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70 Years of Aeropropulsion Research at NASA Glenn Research Center

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Summary

This report presents a brief overview of air-breathing propulsion research conducted at the NASA Glenn Research Center over the past 70 years. It includes a historical perspective of the Center and its various stages of propulsion research in response to the country's different periods of crises and growth opportunities. Glenn's research and technology development covered a broad spectrum, from a short-term focus on improving the energy efficiency of aircraft engines to advancing the frontier technologies of high-speed aviation in the supersonic and hypersonic speed regimes. This report highlights major research programs, showing their impact on industry and aircraft propulsion, and briefly discusses current research programs and future aeropropulsion technology trends in related areas.

Introduction

Ground was broken for the NASA Glenn Research Center on January 23, 1941, in Cleveland, adjacent to the Municipal Airport (now known as the Cleveland Hopkins International Airport), and the Center's rich heritage in air-breathing propulsion research began as soon as Glenn began operations in 1942 as the National Advisory Committee for Aeronautics (NACA) Aircraft Engine Research Laboratory.¹ This report gives an overview of Glenn's significant contributions in the development of air-breathing propulsion over the last 70 years.

In the 1940s, research that Glenn conducted in support of World War II included the turbocharging of reciprocating engines, which enabled the high-altitude flight of the B-29 Superfortress; the testing of the first U.S. turbojet, which gave Glenn hands-on experience with early jet engines and made

¹The Center's name has changed several times over the last 70 years. The Center began operation in 1942 as the NACA Aircraft Engine Research Laboratory (AERL). In 1947 it was renamed the NACA Flight Propulsion Laboratory to reflect the expansion of the research. In September 1948, following the death of the NACA's Director of Aeronautics, George Lewis, the Center's name was changed to the NACA Lewis Flight Propulsion Laboratory. On October 1, 1958, the Center was incorporated into the new NASA space agency and it was renamed the NASA Lewis Research Center. On March 1, 1999, following John Glenn's flight on the space shuttle, the Center's name was changed to its present name: the NASA Glenn Research Center.

Glenn the Government's expert in jet propulsion; and the addition of the Icing Research Tunnel (IRT) to significantly enhance aviation safety by advancing icing technology. In the next decade, Glenn advanced air-breathing propulsion technology through pioneering research in transonic compressors, cooled turbines, stable afterburning, and the use of closed-cycle Brayton or Rankine conversion systems for space power conversion technology. In the 1960s, technologies were developed for noise and emission reductions—10-dB quieter and 60-percent cleaner—along with unique expertise in wind turbine design for power generation. In the next decade, technologies for high-efficiency turbofan engines were developed under programs such as the Energy Efficient Engine (E3) Program. These technologies enabled designs for the highly efficient General Electric GE90 and Pratt & Whitney PW4000, which are now powering Boeing 777 aircraft. In the 1980s, technology advancement included ultraefficient high-speed turboprops (developed under the Advanced Turboprop Project (ATP)), with the potential to reduce fuel consumption by 35 percent. Subsequently, and continuing until the present time, Glenn has been developing technologies for ultralow noise and emissions and for efficiency for subsonic and supersonic aircraft, including icing technologies for significantly increased aviation safety and efforts to overcome barriers to high-speed propulsion, such as hypersonic air-breathing propulsion applicable for access to space.

Glenn's status as the recognized leader in air-breathing propulsion technology is evidenced by the fact that it has received the prestigious Collier Trophy three different times: in 1946 for the development of a thermal ice protection system, in 1987 for the development of the ATP engine, and in 2009 for contributions to the Commercial Aviation Safety Team. In addition, Glenn researchers have received numerous Research and Development (R&D) 100 Awards and patents in recognition of their significant contributions to the advancement of aerospace propulsion technology. The following paragraphs outline a few highlights of these technology advancements.

Aircraft Engines for World War II

Information in this report about Glenn's aeropropulsion research from World War II through around 1990 (this section through the Emissions section) is based on Dawson (1991). At the start of World War II, the primary engines used for aircraft propulsion were radial reciprocating engines. These rugged engines were known for their reliability and fuel conservation,

and American aircraft engine companies were reluctant to accept radical changes to the existing engine designs. However, Europeans, particularly Germans, had begun to develop jet propulsion engines as early as 1935 that could fly at greater speeds and higher altitudes. To keep up with the European technology, the U.S. Government decided to invest in aeronautical research at a significant level during World War II. By assuming the cost of research and testing, Government engine research reduced the risk of innovation, determining the technical feasibility of an engine design or component before handing the design over to the engine companies for development.

The U.S. Aeronautics Research program was directed by an advisory committee, the NACA, which was established by Congress on March 3, 1915 (Gray, 1948). The NACA consisted of 12 prominent members of the U.S. aeronautical community who had been selected for their expertise in aeronautical science or engineering.

The respect that the NACA's careful financial management and its significant role in the development of aeronautics technology in the 1920s and 1930s had earned among Federal Government funding authorities essentially ensured the organization's survival through budget fluctuations.

The credit for the NACA's reputation belongs to George William Lewis (1882 to 1948), who served as the Director of Aeronautical Research from 1923 to 1947. Under Lewis' direction in the 1920s and 1930s, the NACA made significant contributions to aeronautics. Some of the notable accomplishments include the development of the NACA cowling to reduce drag and allow engines to cool more efficiently, retractable landing gear, and studies of the effects of streamlining.

However, by the late 1930s, the NACA seemed to be lagging behind Europe in aircraft technology development. A special committee on aeronautical research facilities concluded that the United States needed better aircraft engines and strongly recommended that an engine research laboratory be built in a location accessible to the engine companies. The laboratory was to include an altitude wind tunnel (AWT) for the altitude testing of aircraft engines, because only three such facilities existed in the United States at that time, and none of those facilities could test engines at the high flight altitudes predicted for the new aircraft. In January 1940, the NACA Power Plants Planning Committee recommended that the research laboratory include (1) an AWT capable of testing at a simulated altitude of 30 000 ft (9.144 km) and a wind tunnel speed of about 805 km/h (500 mph) and (2) a propeller research laboratory. Both proposals were accepted. The added capability would enable a full-scale test of the engine, supercharger, and propeller—separately and as a unit—which could eliminate months of flight testing.

During congressional appropriation testimonies in early 1940, NACA officials described the role of the proposed new research laboratory. They responded to engine companies' concerns that

large amounts of funding would go to the new Government laboratory instead of their own research by stressing that the Government would not compete with private industry. The NACA further clarified that the charter of a Government research laboratory was to address fundamental research problems common to the entire industry and to ensure that the information was available to all companies in a given field. The NACA emphasized that competition within the industry prevented an exchange of information, because each company had to work independently to solve problems of common interest, resulting in an unnecessary duplication of research effort. If the engine companies were funded directly by the Government, they would focus their research on short-term development problems and would neglect fundamental problems.

In June 1940, Congress approved the funding for the proposed new research laboratory (NASA Glenn) as part of the First National Defense Appropriations Act, and the NACA formed a blue ribbon committee to select a site for the laboratory. The criteria for the new laboratory included the need for 0.405 km² (100 acres) of land adjacent to an airport to accommodate flight testing as well as ample water for cooling and adequate power for the large wind tunnel. In addition, the site would need to be accessible to engine companies throughout the country. In July 1940, the Cleveland Chamber of Commerce submitted a formal bid. In spite of stiff competition from 72 sites in 62 cities, Cleveland was selected on November 25, 1940, after negotiations with the electric company resulted in favorable power rates and logistics issues were resolved.

On January 23, 1941, ground was broken (Fig. 1). Almost a year later (on Dec. 31, 1941), a contract was signed for the construction of the Engine Research Building. The building was to contain numerous research laboratories to provide a broad range of research capabilities that could advance



Figure 1.—Groundbreaking for the NASA Glenn Research Center (Dawson, 1991).

U.S. aircraft engine technology to the level of European engines. The planned facilities included multicylinder and single-cylinder test facilities, supercharger rigs, and laboratories for research on exhaust turbines, heat transfer, carburation, fuel injection, ignition, automatic controls, and materials. Research was officially initiated in May 1942, in the recently completed Engine Propeller Research Building, while construction continued on other Glenn buildings.

During World War II, as the country's aircraft engine needs intensified, fundamental research assumed a lower priority than troubleshooting to solve the problems of engines in production. General Henry Harley "Hap" Arnold, Chief of the U.S. Army Air Forces, pushed the NACA to work on solutions, after concluding that the engine companies were responsible for the inferior status of the engine technology and that they lacked the ability to advance the technology to solve the problems. On October 14, 1942, Arnold issued an official directive for the NACA to concentrate on improving existing air-cooled piston engines to assist in winning the war.

Prior to Glenn's construction, researchers at the NACA Langley Research Center had considered engine research to be inferior to aerodynamics research (conducted in wind tunnels), because they believed that advances in air transportation had more to do with aerodynamics than with power plants. However, combustion research by NACA researcher Cearcy Miller led to a method of predicting exactly when an engine would begin to knock—a problem common to all air-cooled radial engines. Miller's success served as an example of how the NACA could carry out fundamental research to address a common problem and put this knowledge in the hands of the industry designers. The NACA also addressed several other fundamental problems, such as the use of fuel additives to increase the performance of combat aircraft, the erosion of engine cylinders because of sand ingestion, and the oil foaming responsible for oil draining during flight—demonstrating the value of fundamental precompetitive research by a Government laboratory.

Glenn research on the exhaust gas turbine, or turbosupercharger, was crucial to enhancing the horsepower of an aircraft engine. Adding turbosuperchargers to reciprocating engines enabled the high-speed, high-altitude flights of the B-17 Flying Fortress and the B-29 Superfortress (Fig. 2). The NACA considered knowledge to be the end product of a research laboratory: research reports were emphasized, and Glenn had high editorial standards that mirrored those of the Langley Editorial Office. A great deal of attention was given to ensure that the reports were accurate and well organized. If these guidelines had not been followed, the innovations proposed by the researchers after laborious testing might never have been reported.



Figure 2.—B-29 Superfortress.

