northwest). The inlet section is in the	
foreground, 2008 (OH_Cuyahoga_Propulsion-Systems-Laboratory_040)	83
Figure 43.—PSL No. 1 panels in the control room, 1957 (OH_Cuyahoga_Propulsion-	
Systems-Laboratory_044)	84
Figure 44.—PSL No. 2 controls in the control as they appeared in 1956	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_045)	84
Figure 45.—PSL No. 1 control panel and camera (on stand) used to record manometer	
readings, 1957 (OH_Cuyahoga_Propulsion-Systems-Laboratory_046).	85
Figure 46.—PSL No. 2 control panels during the RL-10 engine tests, 1961	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_047)	85
Figure 47.—PSL No. 1 control panels in 1973 (OH_Cuyahoga_Propulsion-Systems-	
Laboratory_048).	86
Figure 48.—PSL No. 2 control panels in the control room after years of neglect, 2008	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_049)	86
Figure 49.—PSL No. 1 control panels after much of the equipment had been	
cannibalized, 2008 (OH_Cuyahoga_Propulsion-Systems-Laboratory_050)	87
Figure 50.—Installation of the Wright 48"-diameter ramjet (viewed through the	
bellmouth cowl). The mechanic in the background has crawled through the	
cross-shaped temperature rake to work on the flameholder, 1952	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_052)	87
Figure 51.—Instrumentation used to record data on the TF–10 engine in the PSL, 1968	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_051)	88

Figure 52.—Large compressors that supplied high-speed air to the two altitude	
chambers, 1954 (OH Cuyahoga Propulsion-Systems-Laboratory 053).	88
Figure 53.—PSL compressors in the foreground as they appeared in 1971	
(OH Cuyahoga Propulsion-Systems-Laboratory 054)	89
Figure 54.—Combustion air line elevation, 2007 (OH Cuyahoga Propulsion-	
Systems-Laboratory 055).	89
Figure 55.—Aerial view of PSL No. 1 and 2 showing the combustion air line exiting	
the vertical heating equipment in the top right corner and splitting into two	
separate lines as it traveled to the ground level. Then each line traveled up one	
side of the Shop and Access Building (foreground) and entered the building on	
the second floor, 1955 (OH Cuyahoga Propulsion-Systems-Laboratory 056)	90
Figure 56.—Shop and Access Building (viewed from the north) with the two	
combustion air lines wrapping around the northeast and southeast sides of the	
building and entering on the northwest, 1953 (OH Cuyahoga Propulsion-	
Systems-Laboratory 057).	91
Figure 57.—PSL's three combustion air heaters (to the right), 1955	
(OH Cuyahoga Propulsion-Systems-Laboratory 058)	91
Figure 58.—Construction of an air dryer and its reactivation tank inside the Equipment	
Building. The desiccant dryer could move 40-psi air at 230 lb/s, 1955	
(OH Cuyahoga Propulsion-Systems-Laboratory 059)	92
Figure 59.—Fourth line of exhausters that were added in 1955. The Equipment	
Building was expanded southward to accommodate the new equipment, 1955	
(OH Cuyahoga Propulsion-Systems-Laboratory 060)	93
Figure 60.—Row of Roots-Connersville exhausters in the Equipment Building, 1956	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_061)	93
Figure 61.—Magnaflux Machine employee inspecting No. 42 Roots-Connersville	
exhauster impeller, 1956 (OH Cuyahoga Propulsion-Systems-Laboratory 062)	94
Figure 62.—Exhausters in the Equipment Building with the floor panel removed, 1992	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_063)	94
Figure 63.—Exhausters in the Equipment Building (viewed from the north), 1992	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_064)	95
Figure 64.—PSL No. 1 and 2 diagram that indicates airflow from the test chambers	
through the cooling system and into the exhausters, 2009	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_065)	96
Figure 65.—Pair of primary coolers (right), large exhaust pipe (center), and secondary	
cooler (lower left)-viewed from the east, 2006 (OH_Cuyahoga_Propulsion-	
Systems-Laboratory_066)	97
Figure 66.—PSL No. 1 primary cooler (viewed from the south), 2008	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_067)	97

Figure 67.—Entrance to a primary cooler as seen from the test chamber exhaust	
section, 1959 (OH Cuyahoga Propulsion-Systems-Laboratory 068).	98
Figure 68.—Atmospheric air vent that sat on steel piers between the two primary	
coolers and was used to expel some of the hot exhaust gas, 2008	
(OH Cuvahoga Propulsion-Systems-Laboratory 069)	
Figure 69.—PSL's secondary cooler, 1952 (OH Cuyahoga Propulsion-Systems-	
Laboratory 070).	100
Figure 70.—Equipment Building construction (viewed from the south). The brick	
chimney on the southwest side was used to vent the air from the exhauster	
equipment inside, 1951 (OH Cuyahoga Propulsion-Systems-Laboratory 071)	100
Figure 71.—PSL cooling tower and pump house (set back in the trees near the center	
of the photograph) and the PSL No. 1 and 2 facility (across the road)—aerial	
view from the northwest, 1957 (OH Cuvahoga Propulsion-Systems-	
Laboratory 072).	101
Figure 72.—Circulating Water Pump House (lower left) and wooden cooling tower	
(behind), 1952 (OH Cuyahoga Propulsion-Systems-Laboratory 073).	101
Figure 73.—Roof of the PSL cooling tower showing the fans that exhausted the steam	
heat into the atmosphere, 1950 (OH_Cuyahoga_Propulsion-Systems-	
Laboratory 074).	102
Figure 74.—Layout of the two PSL facilities with the Central Air Building in the	
center, 1985 (OH_Cuyahoga_Propulsion-Systems-Laboratory_075)	102
Figure 75.—PSL Shop and Office Building (viewed from the northeast). The shop is	
further to the right, the Access Building in the center, and the control room area	
at the left, 2006 (OH_Cuyahoga_Propulsion-Systems-Laboratory_076)	103
Figure 76.—Access Building was built in 1952. The combustion air pipes can be seen	
entering on the second floor, 1955 (OH_Cuyahoga_Propulsion-Systems-	
Laboratory_077).	104
Figure 77.—Shop Building (left) added to the Access Building in 1956. It covered up	
the combustion air pipes, 1957 (OH_Cuyahoga_Propulsion-Systems-	
Laboratory_078).	104
Figure 78.—Access Building elevations, 1965 (OH_Cuyahoga_Propulsion-Systems-	
Laboratory_079).	105
Figure 79.—Shop Building Elevations, 1965 (OH_Cuyahoga_Propulsion-Systems-	
Laboratory_080).	106
Figure 80.—Floor layout of Shop and Access Building, 1962	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_081)	107
Figure 81.—Shop and Access Building (isometric view), 2009	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_082)	107
Figure 82.—First floor layout of the Access Building, 2007	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_083)	108

