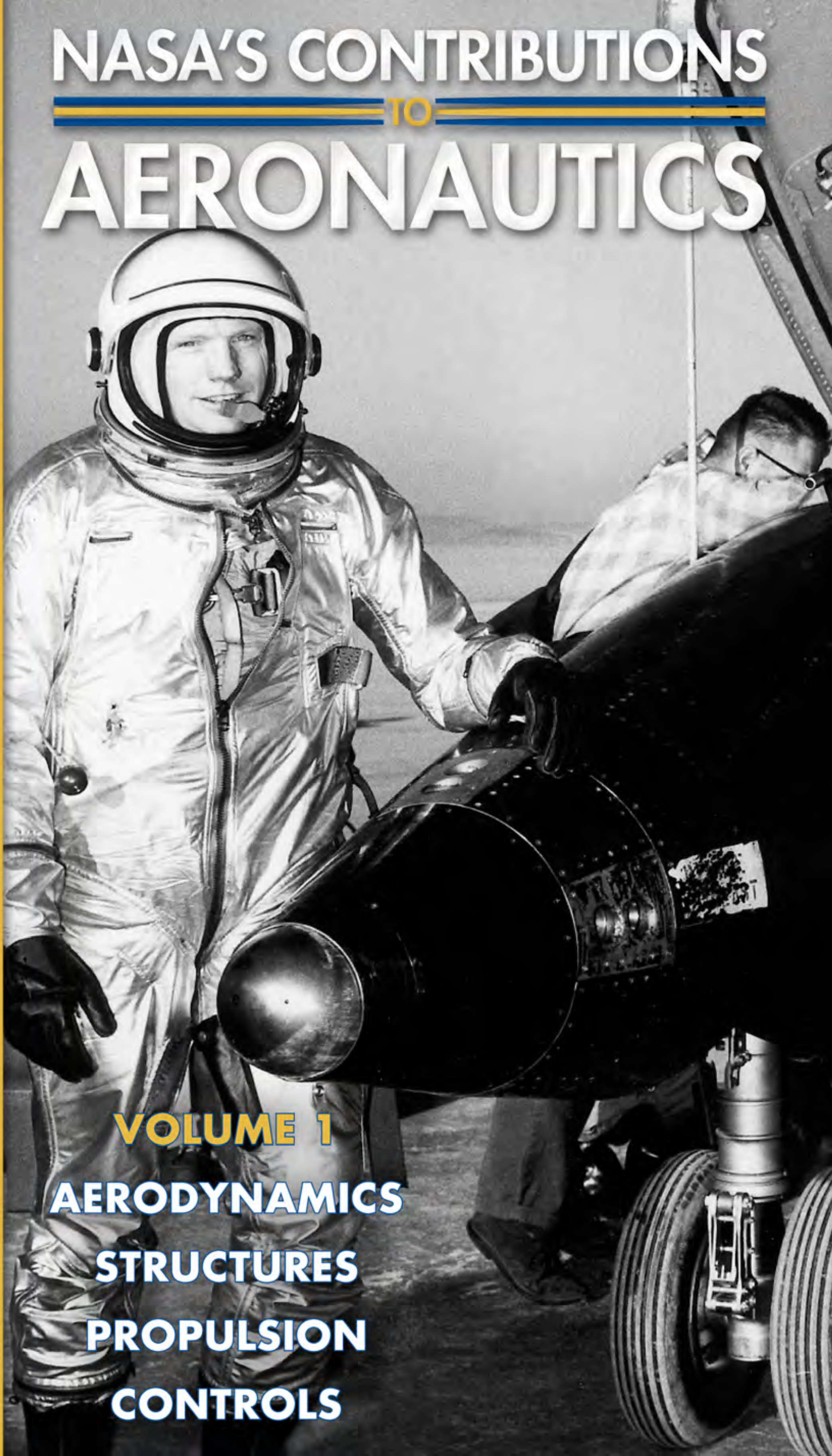
NASA'S CONTRIBUTIONS TO AERONAUTICS



VOLUME 1

AERODYNAMICS
STRUCTURES
PROPULSION
CONTROLS

CASE 11

Advancing Propulsive Technology

James Banke

Ensuring proper aircraft propulsion has been a powerful stimulus. In the interwar years, the NACA researched propellers, fuels, engine cooling, supercharging, and nacelle and cowling design. In the postwar years, the Agency refined gas turbine propulsion technology. NASA now leads research in advancing environmentally friendly and fuel-conserving propulsion, thanks to the Agency's strengths in aerodynamic and thermodynamic analysis, composite structures, and other areas.

EACH DAY, OUR SKIES FILL with general aviation aircraft, business jets, and commercial airliners. Every 24 hours, some 2 million passengers worldwide are moved from one airport to the next, almost all of them propelled by relatively quiet, fuel-efficient, and safe jet engines.[1]

And no matter if the driving force moving these vehicles through the air comes from piston-driven propellers, turboprops, turbojets, turbofans—even rocket engines or scramjets—the National Aeronautics and Space Administration (NASA) during the past 50 years has played a significant role in advancing that propulsion technology the public counts on every day.

Many of the advances seen in today's aircraft powerplants can trace their origins to NASA programs that began during the 1960s, when the Agency responded to public demand that the Government apply major resources to tackling the problems of noise pollution near major airports. Highlights of some of the more noteworthy research programs to reduce noise and other pollution, prolong engine life, and increase fuel efficiency will be described in this case study.

But efforts to improve engine efficiency and curb unwanted noise actually predate NASA's origins in 1958, when its predecessor, the National Advisory Committee for Aeronautics (NACA), served as the Nation's preeminent laboratory for aviation research. It was during the 1920s that

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[1] William H. More, ed., *National Transportation Statistics* (Washington, DC: U.S. Department of Transportation, 2009), p. 72.

