National Aeronautics and Space Administration

NASA Glenn Research Center at Lewis Field

Achieving the Extraordinary

NASA
Glenn Research Center at Lewis Field

Introduction

At the NASA Glenn Research Center, in partnership with U.S. industry, universities, and other Government institutions, we develop critical systems technologies and capabilities that address national priorities. Our world-class research, technology, and capability development efforts are keys to advancing space exploration of our solar system and beyond while maintaining global leadership in aeronautics. Glenn is distinguished by its unique blend of aeronautics and space flight expertise and experience. As we move toward a greater focus on space flight hardware development, we are benefiting from our diverse accomplishments and expertise in aeronautics. Our work is focused on technological advancements in space flight systems development, aeropropulsion, space propulsion, power systems, nuclear systems, communications, and human-related systems.

Glenn's main campus is situated on 350 acres adjacent to the Cleveland Hopkins International Airport. It has more than 140 buildings that include 24 major facilities and over 500 specialized research and test facilities. In addition, Plum Brook Station, located 50 miles west of Cleveland, offers four large, world-class facilities for space technology and capability development on a 6400-acre installation. All Center capabilities are available for Government and industry programs through Interagency or Space Act Agreements.

The Glenn team consists of over 2500 civil service employees and support service contractor personnel. Scientists and engineers comprise more than half of our workforce, while technical specialists, skilled workers, and an administrative staff support them. We aggressively strive for technical excellence through continuing education, increased diversity in our workforce, and continuous improvement in our management and business practices so that we can expand the boundaries of space, science, and aeronautics technology.

The Center's activities support all NASA missions and the major programs of our Agency. We contribute to economic growth and national security by developing technology for safe, superior, and environmentally compatible U.S. aircraft propulsion systems. Glenn leads NASA's research in the fields of fluids, combustion, and reacting flow systems, including gravity variation. Glenn also leads in the testing and evaluation of materials and structures for atmospheric and space environments by utilizing our first-rate facilities and world-class scientists and engineers. Almost every space shuttle science mission has had an experiment managed by Glenn, and we have conducted a wide array of experiments on the *International Space Station*. Glenn's role in space flight, science, and aeronautics research and development continues to support our Agency's strategy and our Nation.

We hope that this information is useful to you. If additional information is desired, you are encouraged to visit Glenn's Web site at www.grc.nasa.gov.

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Contents

History and Overview . . . 1

Space Flight Research and Development . . . 5
- Power and Energy-Conversion Systems . . . 8
  - Power generation . . . 9
  - Energy storage . . . 9
  - Power management and distribution . . . 10
- In-Space Propulsion and Nuclear Systems . . . 11
  - Electric propulsion . . . 11
  - Nuclear propulsion . . . 12
  - Chemical propulsion . . . 13
- Fluids, Combustion, and Reacting Subsystems, Including Gravity Dependence . . . 14
  - Cryogenic propellant management and characterization . . . 14
  - In situ resource utilization on the Moon and Mars . . . 15
- Space Communications Architectures and Subsystems . . . 15
- Systems Integration and Analysis . . . 16
- Human Research . . . 17
- Microgravity Science . . . 18

Aeronautics Research and Development . . . 21
- Advanced Turbine Engine Propulsion and Power Systems . . . 23
  - Compressor technology . . . 23
  - Combustor technology . . . 24
  - Turbine technology . . . 25
- Turbine Engine Noise Reduction . . . 26
  - Fan technology . . . 26
  - Exhaust system technology . . . 26
- Propulsion Control and Engine Health Management . . . 27
- Instrumentation Systems . . . 29
- Avionics . . . 30
- Aircraft Communications . . . 30
- Aircraft Icing Research . . . 30
- Modeling and Simulation . . . 30
- Alternative Fuel Systems . . . 34
  - Hydrogen-powered aircraft . . . 34
  - Propulsion and power systems . . . 34

Research and Development That Advances Both Aeronautics and Space . . . 37
Power and Energy-Conversion Systems . . . 39
Diagnostics and Sensors . . . 39
Avionics and Communications . . . 40
Materials Science and Aerospace Structures . . . 40
High-temperature propulsion materials . . . 40
Advanced metallic materials . . . 40
Polymers and polymer matrix composites . . . 41
Structural ceramics . . . 41
Environmental and thermal barrier coatings . . . 42
Aerospace propulsion structures . . . 42
Analytical, computational, and experimental mechanics . . . 42
Structural mechanics and dynamics . . . 43
Mechanisms and mechanical systems . . . 44
Tribology and surface science . . . 45
Aeronautics and Space Test Facilities . . . 45

Technology Transfer and Partnerships . . . 47
Small Business Innovation Research and Small Business Technology Transfer Programs . . . 49
Strategies and Partnerships . . . 50

Honors and Awards . . . 53
Selected R&D 100 Awards . . . 55
NASA Software of the Year Awards . . . 56
Collier Trophy Awards . . . 56
NASA Government Invention of the Year Awards . . . 56
Government Computer News Awards . . . 56
Other Awards . . . 56

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1941 ground-breaking ceremony for the Aircraft Engine Research Laboratory.

History and Overview

The NASA John H. Glenn Research Center at Lewis Field came

The NASA John H. Glenn Research Center at Lewis Field came into existence in 1941 as the Aircraft Engine Research Laboratory of the National Advisory Committee for Aeronautics (NACA). It was later renamed the Lewis Research Center in honor of the late George Lewis, NACA's Director of Aeronautical Research. The name was changed to its present form in 1999 in honor of Ohio Senator John H. Glenn, the first American to orbit the Earth.

into existence in 1941

The laboratory was conceived as a national resource capable of providing innovations in aircraft engine technology and transitioning these innovations to U.S. industry for use in future propulsion system designs for commercial and military applications. In the early 1960s, Glenn pioneered the use of liquid hydrogen for rocket and aircraft propulsion, allowing the United States to win the race to the Moon.

Over the past 60 plus years, our scientists and engineers have made major technology contributions that have expanded horizons and opened new frontiers for both aviation and space exploration. These technology innovations have enabled U.S. industry to assume a leadership position in the world aerospace marketplace and have contributed to the Nation's safety and security.

Glenn consists of two campuses. Scientists and engineers at our main campus near Cleveland, Ohio (Brook Park and Fairview Park), investigate space operations, aerospace technology, and technologies needed for space exploration: power, propulsion, communications, fluids and combustion, materials, structures, mechanical components, and instrumentation and controls. Scientists and engineers at our Plum Brook Station in Sandusky, Ohio, perform very large and hazardous aerospace tests in one-of-a-kind facilities.

GLENN'S SCIENTISTS AND ENGINEERS
2005

Workforce assignments	Portion of total, percent
Fluid and flight mechanics	8
Materials and structures	11
Propulsion and power	24
Flight systems	11
Measurements and instrumentation	13
Data systems	11
Facilities	14
Management	6
Other	2

We have a unique blend of aeronautics and space flight expertise and experience. Scientists and engineers comprise 57 percent of our workforce. Of these, 36 percent have master's degrees and 39 percent have doctoral degrees.

Our capabilities include in-space propulsion systems; nuclear systems; power and energy-conversion systems; fluids, combustion, and reacting systems, including gravity dependence; aeropropulsion systems; aerospace communications architectures and subsystems; interdisciplinary bioengineering for human systems; and test and evaluation for atmospheric, space, and gravitational environments.

Glenn pioneered the use of liquid hydrogen for rocket and aircraft propulsion, allowing the United States to win the race to the Moon.

The Voyager 1 spacecraft begins its journey aboard a Titan III with a Centaur upper stage. Voyager was the first probe to provide detailed images of the moons of Jupiter and Saturn. It is now more than 8.8 billion miles from the Sun and is the farthest human-made object from Earth.

Space Flight

Research and Development

Glenn successfully develops, manages, and supports flight

Glenn successfully develops, manages, and supports flight systems in four major areas of expertise: power, propulsion, communications, and microgravity science. Our scientists and engineers pioneered the use of liquid hydrogen for aircraft and rocket propulsion in the 1940s and 1950s, which eventually led to our leadership of the development of the highly successful Centaur upper stage with its liquid-hydrogen-fueled RL–10 engines. Centaur, the Nation's highest performing and most used upper stage, has launched spacecraft to Earth orbit, the Moon, the planets (*Voyager*, *Pioneer*, *Viking*, and *Cassini* missions), and beyond for over 40 years. The development of the Centaur's versatile RL–10 engines benefited from at least two Glenn success stories: liquid hydrogen regenerative cooling and coaxial propellant injection.

systems in four major areas of expertise

Glenn's management, development, and operation of expendable launch vehicles spanned 35 years and 119 launches. We developed four Centaur configurations during this period: the Atlas/Centaur D1A, the Titan IIIE/Centaur D1T, and the Shuttle/Centaur G and G-Prime upper stages (where the G-Prime flew on the Titan IV vehicle). The staff experience and facilities used to develop and manage these upper stages, along with management of other boosters and upper stages like Agena and Thor, have continued to be used for other initiatives such as the testing of Boeing's new Delta III cryogenic upper stage.

In electric propulsion, Glenn invented the first Hall and ion thrusters in the late 1950s and flew the first electric propulsion spacecraft demonstrations in the 1960s. We developed, managed, and operated the Space Electric Rocket Test I and II spacecraft; and designed, built, qualified, and delivered the Deep Space 1 ion engine—the first ion engine to be used as the primary propulsion for an interplanetary spacecraft. In addition, we designed, built, qualified, delivered, and operated a pulsed-plasma thruster to demonstrate satellite stationkeeping for the Earth-Observing 1 mission.

For Space Station Freedom, Glenn designed the largest power system ever deployed in space. The technology was transferred to industry and built for the *International Space Station* (ISS).

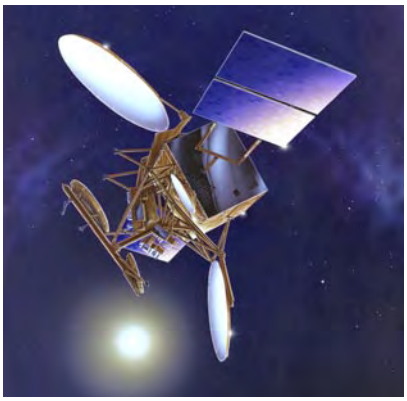
We led a team that investigated and resolved a negative margin on the ISS solar array mast due to unanticipated gas impingement loads during rendezvous and docking with the space shuttle. A negative margin occurs if the amount of energy provided by the solar array is insufficient to recharge the battery and provide for insolation loads. This indicates that batteries cannot be recharged in orbit and will eventually discharge if the negative margin is large enough and lasts long enough. The development of a new complex control and structure interaction method saved $24.5 million in redesign costs.

Mir cooperative solar array (foreground) deployed on Mir.

Glenn worked with the Russian Space Agency and international partners to develop, manufacture, test, and deliver for launch the Mir Cooperative Solar Array in only 18 months, on schedule and $1 million under budget. We also designed, built, qualified, and delivered the Deep Space 1 solar arrays, which were the first successful use of photovoltaic concentrators in space (called the Solar Concentrator Arrays with Refractive Linear Element Technology, SCARLET).

By 1980, communications satellites were competing with each other for the limited space in the usable bandwidth. To address this problem, Glenn developed the Communications Technology Satellite, the first communications satellite in the Ka band. We also developed the Ka-band traveling-wave-tube amplifier to be flown on the

Ion thruster.



Advanced Communications Technology Satellite (ACTS).

Communications Technology Satellite, technology that is used by the Direct Broadcast Services ("dish" network) industry today.

Our development of the Advanced Communications Technology Satellite (ACTS) began a revolution in space-based, broadband communications. ACTS proved that Ka-band transmission is feasible and that it offers many advantages over other frequency bands. ACTS enabled growth in the capacity and utilization of the limited-frequency spectrum and offered the first demonstration of high-quality voice communication (with echo cancellation) from a geosynchronous satellite. Over 150 organizations in 31 states in the United States and in six other countries used ACTS to conduct more than 100 experiments.

We have had a success rate greater than 97 percent in designing, developing, managing, and supporting over 130 diverse microgravity experiments on *Spacelab* and *Spacehab* (reusable laboratories carried in the space shuttle's cargo bay), *Mir* (the Russian space station), and the ISS. For example, Glenn developed Combustion Modules 1 and 2, the largest payloads flown on *Spacelab* and *Spacehab*. The innovative combination of Glenn-led hardware analysis and rack-level tests were used to qualify the Combustion Module 2 hardware, saving the program a costly and mission-threatening requalification process. In addition, our scientists and engineers developed two unique facility-class payloads for the ISS capable of supporting multiple combustion science and fluid physics investigations: the Combustion Integrated Rack and the Fluids Integrated Rack.

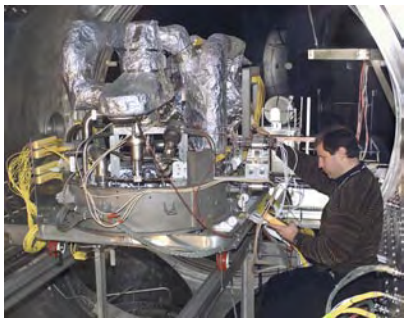
Systems and software engineers conduct final inspections of the Combustion Module 2 flight hardware at Glenn before it is shipped to the launch site.

The primary communications link for an electronic field trip to the South American rainforest was provided by Glenn's ACTS satellite.

Power and Energy-Conversion Systems

Glenn is responsible for the research, design, development, assembly, integration, testing, and operations of power and energy-conversion systems for all NASA missions in aeronautics and space. Power system components include fuel cells and solar cells to generate electricity, batteries to store electric power, and electrical power distribution and control components. Our expertise is currently supporting the development of spacecraft electric power systems for the new Crew Exploration Vehicle being developed to meet the Vision for Space Exploration of the Moon and Mars.

Glenn is the only NASA center performing all elements of space power system



Closed-Brayton-cycle and NASA Solar Electric Propulsion Technology Application Readiness (NSTAR) thruster installed in Glenn's Vacuum Facility 6.

development to enable space exploration, from low technology-readiness levels to flight hardware.

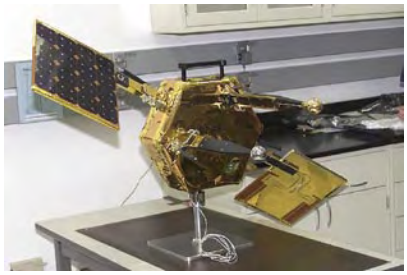
Power generation

Glenn develops power-generation technologies that enable space exploration, including static (photovoltaic and thermophotovoltaic) and dynamic (Brayton and Stirling) power systems. Until now, space power generation has used solar arrays and Radioisotope Thermoelectric Generators, systems that have no moving parts. Tests conducted by Glenn's scientists and engineers are proving that Brayton and Stirling approaches, which use moving parts, would be reliable over the lifetime of a typical space mission.

For example, we successfully operated a 15-kWe closed-Brayton-cycle system for 38,000 hr and demonstrated the world's first test of an integrated solar-dynamic 2-kWe closed-Brayton-cycle power system in a relevant space environment. In addition, we performed the world's first test of a closed-Brayton-cycle power system with an electric propulsion (ion) engine and developed and tested the world's highest power free-piston Stirling engine (25 kWe). A free-piston Stirling power source with a Hall-effect electric thruster also was successfully demonstrated. We are developing and testing components to support transition to flight for Stirling power convertors in a radioisotope power system.

In photovoltaic power generation, Glenn led efforts to analyze on-orbit the electromagnetic interference effects of plasma arcing to the ISS solar arrays, leading to the implementation of the ISS plasma contactor. We designed and developed the Solar Array Module Plasma Interaction Experiment, which was flown in the shuttle payload bay to determine arcing hazards on solar arrays and surrounding structural materials. A floating potential probe was then developed and implemented to guarantee an arc-free environment for astronauts working outside of the ISS.

Our scientists and engineers authored design guidelines for assessing and controlling spacecraft charging effects in geosynchronous and low-Earth orbits and are presently writing Paschen breakdown guidelines for missions to the Moon and Mars. These predict the length of electrical discharges that will be produced by different combinations of gas mixtures, voltages, and atmospheric pressures. Such discharges can result in power loss, cross-circuit and/or short-circuit phenomena, and electromagnetic noise.