Figure 83.—Underside of one of the PSL chambers (viewed from the first floor of the	
Access Building), 2008 (OH Cuyahoga Propulsion-Systems-Laboratory 084)	109
Figure 84.—First floor of the Access Building showing the main walkway	
(foreground) and equipment (behind), 2008 (OH Cuyahoga Propulsion-	
Systems-Laboratory 085)	110
Figure 85.—Walkway heading southeast underneath the control room. The anteroom	
in the background led out the rear of the Access Building to the primary cooler	
area, 2008 (OH Cuyahoga Propulsion-Systems-Laboratory 086).	110
Figure 86.—First floor of the Shop Building (viewed from the west) after it was	
emptied of all of its equipment. The dark combustion air line can be seen in the	
background at the center of the photograph, 2008 (OH Cuyahoga Propulsion-	
Systems-Laboratory_087)	111
Figure 87.—First floor of the Shop Building after it was cleared out (viewed from the	
north). The 500-lb crane is hanging from a rail at the top center of the	
photograph, 2008 (OH_Cuyahoga_Propulsion-Systems-Laboratory_088)	111
Figure 88.—First and second floor layouts of the Shop Building, 2007	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_089)	112
Figure 89.—Second floor of the Access Building with a test chamber in the	
background, 1964 (OH_Cuyahoga_Propulsion-Systems-Laboratory_090)	113
Figure 90.—Display for the 1966 Inspection set up on the second floor of the Access	
Building. PSL No. 1 is on the right, and PSL No. 2 is just out of sight on the left.	
The control room is blocked by the temporary stage and display, 1966	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_091)	114
Figure 91.—Diagram of the second floor of the Access Building, 1954	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_092)	114
Figure 92.—Second floor plan of the Access Building, 2007	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_093)	115
Figure 93.—Control for the crane and test chamber access hatch, 2008	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_094)	116
Figure 94.—Control for the crane and test chamber access hatch. The entrance to the	
control room can be seen in the background at the top middle of the photograph,	
2008 (OH_Cuyahoga_Propulsion-Systems-Laboratory_095)	116
Figure 95.—PSL No. 1 and the western half of the second floor of the Access Building	
(viewed from the Instrumentation Room). The rectangular temporary offices to	
the right were added after the facility was closed down, 2008	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_096)	117
Figure 96.—PSL No. 2 and the western half of the second floor of the Access Building	
(viewed from above). The rectangular temporary offices to the left were added	
after the facility was closed down, 2008 (OH_Cuyahoga_Propulsion-Systems-	
Laboratory_097).	117

Figure 97.—Aerial view of the Access Building. The control room is contained in the	
small square addition at the rear of the building between the two primary	
coolers, 1955 (OH_Cuyahoga_Propulsion-Systems-Laboratory_098).	118
Figure 98.—Layout of PSL No. 1 and 2 control room in 1956 and 1962	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_099)	118
Figure 99.—PSL control room with PSL No. 2 panels (far wall), manometers (to the	
left), cameras set up to photograph manometers, and control station (middle),	
1954 (OH_Cuyahoga_Propulsion-Systems-Laboratory_100)	119
Figure 100.—Rear of the PSL control room after equipment had been removed, 2008	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_101)	119
Figure 101.—Entrance to the control room (against the far wall between the two test	
chambers), 1963 (OH_Cuyahoga_Propulsion-Systems-Laboratory_102)	120
Figure 102.—Control room exit into the main Access Building floor area, 1973	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_103)	120
Figure 103.—Rocket engines on display in the second floor of the Shop Building. The	
Access Building was to the right, 1966 (OH_Cuyahoga_Propulsion-Systems-	
Laboratory_104).	121
Figure 104.—View from above the control room through the Access Building and into	
the Shop Building (background). The temporary office structures throughout the	
two rooms were added after the facility ceased operations, 2008	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_105)	121
Figure 105.—Combustion air line as it entered the second floor of the Shop Building.	
It then connected to the inlet section of PSL No. 1, 2008	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_106)	122
Figure 106.—Inlet section of PSL No. 2 in the Access Building. It connected to the	
combustion air line on the opposite side of this wall, 2008	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_107)	122
Figure 107.—PSL Equipment Building shortly after its completion (viewed from the	
south), 1953 (OH_Cuyahoga_Propulsion-Systems-Laboratory_108)	123
Figure 108.—PSL Equipment Building (viewed from the east). An extension off the	
southeast wall was added to accommodate additional exhauster equipment, 1955	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_109)	123
Figure 109.—PSL Equipment Building (viewed from the west) with the three air	
heaters, combustion air line, and exhaust air line, 1956	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_110)	124
Figure 110.—Eastern half of the PSL Equipment Building (viewed from the west)	
showing the exhauster equipment, 1959 (OH_Cuyahoga_Propulsion-Systems-	
Laboratory_111).	124