Gas Turbine and Jet Propulsion Research

The gas turbine and jet propulsion concept for aircraft was pioneered in Great Britain and Germany simultaneously in the 1920s and 1930s and led to the emergence during World War II of a military jet that revolutionized aerial warfare. Sir Frank Whittle, a British Royal Air Force Officer, obtained the first gas turbine/jet propulsion patent in 1930 and later built the first complete engine that ran on a test stand in 1937. In Germany, Hans von Ohain, a scientist from Gottingen University, patented an aeronautical gas turbine engine in November 1935. Collaborating with aircraft manufacturer Heinkel Company, von Ohain built an engine and flew it on an He178 aircraft on August, 27, 1939. It was the world's first gas-turbine-powered, jet-propelled airplane to fly (Kinney, 2003).

Official American involvement in the development of aeronautical gas turbine engines seemed to be reactionary rather than following the success of the Germans and the British in this area. Chief of the Air Corps, General H. H. Arnold asked the NACA to investigate the feasibility of jet propulsion in 1941, resulting in the creation of a Special Committee on Jet Propulsion headed by William R. Durand. The committee included members from the NACA, naval air, and other military organizations, the Bureau of Standards, leading engineering universities, and industry—represented only by manufacturers of industrial and marine turbines: Westinghouse, Allis-Chalmers, and General Electric (GE, Schenectady) (Kinney, 2003).

Three positive factors of flying a gas turbine compensated for the low efficiency of ground-based industrial turbines and compressors: (1) the low temperatures at high altitudes actually made the engine more efficient, (2) the forward speed of the aircraft created a ram effect that increased the efficiency

of the compressor, and (3) only a portion of the energy released into the turbine was needed to drive the compressor—the rest was used for propulsive thrust. Although the turbojet revolutionized aircraft propulsion, it was not a radical technology break from the reciprocating engine. The technology of the supercharger, which is essentially a compressor, was being used to augment the performance of the reciprocating engine. Because a compressor is an essential part of the turbojet engine, the supercharger technology provided continuity between the old technology and the new. Both Whittle and von Ohain chose centrifugal compressors for their turbojet engines because the centrifugal supercharger was in common use in reciprocating engines. However, it was believed that axial compressors would eventually be used for turbojet engines for better performance and higher power.

A Special Compressor-Turbine Panel was set up by the Durand committee to investigate the potential of the compressor-turbine combination. The panel considered an axial-flow compressor because of its smaller frontal area and higher potential pressure ratio. However, axial compressors that were lighter and more compact had complex aerodynamics across the blades of several stages that presented a challenge to designers and required better understanding of the underlying aerodynamics. In addition, fabrication of the complicated compressor proved to be very difficult, because the compressor blades needed to withstand vibrations to prevent them from breaking and flying off.

The Durand committee recommended that the Government contract with three companies—Westinghouse, Allis-Chalmers, and the GE Turbine Group at Schenectady—to develop aircraft gas turbine engines. The three companies submitted designs for engines that resembled what would become the standard configuration for aeronautical gas turbines: a rotary compressor driven by a turbine wheel with axial rather than centrifugal compressors. Working with the Navy, Westinghouse submitted the design for a turbojet engine called the 19A, which became the only American engine (of the three mentioned) that flew during the war (in 1942). Allis-Chalmers, also working with the Navy, designed a turbine-driven ducted fan, but the work suffered from a slow development program. The GE Turbine Group at Schenectady cooperated with the army to design a turboprop engine—the TG-100 (Kinney, 2003).

The most well-known U.S. aeronautical gas turbine program resulted when the British Royal Air Force helped the U.S. Army import Whittle's design. The British government provided the drawings of the improved Whittle engine, W2B, as well as an actual engine and the plans for the original model, to the GE factory in Lynn in October 1941. GE was chosen for its expertise in turbine and turbosupercharger technology to develop the U.S. military's first jet engine, the I-A. A few other gas turbine development projects, in addition to the ones mentioned here, resulted in multiple engines. By late 1942, the American gas turbine program had a total of eight engines,

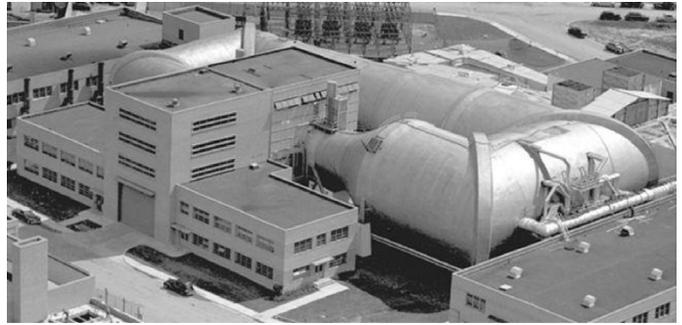


Figure 3.—Altitude wind tunnel.

which included the imported Whittle turbojet and seven U.S.-designed engines (Kinney, 2003). The first turbojet engine, the GE 1-A, was brought to Glenn in late 1943. American researchers were armed with valuable pieces of British technology from the W2B and W1X plans as well as the actual W1X engine. In September 1943, construction of Glenn's Static Test Laboratory was completed to test the GE 1-A turbojet engine.

As the work on jet propulsion continued, Glenn researchers built and tested the first afterburner in October 1943, in Glenn's Propulsion Static Test Laboratory. They continued to gain hands-on research experience by testing the new GE and Westinghouse jet propulsion units in Glenn's AWT (Fig. 3). Glenn research staff built on this experience to become the Government's experts in jet propulsion in the early postwar period.

Supersonics, Rockets, and Nuclear Propulsion

The German V-2 rocket had flown at supersonic speeds in 1944; therefore, supersonic aerodynamics could no longer be viewed as visionary. At the time, it was considered part of the NACA's responsibility to advance the technology needed to make supersonic flight practical. Reports of European advances in supersonics prompted NACA leadership to set up an interlaboratory high-speed panel to coordinate new research in this area. The U.S. Army Air Forces also had ambitious plans for a large-scale engineering development center and supersonic wind tunnels. Because postwar resources were too scarce to meet the demands of both the NACA and the U.S. Army Air Forces, Congress enacted legislation to establish the National Unitary Wind Tunnels Plan (on Oct. 27, 1949). According to the plan, the NACA would build supersonic tunnels at each of its three centers, but the Air Force's Arnold Engineering Center in Tullahoma, Tennessee, would still receive a large portion of the appropriations.

Under the Unitary Wind Tunnels Plan, the 10- by 10-Foot Supersonic Wind Tunnel (10×10)² was built in 1955 at Glenn.

²3.05 by 3.05 m.

The tunnel could operate at speeds between Mach 2.0 and 3.5 (2124 to 3719 km/h; 1320 to 2311 mph) at altitudes of 50 000 to 150 000 ft (15 240 to 45 720 m). Another supersonic tunnel, the 8- by 6-Foot Supersonic Wind Tunnel (8×6),³ could operate at speeds between Mach 0.55 and 2.1, with an altitude range from sea level to 40 000 ft (12 192 m). The 8×6 had been built in 1949 to study propulsion systems, including inlets, exit nozzles, combustion fuel injectors, flame holders, and controls on ramjet and turbojet engines. In the 1960s, a second (9- by 15-ft (2.7- by 4.6-m)) subsonic test section was added to the return leg of the 8×6 for testing scale models of propulsion systems for vertical and short takeoff and landing aircraft. Glenn research in supersonics had begun as early as the summer of 1945 in two wind tunnels, an 18- by 18-in. (45.7- by 45.7-cm) tunnel and a 20-in.- (50.8-cm-) diameter round tunnel, capable of speeds up to Mach 2. Using these facilities and following the theoretical work by the British and Germans, Glenn’s researchers were able to make significant advancements, including the discovery of shock waves during wind tunnel experiments, which led to productive supersonics research accomplishments for many years to come.

In the 1930s, the Cleveland Rocket Society had a small group of amateur rocket enthusiasts, but membership declined drastically in the early 1940s. The flight of the V-2 across the English channel in the summer of 1944 renewed interest in rockets at Glenn. In 1944, after the U.S. Navy’s request that jet propulsion for aircraft and missiles be given priority to meet the military’s needs, Glenn researchers were eager to pursue rocket research. Around the same time, the NACA was authorized to build a complex of four rocket test cells at Glenn. In an effort to keep pace with the technology development following the V-2 flight, in June 1945, Glenn submitted a proposal to conduct research on turbojets, ramjets, and rockets for guided missile powerplants. Initially, Glenn’s rocket program had to be proposed as high-pressure combustion research, because rocket research was believed to be outside of the NACA’s mandate of aircraft improvement. With minimal support for personnel, the group focused on high-energy liquid propellants, combustion, and rocket cooling to evaluate the performance of these propellants both theoretically and experimentally. In spite of underfunding and understaffing, the rocket group slowly built a technical competence that would lead to future achievements in liquid propulsion, and ultimately, to a major role for Glenn in the human exploration of space.

The initiative for nuclear propulsion also came from within Glenn—for a nuclear power plant for aircraft to enable long-range flights without refueling. Following the end of World War II, Glenn personnel who wanted to work with the laboratory at Los Alamos were told to wait until Congress had set up the Atomic Energy Commission. In May 1946, when the U.S. Army Air Forces initiated the Nuclear Energy

Propulsion for Aircraft project, the NACA was placed on a board of consultants for the project along with nine companies and the Navy.

Glenn proposed a basic high-temperature research program in heat transfer and materials to support a gas-cooled nuclear reactor design. In recognition of the expertise of Glenn staff in analytical and experimental heat-transfer studies, the Atomic Energy Commission and the NACA made a formal agreement on a joint research program on July 15, 1948, and a number of Glenn personnel were sent to Oak Ridge National Laboratory for training. Glenn’s long commitment to nuclear propulsion continued until the termination of the nuclear effort in 1972.