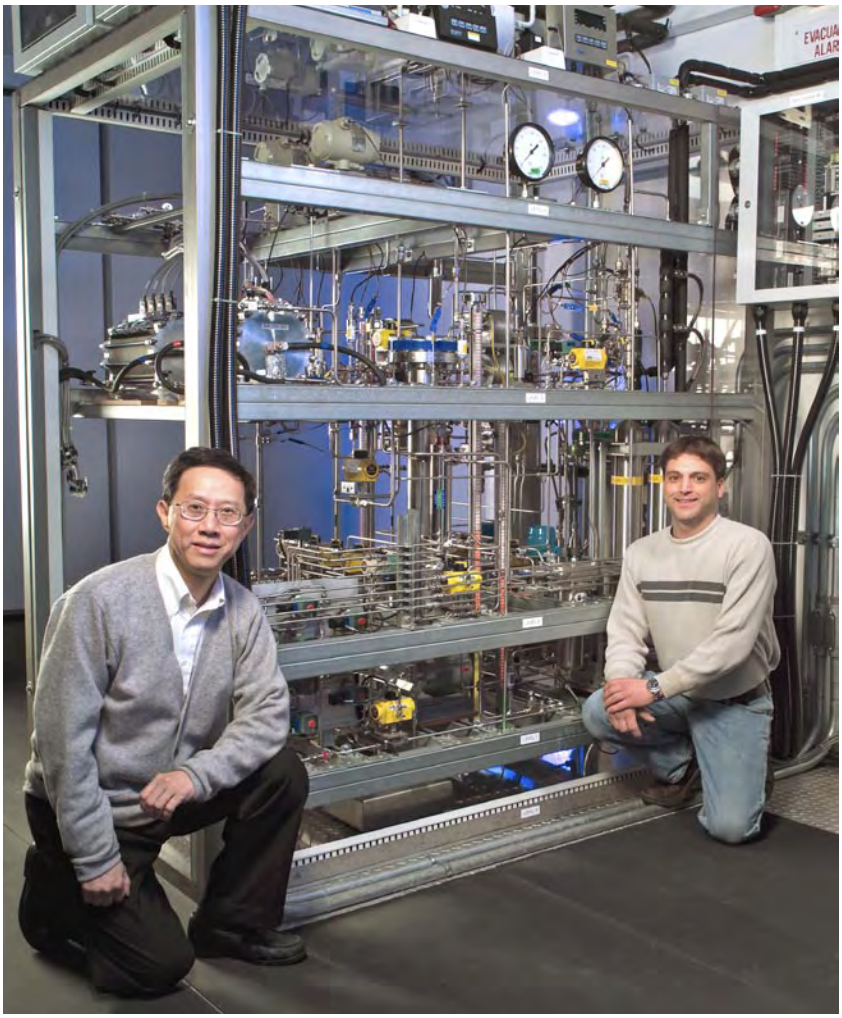
Floating Potential Probe at the NASA Kennedy Space Center before launch.

Energy storage

Glenn conducts research and development in energy-storage technology, including fuel cells, regenerative fuel cells, batteries, and flywheels. We conducted technology advancement programs on the Gemini proton-exchange-membrane fuel cell and on the Apollo alkaline fuel cell. This included developing the technology for and supporting the advanced development of the alkaline fuel cells that provided electric power for the Apollo missions and the space shuttle. We also were responsible for advancing and qualifying the primary fuel cell power technology for the space shuttle onboard power system.

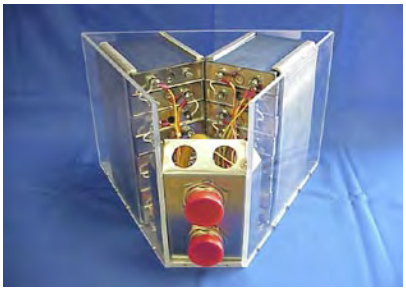
Glenn is leading the development of modular proton-exchange-membrane fuel-cell-stack technology for use in launch vehicles. This technology provides increased peak-to-nominal power and improved reliability. We also are leading the effort to evaluate and develop fuel-cell and regenerative-fuel-cell energy-storage systems for missions with long eclipse periods ("nights"), during which solar cells cannot generate electricity, such as Moon and Mars bases, unmanned aerial vehicles, and high-altitude balloons. Totally passive (nonmoving) components are the focus of this effort to minimize weight, improve energy density, and maximize reliability.

Glenn leads the NASA Aerospace Flight Battery System Program, an Agency-wide effort aimed at ensuring the quality, safety, reliability, and performance of flight battery systems for NASA missions. We evaluated flight battery technologies for the ISS and the Electric Auxiliary Power Unit replacement for the space shuttle. In addition, we developed and validated designs for nickel-hydrogen



Regenerative Fuel Cell test rig.

cells that have been adopted for NASA missions and employed by cell manufacturers and satellite companies. Glenn developed lightweight nickel electrodes, demonstrated the feasibility of bipolar nickel hydrogen battery designs, initiated advances including the use of catalyzed wall-wicks and 26-percent potassium hydroxide, and developed standard test procedures for evaluating separator materials for alkaline cells.



Mars 2001 lander battery.

Currently, we are focusing on lithium-ion battery technology as a replacement for nickel-hydrogen technology. Because of the nominal 100-percent improvement in specific energy and energy density over nickel-hydrogen cells, Glenn-developed lithium-ion cell technologies are candidates for use on many future NASA missions.

A joint Department of Defense and NASA program was established to develop lithium-ion batteries with the capabilities required by future NASA and Department of Defense missions. This collaborative effort between the Jet Propulsion Laboratory, the Air Force Research Laboratory, and Glenn resulted in the development of the lithium-ion technology implemented in the batteries for the Mars Exploration Rovers *Spirit* and *Opportunity*.

Glenn is pioneering the development of the next generation of space-qualified lithium-based technology: a lithium-based polymer electrolyte secondary battery. This concept replaces the liquid electrolyte of the lithium-ion system with an ultrasafe polymer electrolyte that cannot leak or emit toxic fumes. The Polymer Energy Rechargeable System Program is addressing this next-generation technology through a combination of contracted and in-house efforts focusing on the development and evaluation of various polymer electrolytes, as well as cathodes, anodes, and related components.

Glenn developed a new design and a life-prediction method for flywheels that offer long-term energy-storage and attitude-control capabilities. Flywheel technology provides lighter weight power generation and extended mission life when used in combined energy-storage and attitude-control applications. Using an in-house flywheel design and controls, our scientists and engineers demonstrated a single-axis combined attitude-control and energy-storage system.

Power management and distribution

Optimized power management and distribution (PMAD) greatly improves power system efficiency while reducing system size and mass. All aspects of PMAD system development are performed

at Glenn. This includes system studies, technology development, flight hardware development, and end-to-end testbed development.

As part of an ongoing effort to meet NASA needs for advanced electronic components and subsystems to permit power system operation in harsh high-temperature and high-radiation environments, Glenn developed several power technologies, including modular Power Energy Building Blocks and advanced modular digital control. We led the development of high-voltage (over 270 V) and power technologies. In addition, our scientists and engineers developed special-purpose avionics, such as the circuit-interrupt device utilized by astronauts to assemble the ISS, the electrical power control unit for the microgravity Fluids and Combustion Facility for the ISS, and advanced power processors for electric propulsion applications—including Deep Space 1 and NASA's Evolutionary Xenon Thruster (NEXT). Glenn pioneered the development and flight of power electronics for electric propulsion. These electronic designs have been the basis for the majority of flight power electronics.

In addition to these activities, PMAD system studies supported VentureStar (a proposed commercial single-stage-to-orbit reusable launch vehicle) for Lockheed Martin, the space station redesign for the NASA Johnson Space Center, the Integrated Solar Upper Stage for the U.S. Air Force, and the High Altitude Airship for the Missile Defense Agency. In its ISS electric power system independent-verification-and-validation role, Glenn developed the first end-to-end (source-to-load) hardware testbed to emulate the ISS power system. This electric power systems testbed is used to identify and resolve fault control, stability, and other hardware, software, and integration issues for many programs.

Currently, we are developing an end-to-end PMAD testbed for the Prometheus 1 system, which will incorporate Brayton technologies.

In-Space Propulsion and Nuclear Systems

Electric propulsion

The objective of the electric propulsion effort at Glenn is to develop and demonstrate advanced electric propulsion systems that enable more ambitious NASA, U.S. Government, and commercial space missions. Glenn has in-house capabilities for the design, fabrication, and evaluation of electrostatic, electromagnetic, and electrothermal electric propulsion systems from conception through flight qualification. Our facilities include extensive and unique space-simulation chambers (high pumping speed, large diameter, solar simulator, and thermal vacuum), dedicated experimental test infrastructure, and dedicated experienced engineering staff.

We have a significant history of accomplishments in the field of electric propulsion, beginning with the invention of the electron bombardment ion engine in 1958 by researcher Harold Kaufman. There followed a series of successful ion engine demonstration flight experiments: the Space Electric Rocket Test I in

[Glenn's] significant history … in the field of electric propulsion [began] with the invention of the electron bombardment ion engine in 1958 …

NEXT ion thruster array being assembled for testing.

1964 and II in 1970. In 1965, a 200-kW, 1.5-m-diameter ion engine was tested, using mercury as the propellant. Our employees partnered with Hughes to develop 5-, 8- 12-, and 30-cm engines from 1970 until 1982. In 1987, our electric propulsion engineers transferred 1-kW-class arcjet technology to industry for communication satellite propulsion.

Glenn was responsible for the development of the Deep Space 1 ion engines [for] … the first-ever demonstration of electric propulsion as the primary propulsion device for a spacecraft.

With a focus on the space shuttles and the ISS, electric propulsion work was put on hold until interest was renewed in the late 1990s when one of our engineers suggested the use of a nontoxic gas (xenon) as a propellant. The vacuum tanks where the mercury-propellant tests were conducted were scrubbed out and prepared for testing ion engines designed to run on xenon. As a result, in 1997 Boeing produced their Xenon Ion Propulsion Systems, XIPS–13 and XIPS–25, using our technology. Also, in 1997, our engineers developed and demonstrated a Hall effect thruster propulsion system for a Naval Research Laboratory spacecraft.

In that same year, Glenn was responsible for the development of the Deep Space 1 ion engines and power processors, which resulted in the first-ever demonstration of electric propulsion as the primary propulsion device for a spacecraft. This mission, launched in 1998, was the beginning of an upsurge in interest in electric propulsion, because of its amazing fuel efficiency and versatility in comparison to chemical propulsion systems. Electric propulsion could make new missions possible: a spacecraft could visit several destinations in a single mission and select the most promising ones for extended exploration. For example, the Jupiter Icy Moons Orbiter could go into orbit around one moon and study it, then have enough propellant and capability (with nuclear power) to leave orbit and travel to the next moon, orbit it, and study it for a long period of time.

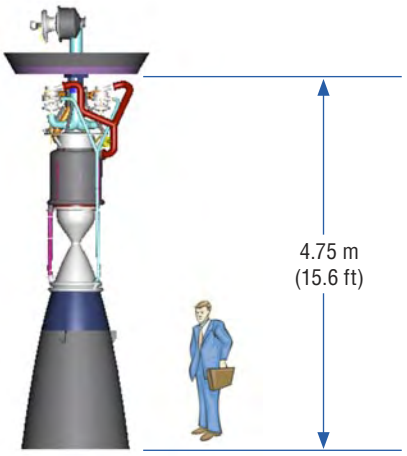
With the increased demand for electric propulsion, Glenn continued to lead in the innovation of thruster technology, demonstrating new capabilities for future space missions. In 2002, a pulsed-plasma thruster, using solid Teflon (DuPont) as a fuel, was used as attitude control and demonstrated in a flight test on the Earth Observing 1 spacecraft. Glenn was chosen to lead the development of the 5-kW NEXT ion propulsion system in 2002, to produce a more capable thruster based on the Deep Space 1 ion engine. Also in 2002, we were chosen to develop a 25-kW-class ion engine for use on nuclear-powered spacecraft.

In 2003, a Glenn-developed, 100-kW Hall effect thruster—the largest Hall thruster ever built—was demonstrated at Glenn. Because of these many successes and the unique capabilities of electric propulsion, Glenn was chosen as lead to develop the Jupiter Icy Moons Orbiter electric propulsion system in 2003. In the same year, we were selected to develop a high-specific-impulse Hall thruster for cost-constrained space science missions. In 2004, we were selected to develop a 150-kW-class Hall thruster in support of NASA's exploration vision, providing capability for delivering payloads to the Moon and Mars cost effectively.

Nuclear propulsion

Glenn has been involved in nuclear propulsion design and development since the 1960s. We were the Agency leader during the Rover/Nuclear Engine for Rocket Vehicle Application programs (1961 to 1972), the special assessment agent for nuclear propulsion and power systems during Exploration Studies (1988 to 1989) and the Space Exploration Initiative (1990 to 1993), and the lead NASA center for nuclear propulsion (1991 to 1994).

Glenn is currently the Agency lead for nuclear propulsion, including nuclear electric propulsion, nuclear thermal propulsion, and variants. Our scientists and engineers developed state-of-the-



Efficient 15-klbf/25-kWe bimodal nuclear thermal rocket engine. Despite its small size, this rocket can provide high thrust and specific impulse.

Artist's concept of an artificial-gravity bimodal nuclear thermal rocket crew transfer vehicle for Mars.

art nuclear rocket engine concepts to reduce launch mass, shorten trip time, allow power generation and bipropellant operations, and support artificial gravity operations. Our designs include the hybrid bimodal nuclear thermal rocket, which also generates electric power, and the liquid-oxygen-augmented nuclear thermal rocket with an oxygen "afterburner" nozzle. In addition, we developed the concept for and determined the benefits of hybrid bimodal nuclear thermal electric propulsion, which has short, high-thrust and long, low-thrust operation.

Glenn demonstrated the feasibility of an oxygen "afterburner" nozzle to increase nuclear thermal propulsion engine thrust via supersonic combustion in the nozzle through tests at Aerojet. A fuel-rich (an oxygen-to-hydrogen mixture ratio of less than 2) liquid oxygen/liquid hydrogen engine was used with a small (25:1) oxygen afterburner nozzle containing three oxygen injectors located azimuthally around the divergent nozzle section. The tests demonstrated approximately 50-percent thrust augmentation via supersonic combustion at mixture ratios of 1 or less as measured on a thrust stand. Thrust augmentation factors of approximately 3 (300-percent increase) were estimated/predicted at mixture ratios of approximately 3, and thrust augmentation of 400 percent was predicted for higher mixture ratios.

We were responsible for the development of three of the four architectures for the human exploration of Mars: nuclear thermal propulsion or bimodal nuclear thermal propulsion, solar electric propulsion with chemical aerobrake, and nuclear electric propulsion.

Chemical propulsion

Glenn played the defining role in the use of liquid hydrogen fuel for rocket and aircraft propulsion, the enabling technology that took us to the Moon. Our scientists and engineers developed the most comprehensive experimental performance and stability characteristics database of hydrogen/oxygen rocket combustors in the world.

Glenn played the defining role in the use of liquid hydrogen fuel for rocket propulsion, the enabling technology that took us to the Moon.

Recently, we developed state-of-the-art combustion stability analysis tools, the Rocket Combustor Interactive Design (ROCCID) and the High Frequency Injection Coupled Combustion Instability Program (HICCIP), and led the revision of the Chemical Propulsion Information Agency standard for stability testing. This is in line with our historic involvement in combustion instability with the Saturn launch vehicle F–1 engine and many of the storable engines used in the space program. We conducted the first laser ignition tests in a rocket environment, liquid oxygen/ethanol igniter testing for the shuttle upgrade, and the first demonstration of the liquid hydrocarbon combustion wave ignition system. As the Agency lead for ignition technology, we tested the breadboard X–33 combustion wave ignition system.

Glenn is a leader in several chemical propulsion areas. These include

- The development and demonstration of alternative propellants, such as oxygen/RP–1/aluminum metallized gelled fuels, oxygen/carbon monoxide in situ propellant for Mars, and oxygen/aluminum in situ propellant for the Moon.

- The study of combustion chamber cooling technologies such as liquid oxygen cooling, high-aspect-ratio channel cooling, propellant coking and material compatibility in cooling channels, and materials technologies for cooled combustion chambers.

- Three-dimensional transient combustion modeling (a world leader), including the Space Shuttle Main

Engine bladed hub baffle simulation, and annular constant-volume combustion-cycle-engine combustor simulation.

Glenn is a pioneer in the modeling and testing of high-performance, high-area-ratio nozzles for space-based engines. We were the first to test a 1000:1 area ratio nozzle at altitude conditions, providing data to calibrate joint Army-Navy-NASA-Air-Force prediction procedures. For satellite propulsion, our scientists and engineers developed iridium-coated rhenium rocket chamber technology, allowing an increase in satellite life from 12 to 15 years and gaining $30 to $60 million in added revenue per satellite.

We specialize in state-of-the-art computational fluid dynamics for flow-field characterization and testing of high-performance, high-area-ratio nozzles for space-based engines. Our Numerical Propulsion System Simulation (NPSS) software enables rapid, affordable computation of performance, stability, cost, life, and certification requirements.

Full-scale demonstration of the X–33 liquid oxygen densifier.

Fluids, Combustion, and Reacting Subsystems, Including Gravity Dependence

Cryogenic propellant management and characterization

Through extensive testing in the 1960s and 1970s, Glenn helped to develop a multilayer insulation system that reduces cryogenic propellant losses during long-duration missions. We are currently developing a hybrid active/passive cryogenic thermal control system to store cryogenic propellants in space indefinitely, using a zero-boiloff approach. Through analysis, we have shown that this approach will reduce mass for certain advanced mission concepts.

Liquid-acquisition devices use surface-tension forces to transport liquid to the bottom of a tank in a zero-gravity environment, leaving vapor at the top. Such devices are used on current NASA and commercial satellites with propellants that are storable at room temperature. Glenn is developing liquid-acquisition devices to enable the use of cryogens for Orbital Maneuvering System/Reaction Control System in-space propulsion systems. So far, we have conducted component and subsystem-level characterization for these devices.