Figure 111.—Interior of the PSL Equipment Building (viewed from the north). A row	
of compressors (foreground), the control room (center), and exhausters	
(background), 1959 (OH Cuyahoga Propulsion-Systems-Laboratory 112)	125
Figure 112.—Layout of the Equipment Building, now known as the Central Air	
Building, 1956 (OH Cuyahoga Propulsion-Systems-Laboratory 113)	126
Figure 113.—Main floor of the Equipment Building as it appeared in the 1990s	
(OH Cuyahoga Propulsion-Systems-Laboratory 114)	127
Figure 114.—Equipment Building control room (viewed from the north), 1971	
(OH Cuyahoga Propulsion-Systems-Laboratory 115)	128
Figure 115.—Interior of Equipment Building control room, 1972	
(OH Cuyahoga Propulsion-Systems-Laboratory 116)	128
Figure 116.—Basement of PSL Equipment Building, 1955	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_117)	129
Figure 117.—Switchgear panels in the basement of the PSL Equipment Building,	
1952 (OH_Cuyahoga_Propulsion-Systems-Laboratory_118)	129
Figure 118.—Layout of Building 60, formerly the PSL Operations Building, 1956	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_119)	130
Figure 119.—PSL Operations Building (viewed from the east), 1957	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_120)	130
Figure 120.—PSL Operations Building during the final phase of its construction, 1950	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_121)	131
Figure 121.—Foyer in the front entrance of the PSL Operations Building. The library	
was to the left, and an office wing was ahead, 1967 (OH_Cuyahoga_Propulsion-	
Systems-Laboratory_122)	131
Figure 122.—Lewis researchers in an office in the PSL Operations Building, 1957	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_123)	132
Figure 123.—Library room on the first floor of the PSL Operations Building, 1966	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_124)	132
Figure 124.—Corridor leading to library auxiliary room in the basement of the PSL	
Operations Building, 1967 (OH_Cuyahoga_Propulsion-Systems-	
Laboratory_125).	133
Figure 125.—PSL infrastructure in disrepair, 2008 (OH_Cuyahoga_Propulsion-	
Systems-Laboratory_126)	133
Figure 126.—Demolition of the Shop and Access Building, 2009	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_127)	134
Figure 127.—Crane ripping apart the PSL No. 1 test chamber, 2009	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_128)	134
Figure 128.—Remnants of the Shop and Access Building, 2009	
(OH_Cuyahoga_Propulsion-Systems-Laboratory_129)	135

Figure 129.—Primary cooler being ripped down, 2009 (OH_Cuyahoga_Propulsion-	
Systems-Laboratory_130)	135
Figure 130.—Damaged primary cooler and debris, 2009 (OH_Cuyahoga_Propulsion-	
Systems-Laboratory_131)	136
Figure 131.—PSL No. 3 and 4 exterior with the Central Air and Equipment Building	
behind to the left, 2006 (OH_Cuyahoga_Propulsion-Systems-Laboratory_132)	136
Figure 132.—Test chamber in PSL No. 3 and 4 that has been modified for icing	
research, 2012 (OH_Cuyahoga_Propulsion-Systems-Laboratory_133).	137

Bibliography

"1962–1972: The First Decade of Centaur," Lewis News, October 20, 1972.

"260-Inch Diameter Motor Feasibility Demonstration Program" (Sacramento, California: Aerojet General Corporation, 1966).

Ad Hoc Aeronautics Assessment Committee, "NASA's Aeronautics Program: Systems Technology and Experimental Programs" (Cleveland, Ohio: NASA CR–164642, 1981), accessed January 8, 2015. http://ntrs.nasa.gov/

"Advanced Chemical Rockets: Presented at 1966 Inspection of the Lewis Research Center. October 4, 1966" (Cleveland, Ohio: NASA Glenn History Collection, Inspections Collection, 1966).

"Aero Engines 1959," Flight, March 20, 1959, 396.

"Answer Line," Lewis News, May 26, 1978.

Robert A. Arrighi, "Pursuit of Power: The Propulsion Systems Laboratory No. 1 and 2" (Washington, DC: NASA/SP—2012-4548, 2012), accessed January 8, 2215. <u>http://ntrs.nasa.gov/</u>

Carl Auckerman and Arthur Trout, "Experimental Rocket Performance of Apollo Storable Propellants in Engines With Large Area Ratio Nozzles" (Cleveland, Ohio: NASA TN D–3566, 1966), accessed January 8, 2015. http://ntrs.nasa.gov/

"Basement Floor Plan and Outside Ramp and Steps Sections and Details," (Cleveland, Ohio: NACA Lewis Research Center, February 1951), drawing CE–104748.