Air pollution is evident as this Boeing B-47B takes off in 1954 with the help of its General Electric J47 jet engines and Rocket Assisted Take Off solid rocket motors. U.S. Air Force.

the NACA invented a cowling to surround the front of an airplane and its radial engine, smoothing the aerodynamic flow around the aircraft while also helping to keep the engine cool. In 1929, the NACA won its first Collier Trophy for the breakthrough in engine and aerodynamic technology.[2]

During World War II, the NACA produced new ways to fix problems discovered in higher-powered piston engines being mass-produced for wartime bombers. NACA research into centrifugal superchargers was particularly useful, especially on the R-1820 Cyclone engines intended for use on the Boeing B-17 Flying Fortress, and later with the Wright R-3350 Duplex Cyclone engines that powered the B-29.

Basic research on aircraft engine noise was conducted by NACA engineers, who reported their findings in a paper presented in 1956 to the 51st Meeting of the Acoustical Society of America in Cambridge, MA. It would seem that measurements backed up the prediction that the noise level of the spinning propeller depended on several variables,

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[2] Roger E. Bilstein, *Orders of Magnitude: A History of the NACA and NASA, 1915–1990*, NASA SP-4406 (Washington, DC: NASA, 1989), p. 9.

including the propeller diameter, how fast it is turning, and how far away the recording device is from the engine.[3]

As the jet engine made its way from Europe to the United States and designs for the basic turboprop, turbojet, and turbofan were refined, the NACA during the early 1950s began one of the earliest noise-reduction programs, installing multitube nozzles of increasing complexity at the back of the engines to, in effect, act as mufflers. These engines were tested in a wind tunnel at Langley Research Center in Hampton, VA. But the effort was not effective enough to prevent a growing public sentiment that commercial jet airliners should be seen and not heard.

In fact, a 1952 Presidential commission chaired by the legendary pilot James H. Doolittle predicted that aircraft noise would soon turn into a problem for airport managers and planners. The NACA's response was to form a Special Subcommittee on Aircraft Noise and pursue a three-part program to understand better what makes a jet noisy, how to quiet it, and what, if any, impact the noise might have on the aircraft's structure.[4]

As the NACA on September 30, 1958, turned overnight into the National Aeronautics and Space Administration on October 1, the new space agency soon found itself with more work to do than just beating the Soviet Union to the Moon.

Noise Pollution Forces Engine Improvements

Fast-forward a few years, to a time when Americans embraced the promise that technology would solve the world's problems, raced the Soviet Union to the Moon, and looked forward to owning personal family hovercraft, just like they saw on the TV show *The Jetsons*. And during that same decade of the 1960s, the American public became more and more comfortable flying aboard commercial airliners equipped with the modern marvel of turbojet engines. Boeing 707s and McDonnell-Douglas DC-8s, each with four engines bolted to their wings, were not only a common sight in the skies over major cities, but their presence could also easily be heard by anyone living next to or near where the planes took off and landed. Boeing 727s and 737s soon followed. At the same

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[3] Edward M. Kerwin, Jr., "Procedures for Estimating the Near Field Noise of Rotating Aircraft Propellers," presented at the *Fifty-First Meeting of the Acoustical Society of America, Cambridge, MA, June 17–23, 1956.*

[4] J.H. Doolittle, *The Airport and Its Neighbors, The Report of the President's Airport Commission* (Washington, DC: U.S. Government Printing Office, 1952), p. 45.

A jet engine is prepared for a test in 1967 as part of an early noise research program at Lewis Research Center. NASA.

time that commercial aviation exploded, people moved away from the metropolis to embrace the suburban lifestyle. Neighborhoods began to spring up immediately adjacent to airports that originally were built far from the city, and the new neighbors didn't like the sound of what they hearing.[5]

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[5] Alain Depitre, "Aircraft Noise Certification History/Development," presented at the *ICAO Noise Certification Workshop, Montreal, 2004*, p. 3.

By 1966, the problem of aircraft noise pollution had grown to the point of attracting the attention of President Lyndon Johnson, who then directed the U.S. Office of Science and Technology to set a new national policy that said:

> The FAA and/or NASA, using qualified contractors as necessary, (should) establish and fund . . . an urgent program for conducting the physical, psycho-acoustical, sociological, and other research results needed to provide the basis for quantitative noise evaluation techniques which can be used . . . for hardware and operational specifications.[6]

As a result, NASA began dedicating resources to aggressively address aircraft noise and sought to contract much of the work to industry, with the goals of advancing technology and conducting research to provide lawmakers with the information they needed to make informed regulatory decisions.[7]

During 1968, the Federal Aviation Administration (FAA) was given authority to implement aircraft noise standards for the airline industry. Within a year, the new standards were adopted and called for all new designs of subsonic jet aircraft to meet certain criteria. Aircraft that met these standards were called Stage 2 aircraft, while the older planes that did not meet the standards were called Stage 1 aircraft. Stage 1 aircraft over 75,000 pounds were banned from flying to or from U.S. airports as of January 1, 1985. The cycle repeated itself with the establishment of Stage 3 aircraft in 1977, with Stage 2 aircraft needing to be phased out by the end of 1999. (Some of the Stage 2 aircraft engines were modified to meet Stage 3 aircraft standards.) In 2005, the FAA adopted an even stricter noise standard, which is Stage 4. All new aircraft designs submitted to the FAA on or after July 5, 2005, must meet Stage 4 requirements. As of this writing, there is no timetable for the mandatory phaseout of Stage 3 aircraft.[8]

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6. *Alleviation of Jet Aircraft Noise Near Airports* (Washington, DC: U.S. Office of Science and Technology, 1966), p. 8.
7. Newell D. Sanders, *Aircraft Engine Noise Reduction*, NASA SP-311 (Washington, DC: NASA, 1972), p. 2.
8. David M. Bearden, *Noise Abatement and Control: An Overview of Federal Standards and Regulations* (Washington, DC: Congressional Research Service, 2006), p. 3.