We also are developing a passive vane approach for liquid management that uses surface tension to position the liquid at the tank discharge. The ability of vane devices to trap liquid can be used to transfer liquid as well. This approach to liquid transfer was demonstrated in the Vented Tank Resupply Experiment, which was flown on Space Transportation System (STS, or space shuttle) flight 77.

We have led the Nation in the development of densification technologies for cryogenic propellants. This approach provides more energy per unit volume than conventional cryogens and thereby enables lighter weight vehicle designs. Glenn developed the first and only full-scale liquid hydrogen and liquid oxygen densification units. In addition, we demonstrated liquid oxygen densification (180,000 gal of liquid oxygen densified) and tanking at the X–33 scale. We also developed slush hydrogen technology for increased hydrogen density, producing over 200,000 gal of slush hydrogen.

To enable fast and accurate mass gauging of cryogenic propellants in low gravity, Glenn is developing several competing technologies that will be suitable for space exploration vehicles and long-duration missions. These technologies will enable efficient use of propellant in orbit, improved operability, and leak detection. In addition, a unique facility was developed at Glenn for the reference characterization of gauging accuracy with hydrogen, oxygen, and other cryogens for investigating the uncertainty of competitive gauging technologies.

To support efficient in-space propellant depot operations, Glenn characterized

fluid transfer technology and demonstrated no-vent fill technology in a large-scale ground test. No-vent fill is a technique for filling liquid in low gravity without having to leave the tank vent open to relieve pressure. Our approach uses liquid subcooling and mixing to condense the vapor generated by the fill process back into liquid and to control the tank pressure within structural limits.

Recently, we developed a pulsed thrust propellant reorientation experiment for the European Space Agency Sloshsat spacecraft, which was launched in February 2005. Heat transfer and the fluid behavior associated with tank mixing for pressure control were demonstrated in the Tank Pressure Control Experiment, which was flown on STS flights 43, 52, and 84.

Understanding the critical frequencies is important to controlling spacecraft in orbit, but most calculations of the critical frequency are made assuming an empty tank with no internal hardware. The Liquid Motion Experiment flown on STS flight 84 demonstrated that vane devices alter critical frequencies for fluid-tank interactions. By showing that internal structures such as vane liquid acquisition can alter the critical frequency, we highlight the need for more complex calculations.

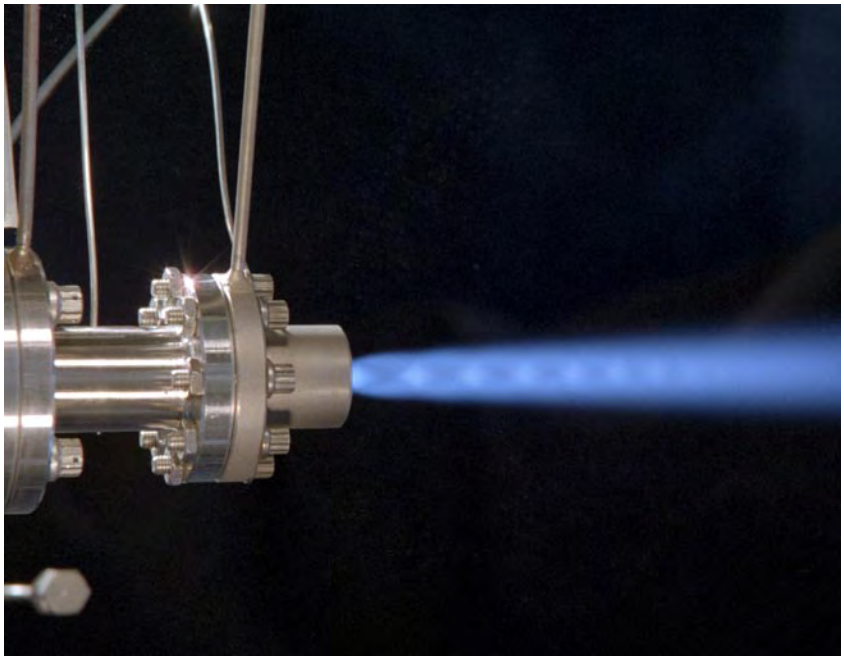
Glenn completed detailed designs of flight experiments for propellant depot technology (Cryogenic Liquid Orbiting Depot—Storage Acquisition and Transfer, COLDSAT, and Cryogenic On-orbit Nitrogen Experiment, CONE).

In situ resource utilization on the Moon and Mars

Glenn is a key partner in the development of technology for the production of propellants and other mission consumables from local materials at the Moon and Mars. We are leading technology development to excavate and transport lunar regolith and are playing key support roles in the thermal and chemical processing of regolith to produce oxygen, water, and hydrogen. Glenn-developed vibrofluidization technology will help to produce up to 10 metric tons of oxygen per year on the lunar surface. Linking our expertise in propulsion, power, and reduced-gravity fluid and reacting systems, we have developed the first end-to-end in situ resource utilization system modeling tool.

In a joint program with the Department of Energy, Glenn is leading advances in fuel reformer technology that can also be applied to lunar and Mars processing plants. The goal is to improve catalyst life by 20 to 40 percent and to reduce size and weight 2 to 3 times. We are leading the development of advanced solid-oxide electrochemical cells with a patent-pending process that could reduce the power required to produce oxygen on Mars by a factor of 8. These cells can also be used for high-temperature water electrolysis in lunar processing plants.

We are also leading the development of methane/oxygen propulsion, the leading candidate for Mars in situ propulsion, and have demonstrated the first ignition and combustion of several other unique in situ propellants for the Moon and Mars.



Research Combustion Laboratory cryogenic ignition hot-fire.

Space Communications Architectures and Subsystems

Glenn is developing architecture technologies, communication system technologies, and subsystem and component technologies to enable NASA's future missions in science and human

Glenn engineers and contractors deploying a surface proximity networking relay station during Arizona desert tests of Moon and Mars equipment.

exploration. Both within NASA and outside of NASA, we developed space communication architectures via commercial ventures and international forums, and we are a major supporter of extending the Internet into space. Technologies are being developed to support intelligent, autonomous communications architectures that enable anytime, anywhere operations and provide end-to-end information delivery from space directly to users.

Through coordinated studies with other NASA centers, Government agencies, industry, and academia, our scientists and engineers are designing feasible communication network architectures that enable the storage, transmission, and dynamic routing of large amounts of data at high rates among space assets and between space and ground assets. We have developed automatic fade compensation, bandwidth on demand, and full-mesh (point-to-point) time-division multiple-access networking. Glenn demonstrated satellite-Earth interoperability (making ACTS the first satellite on the Internet) and tested and analyzed inflatable space structures. We analyzed the radome structure for Raytheon (now in production) and were consulted regarding communications for inspecting the space shuttles via extravehicular activities.

Digital techniques that Glenn has demonstrated include onboard digital processing; software-defined-radio, reconfigurable transceivers; and very high speed modems. We led the Nation in developing solid-state microwave devices, including monolithic microwave integrated circuits (MMICs), wide-band-gap semiconductor and silicon germanium power amplifiers, and microelectromechanical-systems-(MEMS-) based radiofrequency phase shifters.

In communications component technologies, Glenn is the international leader in space-qualified, high-power, high-efficiency amplifiers for enabling high-data-rate Ka-band communication. Glenn also leads in hopping spot-beam antenna technology, which allows several users to transmit and receive at the same frequency on a time-shared basis. We are developing new concepts for lightweight, cost-effective antennas, such as large deployable antennas, ferroelectric steerable phased arrays, antennas integrated with solar cells for power, MEMS-based reconfigurable antennas, space-fed lens antennas, and cryogenic receivers for the Deep Space Network.

Glenn is the international leader in space-qualified, high-power, high efficiency amplifiers for … high-data-rate Ka-band communication.

Glenn led the development of the space communications architecture for the human exploration of the Moon, providing a foundation for the many communication architectures being defined for the lunar exploration vision.

Systems Integration and Analysis

Glenn performs space flight systems integration and analysis for a wide range of flight systems. Our success in this area began in the 1950s with our development of the first mission analysis capability for NASA: the first high-fidelity computer programs to design low-thrust trajectories for Mars missions. In the 1960s, we developed the first calculus of variations program to optimize Earth-to-Orbit trajectories. Recently, our scientists and engineers developed the OTIS version 3 trajectory analysis tool—a Government and industry standard that has been distributed to more than 70 organizations.

Glenn has many trajectory, power, propulsion, and communication models that provide the foundation for design, tradeoff, and analysis efforts. For human Mars exploration, we designed the bimodal nuclear thermal rocket and the solar electric power with chemical aerobrake options. With support from the U.S. Air Force, we led the development of space navigation architecture

for the human exploration of the Moon as part of the Beacon studies.

In 2003, Glenn led one of the four Next Generation Launch Technology architecture definition teams and led the performance discipline team for the Next Generation Launch Technology systems analysis project. Our scientists and engineers performed trajectory design, mission analysis, technology assessment, cost assessment, and requirements tradeoffs for the Jupiter Icy Moons Orbiter.

Human Research

Ensuring the health, safety, security, and effective performance of astronauts is critical for the human exploration of space. The NASA Human Research Program is addressing critical areas in astronaut health, safety, and performance that place NASA missions at risk. Glenn's program is conducted in collaboration with the Space and Life Sciences Directorate at the NASA Johnson Space Flight Center, which manages the NASA Human Research Program. The Human Research Program is a component of the Exploration Systems Mission Directorate at NASA Headquarters. Glenn and its strategic partners are participants in and significant contributors to the NASA Human Research Program. We draw on capabilities from throughout Glenn and our region.

Our efforts capitalize on our experience and capabilities in computational and experimental fluid physics—particularly in reduced-gravity environments; in space flight hardware development for physical science research payloads; and in finite element simulations, sensors, instrumentation, diagnostics, and other key research and development areas. Some of our unique capabilities include a state-of-the-art biophotonics lab containing a two-photon microscope, three-dimensional near-field microscope, and optical coherence tomography system; a vision research lab; a cell culture lab for mammalian cell culture with immunofluorescence staining, cryostorage, ribonucleic acid (RNA) isolation, and gel electrophoresis capabilities; and a quail egg culture lab.

Glenn's enhanced Zero-G Locomotion Simulator.

Our capabilities and experience are complemented by the preeminent clinical care, clinical research, and biomedical engineering capabilities of our strategic partners including the Cleveland Clinic Foundation, Case Western Reserve University, University Hospitals of Cleveland, and the National Center for Space Exploration Research. In fiscal year 2002, the John Glenn Biomedical Engineering Consortium was formed through a Space Act Agreement between Glenn and its partners. Consortium members have leveraged funding from other sources to benefit NASA's program objectives, and consortium funds have helped researchers at the member institutions. Successful consortium projects include noninvasive optical sensors for the early detection of eye diseases (currently being used by the National Institutes of Health and other leading medical centers) and a portable unit for metabolic analysis (PUMA).

Glenn and the Cleveland Clinic also have collaborated through a Space Act Agreement to establish the Cleveland Clinic's Center for Space Medicine. The agreement provides Glenn's scientists and engineers access to a network of more than 2000 Cleveland Clinic physicians and scientists to address the medical problems experienced by humans during long-duration space flight. This agreement also gives the Cleveland Clinic access to Glenn's physical science expertise to support their research and technology projects.

Researcher studying microvascular remodeling for astronaut health.

Finally, in support of the region's economic development goals in the biosciences, Glenn is a technology partner with BioEnterprise Corporation, a Northeast Ohio leader in growing bioscience companies. Glenn's recognized capability in interdisciplinary bioengineering for human systems includes fluid physics, fluids systems, advanced measurement diagnostics and instrumentation, analytic and computational modeling and analysis, optical systems, imaging analysis, biomedical engineering and bioengineering, advanced materials and processing science, materials science engineering, mechanics and durability, power systems, electrical and electronics systems, communications and network engineering, microelectromechanical systems (MEMS), nanotechnology, and extensive capabilities in design and development engineering and engineering science support.

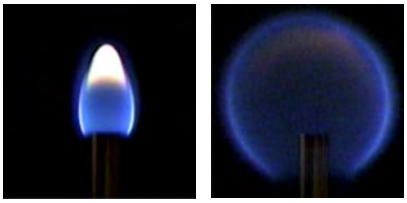
Our skills are coupled with the clinical research expertise of Glenn's partners to conduct applied programmatic research and to develop technology needed for the safe and productive human habitation of space. These efforts utilize the space environment for applied research and as a testbed (in addition to ground-based facilities) to verify technologies and countermeasures. Glenn has extensive experience in utilizing the space environment for basic and applied research, having developed and successfully flown over 125 microgravity science payloads on the space shuttle, *Mir*, and the ISS.

We focus on areas pivotal to astronaut health, safety, and performance under two NASA projects: Exercise Countermeasures and Exploration Medical Capability. The goal of the Exercise Countermeasures Project is to optimize and validate exercise protocols and equipment designs to maximize the health benefits to astronauts, minimize the time required for exercise, and minimize the volume and mass of exercise hardware. The goals of the Exploration Medical Capability Project are twofold: (1) to develop requirements and designs for clinical medical systems requiring little or no real-time support from Earth and (2) to develop a probabilistic risk-analysis model of health care delivery during exploration-class missions.

Microgravity Science

Fluid physics and combustion science research have been long-standing core competencies at Glenn because of their critical role in the success of our aerospace propulsion and power mission. Our work in low-gravity research and technology development began in the early 1960s and focused on the unique system and mission challenges introduced by the "zero-gravity" operating environment. To facilitate this work, we developed unique major low-gravity facilities (our 2.2 Second Drop Tower and 5.2-sec Zero-Gravity Facility) during the Apollo era. The mid-1980s saw a shift and major expansion of low-gravity efforts toward in-space research of a more fundamental nature, and Glenn secured a major role in this arena.

We have successfully conducted a broad space-based and ground-based microgravity research program in fluid physics, combustion science, materials science, acceleration measurement and analysis, and bioscience and technology. This program has produced considerable new knowledge and results that have appeared in prestigious journals,



Video images of ethane jet diffusion flames in quiescent air. Left: 1g (Earth gravity). Right: µg (microgravity).

including Science, Nature, the Journal of Fluid Mechanics, Physical Review Letters, Applied Physics Letters, Physical Review, Physics of Fluids, and Langmuir, and have resulted in several books. Some of the major milestones follow:

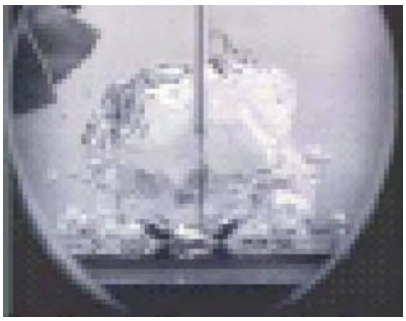
- The first-ever demonstration of sustained combustion in microgravity in the absence of any forced flow, a finding that many considered to be impossible. This has major implications on fire safety in space.

- The generation of unique benchmark data using aircraft and drop tower facilities and predictive modeling of flow regimes and pressure drops for liquid-gas two-phase flows in low- and reduced-gravity conditions.

- Pool boiling experiments conducted on the space shuttles that showed, for the first time, the feasibility of sustaining steady-state pool boiling in microgravity under certain conditions.

The program has to its credit more than 130 flight experiments and packages (including sounding rockets). For those flown after the *Challenger* disaster, 94 percent have had full mission success and 98 percent have had at least partial mission success. We have five hardware packages on the ISS today, with either our Space Acceleration Measurement System (SAMS) or Microgravity Acceleration Measurement System (MAMS) being in continuous operation since June 2001. SAMS and MAMS provide experimenters with critical information about the acceleration environment on the ISS and other microgravity platforms.

Two-phase liquid-gas flows. From top to bottom: normal gravity, lunar gravity, and microgravity.



Pool boiling in microgravity.

Loading an experiment module into Glenn's 5.2-sec Zero-Gravity Facility.

The Vision for Space Exploration has placed increased emphasis on technologies needed to enable exploration. This has resulted in a new focus for both space-flight- and ground-based research in spacecraft fire safety (flammability, detection, and suppression); chemical reacting systems and flows in exploration life support and in situ resource utilization; and thermal and fluid management processes (such as boiling and condensation; multiphase flow of vapor-liquid, solid-liquid, and solid-gas mixtures; and propellant management capillary-dominated fluid behavior and flows).

Glenn was the first to demonstrate more than a 50-percent reduction in jet engine exhaust noise using chevron nozzles in model-scale tests. Chevrons have subsequently been commercialized and tested on aircraft, as shown here on a GE90 engine on Boeing's 777 aircraft. (Copyright Boeing; used with permission.)

Aeronautics

Research and Development

Glenn develops advanced technologies for reduced noise and

Glenn develops advanced technologies such as ultra-low-emission combustors, chevron nozzles, and aspirated fans to improve the performance of and reduce the emissions and noise from aircraft engines.