Thomas Biesiadny, et al., "Summary of Investigations of Engine Response to Distorted Inlet Conditions" (Cleveland, Ohio: NASA TM–87317, 1986), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

L.O. Billig, J. Kniat, and R.D. Schmidt, "IPCS Implications for Future Supersonic Transport Aircraft" (Cleveland, Ohio: NASA N76–31135 22–01, 1976), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

Harry E. Bloomer and Carl E. Campbell, "Experimental Investigation of Several Afterburner Configurations on a J79 Turbojet Engine" (Cleveland, Ohio: NACA RM–E57I18, 1957), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

George Bobula and Leo Burkardt, "Effects of Steady-State Pressure Distortion on the Stall Margin of a J85–21 Turbojet Engine" (Cleveland, Ohio: NASA TM–79123, 1979). <u>http://ntrs.nasa.gov/</u>

Burns and Roe, Inc., "Estimated Cost of Propulsion Science Laboratory as of November 20, 1950" (Cleveland, Ohio: NASA Glenn History Collection, Test Facilities Collection, 1950).

Burns and Roe, Inc., "Progress Report No. 22 for Propulsion Science Lab Phase I Part II. October 6, 1949" (Cleveland, Ohio: NASA Glenn History Collection, Test Facilities Collection, 1949).

Carl E. Campbell and Adam Sobolewski, "Altitude-Chamber Investigation of J73–GE–1A Turbojet Engine Component Performance" (Cleveland, Ohio: NACA RM–E53I08, 1954), accessed January 8, 2015. http://ntrs.nasa.gov/

Carl E. Campbell and Conrad, E. William, "Altitude Performance Characteristics of the J73–GE–1A Turbojet Engine" (Cleveland, Ohio: NACA RM–E53I25, 1954), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

"Center Tests Small Low Cost Jet Engine," Lewis News, March 24, 1972.

Carl Ciepluch, "Status of the 260-Inch Diameter Solid Rocket Motor Program" (Cleveland, Ohio: NASA TM X– 52275, 1967), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

James Connors, "Technical Services," Lewis News, January 4, 1980.

William E. Conrad, Ned P. Hannum, and Harry E. Bloomer, "Photographic Study of Liquid-Oxygen Boiling and Gas Injection in the Injector of a Chugging Rocket Engine" (Cleveland, Ohio: NASA TM X–948, 1964), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

R. Crowl, W.R. Dunbar, and C. Wentworth, "Experimental Investigation of a Marquardt Shock-Positioning Control Unit on a 28-Inch Ram-Jet Engine" (Cleveland, Ohio: NACA RM–E56E09, 1956), accessed January 8, 2015. http://ntrs.nasa.gov/

Virginia Parker Dawson, "Engines and Innovation: Lewis Laboratory and American Propulsion Technology" (Washington, DC: NASA SP-4306, 1991), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

Dwain A. Deets, V. Michael DeAngelis, and David Lux, "HiMAT Flight Program: Test Results and Program Assessment Overview" (Edwards, California: NASA TM-86725, 1988), accessed January 8, 2015. http://ntrs.nasa.gov/

Robert Dengler and Lawrence Macioce, "Small, Low-Cost, Expendable Turbojet Engine—II Performance Characteristics" (Cleveland, Ohio: NASA TM X–3463, 1976), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

James DeRaimo, "Flame Spreader for Cell #2 at PSL. Aug. 12, 1968" (Cleveland, Ohio: NASA Glenn History Collection, Facilities Collection, 1968).

W.J. Deskin and H.G. Hurrell, "Summary of NASA/Air Force Full Scale Engine Research Using the F100 Engine" (Reston, Virginia: AIAA 79–1308, 1979).

John Disher and Leonard Rabb, "Flight Tests of Full-Scale Ramjet Engines" (Cleveland, Ohio: NASA Glenn History Office Collection, Inspections Collection, 1954).

John C. Evans, "Teledyne-Ryan Compass Cope YQM–98A R-Tern," The Garrett AiResearch ATF3 Online Museum, 2011, accessed January 8, 2015. <u>http://www.atf3.org/ATF3_Online_Museum.html</u>

"Existing Building 65 Elevations," (Cleveland, Ohio: NASA Glenn Research Center, January 2007), drawing CD-0065-COF00630-AD-715.

"Existing Building 65 Floor Plans," (Cleveland, Ohio: NASA Glenn Research Center, January 2007) drawing CD-0065-COF00630-AD-713.

"Existing Building 65 Ground Floor Plan," (Cleveland, Ohio: NASA Glenn Research Center, January 2007), drawing CD–0065–COF00630–AD–712.

"Existing Building 66 Elevations and Section," (Cleveland, Ohio: NASA Glenn Research Center, January 2007), drawing CD–0065–COF00630–AD–724.

"Existing Building 66 Floor Plans," (Cleveland, Ohio: NASA Glenn Research Center, January 2007), drawing CD-0065-COF00630-AD-723.

"Existing Building 67 Testing Chamber Sections and Elevations," (Cleveland, Ohio: NASA Glenn Research Center, January 2007), drawing CD–0065–COF00630–AD–736.

"Existing Muffle Building Plans, Elevations, Sections, and Details," (Cleveland, Ohio: NASA Glenn Research Center, January 2007), drawing CD–0065–COF00630–AD–739.

"Existing Process Piping for Test Chamber Plan and Elevations," (Cleveland, Ohio: NASA Glenn Research Center, January 2007), drawing CD–0065–COF00630–AD–735.

James N. Gibson, "The Navajo Missile Project" (Atglen, Pennsylvania: Schiffer Publishing Ltd., 1996).

Jesse Hall, memorandum to Carlton Kemper, "Cleveland Laboratory Test Program for Investigating Ramjet Engines in Free Flight," August 18, 1947.

Richard Hallion, "On the Frontier: Flight Research at Dryden, 1946–1981" (Cleveland, Ohio: NASA SP–4303, 1984), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

R.F. Holsten, "Centaur Propulsion Systems Testing Volume I, December 7, 1962" (East Hartford, Connecticut: Pratt & Whitney FR-431, 1962).