With every new set of regulations, the airline industry required upgrades to its jet engines, if not wholesale new designs. So having already helped establish reliable working versions of each of the major types of jet engines—i.e., turboprop, turbojet, and turbofan—NASA and its industry partners began what has turned out to be a continuing 50-year-long challenge to constantly improve the design of jet engines to prolong their life, make them more fuel efficient, and reduce their environmental impact in terms of air and noise pollution. With this new direction, NASA set in motion three initial programs.[9]

NASA's first major new program was the Acoustically Treated Nacelle program, managed by the Langley Research Center. Engines flying on Douglas DC-8 and Boeing 707 aircraft were outfitted with experimental mufflers, which reduced noise during approach and landing but had negligible effect on noise pollution during takeoff, according to program results reported during a 1969 conference at Langley.[10]

The second was the Quiet Engine program, which was managed by the Lewis Research Center in Cleveland (Lewis became the Glenn Research Center on March 1, 1999). Attention here focused on the interior design of turbojet and turbofan engines to make them quieter by as much as 20 decibels. General Electric (GE) was the key industry partner in this program, which showed that noise reduction was possible by several methods, including changing the rotational speed of the fan, increasing the fan bypass ratio, and adjusting the spacing of rotating and stationary parts.[11]

The third was the Steep Approach program, which was jointly managed by Langley and the Ames Research Center/Dryden Flight Research Facility, both in California. This program did not result in new engine technology but instead focused on minimizing noise on the ground by developing techniques for pilots to use in flying steeper and faster approaches to airports.[12]

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[9] *U.S. Government Support of the U.S. Commercial Aircraft Industry, Prepared for the Commission of the European Communities* (Washington, DC: Arnold and Porter, 1991), pp. 37–43.

[10] Sanders, *Aircraft Engine Noise Reduction*, NASA SP-311 (Washington, DC: NASA, 1972), p. 2.

[11] M.J. Benzakein, S.B. Kazin, and F. Montegani, "NASA/GE Quiet Engine 'A,'" AIAA Paper 72-657 (1972).

[12] Vicki L. Golich and Thomas E. Pinelli, *Knowledge Diffusion in the U.S. Aerospace Industry* (London: Alex Publishing, 1998), p. 61.

Quiet Clean Short Haul Experimental Engine

A second wave of engine-improvement programs was initiated in 1969 and continued throughout the 1970s, as the noise around airports continued to be a social and political issue and the FAA tightened its environmental regulations. Moreover, with the oil crisis and energy shortage later in the decade adding to the forces requiring change, the airline industry once again turned to NASA for help in identifying new technology.

At the same time, the airline industry was studying the feasibility of introducing a new generation of commuter airliners to fly between cities along the Northeast corridor of the United States. To make these routes attractive to potential passengers, new airports would have to be built as close to the center of cities such as Boston, New York, and Philadelphia. For aircraft to fly into such airports, which would have shorter runways and strict noise requirements, the airliners would have to be capable of making steep climbs after takeoff, quick turns without losing control, and steep descents on approach to landing, accommodating short runways and meeting the standards for Stage 2 noise levels.[13]

In terms of advancing propulsion technology, NASA's answer to all of these requirements was the Quiet Clean Short Haul Experimental Engine. Contracts were awarded to GE to design, build, and test two types of high-bypass fanjet engines: an over-the-wing engine and an under-the-wing engine. Self-descriptive as to their place on the airplane, both turbofans were based on the same engine core used in the military F-101 fighter jet. Improvements to the design included noise-reduction features evolved from the Quiet Engine program; a drive-reduction gear to make the fan spin slower than the central shaft; a low-pressure turbine; advanced composite construction for the inlet, fan frame, and fan exhaust duct; and a new digital control system that allowed flight computers to monitor and control the jet engine's operation with more precision and quicker response than a pilot could.[14]

In addition to those "standard" features on each engine, the under-the-wing engine tried out a variable pitch composite low-pressure fan with a 12 to 1 ratio—both features were thought to be valuable in reducing noise, although the variable pitch proved challenging for the GE

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[13] Robert V. Garvin, "Starting Something Big: The Commercial Emergence of GE Aircraft Engines," AIAA Paper 72-657 (1999), pp. 162–165.

[14] A.P. Adamson, "Quiet Clean Short-Haul Experimental Engine (QCSEE) Design Rationale," SAE Paper 750605 (1975).

The giant General Electric GE90 jet engine that powers the Boeing 777 benefited from the Energy Efficient Engine project. General Electric.

team leading the research. Two pitch change mechanisms were tested, one by GE and the other by Hamilton Standard. Both worked well in controlled test conditions but would need a lot of work before they could go into production.[15]

The over-the-wing engine incorporated a higher fan pressure and a 10 to 1 bypass ratio, a fixed pitch fan, a variable area D-shaped fan exhaust nozzle, and low tip speeds on the fans. Both engines directed their exhaust along the surface of the wing, which required modifications to handle the hot gas and increase lift performance.[16]

The under-the-wing engine was test-fired for 153 hours before it was delivered to NASA in August of 1978, while the over-the-wing engine received 58 hours of testing and was received by NASA during July of 1977. Results of the tests proved that the technology was sound and, when configured to generate 40,000 pounds of thrust, showed a reduction in

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[15] Garvin, "Starting Something Big," pp. 162–165.