During the Middle East oil crisis, we developed a new generation of high-speed propellers for commercial aircraft that demonstrated the potential to reduce passenger aircraft fuel consumption by 25 percent. Glenn then led the Energy Efficient Engine Project that developed and demonstrated technologies to significantly reduce the emissions from and improve the fuel economy of jet aircraft engines. The Energy Efficient Engine Project demonstrated a 15-percent reduction in fuel consumption relative to the best commercial aircraft engines in service at the time. These accomplishments enabled the development of the GE90 jet engine, the world's most powerful aircraft engine, which powers Boeing's newest intercontinental aircraft, the Boeing 777.

emissions and improved efficiency

Over the last 35 years, the maximum thrust of commercial aircraft engines has been increased from 40,000 lbf to over 100,000 lbf, while specific fuel consumption at cruise has been significantly decreased. Glenn research and development has played an important role in these advancements.

Advanced Turbine Engine Propulsion and Power Systems

Glenn's expertise in this area includes fundamental research, design, development, and testing of advanced concepts, components, and integrated systems for jet aircraft engines and alternative aircraft propulsion systems. Our scientists and engineers have played critical roles in many NASA programs.

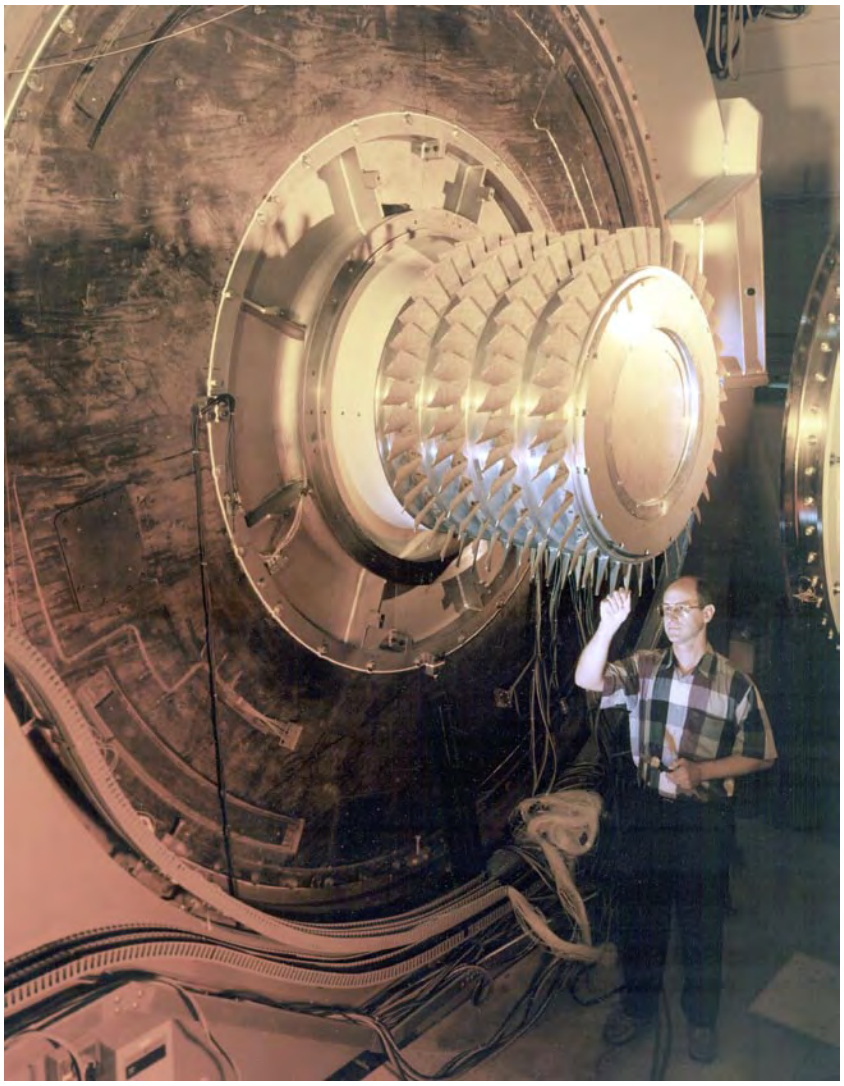
Over the last 30 years, NASA-sponsored technology has enabled the design and development of modern, high-efficiency turbofans with progressively higher thrust for greater aircraft capacity and range, and with progressively lower specific fuel consumption, emissions, and noise.

Modern high-efficiency turbofans ensure high efficiency by delivering limited airflow to the engine core, by achieving high combustion efficiency, and by enabling large airflows through the fan and low-pressure turbine.

Compressor technology

NASA's compressor programs date back to a NACA transonic flow stage that won the Goddard Award in 1967. Modern high-efficiency turbofans require an efficient (compact, higher work) compressor to deliver higher pressure (hotter) air to the combustor, without stall or surge, at lower leakage, without airfoil rubs or seal failures. In the past 40 years,

Project Manager Dr. Chowen Wey (woman in center with light hat) discusses the day's test plans with Aircraft Particle Emissions eXperiment (APEX) team members. Pictured far left is the assembly and probe stand that measures emissions data.



Glenn's large-size, low-speed compressor facility for fundamental turbomachinery research.

compressor operating pressure ratio has been increased from 15 to 55.

In support of NASA's compressor research, Glenn contributed first-generation computer programs for guiding the aerodynamic design and visualizing flows for NASA's Energy Efficient Engine and Engine Component Improvement programs (1975 to 1985). These computer programs enabled the design of more fuel efficient compressors with less tip and end-wall pressure losses, higher operating pressure ratios, and fewer blades, and they helped to reduce performance deterioration, surface erosion, and damage from bird strikes.

In the 1990s, we contributed to NASA's Advanced Subsonic Technology and General Aviation Programs by providing industry with access to NASA's second-generation multi-blade-row performance prediction computer program, APNASA, for analyzing highly three-dimensional flows around complex airfoils with viscoelastic damping and provided access to the Turbomachinery Aeroelastic Analysis (TURBO–AE) computer program to analyze unsteady effects, such as stall-flutter and forced response to surge.

In recent years, our compressor researchers have contributed to Ultra-Efficient Engine Technology (UEET) programs by designing and performing engine demonstrations of active and passive controls to enhance stability, improve stall margin, and even recover from stall, and by designing and demonstrating closed-loop fiber-optic controls to manage surge from inlet distortion at high angles of attack in military engines.

Our performance-prediction computer programs have enabled the design and optimization of complex three-dimensional compressor airfoils, including

- Swept blades to reduce shock loss
- Leaned-back impellers
- Bowed stators to reduce end-wall losses
- Contoured blade roots to prevent flow separation
- Blunt blade leading edges to reduce erosion
- Splitters for higher turning
- Tandem airfoils
- Advanced casing treatments to increase stall margin and counter inlet flow distortion
- Higher operating pressures
- Higher rotation rates
- Higher loading with fewer airfoils on fewer stages
- Reduced vibration and solutions to several performance failures
- Improved seal performance

Combustor technology

Modern high-efficiency turbofans require a stable higher inlet temperature and pressure combustor with a lower pattern factor (less radial temperature variation) to reduce thermal stresses on the turbine. In the last 40 years, emissions of nitrogen oxides (NO_X) have been decreased from 10 percent (for conventional technology) to almost 60 percent (advanced technology) below International Civil Aviation Organization 1996 regulation levels, while turbine inlet temperatures have increased from 2000 °F to goals of 3100 °F in the recent UEET Project.

NASA programs have contributed to lower combustor emissions with advanced fuel injectors and active controls, and durable combustor liners for hotter corrosive environments.

Glenn technologies continue to reduce NO_X emissions while increasing the

Ultra-Efficient Engine Technology (UEET) proof-of-concept compressor, a two-stage highly loaded compressor.

Sector test in Glenn's Advanced Subsonic Combustor Rig.

durability and stability of modern combustors. In support of combustor technology, we designed low-emission combustors, including upgrades with low-smoke and lower NO_X for the Pratt & Whitney JT8D engine. To reduce emissions in large aircraft engines, we developed dual annular combustors with the introduction of full-authority digital engine controls to reduce NO_X by 35 to 40 percent, twin annular premixed swirlers to reduce NO_X by 50 percent, and lean direct injectors with fuel staging to reduce NO_X by 50 percent and air staging to reduce NO_X by 70 percent. Our scientists and engineers designed and performed component testing of rich-quench lean combustors, including shorter rich-quench lean combustors with fuel-air management to reduce NO_X by 50 and 70 percent. We also advanced combustion core competencies: such as laser diagnostics, fuel reformer technology, chemical kinetics, ceramic MEMS multi-injectors, and combustion instability control. These are critical technologies to achieve the aggressive low-NO_X goals.

Glenn developed active pattern factor controls and active combustor stability control with wireless sensors and active feedback. For specialized applications, we created and tested three-dimensional models of slinger combustors with inherently low emissions for small gas turbine engines and developed lean premixed, prevaporized combustors for high mach number flight.

In the area of combustor structures, we developed durable high-temperature combustor liners and developed and tested ceramic liners for high-energy-density slurry fuels, segmented finwall liners of turbine alloys, and shingled liners. After conducting early studies of ceramic liners for missiles, we developed and tested 2200 °F ceramic matrix composites for liners, and thermal and environmental barrier coatings to enable 2400 °F operation and the potential for 2700 °F.

Glenn developed the National Combustor Code (NCC) computer program in 1998. When linked with our turbomachinery performance prediction program, APNASA, the NCC program enabled performance prediction for a complete gas turbine engine.

Turbine technology

The modern high-bypass-ratio turbofan requires high work turbines with high-temperature materials and effective internal cooling to withstand the very high gas temperatures in the engine. Over the last 40 years, turbine inlet temperature has been increased from 2000 °F to over 3000 °F, contributing to the more than doubling of engine thrust from 40,000 lbf to over 100,000 lbf.

NASA's Energy Efficient Engine Project provided first-generation aerodynamic design tools that enabled the design of highly three-dimensional cambered airfoils to optimize turbine loading and efficiency. Glenn also sponsored the development and verification of simplified computer programs for turbine blade design including aerodynamic shape and heat transfer. These tools enabled the design of higher work, higher efficiency turbines, including Pratt & Whitney's first single-stage, high-pressure turbine, with fewer airfoils and higher tip speed.

Glenn developed the National Combustor Code (NCC) computer program … [that with] APNASA … enabled performance prediction for a complete gas turbine engine.

For NASA's Advanced Subsonic Technology, General Aviation Propulsion, and UEET programs, Glenn provided access to NASA's second-generation APNASA multi-blade-row analysis and TURBO–AE unsteady effects computer programs, enabling the first three-dimensional analysis of an entire high-pressure/low-pressure turbine system, including cooling, leakage, and unsteady effects.

Our scientists and engineers developed three-dimensional design tools for the design of blade-coolant passages. Unsteady analyses were developed to optimize rotor-stator spacing and to reduce the effect of unsteady forces on the turbines. These analyses were used to model the migration of combustor hot streaks through the turbines to predict blade heat loads. All of these improved capabilities added to the understanding of turbine aerodynamics and heat

transfer, resulting in improved turbine design methods.

Modern high-bypass-ratio turbofan designs require low-pressure turbines with increased efficiency. Higher work turbines, operating at slower rotational speeds, are required by larger fans. Alternatively, geared turbines require very high specific work designs.

NASA programs contributed to first-generation three-dimensional aerodynamic designs for higher efficiency, low-pressure turbines to harness the exit swirl of the high-pressure turbine. These programs also contributed to second-generation aerodynamic designs that addressed multi-blade-row and unsteady effects. Included in these designs are counterrotating low-pressure turbines with and without first-stage vanes and closely coupled turbines (without a midframe) for substantial weight savings.

NASA supported the development of uncooled and cooled low-pressure turbines, turbine tip clearance controls to reduce fuel burn, turbine flow controls using suction and blowing, turbine health monitoring, and turbine seals including ceramic-coated labyrinth seals, braided rope seals, brush seals, feather seals, and finger seals.

Turbine Engine Noise Reduction

Fan technology

Modern high-bypass-ratio designs require a larger, more efficient fan to deliver higher bypass and thrust-to-weight ratios. The larger fans have to be lighter weight and more robust, and they have to be designed for lower noise. Over the last 40 years, the bypass ratio has been increased to 9, and it is envisioned to increase to between 10 and 20 by 2015 and to 25 by 2025. The technologies developed under NASA programs provide a new generation of quiet, efficient fans that reduce specific fuel consumption by up to 14 percent, with more than 6 dB of potential noise reduction as demonstrated by various industry partners in both rig and full-engine tests.

… technologies developed under NASA programs provide ... quiet, efficient fans that reduce specific fuel consumption by up to 14 percent, with more than 6 dB of potential noise reduction …

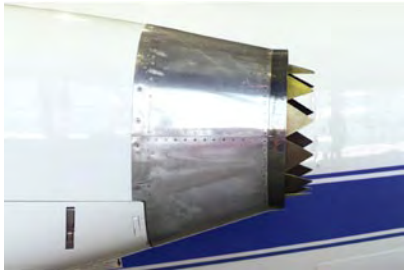
Glenn programs have contributed to first- and second-generation aerodynamic and aeroacoustic fan designs, including wide-chord fans for lower noise, low-tip-speed fans with optimized rotor-stator spacing, fans with swept and leaned airfoils for low shock loss and less broadband noise, and fans with trailing-edge blowing and suction-side bleed for wake control.

Fan aerodynamic performance has been enhanced by using twisted blading for higher efficiency and by using fans with tandem staging and splittered rotors for higher turning. Fan operability has been improved through the development of shroudless fans with less stall-flutter and forced response, advanced casing treatments for improved stall margin, and active controls for stall management and stability enhancement.

Exhaust system technology

Modern high-bypass-ratio turbofan engines require a quiet, fuel-efficient exhaust of lightweight, high-temperature

Fan trailing-edge blowing model in Glenn's 9- by 15-Foot Low-Speed Wind Tunnel.



Chevron nozzle.

materials. In exhaust system technology, Glenn has contributed to the development of daisy-lobed exhaust mixers for reduced noise and fuel burn, and to mixers with chevrons and tabs for significant jet noise reduction. Exhaust mixers have been developed to significantly reduce infrared signature for military applications. In addition, silicon-carbide-reinforced titanium-aluminide nozzle materials have been developed for high-temperature strength and extreme oxidation resistance, and gamma titanium-aluminide nozzle materials have been developed for light weight and high temperatures.

Propulsion Control and Engine Health Management

With the increased emphasis on aircraft safety, enhanced performance, and affordability, and with the need to reduce the environmental impact of aircraft, there are many new challenges being faced by the designers of aircraft propulsion systems.

Glenn, in collaboration with industry, academia, and other Government agencies, has been at the forefront of developing advanced controls and health management technologies for aircraft engines that will help meet these challenges through the concept of an intelligent engine. The key enabling technologies are active control for increased component efficiency, advanced diagnostics and prognostics integrated with intelligent engine control to enhance component life and propulsion system safety, and distributed control with smart sensors and actuators in an adaptive fault-tolerant architecture.

In the late 1970s and early 1980s, Glenn developed technologies for advanced fault detection and isolation in aircraft engines and demonstrated these technologies on F–100 engine tests. This effort contributed to enhancements in aircraft engine reliability and safety, since the technologies form the basis of the fault diagnostics systems on current commercial engines.

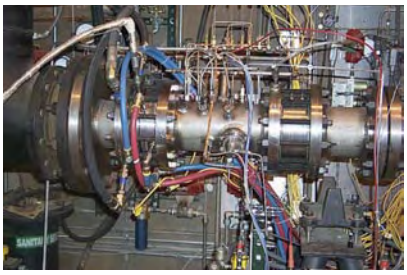
In the late 1980s and early 1990s, Glenn developed a fundamentally new integrated aircraft/propulsion-control-system design method called Integrated Methodology for Propulsion and Airframe Control (IMPAC). This method is applicable to aircraft that have a high degree of coupling between the flight and the propulsion system, such as short-takeoff-and-vertical-landing and hypersonic aircraft. IMPAC was successfully demonstrated on an advanced short-takeoff-and-vertical-landing configuration in fixed-base piloted simulations, establishing Glenn's leadership in applying robust multivariable control technologies to aircraft propulsion systems.

In the late 1990s, in collaboration with the NASA Dryden Flight Research Center and Pratt & Whitney, Glenn tested High Stability Engine Control on the F–15 aircraft, demonstrating that inlet distortion impact on stall margins can be accommodated through active control. This technology will enable the safe operation of aircraft engines with reduced stall margins, thus increasing efficiency and lowering emissions. Glenn also developed the High Reliability Engine Control concept, which uses autoassociative neural networks to create estimates of engine sensors that can be used to reliably control the engine in case of hardware sensor failures. In engine-control hardware-in-the-loop simulations, this technology was demonstrated to allow engine operation with a D10 status (i.e., the engine could be operated safely for 10 days beyond sensor failure before sensor replacement needed to be scheduled).

Glenn is the recognized international leader in aircraft engine stall control and combustion instability control, which are both critical technologies to enable low-emission operation of high-efficiency propulsion systems. In 2001, in collaboration with GE Aircraft Engines, our scientists and engineers

Glenn is the recognized international leader in aircraft engine stall control and combustion instability control, … critical technologies to enable low-emission … high-efficiency propulsion systems.

Glenn researchers fabricate microelectromechanical systems (MEMS) in this clean room. The air quality, humidity, and temperature are controlled to prevent contamination of sensitive material like MEMS.