J.D. Hunley, "The Development of Propulsion Technology for U.S. Space-Launch Vehicles, 1926–1991" (College Station, Texas: Texas A&M University Press, 2007), 270.

"Hypersonic Tunnel Facilities. Sept. 23, 1957" (Cleveland, Ohio: Glenn History Program, Director's Collection, 1957).

Link Jaw and Sanjay Garg, "Propulsion Control Technology Development in the United States" (Cleveland, Ohio: NASA/TM—2005-213978, 2005), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

Lionel Johns, Ray Williamson, and Richard DalBello, "Big Dumb Boosters: A Low-Cost Space Transportation Option?" AN OTA Background Paper, February 1989 (paper presented at the Workshop on Low-Technology, Low-Cost Space Transportation Options, December 1, 1987).

Robert Kempel and Michael Earls, "Flight Control Systems Development and Flight Test Experience With the HiMAT Research Vehicles" (Cleveland, Ohio: NASA TP–2822, 1988), accessed January 8, 2015. http://ntrs.nasa.gov/ Carlton Kemper, et al., "Memorandum for Director, Report of the Special Panel Appointed to Study General Requirements of the Propulsion Sciences Laboratory. March 18, 1948" (Cleveland, Ohio: NASA Glenn History Collection, Facilities Collection, 1948).

John Kobak, Interview. September 1, 2009 (NASA Glenn History Collection, Oral History Collection, 2009).

M.J. Krasnican, et al., "Propulsion Research for Hypersonic and Space Flight. NACA Lewis Flight Propulsion Laboratory Inspection, Oct. 7–10, 1957" (Cleveland, Ohio: NASA Glenn History Collection, Inspections Collection, 1957).

M.J. Krasnican, et al., "Propulsion Research for Hypersonic Flight. NACA Lewis Flight Propulsion Laboratory Inspection, October 7–10, 1957" (Cleveland, Ohio: NASA Glenn History Collection, Inspections Collection, 1957), 4.

"Lewis Recounts Year's Progress, Looks Ahead," Lewis News, January 15, 1971.

Richard Leyes and William Fleming, "The History of North American Small Gas Turbine Aircraft Engines" (Reston, Virginia: AIAA and Washington, DC: Smithsonian Institution, 1999).

Michael Lombardi, "Reach for the Sky: How the Bomarc Missile Set the Stage for Boeing to Demonstrate Its Talent in Systems Integration," Boeing Frontiers, June 2, 2007.

Joseph Lubomski, "Characteristics of Aeroelastic Instabilities in Turbomachinery: NASA Full Scale Engine Test Results" (Cleveland, Ohio: NASA TM–79085, 1979), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

Leslie Main, "Recordation of the Glenn Research Center Propulsion Systems Laboratory No. 1 and 2, Section 106 Check Sheets" (Cleveland, Ohio: NASA Glenn History Collection, Test Facilities Collection, October 11, 2004).

"Major Research Facilities of the Lewis Flight Propulsion Laboratory, NACA Cleveland, Ohio, Wind Tunnels— Propulsion Systems Laboratory. July 17, 1956" (Cleveland, Ohio: NASA Glenn History Collection, Facilities Collection, 1956).

John McAulay and Donald Groesbaeck, "Investigation of a Prototype Iroquois Turbojet Engine in an Altitude Test Chamber" (Cleveland, Ohio: NACA RM–SE58E26, 1958), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

John McAulay and Mahmood Abdelwahab, "Experimental Evaluation of a TF–30–P–3 Turbofan Engine in an Altitude Facility: Afterburner Performance and Engine-Afterburner Operating Limits" (Cleveland, Ohio: NASA TN D–6839, 1972), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

Edward Milner and Leon Wenzel, "Performance of a J85–13 Compressor With Clean and Distorted Inlet Flow" (Cleveland, Ohio: NASA TM X–3304, 1975), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

C.S. Moore, "Appendix A, Proposal for Propulsion Sciences Laboratory" (Cleveland, Ohio: NASA Glenn History Collection, Directors Collection, March 26, 1948).

"NACA: Thirty-second Annual Report of the National Advisory Committee for Aeronautics" (Washington, DC: Government Printing Office, 1946), 26.

"NASA Propulsion Systems Laboratory (PSL) No. 1 and 2," NASA Glenn Research Center Historic Facilities, accessed January 8, 2015. <u>http://pslhistory.grc.nasa.gov/</u>

Sterling Michael Pavelec, "The Jet Race and the Second World War" (Westport, Connecticut: Praeger Security International, 2007).

Daniel Peters and John McAulay, "Some Altitude Operational Characteristics of a Prototype Iroquois Turbojet Engine" (Cleveland, Ohio: NACA RM–SE58F17, 1958), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

"Progress Noted in Jet Engine Control Study," Lewis News, September 14, 1979.

"Progress Report No. 20 for Propulsion Science Lab Phase I Part II. Sept. 8, 1949" (Cleveland, Ohio: NASA Glenn History Collection, Test Facilities Collection, 1949).

"Project Requirements Document for Demolition of the Propulsion Systems Laboratory Cells 1 & 2 at Glenn Research Center. Project No. 630" (Cleveland, Ohio: NASA Glenn History Collection Test Facilities Collection, May 24, 2005).

"Propulsion Systems Division: Data Tabulation, Altitude Chambers, PSL-1" (Cleveland, Ohio: NASA Glenn History Collection, Facilities Collection, 1961).