[16] C.C. Ciepluch, "A Review of the QCSEE Program," NASA TM-X-71818 (1975).

noise of 8 to 12 decibels, or about 60- to 75-percent quieter than the quietest engines flying on commercial airliners at that time. The new technologies also resulted in sharp reductions in emissions of carbon monoxide and unburned hydrocarbons.[17]

Unfortunately, the new generation of Short Take-Off and Landing (STOL) commuter airliners and small airports near city centers never materialized, so the new engine technology research managed and paid for by NASA but conducted mostly by its industry partners never found a direct commercial application. But there were many valuable lessons learned about the large-diameter turbofans and their nacelles, information that was put to good use by GE years later in the design and fabrication of the GE90 engine that powers the Boeing 777 aircraft.[18]

Aircraft Energy Efficiency Program

Approved in 1975 and begun in 1976, the Aircraft Energy Efficiency (ACEE) program was managed by NASA and funded through 1983, as yet another round of research and development activities were put in work to improve the state of the art of aircraft structural and propulsion design. And once again, the program was aimed at pushing the technological envelope to see what might be possible. Then, based on that information, new Government regulations could be enacted, and the airline industry could decide if the improvements would offer a good return on its investment. The answer, as it turned out, was an enthusiastic yes, as the overall results of the program led directly to the introduction of the Boeing 757 and 767.[19]

Driving this particular program was the rapid increase in fuel costs since 1973 and the accompanying energy crisis, which was brought on by the Organization of Arab Petroleum Exporting Countries' decision to embargo all shipments of oil to the United States. This action began in October 1973 and continued to March 1974. As a result of this and other economic influences, the airlines saw their fuel prices as a percentage of direct operating costs rise from 25 percent to as high as 50 percent within a few weeks. With the U.S. still vulnerable to a future oil embargo, along with general concerns about an energy shortage, the

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[17] Ciepluch and W.S. Willis, "QCSEE—The Key to Future Short-Haul Air Transport," *ICAO Bulletin* 34 (1979).

[18] "A Giant Step in Jetliner Propulsion," *Spinoff 1996* (Washington, DC: NASA, 1996), pp. 56–57.

[19] *U.S. Government Support of the U.S. Commercial Aircraft Industry* (1991).

Federal Government reacted by ordering NASA to lead an effort to help find ways for airlines to become more profitable. Six projects were initiated under the ACEE program, three of which had to do with the aircraft structure and three of which involved advancing engine technology. The aircraft projects included Composite Structures, Energy Efficient Transport, and Laminar Flow Control. The propulsion technology projects included Engine Component Improvement, Energy Efficient Engine, and Advanced Turboprop—all three of which are detailed next.[20]

Engine Component Improvement Project

The Engine Component Improvement project was tasked with enhancing performance and lowering fuel consumption of several existing commercial aircraft jet engines, in particular Pratt & Whitney's JT8D and JT9D engines and GE's CF6. The specific goals included:

- Improving the current versions of the engines without requiring a brand-new design or engine replacement.
- Reducing the amount of fuel a typical jet engine would use on any given flight by 5 to 6 percent.
- Significantly slowing the pace at which the engine's components would naturally degrade and cause a loss of performance over time.

To do this, researchers tried and tested several ideas, including reducing the clearance between rotating parts, lowering the amount of cooling air that is passed through the engine, and making refinements to the aerodynamic design of certain engine parts to raise their efficiency. All together, engineers identified 16 concepts to incorporate into the engines.[21]

Ultimately, as a result of the Engine Component Improvement efforts, engine parts were incorporated that could resist erosion and warping, better seals were introduced, an improved compressor design was used, and ceramic coatings were added to the gas turbine blades to increase their performance. Tests of the improvements were so promising that many were put into production before the program ended, benefiting the

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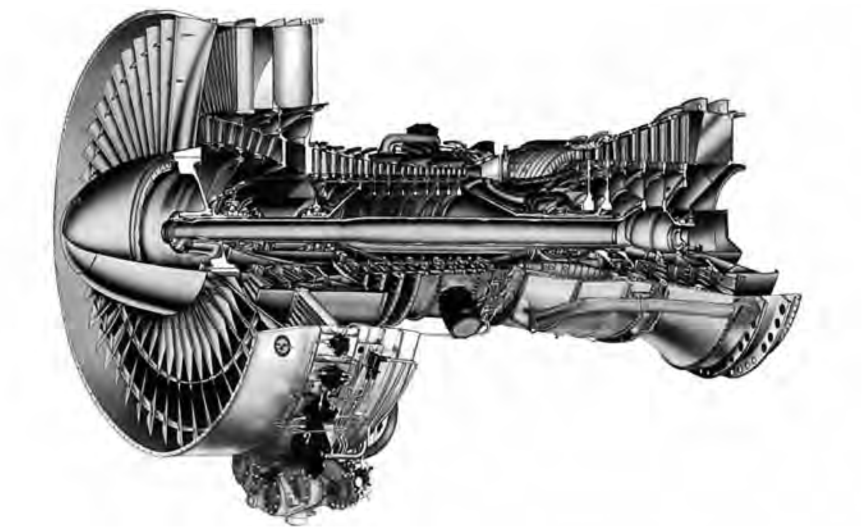
[20] Peter G. Batterton, "Energy Efficient Engine Program Contributions to Aircraft Fuel Conservation," NASA TM-83741 (1984).

[21] Louis J. Williams, *Small Transport Aircraft Technology* (Honolulu: University Press of the Pacific, 2001), pp. 37–39.



The classic Pratt & Whitney JT9D engine interior and its major components: the fan, compressor, combustion chamber, turbine, and nozzle. Pratt & Whitney.

workhorse airliners at the time, namely the McDonnell-Douglas DC-9 and DC-10, as well as the Boeing 727, 737, and 747.[22]

Energy Efficient Engine Project

Taking everything learned to date by NASA and the industry about making turbo machinery more fuel efficient, the Energy Efficient Engine (E Cubed) project sought to further reduce the airlines' fuel usage and its effect on direct operating costs, while also meeting future FAA regulations and Environmental Protection Agency exhaust emission standards for turbofan engines. Research contracts were awarded to GE and Pratt & Whitney, which initially focused on the CF6-50C and JT9D-7A engines, respectively. The program ran from 1975 to 1983 and cost NASA about $200 million.[23]