Liquid-fueled combustor rig used for successful demonstration of combustion instability suppression control in an enginelike environment

demonstrated successful active stall control on an advanced multistage, highly loaded compressor design using air injection in the compressor inlet based on online stall precursor identification from pressure measurements at the compressor exit. This technology will enable efficient operation of highly loaded turbomachinery without compromising safety. In addition, combustion instability modeling and control technologies were developed, and the feasibility of suppressing thermoacoustic instabilities in lean-burning combustors was demonstrated. This was the first such demonstration on a combustion rig that exhibited all the characteristics of an engine combustor. Controlling such instabilities will enable low-emission combustors to operate safely over the whole flight envelope.

Glenn also pioneered the concept of life-extending control, which allows designers to enhance the on-wing life of aircraft engines while achieving the performance required by Federal Aviation Administration regulations. In control hardware in-the-loop demonstrations, an intelligent life-extending control that optimizes the engine acceleration schedule was shown to result in 25-percent less thermomechanical fatigue damage to life-critical parts for typical engine operation. This technology led to efforts within the aircraft engine industry to mature the life-extending control technology.

Under the NASA Aviation Safety and Security Program, our scientists and engineers are working in close collaboration with industry partners to develop and apply model-based controls and diagnostics technology to prevent or mitigate safety-significant propulsion system malfunctions—such as engine surge and stall, asymmetric thrust, and in-flight engine shutdowns—that, when coupled with crew error, have resulted in aircraft accidents and incidents.

In addition to the collaborative efforts with industry, we have developed an advanced approach to fault detection and isolation that will reliably distinguish between sensor failures and component faults even as engine performance degrades because of aging. Current research includes adaptive propulsion control for reducing pilot workload by accommodating the effects of throttle-to-thrust response changes due to engine performance degradation with usage, as well as for enhancing aviation security by safely accommodating the effects of damage to an aircraft or engine from a hit by a shoulder-fired missile.

Underpinning the controls and health management activities just described is the development of diagnostic systems. Glenn developed a posttest diagnostic system for the Space Shuttle Main Engine that reduced test data analysis time from 1 week to 2 days. In addition,

Glenn … pioneered the concept of life-extending control, which allows designers to enhance the on-wing life of aircraft engines while achieving the performance required by Federal Aviation Administration regulations.

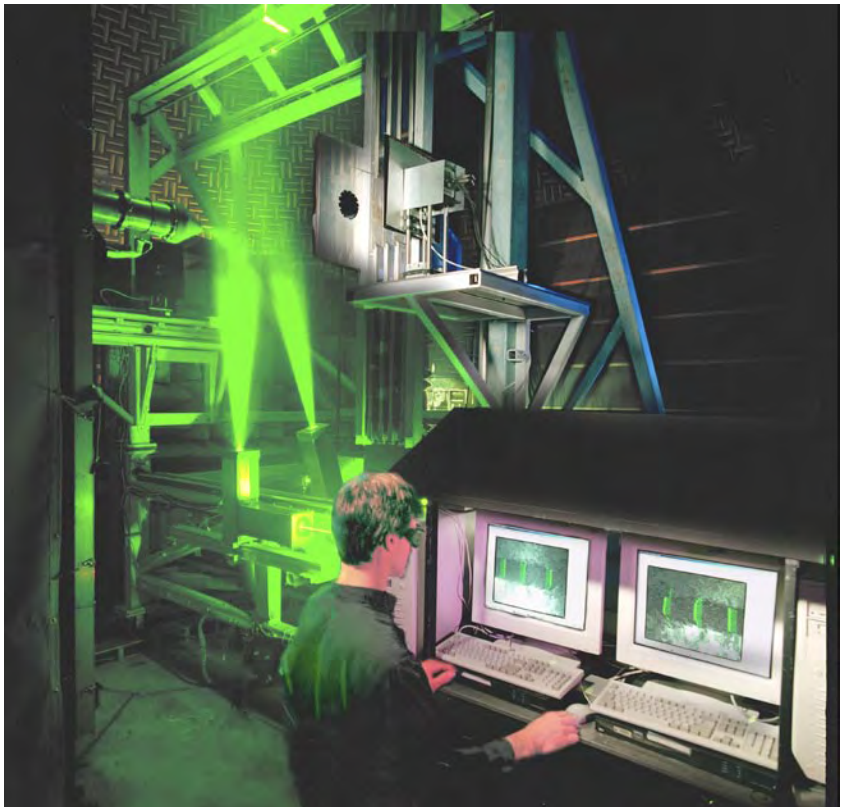
a Web-based system was developed for the X–33, and its benefits in detecting and diagnosing engine anomalies from sensor data were demonstrated in testing on the Rocketdyne X–33 Aerospike engine.

Our scientists and engineers demonstrated fault diagnostics in real time on flightlike hardware under the multicenter Propulsion Integrated Vehicle Health Management Technology Experiment (PITEX) and used data from sources such as sensors and onboard component models for data fusion in support of propulsion health monitoring. Optimal sensor selection technology for the RS–83 and RS–84 rocket engine propulsion systems was developed under the Next Generation Launch Technology Program. This technology allows the choice of the right type and minimal number of sensors to detect and isolate component and system faults.

[For] propulsion systems control and health management … Glenn designed and developed a MEMS-based hydrogen-leak detection sensor and flight tested it on the space shuttles, Hyper-X, and Helios vehicles.

The development of sensors and high-temperature electronics is also a key to propulsion systems control and health management. For this work, Glenn designed and developed a MEMS-based hydrogen-leak detection sensor and flight tested it on the space shuttles, Hyper-X, and Helios vehicles.

Finally, silicon-carbide-based electronic components have been developed and demonstrated that can withstand temperatures up to 600 °C. These electronics have inherent high-radiation tolerance and operate at temperatures 2 times higher than for traditional silicon electronic devices and with efficiencies up to 10 times higher than for traditional silicon power-switching devices.



Particle image velocimetry uses light reflected from seed particles in the flow to measure velocities of the air exhausting through nozzles.

Instrumentation Systems

Measurement systems and research diagnostic methods are key components of experimental aerodynamics research and nondestructive evaluation methods. For more than 30 years, Glenn has developed and demonstrated optical flow and temperature measurement techniques—including laser velocimetry, planar particle imaging velocimetry, and Rayleigh scattering—for collecting flow information in the high-temperature environment of aircraft engine turbomachinery and combustion components and turbulent exhaust jets.

We also advanced the state-of-the-art in pressure-sensitive paint techniques. Our scientists and engineers pioneered the development and application of pressure-sensitive paint technology to collect pressure distribution data on ice formation on aerofoils in our Icing Research Tunnel, significantly reducing the amount of time needed to determine the effect of ice formation on flow over wings. We also developed nondestructive evaluation methods and physics-based models for structural inspection, health

monitoring, and life estimation of aircraft engine components. These techniques, which include acoustic emission, eddy-current, piezopatch, and ultrasonic guided techniques, can also be used for the health monitoring and life estimation of nuclear pressure vessels.

Avionics

Glenn provides electrical and electronic development engineering support to space and aeronautics projects and research activities in the areas of avionics systems; hybrid power systems; radiofrequency/communications systems; electrical power system distribution and control; and electromagnetic interference/electromagnetic compatibility design, analysis, consultation, and failure resolution.

Aircraft Communications

We provide communications system performance analysis, simulation, and research to identify and create system-level products for NASA aeronautics and space missions. Analytical capabilities include orbital coverage analysis, link performance analysis, network analysis, interference analysis, and technology assessment. Major research areas include laboratory system integration, system-level experiments, and performance measurement.

NASA Learjet deicing.

Pilot performing an approach to landing using the Ice Contamination Effects Flight Training Device, with an instructor observing pilot reactions.

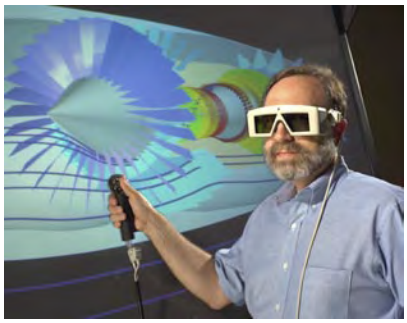
Aircraft Icing Research

NACA and NASA have been involved in icing research since the 1930s, first at the NASA Langley Research Center and then at Glenn (1940s). In support of icing research, Glenn developed ground deicing techniques for large transports and investigated the flight icing difficulties of smaller airplanes, which was driven by the boom in commuter aviation. We also developed ways to prevent ice formation on turbine-powered commercial aircraft, helicopters, and military planes. Ice-formation studies have been conducted utilizing our Icing Research Tunnel and our LEWICE computer program, which models ice accretion on aircraft under various meteorological conditions.

Our Icing Research Tunnel, the largest U.S. wind tunnel that can duplicate aircraft icing conditions, and icing research flights conducted by our research aircraft have also been used to develop aircraft deicing mechanisms, pilot advisory manuals, and video and Web-based training programs to mitigate aircraft crashes due to ice buildup on aircraft surfaces.

Modeling and Simulation

NASA has kept abreast of the computer revolution by investing in mainframe computers (Glenn's Research Analysis



Glenn's Graphics and Visualization Laboratory.

Center), supercomputers (Glenn's Cray 1S and NASA Ames Research Center's National Aerodynamic Simulator), distributed computing networks, parallel computers (e.g., Glenn's IBM SP2–1), and parallel computing clusters (e.g., the Silicon Graphics Origin) to enable the analysis of highly complex system designs and the performance of entire aircraft engine flow paths.

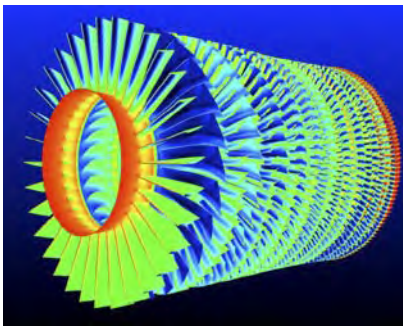
In support of modeling and simulation, Glenn developed computer programs to provide computer-aided design capability to the process of aircraft and rocket engine design. In some cases the actual programs have been used by industry, and in other cases the methodologies have been incorporated by industry into proprietary design methods. Our modeling and simulation advancements are used within the design systems of all jet aircraft engine manufacturers in the United States. These tools reduce design time by 50 percent, guarantee that engine designs meet performance goals, and assess the structural safety of engine components.

- **NPSS, Numerical Propulsion System Simulation**—This software allows multifidelity analysis in designing aircraft engines, offering key technological advances to increasing the competitiveness of the U.S. aerospace industry. GE Aircraft Engines estimates a 55-percent reduction in engine analysis time using this new software. NPSS is an emerging U.S. standard for aerospace simulations and is built and maintained with the full interaction of every major aircraft engine manufacturer in the United States.

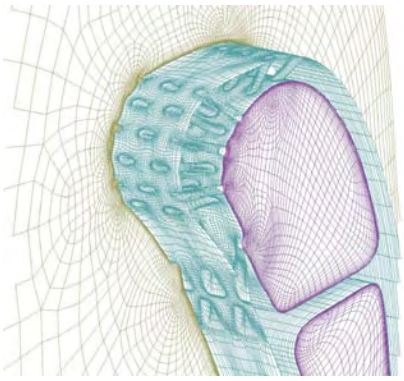
- **APNASA, Average-Passage Turbomachinery Aerodynamics Prediction**—This code simulates the time-averaged three-dimensional flow field within a typical passage of a blade row embedded within a multistage compressor or turbine. The flow field within each blade row is calculated using information from the neighboring blade rows to properly account for the fact that each blade row within a multistage component does not operate in isolation. APNASA has been used in support of numerous aerodynamic designs of axial flow turbomachinery. It can predict the aerodynamic performance at design as well as at off-design conditions. The current version of APNASA runs on clusters of work stations using a Unix operating system.

- **NCC, National Combustion Code**—This code provides aerospace and nonaerospace engineers and designers with a detailed understanding of complex combusting flow fields. It is often used to complement, and sometimes substitute for, the rig test. This leads to reduced costs, deepened insight, and improved foresight. NCC features high-fidelity representation of complex geometry, advanced models for liquid and gaseous turbulent combustion, and massively parallel computing. Scientists and engineers at Glenn have been using NCC to provide analysis and design support for various aerospace propulsion technology projects such as fuel injectors for emissions reduction, revolutionary turbine accelerators, rocket-based combined-cycle engines, and advanced rocket combustor

… GE Aircraft Engines estimates a 55-percent reduction in engine analysis time using … [Glenn's NPSS] software.



Aerodynamic pressure contours from an APNASA simulation of a compressor for the GE90 turbofan engine that powers the Boeing 777 airplane.



Detailed Glenn-HT grid for conjugate film cooling.

concepts. An increasingly popular use of NCC is for the prediction and analysis of unsteady reacting flows in various combustion devices.

- **Glenn-HT, turbine heat transfer prediction**—This is a computational fluid dynamics (CFD) program for the analysis of three-dimensional flow and convective heat transfer in a gas turbine. The code is unique in its ability to give highly detailed representations of flow fields very close to solid surfaces. This ability is necessary for obtaining accurate representations of fluid heat transfer and viscous shear stresses. Another unique feature of this code is the use of a multiblock grid system that includes high-quality grid structures very close to walls, eliminating the need for wall functions for calculating heat transfer. A conventional aspect of the code is the inclusion of a two-equation k-ω mathematical model of turbulence (where k denotes the turbulent kinetic energy and ω denotes the fractional rate of dissipation of k).

  This code has been used extensively to calculate cooling-passage flow and hot-gas-path flow, including detailed calculations of film cooling and of complex tip-clearance-gap flow and heat transfer. The code has been validated for a number of turbine configurations. Although developed and used primarily as a research tool, the code should also be useful for detailed design analysis.

- **TURBO–AE, Turbomachinery Aeroelastic Analysis**—This code predicts aeroelastic and unsteady aerodynamic problems that can cause turbomachinery blades in commercial and military jet aircraft engines to fail because of structural fatigue. The program calculates aeroelastic vibration characteristics (flutter and forced response) by modeling the unsteady flow through turbomachinery blade passages with rotating and vibrating blades and calculating the energy exchange that occurs between the air inside the engine and its blade structure. Reynolds-averaged Navier-Stokes equations are solved numerically to obtain extremely accurate unsteady flow field descriptions through realistic, physics-based modeling. TURBO–AE provides a high-fidelity modeling of subsonic, transonic, and supersonic flow regimes with attached and/or separated flow fields for aeroelastic applications.

  The TURBO–AE software has been released and distributed to U.S. aircraft engine manufacturers, Government organizations, and academia. These agencies consider TURBO–AE to be a world-class turbomachinery aeroelastic simulation tool. Significant cost and time savings are being realized by using the code in the design cycle of new turbomachines. These cost savings come from avoiding program delays by identifying the aeroelastic problems early during the design phase and also from helping to reduce and eliminate in-service problems encountered by the engines.

- **CARES, Ceramics Analysis and Reliability Evaluation of Structures**—This general-purpose series of integrated design software tools provides an innovative, cost-effective approach to systematically optimize the design of brittle material components using probabilistic analysis techniques. CARES is used by over 400 academic, Government, and industrial organizations to predict the durability and lifetime of brittle materials (including monolithic structural ceramics, glasses, intermetallics, and ceramic matrix composites) for automotive, aerospace, medical, power generation, and nuclear applications. Three programs compose the CARES series of computer software:

Hip joint modeled with CARES for a biomedical application.

CARES ... design software tools … systematically optimize the design of brittle material components using probabilistic analysis. CARES is used by over 400 academic, Government, and industrial organizations.

  - **CARES/*Life*** was developed to predict the reliability and life of structures made from advanced ceramics and other brittle materials such as glass, graphite, and intermetallics.

- **CARES/*Creep***, an integrated design program, is used to predict the lifetime of structural ceramic components subjected to multiaxial creep loads.

- **C/CARES** (Composite CARES) was developed to address aerospace design issues relating to ceramic matrix composites. The goal is to predict the time-independent reliability of a laminated structural component subjected to multiaxial load conditions.

SmaggIce project team.

- **GENOA, a failure analysis software program**—GENOA simulates and predicts aging and failure in structural materials, including monolithic or laminated metallic, ceramic, or polymeric material in two- or three-dimensional structures used in airplanes, cars, engines, and bridges. GENOA's progressive failure analysis can predict the crack initiation, growth, and final failure of monolithic and composite materials. On the basis of material-property data, finite-element mathematical models, and service conditions, GENOA–PFA simulates the initiation and progression of damage, ultimately leading to global structural failures in composite-material structures. The composite materials include complex architectures in which fibers are placed in two- or three-dimensional weaves or braids.

- **LEWICE, ice accretion prediction software**—Glenn's Icing Branch has a comprehensive, multidisciplinary research effort aimed at the development of design and analysis tools that can aid aircraft manufacturers, subsystem manufacturers, certification authorities, the military, and other Government agencies in assessing the behavior of aircraft systems in an icing environment. These tools consist of computational and experimental simulation methods that are validated, robust, and well documented. In addition, these tools are supported through the creation of extensive databases used for validation, correlation, and similitude. The primary tools developed and supported by the branch are LEWICE, LEWICE3D, and SmaggIce.