"Ramjets: Some Experimental Applications," Flight, February 3, 1949.

Reino Salmi and James Pelouch, Jr., "Investigation of a Submerged Nozzle for Solid Rockets" (Cleveland, Ohio: NASA TM X–52285, 1967), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

Reino Salmi and James Pelouch, Jr., "1/14.2-Scale Investigation of Submerged Nozzle for SL–3 260-Inch Solid Rocket" (Cleveland, Ohio: NASA Lewis Research Center, 1968).

J.S. Shannon, "Transmittal of Technical Memo No. 73–240 to Wayne Park. March 23, 1973" (Cleveland, Ohio: Glenn History Collection, Facilities Collection, 1973).

Edward R. Sharp, "Appointment of Propulsion Sciences Laboratory Project Engineer. March 17, 1948" (Cleveland, Ohio: NASA Glenn History Collection, Directors Collection, 1948).

"Specifications for Furnishing Architect-Engineer Services for the Propulsion Sciences Laboratory Phase I Project No. 794, NACA Lewis Propulsion Research Laboratory, August 5, 1948" (Cleveland, Ohio: NASA Glenn History Collection, Test Facilities Collection, 1948).

Jerry Steele, email to Robert Arrighi, "Altitude Testing," May 23, 2011.

W.H. Sterbentz and T.J. Nussdorfer, "Investigation of Performance of Bumblebee 18-Inch Ramjet With a Can-Type Flameholder" (Washington, DC: NACA RM–E8E21, 1948), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

John Szuch et al., "F100 Multivariable Control Synthesis Program—Evaluation of a Multivariable Control Using a Real-Time Engine Simulation" (Cleveland, Ohio: NASA TP–1056, 1977), accessed January 8, 2015. http://ntrs.nasa.gov/ "The Fan-Compressor Flutter Team," Lewis News, February 3, 1978.

R.W. Vizzini, T.G. Lenox, and R.J. Miller, "Full Authority Digital Electronic Control Turbofan Engine Demonstration" (Warrendale, Pennsylvania: SAE–801199, 1980).

John P. Wanhainen, et al., "Throttling Characteristics of a Hydrogen-Oxygen, Regeneratively-Cooled, Pump-Fed Rocket Engine" (Cleveland, Ohio: NASA TM X–1043, 1964), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

Leon Wenzel, "Experimental Investigation of the Effects of Pulse Pressure Distortions Imposed on the Inlet of a Turbofan" (Cleveland, Ohio: NASA TM X–1928, 1969), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

Leon Wenzel, to the Record, "Tip-Treated J–85 Program. January 31, 1973" (Cleveland, Ohio: Glenn History Collection, Facilities Collection, 1973).

Roger Werner, "Steady-State Performance of a J85–21 Compressor at 100 Percent of Design Speed With and Without Interstage Rake Blockage" (Cleveland, Ohio: NASA TM–81451, 1980), accessed January 8, 2015. http://ntrs.nasa.gov/

Fred Wilcox, "F106B Retirement, Comments on Its Tour of Duty at Lewis. May 17, 1991" (Cleveland, Ohio: NASA Glenn History Collection, Facilities Collection, 1991).

Ross Willoh, et al., "Engine Systems Technology. Aeronautical Propulsion" (Cleveland, Ohio: NASA SP–381, 1954), accessed January 8, 2015. <u>http://ntrs.nasa.gov/</u>

Bill Yenne, "Attack of the Drones: A History of Unmanned Aerial Combat," Zenith Press, 2004.

Appendix A—Acronyms

- AERL Aircraft Engine Research Laboratory
- AWT Altitude Wind Tunnel
- FADEC Full Authority Digital Engine Control
- FSER Full-Scale Engine Research
- HiMAT Highly Maneuverable Aircraft Technology
- IPCS Integrated Propulsion Control System
- NACA National Advisory Committee for Aeronautics
- NASA National Aeronautics and Space Administration
- OAO Orbiting Astronomical Observatory
- PSL Propulsion Systems Laboratory
- SST Supersonic Transport

Appendix B—Figures and Images





Figure 2.—PSL No. 1 and 2 with its support buildings, 1956 (NASA Glenn Research Center Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 3.—NACA Lewis Flight Propulsion Laboratory (viewed from the east), 1953 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).







Figure 5.—Map of NASA Glenn showing PSL No. 1 and 2, 2009 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 6.—NACA Lewis Flight Propulsion Laboratory (viewed from the north). The PSL was located in the center of the semicircular property, 1954 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 7.—Drawing showing PSL No. 1 and 2, the support buildings, and PSL No. 3 and 4, 1985 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH)



Figure 8.—General Electric J73 turbojet installed in PSL No. 1, 1952 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 9.—Exterior of PSL No. 1 and 2 and a primary cooler, 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 10.—One of two 10-ft-diameter altitude test chambers in the Four Burner Area, 1956 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 11.—General Electric TG–190 [or J47] being readied in the test section of the AWT, 1948 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 12.—A 20"-diameter ramjet is test flown beneath the NACA Lewis B–29 aircraft, 1948 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 13.—Centaur second-stage rocket, which employed two RL–10 engines, in the General Dynamics factory, 1962 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 14.—Chart outlining the PSL validation of computer-simulated concepts such as digital engine controls (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 15.—PSL No. 1 and 2 shortly after its construction, 1952 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 16.—Construction of the PSL No. 1 and 2 primary cooler supports, 1950 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 17.—Installation of the primary coolers at PSL No. 1 and 2, 1951 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 18.—Pieces of PSL No. 1 and 2's test chamber as they arrive at the construction site, 1951 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 19.—Construction of PSL's Equipment Building, 1950 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 20.—Pebble bed heater nozzle in the PSL No. 2 test chamber, 1958 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).