Similar to the goals for the Engine Component Improvement project, the E Cubed goals included a 12-percent reduction in specific fuel consumption (SFC), which is a measure of the ratio between the mass of fuel used to the output power of the jet engine—much like a miles per gallon measurement for automobiles. Other goals of the E Cubed effort included a 5-percent reduction in direct operating costs and a

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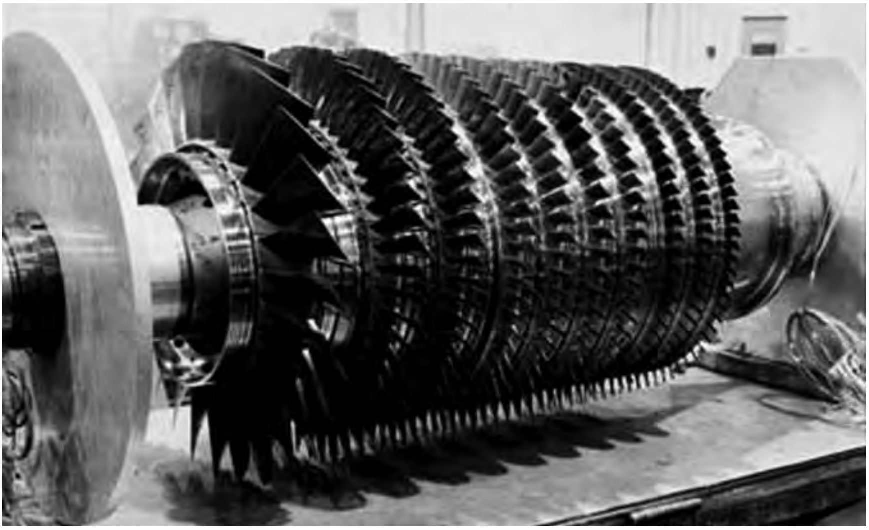
[22] *U.S. Government Support of the U.S. Commercial Aircraft Industry.*

[23] Lawrence. E. Macioce, John W. Schaefer, and Neal T. Saunders, "The Energy Efficient Engine Project," NASA TM-81566 (1980).



A high-pressure 14 to 1 ratio compressor rotor for a prototype Energy Efficient Engine on display in 1984 at Lewis Research Center. NASA.

50-percent reduction in the rate at which the SFC worsens over time as the engine ages. In addition to making these immediate improvements, it was hoped that a new generation of fuel-conservative turbofan engines could be developed from this work.[24]

Highlighting that program was development of a new type of compressor core and an advanced combustor made up of a doughnut-shaped ring with two zones—or domes—of combustion. During times when low power is needed or the engine is idling, only one of the two zones is lit up. For higher thrust levels, including full power, both domes are ignited. By creating a dual combustion option, the amount of fuel being burned can be more carefully controlled, reducing emissions of smoke, carbon monoxide, and hydrocarbons by 50 percent, and nitrogen oxides by 35 percent.[25]

As part of the development of the new compressor in particular, and the E Cubed and Engine Component Improvement programs in general, the Lewis Research Center developed first-generation computer programs for use in creating the new engine. The software helped engineers

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[24] Saunders, "Advanced Component Technologies for Energy-Efficient Turbofan Engines," NASA TM-81507 (1980).

[25] Guy Norris and Mark Wagner, *Boeing 777: The Technological Marvel* (Osceola, WI: MBI Publishing, 2001).

with conceptualizing the aerodynamic design and visualizing the flow of gases through the engine. The computer programs were credited with making it possible to design more fuel-efficient compressors with less tip and end-wall pressure losses, higher operating pressure ratios, and the ability to use fewer blades. The compressors also helped to reduce performance deterioration, surface erosion, and damage from bird strikes.[26]

History has judged the E Cubed program as being highly successful, in that the technology developed from the effort was so promising—and proved to meet the objectives for reducing emissions and increasing fuel efficiency—that both major U.S. jet engine manufacturers, GE and Pratt & Whitney, moved quickly to incorporate the technology into their products. The ultimate legacy of the E Cubed program is found today in the GE90 engine, which powers the Boeing 777. The E Cubed technology is directly responsible for the engine's economical fuel burn, reduced emissions, and low maintenance cost.[27]

Advanced Turboprop Project—Yesterday and Today

The third engine-related effort to design a more fuel-efficient powerplant during this era did not focus on another idea for a turbojet configuration. Instead, engineers chose to study the feasibility of reintroducing a jet-powered propeller to commercial airliners. An initial run of the numbers suggested that such an advanced turboprop promised the largest reduction in fuel cost, perhaps by as much as 20 to 30 percent over turbofan engines powering aircraft with a similar performance. This compared with the goal of a 5-percent increase in fuel efficiency for the Engine Component Improvement program and a 10- to 15-percent increase in fuel efficiency for the E Cubed program.[28]

But the implementation of an advanced turboprop was one of NASA's more challenging projects, both in terms of its engineering and in securing public acceptance. For years, the flying public had been conditioned to see the fanjet engine as the epitome of aeronautical advancement. Now they had to be "retrained" to accept the notion that a turbopropeller engine could be every bit as advanced, indeed, even more advanced, than the conventional fanjet engine. The idea was to have a jet engine firing

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26. *NASA Glenn Research Center at Lewis Field: Achieving the Extraordinary* (Cleveland: NASA, 1999), p. 24.

27. "A Giant Step in Jetliner Propulsion," *Spinoff 1996* (Washington, DC: NASA, 1996).