Emphasis on Fundamental Research

The transition from the piston engine to jet propulsion at Glenn happened in a relatively short time, and this transition was liberating to leaders who had worked for years at Langley. Most of the work carried out at Glenn during World War II was developmental in nature, and it came largely at the expense of fundamental research. It was hoped that after the war, the emphasis would return to the fundamental research that was characteristic of the NACA before World War II. In December 1945, Glenn sent a list of research topics, the Survey of Fundamental Problems Requiring Research, to the NACA’s Washington office (Headquarters), reflecting a desire to return to fundamental research. Glenn hoped to expand the scope of its research to further advance emerging jet propulsion technologies, such as turbojets, ramjets, rockets, and possibly aircraft nuclear propulsion. Table I shows the nine engine types in the December 1945 plan, along with the percentage of effort for each. The list was later revised to replace specific engine types with more general topics, such as compressor, turbine, combustion, fuels, materials, supersonics, and nuclear, because of criticism by the engine companies that the proposed research was not quite fundamental.

TABLE I.—RESEARCH IN DECEMBER 1945 PLAN

Engine type to be researched	Planned effort, percent
Turbojet engines	20.0
Turbopropeller engines	20.0
Continuous ramjet engines	12.5
Intermittent ramjet engines	5.5
Rocket engines	4.0
Reciprocating engines	13.0
Compound engines ^a	15.0
Icing	5.0
Engines for supersonic flight	5.0

^aReciprocating engine plus turbosupercharger.

Even with a well-defined research portfolio, Glenn had to balance its efforts in the early postwar period between addressing the industry’s immediate development problems and generating long-term scientific and engineering knowledge to serve national interests. Between the two world

³2.44 by 1.84 m.

wars, the airframe industry had benefited from and relied on NACA innovations, such as the discovery, through testing in the NACA wind tunnels, that a change in the configuration of a wing, tail, or propeller could dramatically improve aircraft performance without affecting the overall design of the aircraft significantly. In an engine, however, even a small change in a component would usually affect the entire system because of the strong interrelationship among and complexity of the engine's components, and it was not certain that Glenn would ever enjoy the same favorable relationship with engine companies that the NACA had enjoyed with airframe designers. There was intense rivalry among the engine companies at the time, and Glenn had to ensure that its research would be available to the entire industry without benefiting any company more than another.

The turbojet was not considered to be a mature technology around the end of World War II, and it was not clear that it would be suitable for the commercial market. The technology seemed suitable for fighter aircraft, where speed was more important than other issues, such as fuel consumption and life. However, it was not clear how it would benefit commercial applications during peacetime. Many design issues remained, such as axial versus centrifugal compressor, problems of high temperatures for combustor and turbine design, and whether new material development or turbine cooling technology advancement needed to be pursued. As a concept, the gas turbine seemed simpler than the piston engine, but the complex physical processes involved in passing air through a compressor, combustor, and turbine required a much more in-depth theoretical understanding of flow physics than had been necessary during World War II.

In May 1945, the first American conference on gas turbine engineering, sponsored jointly by GE and the U.S. Army Air Forces, was held in Swampscott, Massachusetts. Nearly 200 members of the aeronautical community, including representatives from Great Britain, attended. Abe Silverstein, Chief of Glenn's Wind Tunnels and Flight Division, presented a paper about the NACA's contributions, including the test program in the AWT that helped GE to transform its prototype I-16 into the more reliable I-40. By the end of World War II, the I-40 had proved to be superior to the Rolls Royce engines based on Whittle's design. Silverstein evaluated and compared the performance of five different gas turbine engines: two with centrifugal compressors, the GE I-16 and I-40, and three with axial compressors, including the Westinghouse 19-B and 19-XB.

Ben Pinkel, Chief of the Fuels and Thermodynamics Division, led Glenn's work to evaluate the weight, altitude, range, and fuel consumption of different types of propulsion systems. Members of his division presented the results at the Second Annual Flight Propulsion Meeting of the Institute for Aeronautical Sciences held in Cleveland in March 1947. The group had evaluated six engines—the compound engine (piston engine with turbosupercharger), the turbine-propeller

engine, the turbojet engine, the turboramjet engine, the ramjet engine, and the rocket engine—by weighing different parameters, such as thrust versus engine weight, frontal area, rate of fuel consumption, speed, and altitude to assess the advantages and disadvantages of each system. The analysis distinguished Glenn as the only U.S. institution that had a basic understanding of the entire aircraft propulsion picture, and it provided engine companies with the necessary basis for creating a realistic technology plan for developing different engine types.

Emphasis on fundamental research led to Glenn's reorganization in 1945, which was also consistent with the National Aeronautical Research policy that was approved in March 1946. The resulting management structure remained unchanged until the NACA became NASA in 1958. Much of the research scope for Glenn through the 1950s followed the framework set by NASA (in 1945). As the superiority of the turbojet over the turboprop and compound engine was demonstrated, further advancement of turbojet technology demanded the development of alloys, ceramics, and metal compounds that could withstand the high temperatures of gases. The resulting advancement of materials technology and early research in high-energy liquid propellants for rockets would lead to a prominent role for Glenn in rocket propulsion, including the success of the Centaur rocket. Research work on the supersonic ramjet led to stimulating basic research in aerodynamics and heat transfer, which was a key to the success of the Navaho, Bomarc, and T series of missiles for the Navy. Glenn's nuclear propulsion initiative, though never considered to be a viable project, had inspired basic research in materials.

Although the NACA had a good reputation for technical talent, it had few employees with advanced training in science and engineering. After World War II, the NACA's relatively low civil servant salaries made it difficult to convince candidates with advanced degrees in science and engineering to choose Government employment over more lucrative offers from the industry, where their qualifications were in great demand. Between 1945 and 1958, the NACA and many national laboratories began to lose staff to universities and industry. Despite support from the Industry Consulting Committee for legislative change, it was not until in 1956 that Congress passed laws enabling the NACA to offer competitive compensation.

Glenn's contributions in basic research continued as it began to study solid and air-cooled turbine blades. Ernst Eckert, a well-known scientist who specialized in heat transfer and had worked in Germany during World War II, was brought to Glenn from Wright Field in 1949 and led the turbine cooling work. He understood the limitations of existing methods of internal air cooling and, on the basis of his experience in Germany, encouraged Glenn to consider other potentially more effective approaches like transpiration, film, and natural convection liquid cooling. Together with members

of Glenn's Turbine Cooling Branch, Eckert developed the theory of these cooling methods by analysis and advanced their development by experiments. Film cooling, now widely used in aircraft engine turbines, particularly attracted him, and he advocated further basic research for this method. While at Glenn, Eckert developed theories for transpiration cooling and natural convection liquid cooling, and he initiated experiments for applying these new theories.

Glenn provided a nurturing environment for outstanding young laboratory theoreticians. In the mid-1950s, researchers Simon Ostrach, Franklin Moore, Harold Mirels, and Steven Maslen were part of the Applied Mechanics Group, which worked on the fundamental research problems of three-dimensional unsteady boundary layer theory (Moore and Ostrach) and acoustic screaming (Mirels and Maslen). By 1987, they had all received the highest professional recognition—membership in the National Academy of Engineering. The theoretical skills of the Applied Mechanics Group were supported by the mechanical skills and creativity of Glenn's support service personnel, who could build a small wind tunnel or a test rig, or modify a computer to validate theoretical models with experimental data. The NACA leadership strongly believed that basic research was the Nation's technical capital. Although they were more comfortable with creativity expressed in tangible products, such as a new compressor, turbine, or afterburner, the principal part of Glenn's mission still remained the full-scale testing of turbojet engines and components.

During basic research advancements, Glenn staff collaborated with several universities, including Case Western Reserve University, Brown University, the University of Minnesota, the University of California at Berkeley, the University of Akron, the University of Pennsylvania, and the University of Rhode Island. Glenn's basic research work with universities complemented very well its technology development collaborations with the aer propulsion industry. These cooperative efforts enabled Glenn to pursue efforts ranging from fundamental research to focused technology development and transfer to the industry. Some of these technologies are being flown today in commercial as well as military applications. Glenn's practice of working with academia, as well as industry, continues to the present day, and Glenn currently maintains a healthy balance between fundamental research and focused technology development by working with universities across the country and with all the aer propulsion companies.

Icing Research—Aviation Safety

Operations research—dealing with the certification of an airplane—was considered to be at the applied end of the research scope. However, even in this area, the NACA made significant contributions to solving general problems that were of interest to the entire aircraft industry.

During World War II, icing research dealt with providing a short-term solution to the icing problems of military aircraft. The development of anti-icing hardware was clearly considered to be development, but a fundamental understanding of the icing cloud was needed to determine how icing develops on aircraft flying under different conditions. In 1944, the NACA began a program to compile statistical data to define icing conditions. By the 1950s, Glenn's guidelines for the design of ice-protection systems had become the basis for the Federal regulations used to certify these systems. As icing research advanced, it became necessary to combine theoretical analyses with experimental studies. The type of ice accretion on an aircraft depends on the size of the supercooled droplets in the icing cloud that strike the aircraft surfaces. Small droplets result in a porous white mass called rime ice. However, larger droplets can accumulate on a surface until enough heat is dissipated to freeze the water into a clear hard mass called glaze ice.

In 1942, while the AWT was being built, Glenn proposed to build an IRT to help researchers understand ice accretion phenomena. The IRT would take advantage of the extensive sophisticated refrigeration system needed for the AWT. The IRT was completed in the spring of 1944 (Fig. 4). As Glenn staff tried to simulate the atmospheric conditions of an icing cloud, they realized that this was a very difficult engineering problem. They had no design experience for creating icing conditions in a wind tunnel, and therefore they used logic, theory, and speculation. It was not until the tunnel's spray system was replaced in the early 1950s that the tunnel tests



Figure 4.—Glenn's Icing Research Tunnel.

could yield icing data as accurate and reliable as flight research data. The research and technology advancement in the icing tunnel earned Glenn and the NASA-industry team the prestigious Collier Trophy in 1946 from the National Aeronautic Association for an outstanding contribution in the development of thermal ice-protection systems.