GLENN RESEARCH CENTER, PROPULSION SYSTEMS LABORATORY NO. 1 AND 2 HAER OH-136 Page 71



Figure 21.—Marquardt ramjet for the Bomarc missile in PSL No. 2, 1954 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 22.—Technicians install a General Electric J–73 in PSL No. 1, 1952 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 23.—Researchers examine an Iroquois PS.13 turbojet in PSL No. 1, 1957 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).


Figure 24.—Installation of a hydrogen peroxide rocket engine in PSL No. 1, 1960 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 25.—Pratt & Whitney RL–10 rocket engine in PSL No. 2, 1961 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 26.—Apollo engine for storable propellant test in PSL No. 2, 1964 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 27.—Solid rocket test setup in PSL No. 2, 1965 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 28.—ATF3 SN 16 engine in the PSL for analysis for the Compass Cope program, 1973 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 29.—Technicians work on an F100 engine in the PSL, 1978 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 30.—Chart outlining the PSL validation of computer-simulated concepts such as digital engine controls, 1983 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 31.—Combustion air and exhaust system panel for PSL No. 2 in the control room, 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).







Figure 33.—Cutaway of the second floor of the Shop and Access Building where the technical staff spent most of its time. The test chambers, control room, and tool crib were located in the area (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 34.—Closed main hatch on PSL No. 1 (viewed from the northwest), 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 35.—Diagram highlighting the various sections and components of each of the two PSL test chambers, 1954 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 36.—Overhead view of PSL test chamber, 1956 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 37.—Interior of PSL No. 1 inlet section. The airflow entered from the right, 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 38.—Hatch open to PSL No. 1 inlet section, 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 39A and 39B.—Inlet section with air flowing left to right into large nozzle (view down the exhaust section with the diffuser in the background), 1954 and 1953 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 40.—PSL No. 1. The air entered from the right and exited to the left. The overhead crane, open test section hatch, and open inlet section hatch are visible, 1952 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 41.—Rocket nozzle test setup in PSL No. 1, 1964 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 42.—Side of PSL No. 2 (viewed from the northwest). The inlet section is in the foreground, 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 43.—PSL No. 1 panels in the control room, 1957 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 44.—PSL No. 2 controls in the control as they appeared in 1956 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 45.—PSL No. 1 control panel and camera (on stand) used to record manometer readings, 1957 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 46.—PSL No. 2 control panels during the RL–10 engine tests, 1961 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 47.—PSL No. 1 control panels in 1973 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 48.—PSL No. 2 control panels in the control room after years of neglect, 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 49.—PSL No. 1 control panels after much of the equipment had been cannibalized, 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 50.—Installation of the Wright 48"-diameter ramjet (viewed through the bellmouth cowl). The mechanic in the background has crawled through the cross-shaped temperature rake to work on the flameholder, 1952 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 51.—Instrumentation used to record data on the TF-10 engine in the PSL, 1968 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 52.—Large compressors that supplied high-speed air to the two altitude chambers, 1954 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 53.—PSL compressors in the foreground as they appeared in 1971 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 54.—Combustion air line elevation, 2007 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 55.—Aerial view of PSL No. 1 and 2 showing the combustion air line exiting the vertical heating equipment in the top right corner and splitting into two separate lines as it traveled to the ground level. Then each line traveled up one side of the Shop and Access Building (foreground) and entered the building on the second floor, 1955 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 56.—Shop and Access Building (viewed from the north) with the two combustion air lines wrapping around the northeast and southeast sides of the building and entering on the northwest, 1953 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 57.—PSL's three combustion air heaters (to the right), 1955 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 58.—Construction of an air dryer and its reactivation tank inside the Equipment Building. The desiccant dryer could move 40-psi air at 230 lb/s, 1955 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 59.—Fourth line of exhausters that were added in 1955. The Equipment Building was expanded southward to accommodate the new equipment, 1955 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 60.—Row of Roots-Connersville exhausters in the Equipment Building, 1956 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 61.—Magnaflux Machine employee inspecting No. 42 Roots-Connersville exhauster impeller, 1956 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 62.—Exhausters in the Equipment Building with the floor panel removed, 1992 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 63.—Exhausters in the Equipment Building (viewed from the north), 1992 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 64.—PSL No. 1 and 2 diagram that indicates airflow from the test chambers through the cooling system and into the exhausters, 2009 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 65.—Pair of primary coolers (right), large exhaust pipe (center), and secondary cooler (lower left)—viewed from the east, 2006(NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 66.—PSL No. 1 primary cooler (viewed from the south), 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 67.—Entrance to a primary cooler as seen from the test chamber exhaust section, 1959 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 68.—Atmospheric air vent that sat on steel piers between the two primary coolers and was used to expel some of the hot exhaust gas, 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 69.—PSL's secondary cooler, 1952 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 70.—Equipment Building construction (viewed from the south). The brick chimney on the southwest side was used to vent the air from the exhauster equipment inside, 1951 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 71.—PSL cooling tower and pump house (set back in the trees near the center of the photograph) and the PSL No. 1 and 2 facility (across the road)—aerial view from the northwest, 1957 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 72.—Circulating Water Pump House (lower left) and wooden cooling tower (behind), 1952 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 73.—Roof of the PSL cooling tower showing the fans that exhausted the steam heat into the atmosphere, 1950 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 74.—Layout of the two PSL facilities with the Central Air Building in the center, 1985 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 75.—PSL Shop and Access Building (viewed from the northeast). The shop is further to the right, the Access Building in the center, and the control room area at the left, 2006 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 76.—Access Building was built in 1952. The combustion air pipes can be seen entering on the second floor, 1955 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 77.—Shop Building (left) added to the Access Building in 1956. It covered up the combustion air pipes, 1957 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 78.—Access Building elevations, 1965 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 79.—Shop Building Elevations, 1965 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 80.—Floor layout of Shop and Access Building, 1962 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 81.—Shop and Access Building (isometric view), 2009 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).