  - **LEWICE**, Lewis Ice Accretion Program, is a software program used by literally hundreds of users in the aeronautics community for predicting ice shapes, collection efficiencies, and anti-icing heat requirements. LEWICE performs its analysis for two-dimensional geometries in minutes on a desktop personal computer, allowing a user to run several parameter studies for design purposes. The ice-shape predictions have been used to assess performance degradation both as input to a CFD program or experimentally in flight or in a wind tunnel. The ice-shape predictions have been validated against a wide variety of experimental conditions.

  - **LEWICE3D**, LEWICE Three-Dimensional, is a computational tool developed by Glenn's Icing Technology Branch to determine the icing characteristics of full three-dimensional aircraft. The tool can be used as an aid in the design, development, and certification of aircraft ice-protection systems. It can predict water loading and single-time-step ice shapes for a variety of aircraft surfaces including wings, inlets, fuselages, and radomes.

  - **SmaggIce**, Surface Modeling and Grid Generation for Iced Airfoils, is a software toolkit being developed at Glenn for the aerodynamic performance prediction of iced airfoils with grid-based CFD. It includes tools for data probing, boundary smoothing, domain decomposition, and structured

grid generation and refinement. SmaggIce provides the underlying computations to perform these functions, a graphical user interface to control and interact with those functions, and graphical displays of results.

Alternative Fuel Systems

Hydrogen-powered aircraft

The use of hydrogen as an aircraft fuel has tremendous environmental benefits with the elimination of carbon monoxide, carbon dioxide, sulfur oxides, unburnt hydrocarbons, and smoke. For combustion-based systems, the remaining emissions are trace amounts of unburnt hydrogen, water, and nitrogen oxides (NO_X). With electric-based systems, even the NO_X emissions can be eliminated.

The earliest flight of a hydrogen-based aircraft was in 1956, when our researchers flew one gas turbine engine of a Boeing B–57 on hydrogen. However, the use of hydrogen does not eliminate the potential for increased NO_X production due to higher flame temperatures. The problem can be resolved for hydrogen systems by taking advantage of the wide flammability range of hydrogen and running the combustion systems lean. Glenn has been working on and recently tested several hydrogen fuel injector concepts that obtain excellent combustion efficiency while significantly reducing NO_X.

Glenn's scientists and engineers started to take a new look at hydrogen aircraft in the mid-1990s under the Zero Carbon Dioxide Emissions Technology project. Because of the low density of hydrogen, even in the liquid state, design changes must be made to the aircraft propellant storage system. Fuel can no longer be stored easily in wing fuel tanks. Over the years, a number of solutions have been proposed. The key will be to maximize the amount of propellant available in a lightweight, low-boiloff system. In recent years, we have made advancements in lightweight composite polymer tanks and aerogel insulation that could significantly reduce the propellant storage system weight for cryogenic hydrogen-based systems.

The processes and operation procedures for cryogenic systems also can have a significant impact on aircraft configurations. One such technology is propellant condition. In support of the space program, our scientists and engineers developed techniques to increase the density of hydrogen with subcooling. For example, subcooling propellants to 27 °R (15 K) may increase density by 9 percent.

Closeup of the Helios prototype on a lake bed.

Propulsion and power systems

The Environmental Research Aircraft and Sensor Technology (ERAST) program, which ended in 2003, was a

joint NASA-industry initiative to develop and demonstrate aeronautical technologies that could lead to a family of uninhabited aerial vehicles, and included the Helios prototype aircraft. Glenn supported the ERAST program by providing technical expertise and guidance on power and propulsion.

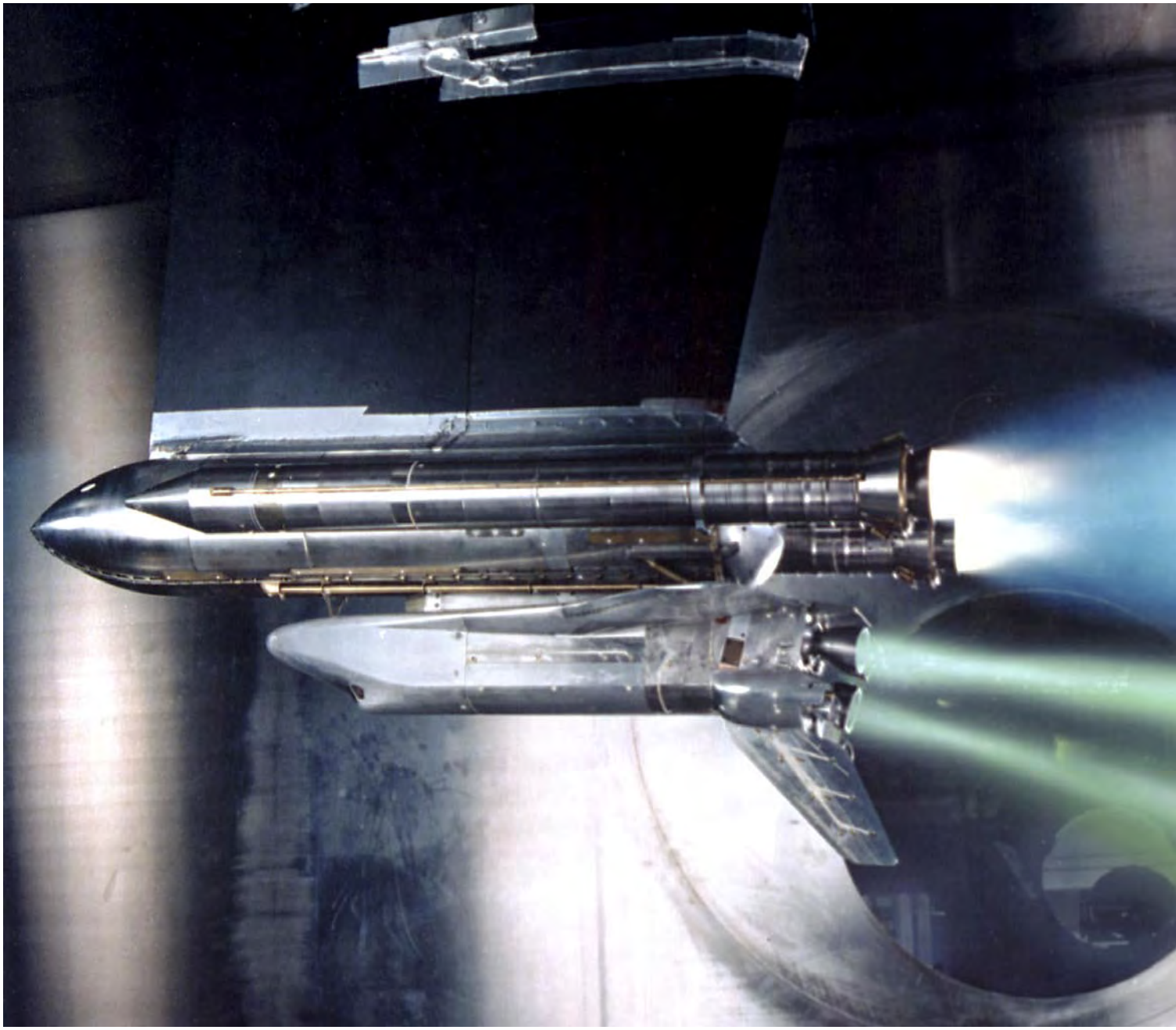
Glenn was the first NASA center to demonstrate a fully closed loop charge/discharge cycle of a hydrogen-oxygen regenerative fuel cell system where the reactants and products are completely contained.

We also initiated an effort to develop a fuel-cell energy-storage system to help an industry partner address unresolved technical challenges that prevented a regenerative fuel cell system from being used on the Helios prototype aircraft. Specifically, we established a regenerative fuel cell testbed that is currently being used to address operational issues with fuel cells and to evaluate performance and degradation mechanisms.

Glenn was the first NASA center to demonstrate a fully closed loop charge/discharge cycle of a hydrogen-oxygen regenerative fuel cell system where the reactants and products are completely contained. This accomplishment demonstrated the potential of the system to be recycled indefinitely. The work continues under the Low Emissions Alternative Power project. Glenn also is developing advanced batteries and fuel cells to meet the energy production and storage needs for future High Altitude Long Endurance (HALE) missions.

We are pursuing advanced rechargeable lithium batteries for space applications, with a focus on improving specific energy, increasing cycle life, and improving low-temperature performance. Our scientists and engineers are also advancing high-temperature fuel-cell technologies, including high-temperature proton exchange membrane and solid oxide fuel cells by developing new materials, material processes, and cell designs to enable high-specific-power (kilowatt per kilogram) fuel-cell stacks. A recently demonstrated fabrication process for an innovative solid oxide fuel cell design will likely improve specific power by an order of magnitude greater than for designs being pursued for ground-based applications.

Glenn successfully developed and demonstrated in a dynamometer altitude chamber a three-stage turbocharged spark-ignited (SI) engine for atmospheric science uninhabited aerial vehicles to altitudes exceeding 90,000 ft. In addition, low-Reynolds-number heat exchanger cores were designed, developed, and tested in an altitude chamber flow facility. A 40-percent improvement in heat transfer (same pressure drop) was demonstrated over the previous state of the art.



Space shuttle engine-out test performed in Glenn's 10- by 10-Foot Supersonic Wind Tunnel.

Research and Development

That Advances Both Aeronautics and Space

Glenn is distinguished by its unique blend of aeronautics and

Glenn is distinguished by its unique blend of aeronautics and space flight expertise and experience. The benefits of this synergy can be seen most clearly in our research and development activities in power and energy-conversion systems, diagnostics and sensors, avionics and communications, materials science, and aerospace structures.

Power and Energy-Conversion Systems

We are leading the effort to evaluate and develop fuel-cell and regenerative-fuel-cell energy-storage systems for space missions with long eclipse periods ("nights"), during which solar cells cannot generate electricity, such as Moon and Mars bases. This technology is also applicable to unmanned aerial vehicles and high-altitude balloons. Totally passive (nonmoving) components are the focus of our efforts to minimize the weight, improve the energy density, and maximize the reliability of these systems.

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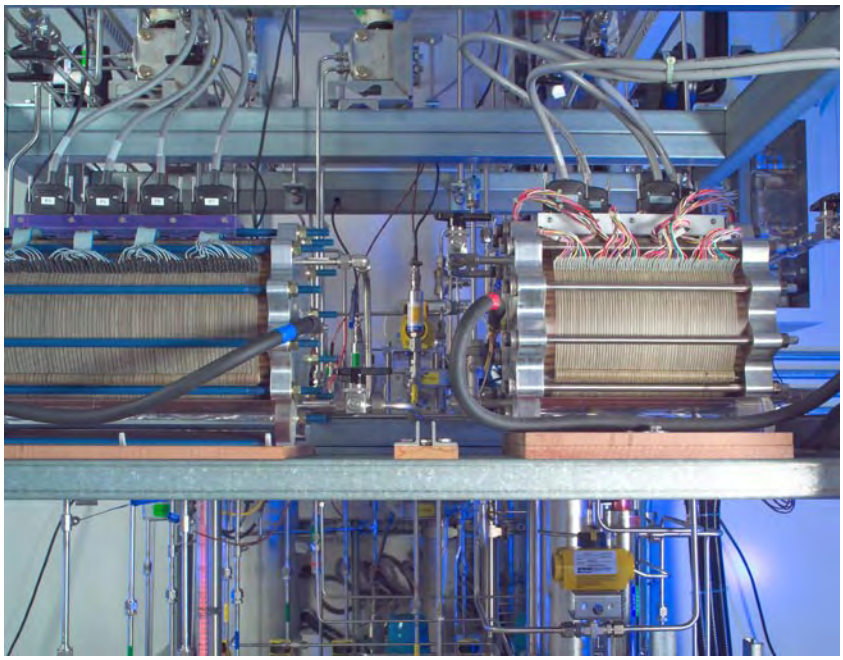

Closed-loop regenerative fuel cell test and integrated equipment assembly.

Diagnostics and Sensors

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Materials Science and Aerospace Structures

Our materials and structures research and development was initiated in 1943. Since then, Glenn has become a world leader in materials and processing, protective coatings, mechanics of materials, life prediction, structural mechanics, impact mechanics, structural dynamics, aeroelasticity, mechanical components, seals, and most recently, tribology and surface sciences, with a focus on structures technologies and structural systems for aerospace propulsion and power.

Advanced materials and structures are necessary to enable propulsion systems to operate at high temperatures for improved performance and for reduced undesirable emissions. Lightweight materials and structures help to reduce the weight of propulsion and power systems, which in turn reduces the fuel burnt. Reduced fuel burn minimizes the emission of undesirable gases, reduces the cost of air flight for the public, and increases usable payload for spacecraft.

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Depending on the operating conditions at various locations within a propulsion system, structural components need to be made of different materials—such as metals, ceramics, and polymers. Also, depending on the thermal and chemical environment, thermal and environmental protective coatings need to be developed and used to ensure that the structure does not degrade in time and result in system failure.

Utilizing these advanced materials, in collaboration with individual manufacturers, Glenn has developed a wide range of materials and coatings for aircraft engine components, including advanced directionally solidified single-crystal turbine alloys, advanced high-temperature alloys without the cost of single crystals, thermal and environmental barrier coatings for turbine blades and combustors, dual-property powder metallurgy disk alloys, ceramic-coated structural materials, and gamma-titanium aluminide components such as nozzles and compressors and low-pressure turbine airfoils.

In addition, Glenn has developed materials for power systems such as solid-oxide fuel cells and lithium/polymer batteries, which can be used as power sources for both aircraft and spacecraft. These systems have high specific power to enable NASA's exploration missions.

High-temperature propulsion materials

Advanced metallic materials

NASA initiated the development of oxide-dispersion-strengthened alloys in the mid-1960s. Glenn contributed to the thermomechanical processing of these alloys and to elucidating their unique failure modes. This research with the International Nickel Company and several universities yielded iron-base MA956 and nickel-base MA754 alloys—popular commercial sheet alloys.

Superalloys for aircraft engine disks and turbine blades represented the next chapter in our research and development accomplishments. The world's most advanced single-crystal superalloy, EPM102, and a powder metallurgy disk

Our recently developed copper alloy GRCop-84 has become the most significant advancement in rocket combustion chamber materials in over 30 years.

alloy, ME3, are being incorporated into current aircraft propulsion systems. Our recently developed copper alloy GRCop-84 has become the most significant advancement in rocket combustion chamber materials in over 30 years. Structural designs to enable lighter weight, higher performance, and longer life combustion chambers are now baselined for combustor and flowpath applications by all three rocket propulsion companies: Aerojet, Pratt & Whitney, and Northrup Grumman Corporation.

In addition, Glenn's expertise in high-temperature metallic materials supported the NASA Engineering and Safety Center (NESC) in their investigation of cracking discovered during routine inspection of the space shuttle orbiter reaction control system. Extensive material testing, evaluation, and stress and fracture analysis established the root cause of the cracking and determined that the thrusters with cracks have sufficient safety margins to fly for the remainder of the space shuttle program. This investigation also determined that processes currently used to rejuvenate the thrusters need to be modified to prevent exposure to hydrogen that can compromise the thruster material properties.

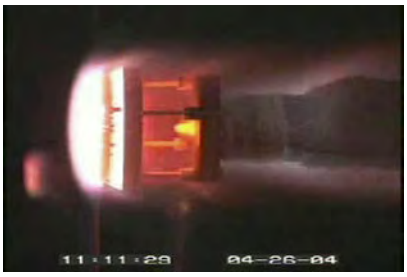
A thruster for the space-shuttle-orbiter reaction control system being examined in Glenn's Optics Laboratory.

Polymers and polymer matrix composites

In the mid-1970s, Glenn created a family of high-temperature polymers: Polymerization of Monomer Reactants (PMR) polyimides, which combined good processability and high-temperature performance. The principle polyimide in this family, PMR–15, offered long-term use (10,000 hr) at 550 °F and could be processed into components having void contents below 3 percent. PMR–15 is widely used in both military and commercial aircraft engine components, including the F–404 outer bypass duct, the GE90 center vent tube, and the F–100–229 exit flaps. Recent emphasis has focused on low-cost processing research and development of 700 °F-capable composites.

Structural ceramics

Since the 1960s, Glenn has investigated silicon-based monolithic ceramics, such as silicon carbide (SiC) and silicon nitride (Si_3N_4), for their high-temperature strength, thermal stability, and resistance to both thermal shock and oxidation. In the mid-1980s, Glenn emphasized silicon-based ceramic matrix composites, such as SiC-fiber-reinforced SiC, to mitigate the brittle failure mechanisms of monolithic ceramics. Research and development includes the development of fibers, interfaces, and matrices; composite processing; measurement of thermal-mechanical and physical properties; subcomponent testing; and property and life modeling. Both ceramic matrix composites and advanced monolithic ceramics have been promoted for use in demanding aeronautics and space applications.



Reinforced carbon/carbon specimen plug-repaired using GRABER 5A as the sealant, shown during arcjet testing.

Our expertise in this area also helped us to develop repair methods for the space shuttle reinforced-carbon composite wing leading edge, including Glenn Refractory Adhesive for Bonding and Exterior Repair (GRABER), which won an R&D 100 award.