Glenn's icing research contributed to better understanding of the icing phenomena through the development of instruments to determine the mean size and distribution of water droplets, instruments to determine liquid water content in the icing cloud, complex analysis of the supercooled water droplet trajectories, and analysis of the accretion mechanism by which droplets strike the aircraft surfaces and freeze. With their enhanced understanding of the natural icing cloud phenomena, the icing tunnel engineering staff set about the redesign of the spray system. In the early 1950s, the advent of high-speed, high-altitude turbojet aircraft brought new requirements for thermal anti-icing systems, which had required large amounts of hot air to be bled from the engine, severely impacting engine performance. Glenn researchers were able to attain a new level of sophistication in the heat transfer and aerodynamics required for the study of thermal cyclic deicing systems. In 2009, Glenn received the prestigious Collier Trophy (as a member of the Commercial Aviation Safety Team) for technology advancements that had improved aviation safety, and icing research continues to be a strong technical competency at the Center.

Compressor Research

Glenn's Compressor and Turbine Division conducted research on both centrifugal and axial compressors. Early on, expertise in centrifugal compressors had been established by Stanitz (1948). However, the compressor researchers always had an interest in axial compressors. The axial compressor was considered a better choice for aircraft gas turbine engines because of its smaller frontal area, more compact dimensions, and lighter weight. However, the complex aerodynamics across the blades of several stages presented serious technical challenges to designers, who needed a better understanding of the underlying key flow physics to design axial-flow compressors with smooth flow across the blade rows with minimal losses. Research was initiated in 1944, with work on an eight-stage axial compressor designed by Eastman Jacobs and Eugene Wasielewski forming the basis for compressor research at Glenn and leading to many accomplishments in this area. The isolated airfoil theory used in the design of the Jacobs-Wasielewski compressor was adopted as the accepted standard approach by American compressor designers until the mid-1950s (Nichelson, 1988). Later, Wu and Wolfenstein (1949) developed a radial equilibrium theory for compressible flow across stages of an infinite number of blades to overcome the limitations of the isolated airfoil theory.

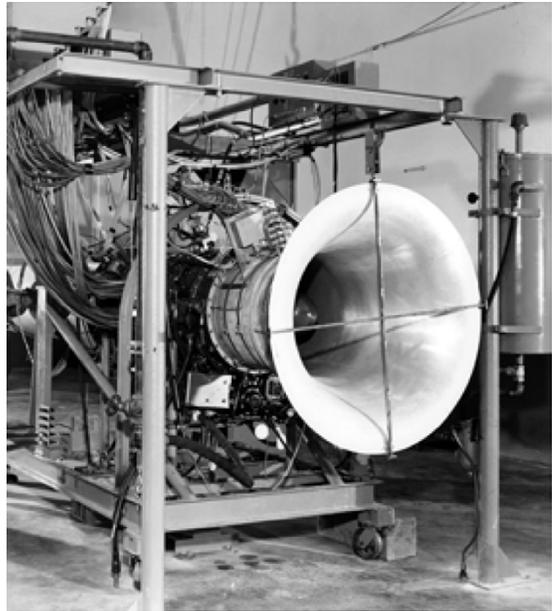


Figure 5.—Testing of transonic compressors.

In 1952, researchers in Glenn's Compressor and Turbine Division began to develop a transonic compressor. Robert Bullock and his team proposed a flow model developed to estimate losses caused by shocks in supersonic parts of the airflow through the transonic compressor. Seymour Lieblein developed a parameter called the diffusion factor D to represent the level of blade loading in a compressor. This factor is now universally accepted and used in the design guidelines. Ten years of research in single-stage and multi-stage compressors led to the development of an eight-stage axial transonic compressor test bed that was used extensively by in-house researchers (Lieblein, 1960). As the compressor research continued, Glenn staff designed and built a number of test rigs to test single-stage and multistage compressor configurations to provide essential data for industry engine designers, as well as to validate the analytical theories proposed by researchers (Fig. 5). NACA reports published with these data were used extensively by the engine community and referred to as the Compressor Bible. The Compressor Division prepared a manual summarizing compressor research and published it as a three-volume NACA Confidential Research Memorandum in 1956 (edited by Johnsen and Bullock). A declassified edition was published later (Members of the Staff of Lewis Research Center, 1965).

The unique engine test facilities developed by the NACA, and the associated research at Glenn, played a key role in securing U.S. dominance in aircraft engines. The American turbojet industry benefited and matured from this technology advancement, and market forces gradually narrowed the field to two companies: Pratt & Whitney and GE. During the Cold War, the United States was allowed continued access to

British engine technology. In turn, Glenn shared its research experience in British engine technology with Pratt & Whitney and GE. As the United States started to strengthen its military power, American engine companies received large defense contracts. This enabled the military services and industry to develop new facilities that were comparable or superior to those at Glenn, resulting in the marked decline of Glenn's influence in the 1950s. It was time to reassess Glenn's future role in the Nation's propulsion research.

Space Propulsion

In July 1955, President Eisenhower announced the United States' plans to launch the first Earth-orbiting satellite as America's part in the International Geophysical Year. Glenn would be involved in propulsion problems related to space exploration. Late in 1956, Glenn Research Chief, Silverstein, decided to shift the focus away from turbojet engine research to rocket propulsion and began to consider a major reorganization. In September 1957, Silverstein proposed that rocket research be expanded and that turbojet engine research be reduced proportionately. The launch of Sputnik by the Soviet Union in October 1957 led to President Eisenhower's decision to form a space agency around the NACA in March 1958. The official formation of NASA occurred on October 1, 1958. Glenn became involved in developing high-performance upper-stage rocket engines (including the Centaur upper stage) that used a combination of liquid hydrogen and liquid oxygen fuel. Work continued into the Apollo Program after President John F. Kennedy announced, in May 1961, that the United States planned to land an American on the Moon before the end of the decade.

Aircraft Engine Noise Reduction

The emphasis on rocket research had shifted Glenn's focus away from air-breathing engines for almost a decade. In 1966, NASA and Glenn began to return their focus to aeronautical research. Several new aeronautics projects were initiated, but the majority of Glenn's research efforts remained space related. Air travel had grown at a very rapid pace, and airports had become more congested. Environmental issues, such as noise and pollution-causing emissions, needed to be addressed. New aeronautics projects included the development of quieter engines and of aircraft that could take off and land on short runways to relieve airport congestion. Glenn also took part in planning the technology development for the supersonic transport (SST) airplane initiative proposed in response to British and French plans to develop a supersonic cruise aircraft: the Concorde. However, after 9 years without wind tunnel testing, Glenn's facilities were no longer unique. The U.S. Air Force and aircraft engine industry facilities that had been developed in the postwar period were comparable or

superior to those at Glenn. For example, the wind tunnels at the Air Force Arnold Engineering Development Center in Tullahoma, Tennessee, had capabilities similar to those of Glenn's major wind tunnels, such as the 10×10.

Silverstein retired as Glenn's director in 1969 after serving for 8 years, and Bruce Lundin became Glenn's director. After the successful Apollo Program and Glenn's successful participation in the Centaur and Agena upper-stage-rocket development programs, support for NASA's human space programs started declining because of budget pressures from the Vietnam War and President Johnson's War on Poverty. Because the prospect for healthy human space programs did not look very promising, Lundin directed more Glenn work toward aeronautics. The Quiet Engine Program effort that had begun under Silverstein had progressed to a full-scale engine demonstration in collaboration with the Federal Aviation Administration (FAA) and the Department of Transportation. The goal was to develop engine-noise-reduction technologies for a 22 000-lb (9979-kg) thrust engine that would demonstrate a noise reduction of 15 to 20 dB in comparison with the current commercial transport jets (Fig. 6).

Glenn's engine noise suppression research had begun in 1957, but the early collaborations with industry had never reached the level of an engine demonstration. Air-breathing gas turbine engine technology had rapidly advanced after World War II, and by the late 1960s, the engine companies had introduced the turbofan engine, which was more efficient than the turbojet engine. In a turbofan engine, only a small portion of the air producing thrust passes through the compressor and the core. Most of the thrust comes from air that passes through the fan and bypasses the core. GE was awarded a \$20 million Government contract to design and build three different fans and integrate them with an engine



Figure 6.—Engine noise reduction testing.

core to demonstrate noise reduction. Glenn assumed leadership of the test program to measure fan noise through a contractual relationship with GE. In another effort to reduce engine noise, Glenn, Pratt & Whitney, Boeing, and Douglas Aircraft entered into a no-fee, cost-sharing contract in 1973 to refine an existing engine and test it at Glenn. Pratt & Whitney designed a single-stage fan to replace the existing two-stage fan in their JT8D engine, and Boeing and Douglas Aircraft developed acoustic liner materials to install in the nacelles that housed the engines.

The renewed emphasis on air-breathing engine research also included technology advancement in the small engines used for helicopters. This led to the establishment of a joint research program in low-speed rotary-wing transportation aviation with the U.S. Army Materiel Command. The program continued for four decades, with NASA and the Army leveraging their resources to advance technologies of mutual interest until 2010, when the Base Realignment and Closure mandated by Congress resulted in a major reorganization of the Army research and technology groups.

Emissions

In the early 1970s, heavy industry near downtown Cleveland produced significant air and water pollution. When industrial waste caught fire on the surface of the Cuyahoga River in 1969, the negative publicity from the national media increased the city's commitment to clean up the air, the river, and nearby Lake Erie. In 1971, as support to address pollution strengthened, Glenn formed an Environmental Research Office to conduct research and advance sensor technology for accurately monitoring trace elements and compounds in Cleveland's atmosphere. The researchers were able to develop neutron activation analysis, which can accurately detect minute amounts of mercury, arsenic, cadmium, and nickel in air samples. This success led to a new project funded by the Environmental Protection Agency (EPA) to study the effect of treated wastes on algae growth in Lake Erie.

In 1972, Glenn staff began a campaign that monitored air samples from eight meteorological stations in and around Cleveland. The data were used to estimate the impact of various factors on pollution levels and to adjust the mitigation strategy as needed. The research in the emissions area and the resulting expertise gained by Glenn staff would become a key competency in reducing emissions from aircraft engines during takeoff and landing to conform to emission standards proposed by the EPA to regulate local air quality in the vicinity of the airports. Later, this became part of the certification requirement.