Figure 83.—Underside of one of the PSL chambers (viewed from the first floor of the Access Building), 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 84.—First floor of the Access Building showing the main walkway (foreground) and equipment (behind), 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 85.—Walkway heading southeast underneath the control room. The anteroom in the background led out the rear of the Access Building to the primary cooler area, 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 86.—First floor of the Shop Building (viewed from the west) after it was emptied of all of its equipment. The dark combustion air line can be seen in the background at the center of the photograph, 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 87.—First floor of the Shop Building after it was cleared out (viewed from the north). The 500-lb crane is hanging from a rail at the top center of the photograph, 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 88.—First and second floor layouts of the Shop Building, 2007 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 89.—Second floor of the Access Building with a test chamber in the background, 1964 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 90.—Display for the 1966 Inspection set up on the second floor of the Access Building. PSL No. 1 is on the right, and PSL No. 2 is just out of sight on the left. The control room is blocked by the temporary stage and display, 1966 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 91.—Diagram of the second floor of the Access Building, 1954 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 92.—Second floor plan of the Access Building, 2007 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).

GLENN RESEARCH CENTER, PROPULSION SYSTEMS LABORATORY NO. 1 AND 2 HAER OH-136 Page 116



Figure 93.—Control for the crane and test chamber access hatch, 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 94.—Control for the crane and test chamber access hatch. The entrance to the control room can be seen in the background at the top middle of the photograph, 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 95.—PSL No. 1 and the western half of the second floor of the Access Building (viewed from the Instrumentation Room). The rectangular temporary offices to the right were added after the facility was closed down, 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 96.—PSL No. 2 and the western half of the second floor of the Access Building (viewed from above). The rectangular temporary offices to the left were added after the facility was closed down, 2008(NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 97.—Aerial view of the Access Building. The control room is contained in the small square addition at the rear of the building between the two primary coolers, 1955 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 98.—Layout of PSL No. 1 and 2 control room in 1956 and 1962 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 99.—PSL control room with PSL No. 2 panels (far wall), manometers (to the left), cameras set up to photograph manometers, and control station (middle), 1954 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 100.—Rear of the PSL control room after equipment had been removed, 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 101.—Entrance to the control room (against the far wall between the two test chambers), 1963 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 102.—Control room exit into the main Access Building floor area, 1973 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 103.—Rocket engines on display in the second floor of the Shop Building. The Access Building was to the right, 1966 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 104.—View from above the control room through the Access Building and into the Shop Building (background). The temporary office structures throughout the two rooms were added after the facility ceased operations, 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 105.—Combustion air line as it entered the second floor of the Shop Building. It then connected to the inlet section of PSL No. 1, 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 106.—Inlet section of PSL No. 2 in the Access Building. It connected to the combustion air line on the opposite side of this wall, 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 107.—PSL Equipment Building shortly after its completion (viewed from the south), 1953 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 108.—PSL Equipment Building (viewed from the east). An extension off the southeast wall was added to accommodate additional exhauster equipment, 1955 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 109.—PSL Equipment Building (viewed from the west) with the three air heaters, combustion air line, and exhaust air line, 1956 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 110.—Eastern half of the PSL Equipment Building (viewed from the west) showing the exhauster equipment, 1959 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 111.—Interior of the PSL Equipment Building (viewed from the north). A row of compressors (foreground), the control room (center), and exhausters (background), 1959 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 112.—Layout of the Equipment Building, now known as the Central Air Building, 1956 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 113.—Main floor of the Equipment Building as it appeared in the 1990s (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 114.—Equipment Building control room (viewed from the north), 1971 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 115.—Interior of Equipment Building control room, 1972 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 116.—Basement of PSL Equipment Building, 1955 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 117.—Switchgear panels in the basement of the PSL Equipment Building, 1952 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 118.—Layout of Building 60, formerly the PSL Operations Building, 1956 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 119.—PSL Operations Building (viewed from the east), 1957 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 120.—PSL Operations Building during the final phase of its construction, 1950 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 121.—Foyer in the front entrance of the PSL Operations Building. The library was to the left, and an office wing was ahead, 1967 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 122.—Lewis researchers in an office in the PSL Operations Building, 1957 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 123.—Library room on the first floor of the PSL Operations Building, 1966 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 124.—Corridor leading to library auxiliary room in the basement of the PSL Operations Building, 1967 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 125.—PSL infrastructure in disrepair, 2008 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 126.—Demolition of the Shop and Access Building, 2009 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 127.—Crane ripping apart the PSL No. 1 test chamber, 2009 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 128.—Remnants of the Shop and Access Building, 2009 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 129.—Primary cooler being ripped down, 2009 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 130.—Damaged primary cooler and debris, 2009 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 131.—PSL No. 3 and 4 exterior with the Central Air and Equipment Building behind to the left, 2006 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).



Figure 132.—Test chamber in PSL No. 3 and 4 that has been modified for icing research, 2012 (NASA Glenn Research Center, Propulsion Systems Laboratory No. 1 and 2, Cleveland, Cuyahoga County, OH).