Environmental and thermal barrier coatings

In the mid-1970s, Glenn demonstrated a thermal barrier coating to extend aircraft engine metallic turbine blade and vane life. Researchers optimized the composition to produce the industry standard (6- to 8-wt% Y_2O_3-ZrO_2). Early efforts identified bond-coat oxidation and thermal cycling as key failure elements. Popular pack aluminide (NiAl) coatings were first modeled in a thermodynamic and kinetic deposition model and shown to degrade primarily by substrate interdiffusion. A unique laser thermal shock test was developed to faithfully reproduce the high thermal gradient and heat fluxes in an actual engine. Our scientists and engineers codeveloped the first generation of environmental barrier coatings to protect silicon-based ceramics from water vapor attack. Higher-temperature-capable environmental barrier coatings are now emerging. This expertise was also used to assess the aging of the space shuttle reinforced-carbon composite wing leading edge, which is coated for thermal and environmental protection.

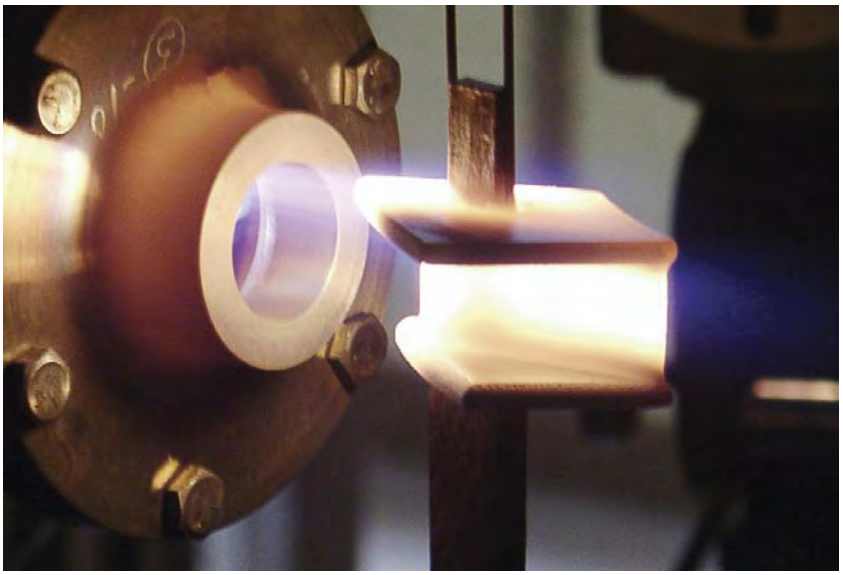
Aerospace propulsion structures

Analytical, computational, and experimental mechanics

Since propulsion system structures are exposed to very high temperatures and have to carry the thermal and mechanical loads associated with engine operation, they need to be extremely durable and reliable. The first step toward incorporating advanced materials into engine component applications is to experimentally characterize material properties and capture them in models that mathematically represent their behavior under conditions representative of the actual conditions experienced within the engine.

Mechanics efforts, work that captures the behavior of engine materials and structures, have been conducted over the past several decades. An understanding of the nonlinear deformation in alloys and of the fatigue of hot components was developed during the 1950s. Glenn explored fracture mechanics, crack growth, and thermomechanical fatigue during the 1960s. During the 1970s, we simulated composites and utilized computer technology to conduct extensive computations that were used in the 1980s to determine the life of engine components. We advanced the art during the 1990s to predict the response of high-temperature composite structures made of polymer, metal, and ceramic matrix composites as well as carbon/carbon materials. During the 2000s, we created complex three-dimensional composite structural models to study the deformation and lifing of advanced anisotropic (directional properties are different) alloys and investigated the effects of extreme environments to a point where advanced structural concepts can be designed and optimized for a required response.

Glenn's experimentally validated modeling and analysis tools are widely used by hundreds of aerospace, automotive, electronic, energy, biomedical,



Mach 0.3 burner rig evaluating a thermal/environmental barrier coating on a silicon nitride vane.

In-plane biaxial load frame with an ultrahigh strength fabric specimen mounted for a stretching test.

and power companies. NASA estimates that the benefit to these companies over the past 5 years has been greater than $50 billion.

Our scientists and engineers developed and demonstrated lifing and durability technologies for a ceramic combustion liner for a GE CFM 56 technology demonstrator engine. We also collaborated with GE to develop analysis tools to design and demonstrate an advanced, stiffness-tailored composite fan blade for the GE90 jet engine, resulting in fuel savings greater than 10 percent and emission reductions greater than 15 percent. This engine powers the Boeing 777 aircraft. Analytical tools and methods also were developed for designing nickel-based advanced metallic alloy turbine disks for GE engines, including probabilistic methods to account for material and geometric variability.

Glenn created a new design for crack-growth mitigation of the Space Shuttle Main Engine alternate turbopump (fuel pump). We also developed life prediction tools that reduced the turbopump metal-matrix-composite flange weight by 25 percent, a capability now used by many aerospace organizations.

Our scientists and engineers conducted ceramic turbine damping analysis that enables blisk designs for high-temperature propulsion system requirements. In addition, we developed probabilistic analysis methods for predicting the life of brittle materials and structures that are used widely by industry. At the request of the NASA Engineering and Safety Center, Glenn participated on the team determining the root cause of liquid hydrogen flowliner cracking for the Space Shuttle Main Engine.

Structural mechanics and dynamics

This area of structures deals with the dynamic response and damping of rotating engine components, and aeroelastic behavior that is due to rotating members—such as engine fan blades interacting with incoming air, and compressor and turbine blades rotating in hot engine gases. The uncontrolled dynamic and aeroelastic response of these components can result in the catastrophic failure of an aircraft engine or rocket turbopump.

During the fuel crisis triggered by the 1980's oil embargo, Glenn's structural engineers contributed to the development of a new fuel-efficient turboprop propulsion system for aircraft. It increased propfan aircraft speed from 350 to 550 mph, the speed of commercial jetliners, and saved about 30 percent in fuel burn. This development resulted in a Collier Trophy in 1987.

We also formulated probabilistic structural analysis methods during the 1990s that account for variations in loading conditions. The resulting Numerical Evaluation of Stochastic Structures Under Stress (NESSUS) computer code, developed in collaboration with Southwest Research Institute, was commercialized and has been sold to over 30 aerospace and automotive companies. This design approach will lead to safer, more reliable engines and other structural systems.

Our scientists and engineers developed technologies to balance high-speed engine rotors and demonstrated these on the F–100 engine fan. This method is currently used widely in high-speed machinery. We also developed advanced transient engine rotordynamics techniques to predict an engine's response to a blade-loss event. Every engine manufacturer has benefited from the proprietary analysis codes resulting from this effort.

During the 2000s, Glenn developed the TURBO–AE computer program that is being used by major aircraft engine companies (GE Aircraft Engines, Honeywell, and Williams International) to rapidly and accurately design structurally safe engines for commercial and military aircraft. Glenn's structures expertise has also contributed to advances in the engine blade containment structure that surrounds aircraft engines. To ensure passenger safety, this structure must be able to absorb the energy from a ballistic impact if an engine blade separates from a rotor disk. The challenge is to develop analysis methods, validate them using relevant experiments, and then use them to properly design these structures to be lightweight and to withstand engine blade structural failures.

These methods were used to develop an advanced composite containment case

for engines. This innovation is estimated to reduce engine weight by 30 percent. The technology is being implemented on the GEnx, the Williams J44–4, and the Honeywell HTF–7000, HTF–3000, and HTF–5000 engines.

Glenn's ballistic impact expertise was also used to prove that impact of foam from the space shuttle orbiter external tank caused the Space Shuttle Columbia accident.

Glenn's ballistic impact expertise was also used to prove that impact of foam from the space shuttle orbiter external tank caused the *Space Shuttle Columbia* accident. Our scientists and engineers conducted full-scale and laboratory tests (at Southwest Research Institute) to develop new impact analysis methods to complement empirical methods for various debris and space shuttle impact scenarios.

Mechanisms and mechanical systems

Propulsion systems and other aircraft systems rely on drive systems for power transmission, bearings to support rotating components, lubrication systems to reduce friction between contacting surfaces, and seals to contain gases and fluids. For over 50 years, Glenn has contributed to technology advances in these systems.

In 1951, the rolling-element bearing life in jet engines was approximately 300 hr. In 1955, Glenn initiated efforts to extend bearing fatigue life, and by 1985 had improved rolling-element fatigue life by nearly 40 times. NASA's work also increased seal speed by approximately 50 percent, with a significant reduction in gas leakage. In the early 1990s, NASA pioneered the use of brush seals in liquid hydrogen, which are now used in the RS–68 engine on the DELTA–4 rocket.

NASA's work on gears and mechanical transmission technology began in 1969, and from 1977 to 1984, our research and development led to a 50-percent increase in the power-to-weight ratio for helicopter transmission systems without a reduction in transmission life, reliability, or efficiency. NASA-developed superfinishing technology has extended gear life by a factor of 4 and is used on Sikorsky's S–92 helicopter.

Mechanical component health-monitoring technologies for drive systems were developed during the 2000s. Gear-damage-detection methodologies developed at Glenn are being used in the U.S. Army Vibration Management Enhancement Program health-monitoring system currently installed on more than 70 Black Hawk helicopters.

Glenn led an effort with engine manufacturers to develop self-seating turbine blade tip seals, including developing and testing material combinations for hot erosion and wear. These material combinations were refined by the manufacturers and are used in proprietary engine seals.

Structural seals research and development for hypersonic engines, which began in the late 1980s, led to innovative rope seal designs for reliable solid rocket motor operations. These designs were successfully incorporated into and tested on the space shuttle solid rocket motor and were incorporated into the Atlas 5 rocket, first launched in 2003. Glenn received a National Invention of the Year Award for this effort. We have also developed innovative rotating bearings and seals for rocket engine turbopumps with longer life and higher reliability.

Testing with space shuttle foam insulation in Glenn's Ballistic Impact Facility.

Oil-Free rotor simulation rig.

Research on the lubrication and tribology of space mechanisms began in the 1970s, resulting in the 1999 publication of the *NASA Space Mechanisms Handbook* used by over 800 people in the aerospace industry today. The expertise in this area was utilized to lead NASA in space mechanisms and mechanical components, providing failure analysis and best service practices for mechanical flight control actuators under the space shuttle Return to Flight program.

Tribology and surface science

Engine wear research began with studies of aircraft reciprocating engine wear during the 1940s and turbine engine lubrication and wear, bearings, and seals during the 1950s. With the formation of NASA in 1958, some of the fundamental knowledge gained earlier helped guide the development of lubricants for space applications. Glenn investigated the fundamentals of higher temperature solid and liquid lubricants during the 1970s and created the award-winning PS200-series high-temperature solid lubricants during the 1980s. In the 1990s, Glenn developed and demonstrated an Oil-Free turbocharger. The spiral orbit tribometer developed by Glenn during the early 2000s provides rapid comparative lifetime evaluations for both solid and liquid lubricants and is being considered by ASTM International for a new standards publication.

Glenn has continued to contribute to the area of tribology and surface science by successfully demonstrating a foil-air hot bearing designed for the core rotor shaft of an Oil-Free turbine engine. Current work to revolutionize small aviation engines with Oil-Free designs is being enabled by Glenn-developed high-temperature solid lubricants.

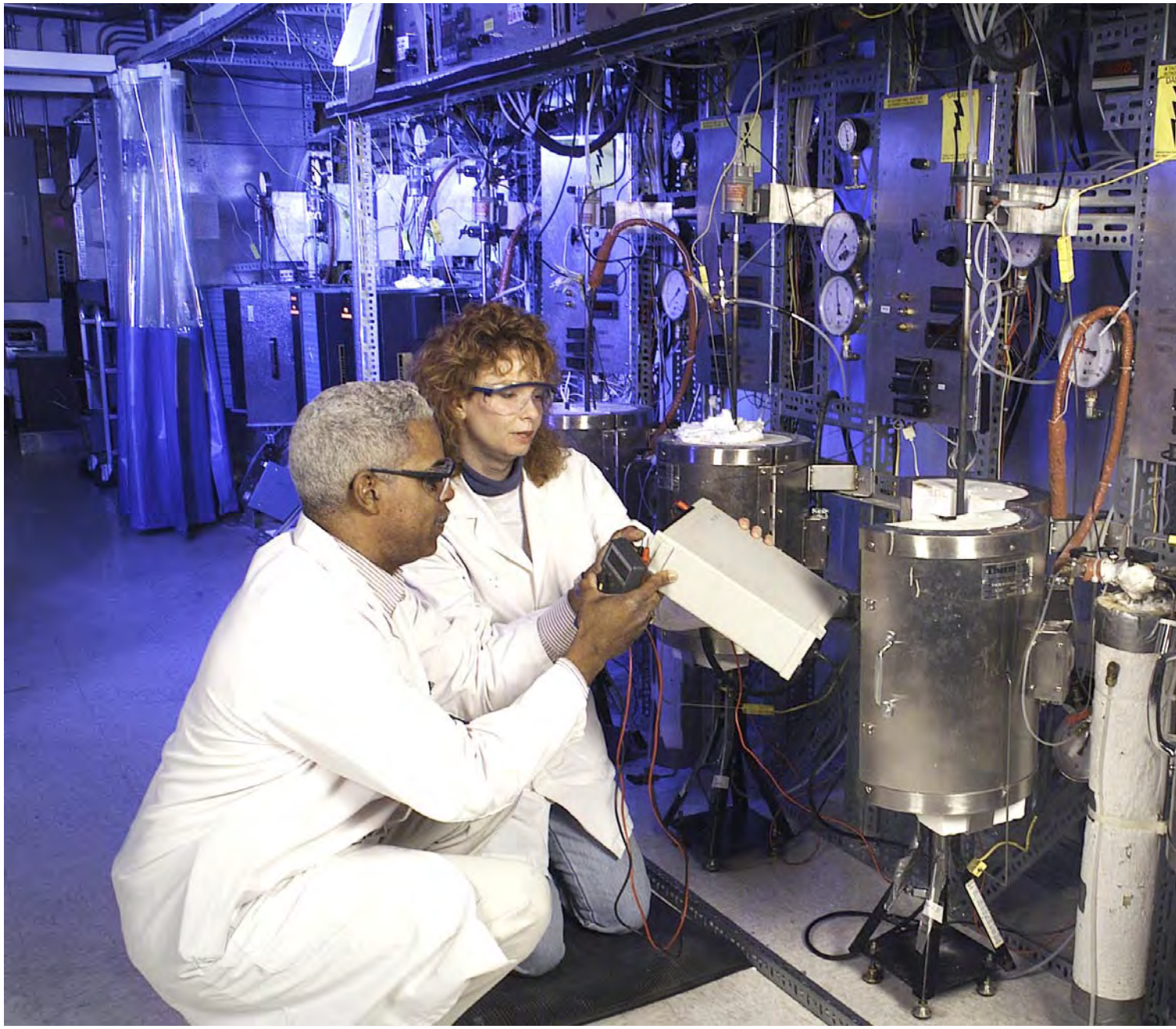
Fundamental work on Oil-Free turbine design is also being applied in space power conversion. We recently demonstrated Oil-Free Brayton-cycle power conversion for NASA's Space Exploration program. In addition, synthetic liquid lubricants for space, which have been studied for more than two decades, were recently applied to understanding space shuttle rudder/speed brake and body flap actuator grease issues for the Return to Flight program.

Aeronautics and Space Test Facilities

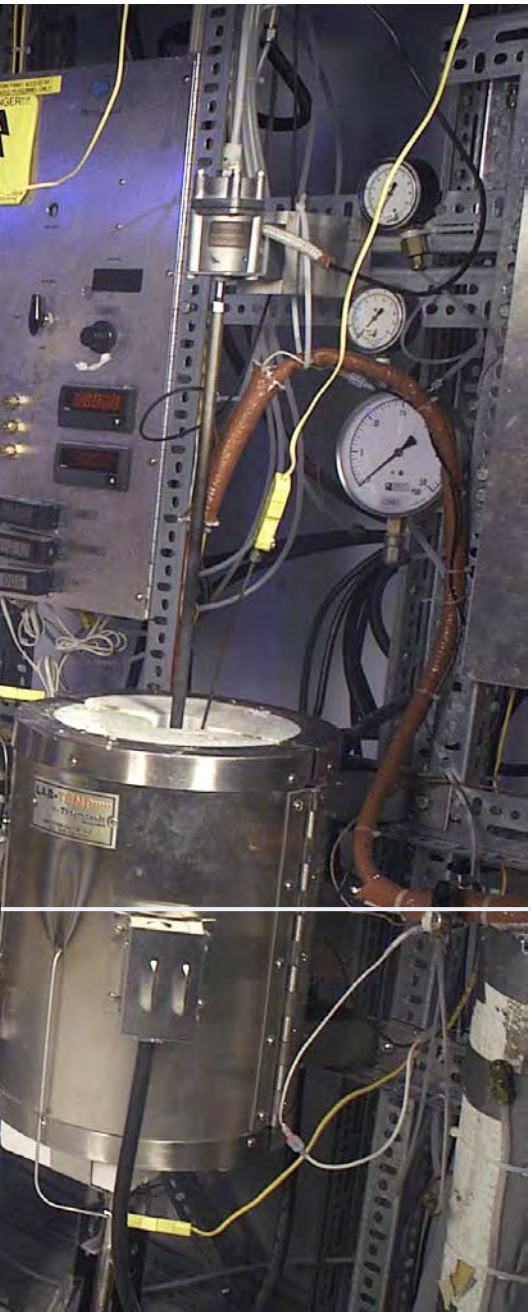
Glenn is home to 24 major test facilities and over 100 research and development laboratories located at our site near Cleveland, Ohio, and at our Plum Brook Station in Sandusky, Ohio. Our ground test facilities include the world's largest thermal vacuum facility, large aeropropulsion wind tunnels, engine test cells, flight research aircraft, and research and development laboratories. Our ground test facilities are available for use by our NASA research and development programs, other Government organizations, industry, and academia.