In 1970, Glenn turned its attention to pollution from automobiles and formed the Automotive Systems Office, also funded through the EPA. It was proposed that the Automotive Systems Office develop a gas-turbine automobile engine

because studies had shown that the Brayton cycle is more fuel efficient and cleaner than the piston engine. Glenn's advancements included a thermal reactor with very high combustion efficiency and advanced materials, such as ceramics, that could operate in a high-temperature, corrosive combustion environment. Technologies aimed at automotive engines continued to advance at Glenn, and in the mid-1970s, staff expanded the research scope by broadening the technology portfolio to include the Stirling engine and electric-powered cars.

Energy Crisis

In the early 1970s, environmental concerns and the country's dependence on fossil fuels were top priorities for the U.S. public. Two senior managers at Glenn, Robert Graham and Robert English, urged Center Director Bruce Lundin to tackle the problems by employing Glenn's unique expertise in thermodynamics, fluid mechanics, heat transfer, materials, chemistry, nuclear physics, plasma physics, and cryogenic physics, which were also relevant to energy conversion. Glenn's expertise in Brayton cycle technology for gas turbine engines, as well as in closed Brayton-cycle technology for space power applications, was believed to be adaptable for ground power generation and mass transportation. Buses and trains running with cleaner and more energy-efficient engines showed great promise for the future. Glenn's staff and management recognized that most of the aer propulsion research and technologies that were being advanced by Glenn would cause significant progress toward more efficient and cleaner ground power generation and mass public transportation.

Lundin, the U.S. Department of Transportation, and the EPA discussed ideas for pursuing research in clean coal burning based on Glenn's experience in using the potassium Rankine system for space power generation. The Rankine system could be used as a topping cycle to extract more energy from coal for power generation. When the Arab oil embargo led to a U.S. energy crisis in 1973, President Nixon asked Dixie Lee Ray of the Atomic Energy Commission to form a task force to define the problems and offer solutions. Prominent Glenn staff members participated in 4 of the 15 panels on the task force: the Energy Conversion Panel, Solar Energy Panel, Fusion Energy Panel, and the Advanced Transportation Systems Panel.

The Solar Energy Panel included wind energy in its investigations because wind is driven by the Sun. Glenn representatives on this panel translated their experience in gas turbine technology into advances in wind turbine technology. At the request of the Secretary of the Interior of Puerto Rico, Cruz Matos, Glenn designed a wind turbine to generate electricity on the island of Culebra. The successful design led to the National Science Foundation authorizing funds in 1973 to construct and operate an experimental 100-kW wind turbine



Figure 7.—Wind turbine at Plum Brook Station.

at Glenn's Plum Brook Station campus, 50 mi (80.5 km) west of Glenn's Lewis Field campus in Cleveland (Fig. 7). The wind turbine generated about 180 000 kW/h/year for an average wind speed of 29 km/h (18 mph) and was upgraded to a capacity of 200 kW of power. In 1974, the National Science Foundation and the Energy Research and Development Administration provided \$1.5 million for Glenn's wind energy technology development. Subsequent funding by the Energy Research and Development Administration and its successor, the Department of Energy, resulted in 13 experimental wind turbines being put in operation between 1975 and 1979. The largest of these, a 3.2-MW Mod-5B wind turbine, is still operating on the island of Oahu in Hawaii.

Aircraft Energy Efficiency

The information in this section and the next section is based on Bowles (2010). In 1975, the Aeronautical and Space Sciences Committee of the U.S. Senate directed NASA to initiate planning exercises to explore new fuel-saving technologies to address aircraft fuel conservation. Aircraft fuel prices had tripled between 1973 and 1975 as a result of the oil embargo. The efforts led to the Aircraft Energy Efficiency (ACEE) program (United States Senate, 1976), which was fully funded by 1976 as a 10-year, \$500 million R&D program. The goal of the program was to reduce the amount of fuel used by the Nation's commercial and military aircraft by

50 percent. Of the six aeronautical projects that made up the ACEE program, Glenn was given responsibility for three dealing with propulsion: the Engine Component Improvement (ECI) project, which was to increase the efficiency of existing engines by making short-term, incremental changes to the components; the E3 project, which was to develop a new engine that would be significantly more efficient than the existing turbine-powered jet engines; and the ATP, which was an intensive effort to replace the turbojet with a much more efficient propeller.

The first of the three propulsion projects, ECI, focused on improving existing turbofan engines by redesigning the engine components that were most prone to wear. It was the least technically challenging of the three projects and aimed for a 5-percent improvement in fuel efficiency. It was expected to return quick results, with new technologies being incorporated into engines within 5 years. Glenn worked with the engine companies, GE and Pratt & Whitney, through two major contracts. In addition, airframe companies and a number of airlines were subcontracted to participate in the project. The two main thrusts of the project were performance improvement and engine diagnostics. The performance improvement technologies included thermal barrier coatings and active clearance control for turbines, improved aerodynamics for the fan and the high-pressure turbine, nacelle drag reduction, and compressor bleed reduction. The engine diagnostics work included evaluating existing data on performance deterioration, as well as developing special ground tests to simulate operating conditions. The ground tests were designed to determine the sources of performance deterioration and to identify components with failure rates that could be improved. The ECI project achieved the projected fuel-reduction technology and helped to maintain the competitive advantage of the U.S. commercial aircraft industry.

As part of the E3 project, Glenn had contracts with GE and Pratt & Whitney to develop new engines to improve fuel efficiency. Both companies were very much interested in working with Glenn—not only because of the financial and technical assistance but because continued innovation would help the companies continue to dominate the world engine market as competition from Japanese and European engine makers increased. NASA provided \$90 million to each company, with the stipulation that each would share in the effort by spending \$10 million of its own money as a cost share. The project's four main goals were to (1) reduce fuel burn by 12 percent, (2) reduce operating costs by 5 percent (in comparison to existing turbine engines), (3) meet FAA noise regulations for areas around airports, and (4) conform to proposed EPA emission standards to regulate local air quality in the vicinity of the airports. It was expected that the new turbofan engine would be ready for commercial use by the late 1980s or early 1990s. Because the propulsive efficiency is maximum when the jet velocity is close to the flight velocity of the vehicle, high-bypass turbofan engines with a large

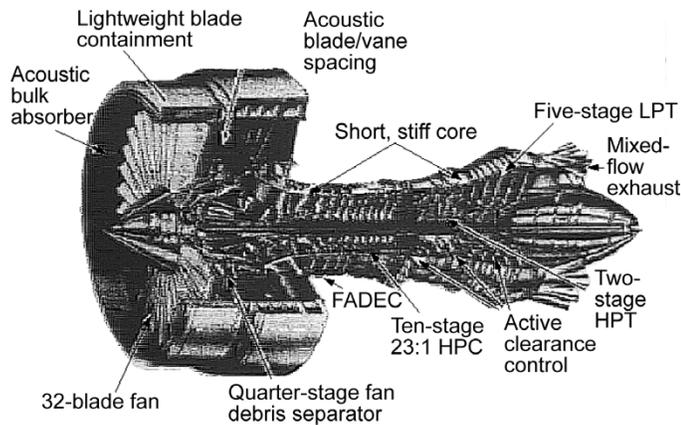


Figure 8.—Energy Efficient Engine (E³) technologies. LPT, low-pressure turbine; FADEC, full authority digital engine control; HPC, high-pressure compressor.

amount of air exiting at lower fan jet velocities would be more efficient than low-bypass turbofans or no-bypass turbojets.

The potential of the high-bypass turbofan engine was the main focus of the E3 project (Kerrebrock, 1982), and both GE and Pratt & Whitney were awarded contracts to design and build a new turbofan. The turbofans were to be used primarily as test beds, not as commercially ready engines. The new engines would need advanced component technologies—compressor, fan, and turbine gas path improvements—as well as structural advances—improved blading and clearance control. Pratt & Whitney and GE used different strategies for the research, with Pratt & Whitney developing individual component technologies and GE integrating the advanced components into an engine. Because of budget reductions, in 1982, NASA had to redirect the E3 project, and GE had its core engine demonstration test without the emission goal. Pratt & Whitney proceeded with its component technology focus. GE successfully met the program goal in 1983 by producing the “world’s most fuel efficient and best-performing turbofan” (Design News, 1983) (Fig. 8). GE incorporated its E3 technology in its engine designs, including the CF6–80E and the GE90 engine. Even though Pratt & Whitney’s component-level strategy technologies advanced at a slower pace, they helped lead to its energy-efficient Geared Turbofan engine in 2007.

The ATP was one of the more radical and risky projects in the ACEE program. The ATP goals were to reduce fuel consumption by 20 to 30 percent in comparison with existing turbofan engines without any performance degradation or passenger discomfort at speeds to Mach 0.8 and altitudes to 30 000 ft (9144 m). Glenn had been working with Hamilton Standard, a division of United Technologies, as early as 1973 on the design for a propfan, a propeller powered by a gas turbine. The potential for reducing fuel consumption had seemed attractive in spite of the disadvantages of turboprops in terms of slower speed, higher noise, and the complexity of gear boxes to drive the propeller. Daniel Mikkelson of Glenn

and Carl Rohrbach of Hamilton Standard came up with the technique of using propeller blade sweep to reduce noise and increase efficiency simultaneously. Initially, only Hamilton Standard was interested, but later other engine companies and airframe companies became interested in the turboprop, which had become more acceptable technically and socially, because it reduced fuel burn and noise. However, in spite of these demonstrated advantages, the airframe companies—Boeing, McDonnell-Douglas, and Lockheed—still had concerns regarding propeller efficiency at cruise speeds, internal and external noise problems, installation aerodynamics, and maintenance costs (Hager and Vrabell, 1988).

There were four technical stages in the ATP: concept development from 1976 to 1978; enabling technology from 1978 to 1980; large-scale integration from 1981 to 1987; and flight research (demonstration) in 1987. During all of these stages, Glenn researchers worked with the aircraft engine industry to identify and solve technical problems in order for the ATP to meet its objectives. Even before the ATP was formalized, Glenn and Hamilton Standard collaborated to build and test an SR–1, a 0.61-m- (2-ft-) diameter single-rotation model propfan. High efficiency rates were demonstrated, providing data that helped lead to the formal award of the project in 1978. The enabling technology phase addressed the four areas that had concerned the airframe companies: modification of propeller aerodynamics for cruise efficiency, cabin and community noise, installation aerodynamics, and drive systems for reducing maintenance cost.