28. Williams, *Small Transport Aircraft Technology*, p. 38.

as usual with air being compressed and ignited with fuel and the exhaust expelled after first passing through a turbine. But instead of the turbine spinning a shaft that turned a fan at the front of the engine, the turbines would be spinning a shaft, which fed into a gearbox that turned another shaft that spun a series of unusually shaped propeller blades exterior to the engine casing.[29]

Begun in 1976, the project soon grew into one of the larger NASA aeronautics endeavors in the history of the Agency to that point, eventually involving 4 NASA Field Centers, 15 university grants, and more than 40 industrial contracts.[30]

Early on in the program, it was recognized that the major areas of concern were going to be the efficiency of the propeller at cruise speeds, noise both on the ground and within the passenger cabin, the effect of the engine on the aerodynamics of the aircraft, and maintenance costs. Meeting those challenges were helped once again by the computer-aided, three-dimensional design programs created by the Lewis Research Center. An original look for an aircraft propeller was devised that changed the blade's sweep, twist, and thickness, giving the propellers the look of a series of scimitar-shaped swords sticking out of the jet engine. After much development and testing, the NASA-led team eventually found a solution to the design challenge and came up with a propeller shape and engine configuration that was promising in terms of meeting the fuel-efficiency goals and reduced noise by as much as 65 decibels.[31]

In fact, by 1987, the new design was awarded a patent, and the NASA–industry group was awarded the coveted Collier Trophy for creating a new fuel-efficient turboprop propulsion system. Unfortunately, two unexpected variables came into play that stymied efforts to put the design into production.[32]

The first had to do with the public's resistance to the idea of flying in an airliner powered by propellers—even though the blades were still

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[29] Roy D. Hager and Deborah Vrabel, *Advanced Turboprop Project*, NASA SP-495 (Washington, DC: NASA, 1988), p. 5.

[30] Mark D. Bowles and Virginia P. Dawson, "The Advanced Turboprop Project: Radical Innovation in a Conservative Environment," in *From Engineering Science to Big Science, The NACA and NASA Collier Trophy Research Project Winners*, NASA SP-4219 (Washington, DC: NASA, 1998), p. 323.

[31] Glenn A. Mitchell, "Experimental Aerodynamic Performance of Advanced 40 Degree-Swept, 10-Blade Propeller Model at Mach 0.6 to 0.85," NASA TM-88969 (1988).

[32] Bowles and Dawson, "The Advanced Turboprop Project," p. 323.

A General Electric design for an Unducted Fan engine is tested during the early 1980s. General Electric.

being turned by a jet engine. It didn't matter that a standard turbofan jet also derived most of its thrust from a series of blades—which did, in fact, look more like a fan than a series of propellers. Surveys showed passengers had safety concerns about an exposed blade letting go and sending shrapnel into the cabin, right where they were sitting. Many passengers also believed an airliner equipped with an advanced turboprop was not as modern or reliable as pure turbojet engine. Jets were in; propellers were old fashioned. The second thing that happened was that world fuel prices dropped to the lower levels that preceded the oil embargo and the very rationale for developing the new turboprop in the first place. While fuel-efficient jet engines were still needed, the "extra mile" in fuel efficiency the advanced turboprop provided was no longer required. As a result, NASA and its partners shelved the technology and waited to use the archived files another day.[33]

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[33] Ibid.

The story of the Advanced Turboprop project had one more twist to it. While NASA and its team of contractor engineers were working on their new turboprop design, engineers at GE were quietly working on their own design, initially without NASA's knowledge. NASA's engine was distinguished by the fact that it had one row of blades, while GE's version featured two rows of counter-rotating blades. GE's design, which became known as the Unducted Fan (UDF), was unveiled in 1983 and demonstrated at the 1985 Paris Air Show. A summary of the UDF's technical features is described in a GE-produced report about the program:

> The engine system consists of a modified F404 gas generator engine and counterrotating propulsor system, mechanically decoupled, and aerodynamically integrated through a mixing frame structure. Utilization of the existing F404 engine minimized engine hardware, cost, and timing requirements and provided an engine within the desired thrust class. The power turbine provides direct conversion of the gas generator horsepower into propulsive thrust without the requirement for a gearbox and associated hardware. Counterrotation utilizes the full propulsive efficiency by recovering the exit swirl between blade stages and converting it into thrust.[34]

Although shelved during the late 1980s, the Alternate Turboprop and UDF technology and concept is being explored again as part of programs such as the Ultra-High Bypass Turbofan and Pratt & Whitney's Geared Turbofan. Neither engine is routinely flying yet on commercial airliners. But both concepts promise further reductions in noise, increases in fuel efficiency, and lower operating costs for the airline—goals the aerospace community is constantly working to improve upon.

Several concepts are under study for an Ultra-High Bypass Turbofan, including a modernized version of the Advanced Turboprop that takes advantage of lessons learned from GE's UDF effort. NASA has teamed with GE to start testing an open-rotor engine. For the NASA tests at Glenn Research Center, GE will run two rows of counter-rotating fan blades, with 12 blades in the front row and 10 blades in the back row. The composite fan blades are one-fifth subscale in size. Tests in

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[34] "Full Scale Technology Demonstration of a Modern Counterrotating Unducted Fan Engine Concept: Design Test," NASA CR-180867 (1987).

a low-speed wind tunnel will simulate low-altitude aircraft speeds for acoustic evaluation, while tests in a high-speed wind tunnel will simulate high-altitude cruise conditions in order to evaluate blade efficiency and performance.[35]

"The tests mark a new journey for GE and NASA in the world of open rotor technology. These tests will help to tell us how confident we are in meeting the technical challenges of an open-rotor architecture. It's a journey driven by a need to sharply reduce fuel consumption in future aircraft," David Joyce, president of GE Aviation, said in a statement.[36]

In an Ultra-High Bypass Turbofan, the amount of air going through the engine casing but not through the core compressor and combustion chamber is at least 10 times greater than the air going through the core. Such engines promise to be quieter, but there can be tradeoffs. For example, an Ultra-High Bypass Engine might have to operate at a reduced thrust or have its fan spin slower. While the engine would meet all the goals, it would fly slower, thus making passengers endure longer trips.