Our main campus in Cleveland includes 150 buildings on 350 acres, which support component testing in power, propulsion, communications, fluids and combustion, materials, structures, mechanical components, and instrumentation and controls. Very large and hazardous aerospace tests are run at our 6400-acre Plum Brook Station complex.

Detailed descriptions and capabilities of Glenn's facilities are provided in the brochure *Glenn Research Center Test Facilities* (B–1128), available from Glenn's Facility Management and Planning Office and online (http://facilities.grc.nasa.gov). This Web site also gives information about how to do work in our facilities.



Small Business Innovation Research (SBIR) partner, Technology Management, Inc.



Technology Transfer

and Partnerships

We have transferred knowledge and technologies to many

We have transferred knowledge and technologies to many areas outside of NASA and have a long history of successful collaborations and repeat partners and customers. Glenn enters into over 100 Space Act Agreements with many different Government, university, and corporate partners each year. A few examples of our role in advancing the state of the art in aerospace technology follow:

- The Energy Efficient Engine Project (1976 to 1984) advanced high-bypass-ratio fan technology. This accomplishment included mixers for core flow and fan bypass flows. These technologies paved the way for the GE90 and PW4084 high-bypass engines (which entered service in 1993). These engines power the Boeing 777 commercial aircraft and are currently the largest, most powerful commercial aircraft engines.

- Under the Advanced Subsonic Technology Program, NASA developed the chevron nozzle technology for noise reduction, which can attenuate jet noise by up to 4 dB. This technology is in production on the GE CF34 engine and is flying on the Bombardier CRJ–700 and CRJ–900 aircraft.

- NASA research into the damage to satellites caused by atomic oxygen in low Earth orbit led to a new way to restore damaged artwork. Glenn's Electro-Physics Branch facilities produce atomic oxygen for ground-based simulation of on-orbit damage. In 1996, Glenn researchers Bruce Banks and Sharon Miller were contacted by conservators from the Cleveland Museum of Art about using the new artwork restoration techniques that the Glenn researchers had developed using atomic oxygen. The first tests were done on two religious paintings damaged by an arson fire at St. Alban's Church in Cleveland Heights, Ohio. Both paintings were found to be unsalvageable by conventional art restoration wet chemistry techniques. Glenn's atomic oxygen cleaning process not only removed the soot, but it cleaned the paintings so effectively that colors that had been faded by time were brighter, and more detail could be seen than before the fire. The success encouraged the art community to risk more important works of art to test the technique further.

Painting "Madonna of the Chair" damaged in a 1989 fire at St. Alban's Church. Left: Before restoration with atomic oxygen. Right: After restoration with atomic oxygen.

Small Business Innovation Research and Small Business Technology Transfer Programs

Glenn is the Agency leader in awarding Small Business Innovation Research and achieving success stories (140) from these programs. The Small Business Innovation Research and Small Business Technology Transfer Programs provide NASA with high-quality research and development from small businesses and enable small businesses to grow by moving ideas from the drawing board to the marketplace.

A few of our small business success stories follow:

- ViGYAN Inc., Hampton, Virginia, developed the Pilot Weather Advisory system, which is currently under Federal Aviation Administration certification. The system uses state-of-the-art satellite technology to substantially increase the amount of weather information available to pilots in flight. The Pilot Weather

R&D 100 Award Winner—ViGYAN Pilot Weather Advisor/WSI, Inc. (Weather Services International) Inflight, a Small Business Innovation Research (SBIR) project.

Advisor covers the entire continental United States with around-the-clock weather updates every 5 min.

- Cox & Company, New York, New York, developed the first new aircraft ice-protection system in 40 years. It was certified by the Federal Aviation Administration in 2001 for use on Raytheon Aircraft Company's Premier I business jets and the Hawker Horizon business jet.

- Eveready has partnered with Glenn to prototype new lithium battery designs for space missions that have extremely high power requirements, including planetary rovers, reusable launch vehicles, and low-Earth-orbit spacecraft, accelerating NASA's development of a new lithium battery for space applications. Glenn developed a dual-phase polymer material for the electrolyte in the batteries. A "rod" phase gives the polymer mechanical stability, and a "coil" phase gives the polymer good conductivity at low temperatures. Eveready's considerable battery design and manufacturing experience is speeding up the design process. So far, the partnership has given us direction for improving the rod-coil electrolyte material, especially in regards to the thickness and consistency of the electrolyte material, which significantly affect lithium battery performance. These advances will lead to the more widespread use of lithium batteries in electronic products that have power requirements beyond what alkaline batteries can meet, such as digital cameras and portable compact disc players.

- ADMA, Twinsburg, Ohio, licensed NASA's patent for PS304, a self-lubricating, high-temperature metal bearing material that starts as a powder and is applied via plasma-spraying methods. They used this technology to develop PM304, a form of PS304 that can be pressed, shaped, and heat treated to create solid parts. ADMA now manufactures both materials and has produced PM304 bushings that are being used in Lincoln Electric furnaces that operate at temperatures up to 1000 °F. Previously, bushings would crack when used in a furnace, and oils and greases could not be used as lubricants because they would burn up. The PM304 bushings will save Lincoln Electric over $1 million over the next 5 years and over $225,000 for each subsequent year. Glenn is evaluating the bushings for variable stator vanes. The results generated as Lincoln Electric uses the PM304 bushings are providing life and design data to help NASA's aerospace customers more quickly and economically incorporate PM304 into their aerospace applications.

Read more success stories at http://technology.grc.nasa.gov/successes.asp.

Strategies and Partnerships

Glenn created innovative procurement mechanisms that have been modeled throughout NASA, pioneering the first commercial launch services procurement for the U.S. Government and establishing a 100-percent mission success record with less than 3-percent cost growth. We developed innovative procurement mechanisms for technology development, such as the Revolutionary Aerospace Engine Research Contract, which enabled multiple contracts for multiple technologies across space and aeronautics programs.

We built many successful international partnerships based on our technical

NASA's Mod-5B wind turbine in Hawaii generated enough power for 2500 homes.

and programmatic expertise. Critical solutions have been provided even in crises. For example, Glenn was a significant member of the *Mir* oxygen generator failure investigation. Our strategy provided critical power that enabled continued operation of *Mir* after the near-disastrous attempt at docking *Progress* with *Mir* in 1997. Glenn represented NASA during power quality testing and analysis of the Japanese Experiments Module flight model at Tsukuba Space Center in Japan. We developed and built the Mir Cooperative Solar Array in just 18 months and $1 million under budget. In addition, joint microgravity experiments with the European Space Agency, National Space Development Agency (of Japan), Canadian Space Agency, French space agency (CNES), and Russia Space Agency were successfully flown on *Spacelab*, *Mir*, and the ISS.

Glenn played a key role in making wind energy the most successful renewable energy in the world today.

Glenn played a key role in making wind energy the most successful renewable energy in the world today. From 1974 to 1988, we led the U.S. Wind Energy Program for large wind horizontal-axis turbines (the predominant systems used today). This was an extraordinarily efficient and successful Government research and development activity. A total of 13 experimental wind turbines, with five major turbine designs, were put into operation. This included the Mod-5B, installed in Hawaii, which produced 3.2 MW—enough power for 2500 homes—and had a diameter of 100 m, making it the largest wind turbine in the world.

In 1997, Glenn established the first science institute for microgravity science, the National Center for Microgravity Research on Fluids and Combustion (now the National Center for Space Exploration Research, NCSER), through a cooperative agreement with Universities Space Research Association and Case Western Reserve University. In 2001, we established the John Glenn Biomedical Engineering Consortium through a Space Act Agreement with the Cleveland Clinic Foundation, University Hospitals of Cleveland, Case Western Reserve University, and the National Center for Microgravity Research.

Glenn established Interagency Agreements with National Institutes of Health/National Eye Institute in 2001 and with the Food and Drug Administration in 2003 for laser-light-scattering ocular probe diagnostics and applications. We also established an interagency agreement with the Army Medical Research Institute for collaborative study on probabilistic and micromechanics structural analysis and modeling. We welcome new business partners.

Head-mounted LDF instrument on a volunteer subject monitors ocular blood flow in 0g onboard the KC–135 aircraft.

The Edison Award recognizes an organization's global leadership in fostering or implementing innovation and in positively utilizing technology to impact its operation and the community.

Honors and Awards

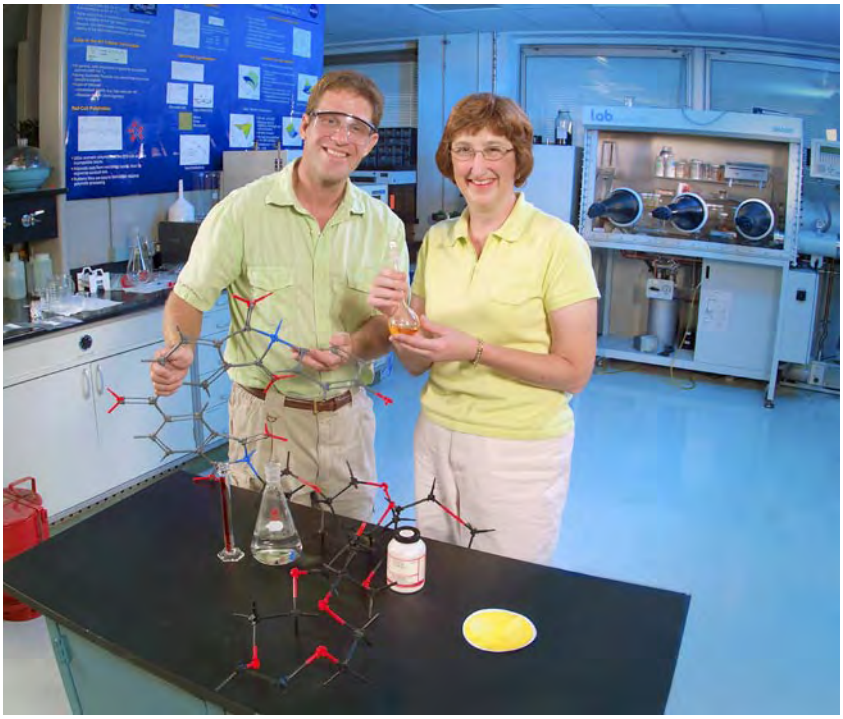
Glenn's world-class technologists are consistently recognized

Glenn's world-class technologists are consistently recognized for their contributions to scientific advancements in aerospace. Glenn was the first NASA center to receive an R&D 100 Award from R&D Magazine (each year, the magazine selects the 100 most technologically significant new products from among the entries) and has won 98 of the 150 awards granted to NASA since 1966, more than all the other NASA centers combined. Of over 600 national laboratories, Glenn places among the top 10 for these awards.

Over 2000 invention disclosures have been reported by Glenn since 1991. Over 125 patents are currently available for licensing in power, communications, electric propulsion (dished ion grids, ring-cusp engine, and xenon hollow cathodes), combustion, instrumentation, materials, seals, silicon carbide growth, and coatings.

for their contributions to scientific advancements

Over the last 5 years, Glenn has contributed 166 articles for the NASA Tech Briefs magazine. We won an average of nine awards per year from the NASA Inventions and Contributions Board and have received 4 of 21 NASA Software of the Year Awards.



R&D 100 winners Drs. James Kinder and Mary Ann Meador pictured with their award-winning rod-coil block copolymers in their laboratory at Glenn.

Selected R&D 100 Awards

- Innovations in metal alloys
  - Ductile Precipitate Strengthened Tungsten Alloy (1967)
  - Ferromagnetic Superalloy (1968)
  - Refractory Fiber Superalloy (1968)
  - High Purity Metal Powders (1971)
  - Low Temperature Alloys (1978)
  - Superalloy Strength-Enhanced Fabrication Process (1978)
  - CARES/*Life* Integrated Design Software (1995)
  - GENOA—PFA Progressive Failure Analysis Software (2000)

R&D 100 winners Tarah Shpargel (left) and Dr. Mrityunjay Singh (right) working with GRABER in their Glenn laboratory.

- Ceramic matrix composite materials development
  - Float Zone Fiber Drawing Process (1971)
  - Melt Modulated Fiber Growth System (1993)
  - Affordable Fiber Reinforced Ceramic Composites (1995)
  - Convoluted Thermocouples for Ceramic Temperature Measurement (1998)
  - Affordable Robust Ceramic Joining (1999)
  - Glenn Refractory Adhesive for Bonding and Repair (GRABER) (2005)
- Alloys and coatings
  - Ceramic Thermal Barrier Coatings (1976)
  - Corrosion-Resistant Thermal Barrier Coatings (1979)
  - High Strength Nickel-Based Alloy (WAZ-26) for 2200 °F (1978)
  - Oxide-Dispersed Ni-based Superalloys, which can reach 2010 °F (1980)
  - Thermal Barrier Coating Systems (1980)
- Polymers
  - Polyimide Rod-Coil Block Copolymers as Membrane Materials for Ion Construction (2005)
- Seals, bearings, and lubricants
  - Hexagonal Bearings and Stable HC Bearing Materials (1966)
  - Gas Lubricated Self-Acting Seals (1973)

- Oxidation Resistant Self-Lubricating Bearing Materials (1974)
- NASA Self-Lubricating Composite Coating (1985)
- High Temperature Flexible Ceramic Wafer Seal (1990)

- Sensors and analysis systems
  - Analysis of Rotordynamic Systems and Photo Optical Blade Vibration Data Acquisition Systems (1984)
  - Blade Tip Clearance Rig, for an optical-fiber current sensor (1991)
  - Multi-Parameter, Micro-Sensor-Based Low False Alarm Fire Detection System (MMFDS) (2005)

- Propulsion systems
  - Electron Bombardment Ion Thrusters (1970)
  - Ring Cusp Ion Thruster (2001)

- Software
  - NESSUS Version 8 Probabilistic Engineering Analysis Software (2005)

TEMPEST—1998 NASA Software of the Year.

NASA Software of the Year Awards

- Ceramics Analysis and Reliability Evaluation, CARES (1994)
- TEMPEST Embedded Web Technology (1998)
- GENOA, a failure analysis software program (1999)
- National Propulsion System Simulation, NPSS (2001)
- Microgravity Analysis Software System, MASS (runner-up in 2002)
- System Power Analysis for Capability Evaluation, SPACE (runner-up in 2003)

Collier Trophy Awards

These awards are given for the greatest U.S. achievement in aeronautics or astronautics, with respect to improving the performance, efficiency, and safety of air or space vehicles, the value of which has been thoroughly demonstrated by actual use during the preceding year.

- Development and practical application of a thermal ice-prevention system for aircraft (1946)
- Development of a new fuel-efficient turboprop propulsion system (1987)

Glenn's 1987 Collier trophy.

NASA Government Invention of the Year Awards

- High Temperature, Flexible, Ceramic Fiber Seal (1996)—can bend around sharp radii, conforming to and sealing complex components
- Hollow Cathode Assembly for the International Space Station Plasma Contactor and Hollow Cathode Technology (2001)—was used to rid the space station of ion buildup on its surface, preventing dangerous electric arcs during space walks and shuttle dockings
- Rocket Motor Joint Construction Including Thermal Barrier (for the space shuttle) (2004)—This unique braided carbon-fiber thermal barrier was designed to withstand extreme temperature environments in current and future solid rocket motors. It solves the vexing problem of blocking 5500 °F rocket combustion gases from reaching temperature-sensitive O-rings while still allowing 900-psi gases to position the O-rings in their grooves for proper sealing.

Government Computer News Awards

- ACTS High Rate Program (1996)
- Space Internet (1999)

Other Awards

- NASA's first Emmy from the National Academy of Television Arts and Sciences for technology to enable direct-to-home color broadcast of television images with the Communications Technology Satellite (1988)
- Federal Research Laboratories Consortium Award for technology transfer in high-temperature superconductors (1992)

Glenn's Emmy award.

- Space Technology Hall of Fame inductee for the Advanced Communications Technology Satellite, ACTS (1995)
- Mobile and Wireless Magazine Award for Business Applications for Mobile and Wireless Computing in Government based on Mobile Router (2000)
- Thomas Edison Award for Glenn's partnerships with Government, industry, and academia to increase national wealth, safety, and security; for the development of critical technologies that address national priorities for safe and reliable aeronautics, aerospace, and space applications; and for leading the way in making Ohio a high-technology leader in the 21st century (2001).

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