In the late 1970s, computational fluid dynamics (CFD) tools were beginning to be used in designing engine components, and for the first time, CFD tools were used for an aerodynamic propeller design, helping to improve aerodynamic efficiency and reduce noise. Numerous installation options—including the push or pull configuration and the most effective integration of the propeller, nacelle, and the wing—were investigated to determine the most advantageous configuration. Various drive-train problems, including in the gear boxes, were studied to determine the best option to achieve the project goals. The final stage of the project, flight testing, took place in 1987 with a successful flight of the SR–7A propfan (Fig. 9) on a modified Gulfstream II aircraft in Savannah, Georgia. The flight tests demonstrated that the project had achieved its goal of 20- to 30-percent fuel savings.

In 1981, GE started to explore engines that were more efficient in comparison to the existing ones, and in 1983, GE announced an innovative effort similar to NASA’s ATP, called the Unducted Fan (UDF). Like the ATP, GE’s design also had two rows of counterrotating blades, but the UDF propeller was driven directly by the low-pressure turbine, with each blade row connected to multiple turbine blade rows without any need for a gear box. In this novel low-speed, seven-stage free turbine, the turbine rotors drove one propeller in one direction, while the free turbine stators rotated the other propeller in the opposite direction. In addition, the UDF would



Figure 9.—Advanced Turboprop Project technology.

be installed on the airplane's tail, not under the wings, to allow room for the propeller disk and to keep noise out of the cabin. GE teamed with Boeing to fly the full-scale demonstrator on the Boeing 727 test bed in 1986 (Sweetman, 2005).

The technology advancement under the ATP earned Glenn, NASA, and industry team the prestigious Collier Trophy for the outstanding contributions to aeronautics in 1987 from the National Aeronautic Association. By 1988, the energy crisis had passed, and the interest and need for the advanced turboprop vanished: the fuel savings would have been less than the higher initial cost (Facey, 1988). However, Glenn staff involved in the ATP remained confident that future economic conditions would make the turboprop attractive again. Apparently, their confidence was warranted. GE is currently exploring open rotor technology for next-generation aircraft, and Glenn and GE are collaborating to advance open rotor technology to meet the fuel efficiency and noise goals set by NASA's Subsonic Fixed Wing project.

Interest in High-Speed Flight

The price of oil and the Nation's interest in fuel efficiency have risen and fallen together like synchronized swimmers. The increased cost of oil in the 1970s led to the ACEE program. During the late 1980s and 1990s, with the perception of oil abundance and the resulting oil price decrease, the national emphasis on fuel efficiency was abandoned. Consequently, in 1990, NASA's interest in high-speed flight returned in the form of the High Speed Research (HSR) program. The desire for addressing technology barriers for high-speed flight had followed the need to address fuel efficiency. One example is America's interest in the development of an SST, evidenced by three Government attempts since the 1950s to advance technologies to enable the commercial viability of a supersonic aircraft (Bowles, 2010). The first attempt, the national SST program, began in 1961 and was terminated in 1971. The second attempt, the



Figure 10.—Artist's concept of High Speed Research aircraft.

Supersonic Cruise Aircraft Research program, began in 1972 to advance technology for flight in the 1980s. It was terminated in 1981 (Bowles, 2010). The third attempt, the HSR program, began in 1990 and was terminated in 1998 (Conway, 2005).

Glenn supported the development of propulsion technology in all three high-speed programs, utilizing its unique wind tunnels, such as the 10×10 and the 8×6, to study supersonic propulsion systems, including inlets, exit nozzles, combustion fuel injectors, flameholders, controls on ramjets, and turbojet engines. The 10×10 could operate between Mach 2.0 and 3.5 at altitudes from 50 000 to 150 000 ft (15.24 to 45.72 km). The 8×6 could operate between Mach 0.55 and 2.1 with an altitude range from sea level to 40 000 ft (12.19 km).

Glenn also took part in planning all three SST airplane technology development programs. From several studies, it was believed that supersonic aircraft, if environmentally acceptable and economically viable, could successfully compete in the 21st century marketplace (Fig. 10). However, several barriers needed to be resolved to make these aircraft a reality. The HSR program was established to address these barriers through collaboration between NASA and industry. The Critical Propulsion Components (CPC) element of HSR was created to develop the propulsion component technologies needed to (1) reduce cruise emissions by a factor of 10 and (2) meet ever-increasing airport noise restrictions (Federal Aviation Regulation Part 36 Stage III) with an economically viable propulsion system. The emission goal was an Emission Index of less than 5 for nitrogen oxide (NO_x) at cruise. The noise goals were a reduction of 4 to 6 in effective perceived noise in decibels (EPNdB) at the sideline, 8 to 10 EPNdB at cutback, and 5 to 6 EPNdB during approach.

The CPC identified the critical components as ultra-low-emission combustors; low-noise/high-performance exhaust nozzles; low-noise fans; and stable, high-performance inlets. Propulsion cycle studies, coordinated with Langley-sponsored airplane studies, were conducted throughout the CPC program

to help evaluate candidate components and select the best concepts for the more complex and larger-scale research efforts. The propulsion cycle and components ultimately selected were a mixed-flow turbofan engine employing a lean, premixed, prevaporized combustor coupled to a two-dimensional mixed compression inlet and a two-dimensional mixer/ejector nozzle. The CPC program began in 1994 and was planned for completion in 2002. Unfortunately, in 1999, NASA chose to end the HSR program prematurely. Nevertheless, the HSR program demonstrated that an economically viable and environmentally acceptable supersonic aircraft and propulsion system were achievable.

Air-Breathing Hypersonic Propulsion

For air-breathing propulsion in the hypersonic speed regime, access to space seems to be the only area relevant to civilian applications in the foreseeable future. In comparison with conventional rocket propulsion, air-breathing propulsion offers a significant advantage of higher effective specific impulse for space access to low Earth orbit. The combined-cycle propulsion research includes turbine-based and rocket-based cycles, as well as concepts such as pulsed-detonation rocket engines. In addition to a higher specific impulse, combined-cycle engines with air-breathing propulsion offer the following advantages over conventional rocket propulsion:

- (1) The higher propulsion performance allows for more robust structural mass fraction and reusability, especially for turbine-based systems, resulting in lower life-cycle cost and higher payload fraction.
- (2) Combined-cycle systems are amenable to improved operations, translated from the efficiency requirement in civil aircraft operations, enabling efficient abort scenarios and ground operations.

However, combined-cycle systems also have several disadvantages in comparison to traditional rocket propulsion:

- (1) Because of their complex nature, combined-cycle systems have higher development and manufacturing costs and are susceptible to more failure modes.
- (2) Because these systems follow higher dynamic pressure trajectories to benefit from longer air-breathing propulsion durations, they are subject to higher aerodynamic heating and structural loads and complicated staging issues.
- (3) Combined-cycle propulsion technology is considered to be relatively immature in comparison to rocket propulsion and must have significant further development before it can be applied for space access as readily as rocket propulsion.

Hypersonic air-breathing propulsion technologies—especially combined-cycle and scramjet engine technologies—are of very

high interest to the Department of Defense for cruise missiles; intelligence, surveillance, and reconnaissance; and long-range-strike aircraft applications. Consequently, NASA has worked in hypersonic air-breathing propulsion and airframe technologies over the last several decades, even though there was not a significant technology pull from space technology missions. Although hypersonic air-breathing propulsion has been studied for 60 years in the United States, through numerous scramjet tests in several ground facilities (Guy et al., 1996; Andrews and Mackley, 1994; Anderson et al., 1987; Guy and Mackley, 1979; Stalker et al., 1994), there have been only four attempts to develop a flight vehicle and, of those, only two resulted in flight. The first effort, the Hypersonic Research Engine project of the 1960s, focused on flying an axisymmetric scramjet mounted on the X-15 rocket-powered aircraft. The X-15 project was canceled before an operating Hypersonic Research Engine could fly (Freeman et al., 1997).

The second effort was the National Aerospace Plane (NASP) funded by NASA and the U.S. Department of Defense (funding was divided approximately equally between NASA, the Defense Advanced Research Projects Agency, the U.S. Air Force, the Strategic Defense Initiative Office, and the U.S. Navy). In 1986, the NASP began as an advanced technology demonstrator project to create a single-stage-to-orbit (SSTO) spacecraft and passenger spaceliner. Research suggested a maximum speed of Mach 8 for scramjet-based aircraft, because the heat generated by atmospheric friction would cost considerable energy. The NASP project showed that much of this energy could be recovered by passing hydrogen over the aircraft skin and carrying the heat into the combustion chamber. Mach 20 seemed possible. McDonnell Douglas, Rockwell International, and General Dynamics competed to develop technology for a hypersonic air-breathing SSTO vehicle, while Rocketdyne and Pratt & Whitney competed to develop engines. In 1990, the companies joined under the leadership of Rockwell International to overcome technical and budgetary obstacles. Development on the X-30 (Fig. 11), as it was then designated, continued until 1993, when it was terminated amid budget cuts and technical concerns.

As the NASP project came to an end, the Hypersonic Systems Technology Program (HySTP) was initiated to continue joint NASA and U.S. Air Force cataloguing of hypersonic technology. In January 1995, the Air Force ended its participation in HySTP, marking the true end of NASP. Glenn researchers were fully involved in NASP from its initial planning stages, through its implementation, its termination, and even beyond in the generic hypersonic research that followed NASP on a smaller scale. Glenn staff made significant contributions to air-breathing hypersonic propulsion under NASP, including advancing fundamental technologies, such as the fuel-air mixing mechanism for effective supersonic combustion and technologies for components, including inlets, isolators, and nozzles. A number of computational and experimental studies were carried out to

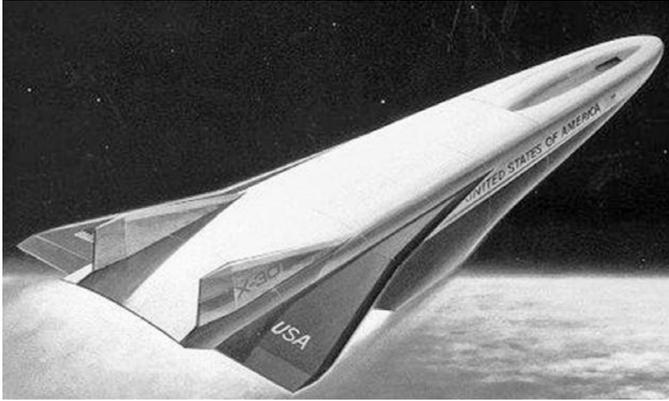


Figure 11.—Artist's concept of X-30 single-stage-to-orbit vehicle.