In the case of Pratt & Whitney's Geared Turbofan engine, the idea is to have an Ultra-High Bypass Ratio engine, yet spin the fan slower (to reduce noise and improve engine efficiency) than the core compressor blades and turbines, all of which traditionally spin at the same speed, as they are connected to the same central shaft. Pratt & Whitney designed a gearbox into the engine to allow for the central shaft to turn at one speed yet turn a second shaft connected to the fan at another speed.[37]

Alan H. Epstein, a Pratt & Whitney vice president, testifying before the House Subcommittee on Transportation and Infrastructure in 2007, explained the potential benefits the company's Geared Turbofan might bring to the aviation industry:

> The Geared Turbofan engine promises a new level of very low noise while offering the airlines superior economics and environmental performance. For aircraft of 70 to 150 passenger size, the Geared Turbofan engine reduces the fuel burned,

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[35] Deb Case and Rick Kennedy, "GE and NASA To Begin Wind-Tunnel Testing This Summer of Open Rotor Jet Engine Systems," GE Aviation News Release (Evendale, OH: General Electric, 2009).

[36] Ibid.

[37] Jeff Schweitzer, "An Overview of Recent Collaboration Research with NASA in Ultra High Bypass Technology," presented at the *NASA Fundamental Aeronautics 2007 Annual Meeting, New Orleans, Oct. 30–Nov. 1, 2007.*

> and thus the CO2 produced, by more than 12% compared to today's aircraft, while reducing cumulative noise levels about 20dB below the current Stage 4 regulations. This noise level, which is about half the level of today's engines, is the equivalent difference between standing near a garbage disposal running and listening to the sound of my voice right now.[38]

Pratt & Whitney's PW1000G engine incorporating a geared turbofan is selected to be used on the Bombardier CSeries and Mitsubishi Regional Jet airliners beginning in 2013. The engine was first flight-tested in 2008, using an Airbus A340-600 airliner out of Toulouse, France.[39]

Digital Electronic Engine Controls

As one set of NASA and contractor engineers worked on improving the design of the various types of jet engines, another set of researchers representing another science discipline were increasingly interested in marrying the computer's capabilities to the operation of a jet engine, much in the same way that fly-by-wire systems already were in use with aircraft flight controls.

Beginning with that first Wright Flyer in 1903, flying an airplane meant moving levers and other mechanical contrivances that were directly connected by wires and cables to control the operation of the rudder, elevator, wing surfaces, instruments, and engine. When Chuck Yeager broke the sound barrier in 1947 in the X-1, if he wanted to go up, he pulled back on the yoke and cables directly connecting the stick to the elevator, which made that aerosurface move to effect a change in the aircraft's attitude. The rockets propelling the X-1 were activated with a switch throw that closed an electrical circuit whose wiring led directly from the cockpit to the engines. As planes grew bigger, so did their control surfaces. Aircraft such as the B-52 bomber had aerosurfaces as big as the entire wings of smaller airplanes—too bulky and heavy for a single pilot to move using a simple cable/pulley system. A hydraulic system was required and "inserted" between the pilot's input on the yoke and the control surface needing to be moved. Meanwhile, engine

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[38] Alan H. Epstein, *Statement Before the Subcommittee on Aviation Committee on Transportation and Infrastructure, U.S. House of Representatives Hearing on Aviation and Environment: Noise, Washington, DC, Oct. 24, 2007.*

[39] "Pratt & Whitney Pure Power PW1000G Engines," Pratt & Whitney S16154.9.08 (2008).

operation remained more or less "old fashioned," with all parameters such as fuel flow and engine temperatures reported to the cockpit on dials the pilot could read, react to, and then make changes by adjusting the throttle or other engine controls.

With the introduction of digital computers and the miniaturization of their circuits—a necessity inspired, in part, by the reduced mass requirements of space flight—engineers began to consider how the quick-thinking electronic marvels might ease the workload for pilots flying increasingly more complex aircraft designs. In fact, as the 1960s transitioned to the 1970s, engineers were already considering aircraft designs that could do remarkable maneuvers in the sky but were inherently unstable, requiring constant, subtle adjustments to the flight controls to keep the vehicle in the air. The solution—already demonstrated for spacecraft applications during Project Apollo—was to insert the power of the computer between the cockpit controls and the flight control surfaces—a concept known as fly-by-wire. A pilot using this system and wanting to turn left would move the control stick to the left, apply a little back pressure, and depress the left rudder pedal. Instead of a wire/cable system directly moving the related aerosurfaces, the movement of the controls would be sensed by a computer, which would send electronic impulses to the appropriate actuators, which in turn would deflect the ailerons, elevator, and rudder.[40]

Managed by NASA's Dryden Flight Research Facility, the fly-by-wire system was first tested without a backup mechanical system in 1972, when a modified F-8C fighter took off from Edwards Air Force Base in California. Testing on this aircraft, whose aerodynamics were known and considered stable, proved that fly-by-wire could work and be reliable. In the years to follow, the system was used to allow pilots to safely fly unstable aircraft, including the B-2 bomber, the forward-swept winged X-29, the Space Shuttle orbiter, and commercial airliners such as the Airbus A320 and Boeing 777.[41]

As experienced was gained with the digital flight control system and computers shrunk in size and grew in power, it didn't take long for propulsion experts to start thinking about how computers could monitor

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[40] C.R. Jarvis, "An Overview of NASA's Digital Fly-By-Wire Technology Development Program," NASA 75N18246 (1975).

[41] James E. Tomayko, *Computers Take Flight: A History of NASA's Pioneering Digital Fly-By-Wire Project*, NASA SP-4224 (Washington, DC: NASA, 2000), p. vii.

engine performance and, by making many adjustments in every variable that affects the efficiency of a jet engine, improve the powerplant's overall capabilities.