Figure 12.—X-43 scramjet test aircraft.



Figure 13.—X-51 scramjet test vehicle.

provide much needed understanding of the flow physics involved in the performance of key propulsion system components—the inlet, combustor, isolator, and nozzle—which were highly integrated with the airframe of the hypersonic vehicle. The performance of these key components, as the vehicle transitions from lower speeds to hypersonic speeds, is crucial to the stability and overall performance of the vehicle. Glenn played a key role in enhancing the fundamental understanding of and advancing

the technology for stable and efficient operation of the highly integrated propulsion system for the entire range of the vehicle operating conditions for the mission.

After NASP and HySTP ended, NASA management issued small contracts to examine scaled-down, but realistic, vehicles (size was a major cost driver) that could be constructed and flown to demonstrate the NASP technology. NASA initiated a third effort to develop a flight vehicle, the Hyper-X program, to demonstrate that scramjet engines could be designed, constructed, and flown at the high specific impulses necessary for access-to-space vehicles. Looking much like a scaled-down X-30, the Hyper-X (known as X-43) was a small, unpowered vehicle intended to test an integrated scramjet engine from Mach 7 to 10. The X-43 was designed to be mounted on the nose of a Pegasus rocket carried aloft and released by a B-52. After the Pegasus powered the test craft to about 100 000 ft (30 480 m), the X-43 would separate and its scramjet engine would be ignited. The Hyper-X would fly for only a few seconds before falling into the ocean, but the data collected from these test flights were to be used to develop practical hypersonic scramjet engines for future vehicles. Three unpowered X-43A (Fig. 12) research aircraft were built. Each of the 12-ft-long, 5-ft-wide (3.7-m-long, 1.5-m-wide) lifting-body vehicles was designed to fly once and not be recovered. The first and second vehicles were designed to fly at Mach 7 and the third at Mach 10. The first flight attempt in June 2001 failed when the booster rocket went out of control, but the second and third attempts resulted in highly successful, record-breaking flights. Mach 6.8 was reached in March 2004, and Mach 9.6 was reached in the final flight in November 2004.

The most recent hypersonic vehicle effort is the X-51 program, a collaborative effort of the U.S. Air Force Research Laboratory, the Defense Advanced Research Projects Agency, Pratt & Whitney Rocketdyne, and Boeing. The X-51A (Fig. 13) was designed to demonstrate the flight of a scalable, robust endothermic hydrocarbon-fueled scramjet propulsion system in the Mach 4.5 to 6.5 range. During its first flight test in May 2010, after being released from a B-52, the solid rocket U.S. Army Tactical Missile booster ignited and took the X-51A Waverider to approximately Mach 4.5; then the scramjet engine took over and accelerated the vehicle to approximately Mach 5.0 for about 140 s. The scramjet engine decreased thrust and acceleration for another 30 s before the test was terminated. The test was the longest of its kind, beating the previous record of 10 s set by the X-43. The data are being analyzed before the next flight is scheduled. Glenn support of the computational investigation of the scramjet flow field in ground test and flight configurations helped significantly in validating the CFD tools and in meeting the need for physics-based models to accurately simulate the effect of key flow phenomena, and therefore performance could be predicted with reasonable accuracy.

Return to Subsonic Transportation, Energy, and Environment: 1990s–2000s

A subsonic transportation technology project was established in the 1990s, a few years after HSR commenced. The Advanced Subsonic Technology (AST) program was an intellectual offspring of the ACEE program of the 1980s and was one of the major NASA aeronautics programs that began in 1993. It involved research at Glenn in combustor emissions, fuel efficiency, composites technology, and noise reduction. It included NASA, GE Aircraft Engines, Pratt & Whitney, Allison Engines, and AlliedSignal Engines. The high-level objectives of the propulsion portion of AST included a demonstration of a 1500 °F (816 °C) compressor, a demonstration of a low-emissions combustor at 3000 °F (1649 °C), an integrated component technology demonstration in a high-pressure ratio core, a large-scale demonstration of a high-efficiency turbine, and a demonstration of technology to reduce, in just 6 years, the uninstalled engine noise levels by 3 to 4 dB, relative to the state of the art. Although AST was an important technology program, its funding support was short-lived, and AST was terminated in 2000.

AST was replaced in 2000 with the Ultra-Efficient Engine Technology (UEET) program, which had fewer resources and less industry involvement in comparison with AST (National Research Council, 2002). UEET's mission was to develop and transfer revolutionary turbine engine propulsion technologies to industry. The technology development program was designed to address fuel efficiency and emissions reduction to decrease ozone depletion and the role of airplanes in global warming (Shaw, 2001). The goal for emissions reduction was 70 percent below 1996 International Civil Aviation Organization standards for NO_x emissions at landing and takeoff. In addition, UEET was to address potential ozone depletion concerns by demonstrating combustor technologies that would prevent any discernible aircraft impact on the ozone layer during cruise operation (up to a 90-percent reduction). The goal for fuel efficiency was an overall fuel savings of about 15 percent for large subsonic transport and up to 8 percent for supersonic or small aircraft. Glenn managed the program, but other NASA centers, engine companies (GE, Pratt & Whitney, Honeywell, Allison/Rolls-Royce, and Williams International), and airplane manufacturers (Boeing and Lockheed Martin) also participated. In addition, the team collaborated with other Government agencies, such as the Department of Defense, Department of Energy, EPA, and FAA.

Glenn's organizational structure has adapted over the last 70 years depending on the focus of the Agency's mission and the work assigned to the Center. During the early years of World War II, the focus was on developing gas turbine engine technology equal to that in Europe, but in the postwar period, the focus was on fundamental research in various technical disciplines. When Glenn became part of NASA, space

propulsion received more emphasis; and when the energy crisis occurred, energy efficiency received more attention. Subsequently, environmental issues, such as noise and emissions, were added to energy efficiency, and the current aeronautics projects reflect these priorities. Glenn's current organizational structure is based on assigned work for current aeronautics and space projects that are based on the Center's core competencies.

Current Aeronautics Research Programs

NASA's aeronautics research programs were restructured in 2005 when Lisa Porter was appointed NASA's Associate Administrator for the Aeronautics Mission Directorate. Aeronautics research was reorganized into four programs: the Fundamental Aeronautics Program (FAP) to conduct long-term, cutting-edge research in the core competencies of aeronautics in all flight regimes, the Aviation Safety Program (AvSP) to develop unique safety-related research capabilities to improve the safety of new and legacy vehicles as well as to overcome safety technology barriers, the Airspace Systems Program to address air traffic management R&D needs, and the Aeronautics Test Program to protect and maintain key research and test facilities. The FAP produced knowledge, data, capabilities, and design tools in the old NACA style. Industry partnerships were to be transformed from near-term, evolutionary procurements to long-term, intellectual partnerships to provide long-term, stable investment in capabilities that would benefit all of the aviation industry. The FAP was organized into four projects: Subsonic Fixed Wing, Subsonic Rotary Wing, Supersonic, and Hypersonic. In 2010, a fifth program, the Integrated Systems Research Program was added to mature technologies that had already proven their merit at the fundamental research level and to transition them more quickly to the aviation community. The emphasis is on integrated system-level research of interest and importance to the aviation stakeholder community. AvSP consists of three projects: the System-wide Safety Assurance Technologies project, Vehicle System Safety Technologies, and Atmospheric Environmental Safety Technologies (AEST). Glenn is advancing air-breathing propulsion technology at the fundamental, component, and system level in all the programs within the Aeronautics Mission Directorate.

The National Aeronautics Research and Development Policy was established by an Executive Order for the first time in December 2006 to help guide U.S. aeronautics R&D programs through 2020 (National Science and Technology Council, 2006). NASA's Aeronautics Research Mission Directorate's plan, developed in conjunction with the National Aeronautics Research and Development Policy, established aeronautics R&D challenges, prioritized goals, and time-phased, long-term objectives for the Nation's research to benefit the public in civil aviation (Porter, 2007; Alonso,

2008). The plan calls for collaborative partnerships with other Government agencies, academia, and industry and ensures the availability of world-class personnel, facilities, knowledge, and expertise. The Aeronautics Research Mission Directorate's FAP has identified near-term, midterm, and long-term technology development goals in subsonic and supersonic air transport, as well as in the hypersonic technology advancement needed to enable affordable space access for low-Earth-orbit applications.

In the subsonic regime, goals for the near and long term (extending to 2025) are in the areas of (1) emissions— NO_x , particulate, and green-house gases, (2) noise, and (3) fuel efficiency. The quantitative targets for near-term, midterm, and long-term technology development, and the baseline subsonic and supersonic reference vehicles were presented at the second annual meeting of the FAP (Alonso, 2008). The goals and the timeframes were based on consultations with industry and on studies of system-level impacts that the various technology advancements are likely to have in the corresponding timeframes. The goals will be reviewed periodically and adjusted as necessary to reflect the revised outlook of the technology advancement path. The noise, emission, and performance goals for subsonic aircraft are consistent with those of Europe, as outlined in their aviation and aeronautics research plans. One example is the integrated approach of focused propulsion research along with cross-cutting applications under the Clear Sky Technology project sponsored by the Advisory Council for Aeronautics Research in Europe in 2001: Vision 2020. Glenn's research is aimed at advancing propulsion technology and meeting the propulsion system targets (which were based on systems analysis) in all three areas. To meet the stringent, long-term goals (2025), we anticipate that unconventional architecture may be needed for the airframe as well as the propulsion systems (Fig. 14).

For supersonic transportation—in addition to emission and noise reduction goals during takeoff and landing—sonic boom, high-altitude emissions, and cruise efficiency have been identified as areas of research. Quantifiable goals must be met to enable economically viable supersonic air transport while minimizing the impact on the environment. Sonic boom reduction, cruise-efficient propulsion, aeroservoelasticity, high-altitude emissions, and the development of lightweight and high-temperature materials are the areas of active research at Glenn. Near-term, midterm, and long-term system-level targets in fuel consumption, sonic boom, airport noise, and emission reductions have been established. For the near term, technology development is planned for business-jet-sized aircraft flying at Mach 1.6 to 1.8. For the midterm, the goal is a commercial jet with 70 to 80 passengers flying at Mach 1.6 to 1.8. For the long term, the aircraft will approach the size of a large commercial jet with about 200 passengers flying at Mach 1.8 to 2.0 (Fig. 15).

For hypersonic speeds, a balanced portfolio of combined-cycle air-breathing propulsion and entry, descent, and landing



Figure 14.—Subsonic advanced architecture concept to meet long-term project goals (Kim et al. 2008).



Figure 15.—Notional N+3 (long-term) supersonic aircraft (Alonso 2008).

(EDL) on planets with an atmosphere have been identified as the major technology areas for supporting affordable access to space. However, all the R&D work related to EDL was recently moved to the purview of the Office of the Chief Technologist, which funds advancements in space technology. Glenn and Langley are carrying out the remaining hypersonics work in combined-cycle and scramjet air-breathing propulsion work. Starting in fiscal year 2013, because of budget constraints, NASA terminated all hypersonic air-breathing propulsion research. Glenn's hypersonic air-breathing propulsion work included turbine-based combined-cycle propulsion research and the advancement of fundamental technologies, such as the fuel-air mixing mechanism for effective supersonic combustion; technologies for components, such as inlets, isolators, and nozzles; and technologies for integrating the components using computational and experimental techniques. Mode transition from low-speed (Mach 3 to 4) to high-speed dual-mode scramjet operation is considered to be a critical technology challenge to make combined-cycle propulsion viable for hypersonic air-breathing propulsion. To address this challenge, Glenn staff have designed and built, and tested in Glenn's 10×10, the combined-cycle-engine large-scale inlet mode transition experimental configuration (Fig. 16).

Under the AEST project of the AvSP, Glenn is building on its strong competency and is continuing to make significant contributions to advancements in icing research. Glenn

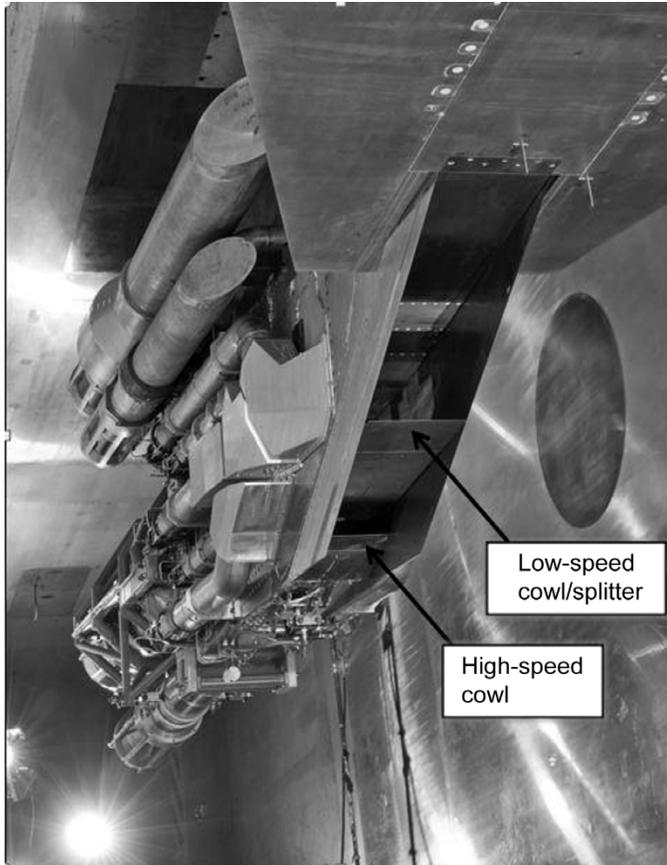


Figure 16.—Combined-cycle engine—large-scale inlet mode transition model in the 10- by 10-Foot Supersonic Wind Tunnel.

researchers are working to reduce flight test cost and to improve safety by developing methods to simulate, experimentally and computationally, the process of ice growth on aircraft surfaces. The aircraft industry and the Government use these methods for design, analysis, and certification efforts. Ice growth needs to be modeled on swept wings and on future-generation aircraft configurations (e.g., the blended-wing body). In addition, supercooled-large-droplet ice growth needs to be modeled and validated with a comprehensive database, which is lacking at present, to understand the ice accretion phenomena and to develop intelligent controls that can respond to an icing encounter. After icing in engines recently caused several engines to lose power when the aircraft flew in convective cloud environment with high-ice-water-content ice crystals, the FAA and the aircraft industry asked Glenn to lead engine icing research to improve understanding of the ice growth process within engine flow paths and how it affects engine performance. In response, Glenn, along with domestic and international partners, initiated a High Ice Water Content Flight Campaign under AEST to provide insight into cloud properties that cause engine power loss. In addition, Glenn has added icing capability in its Propulsion System Laboratory to enable full-scale engine testing in icing environments. For this effort, methods will be developed

to simulate, experimentally and computationally, the degradation in aircraft engine performance during in-flight icing conditions. These methods will then be used for design, analysis, and certification efforts by the aircraft industry and Government, and to add input to controls-based remediation efforts.

Future Technology Trends

On the basis of the global energy demand forecast, there will be extraordinary pressure on the transportation industry in general and on aviation in particular to advance technologies to improve fuel efficiency. Aircraft engine technologies that will increase the overall efficiency of engines will be the focus of the aviation propulsion research community for the foreseeable future. For the long-term (2025 to 2030), a number of advanced propulsion concepts are being considered because of the possibility of some emerging technologies. For example, the maturing of high-temperature superconductor technology during this timeframe will enable some alternative propulsion concepts, such as the electric drive and hybrid propulsion devices. Even in conventional gas turbines, concepts such as recuperative cycles, including interstage cooling of the compressor for very high operating pressure ratios (100 and above), are being considered. Advances in materials technology are anticipated to lead to lightweight materials that can enable the very lightweight heat exchangers needed for these aggressive cycles. Other concepts, such as constant-volume combustion to increase thermal efficiency, integrated energy optimization for propulsion and power-consuming devices, such as auxiliary power units, and the utilization of energy dissipated during landing also are being considered for long-term propulsion (Reddy and Blankson, 2010).

Alternative fuels with low carbon content, such as liquefied natural gas combined with optimal operations, such as flying at lower cruise speeds and formation flying might help to reduce the carbon footprint of aircraft, which are likely to receive increasing emphasis over the next 30 years. Alternative power plant concepts, such as fuel cells, need to have power densities (power per unit weight) comparable to those of modern gas turbine engines to be considered for aircraft propulsion. Even though research in these concepts is being actively pursued for terrestrial applications (e.g., automotive and electric power), based on the current rate of technology advancement, the power densities of fuel cells are not going to be comparable with those of gas turbines within the next 15 years. However, with technology advances in high-energy-density batteries and lightweight electric motors, the aircraft engine industry is exploring the possibility of developing some form of hybrid propulsion technology (a combination of battery/fuel cell and gas turbine engine) or all-electric propulsion within 25 years.

For the very distant future (~50 years), concepts such as low-energy nuclear reaction might hold some promise depending on how the feasibility of the technology progresses

for aeropropulsion applications. The ongoing and anticipated advances in high-temperature superconducting electric technology are expected to yield the needed breakthroughs to make electric turbine power transmission an efficient mechanism to meet the efficiency and noise goals for the near term to midterm. Lightweight generators and motors can be exploited (Kim et al., 2008) to distribute the fans over a wide area and to exploit the very large bypass ratio and boundary layer ingestion configuration advantages, yielding very high overall engine efficiency. Control and aerodynamic benefits are possible if the power-generating gas turbines are distanced from the fans in an optimum location (Fig. 14).

Commercial viability will be the dominant factor in technology development roadmaps for supersonic propulsion. Sonic boom mitigation for overland supersonic flight, cruise efficiency, and cruise emissions, in addition to airport noise and emission limits, will continue to be enabling technologies for commercial applications. Future technologies might include near-stoichiometric combustion; staged combustion; multifunctional components, such as continuous-wave combustion, and adaptive structural and material systems; multi-axis turbine engines; multifan cores; off-axis topping cycle cores for distributed thrust acoustics at takeoff and improved cruise efficiency; and highly integrated and continuously variable airframe and propulsion systems.

In the hypersonic speed regime, if the technology development satisfactorily addresses all the technical challenges and reaches a technology readiness level that can fully exploit the higher effective specific impulse of the air-breathing system, air-breathing propulsion will become more attractive than rocket propulsion for access to space. Some of the challenges include the higher aerodynamic heating and structural loads caused by the higher dynamic pressure trajectories needed to derive benefit from longer air-breathing propulsion durations and the associated complicated staging issues. Significant advancements in materials and better understanding of the various underlying key flow phenomena and their complex interactions will be needed to address these challenges. In addition, computational tools will need to be advanced significantly at the component and system levels to reduce uncertainty and to be used effectively in trade studies so that different propulsion systems can be assessed and compared accurately.

Concluding Remarks

This report briefly outlined the research and technology development programs and accomplishments in air-breathing propulsion at the NASA Glenn Research Center since its inception in 1941. Through the initial stages of growing pains and various budget priority cycles, Glenn management and staff have always been able to maintain a healthy balance between conducting fundamental research and advancing

technology to higher levels to enable effective technology transfer to industry. Partnerships with academia, the aeropropulsion industry, and other Government agencies, wherever appropriate, have played a key role in enabling Glenn to maintain its leadership in the development and transfer of aeropropulsion technology. As we face the current austere budget environment, knowledge of how the Center has been able to adapt to the changing needs and political climate of our Nation while maintaining its focus on core NASA values could be a very valuable guide as we plan the future.

Glenn Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, September 9, 2013

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