The first step toward enabling computer control of engine operations was taken by Dryden engineers in managing the Integrated Propulsion Control System (IPCS) program during the mid-1970s. A joint effort with the U.S. Air Force, the IPCS was installed on an F-111E long-range tactical fighter-bomber aircraft. The jet was powered by twin TF30 afterburning turbofan engines with variable-geometry external compression inlets. The IPCS effort installed a digital computer to control the variable inlet and realized significant performance improvements in stallfree operations, faster throttle response, increased thrust, and improved range flying at supersonic speeds. During this same period, results from the IPCS tests were applied to NASA's YF-12C Blackbird, a civilian research version of the famous SR-71 Blackbird spy plane. A digital control system installed on the YF-12C successfully tested, monitored, and adjusted the engine inlet control, autothrottle, air data, and navigation functions for the Pratt & Whitney-built engines. The results gave the aircraft a 7-percent increase in range, improved handling characteristics, and lowered the frequency of inlet unstarts, which happen when an engine shock wave moves forward of the inlet and disrupts the flow of air into the engine, causing it to shutdown. Seeing how well this computer-controlled engine worked, Pratt & Whitney and the U.S. Air Force in 1983 chose to incorporate the system into their SR-71 fleet.[42]

The promising future for more efficient jet engines from developing digitally controlled integrated systems prompted Pratt & Whitney, the Air Force, and NASA (involving both Dryden and Lewis) to pursue a more robust system, which became the Digital Electronic Engine Control (DEEC) program.

Pratt & Whitney actually started what would become the DEEC program, using its own research and development funds to pay for configuration studies beginning during 1973. Then, in 1978, Lewis engineers tested a breadboard version of a computer-controlled system on an engine in an altitude chamber. By 1979, the Air Force had approached NASA and asked if Dryden could demonstrate and evaluate a DEEC system using an F100 engine installed in a NASA F-15, with flight tests beginning in

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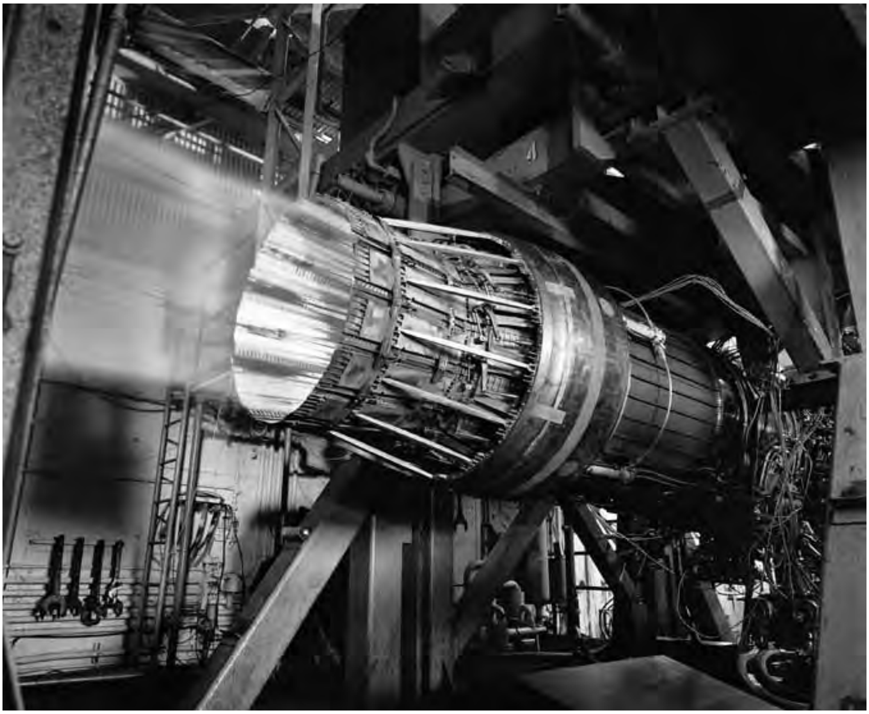
[42] James F. Stewart, Frank W. Burcham, Jr., and Donald H. Gatlin, "Flight-Determined Benefits of Integrated Flight-Propulsion Control Systems," NASA TM-4393 (1992), pp. 2–4.



The Digital Electronic Engine Control system was tested on a Pratt & Whitney F100 turbojet, similar to the one shown here undergoing a hot fire on a test stand. Pratt & Whitney.

1981. At every step in the test program, researchers took advantage of lessons learned not only from the IPCS exercise but also from a U.S. Navy-funded effort called the Full Authority Digital Engine Control program, which ran concurrently to the IPCS program during the mid-1970s.[43]

A NASA Dryden fact sheet about the control system does a good job of explaining in a concise manner the hardware involved, what it monitored, and the resulting actions it was capable of performing:

> The DEEC system tested on the NASA F-15 was an engine mounted, fuel-cooled, single-channel digital controller that received inputs from the airframe and engine to control a wide range of engine functions, such as inlet guide vanes, compressor stators, bleeds, main burner fuel flow, afterburner fuel flow and exhaust nozzle vanes.

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[43] T.W. Putnam, "Digital Electronic Engine Control History," NASA 86N25344 (1984), p. 2.

> Engine input measurements that led to these computer-controlled functions included static pressure at the compressor face, fan and core RPM, compressor face temperature, burner pressure, turbine inlet temperature, turbine discharge pressure, throttle position, afterburner fuel flow, fan and compressor speeds and an ultra violet detector in the afterburner to check for flame presence.
>
> Functions carried out after input data were processed by the DEEC computer included setting the variable vanes, positioning compressor start bleeds, controlling gas-generator and augmentation of fuel flows, adjusting the augmenter segment-sequence valve, and controlling the exhaust nozzle position. These actions, and others, gave the engine—and the pilot—rapid and stable throttle response, protection from fan and compressor stalls, improved thrust, better performance at high altitudes, and they kept the engine operating within its limits over the full flight envelope.[44]

When incorporated into the F100 engine, the DEEC provided improvements such as faster throttle responses, more reliable capability to restart an engine in flight, an increase of more than 10,000 feet in altitude when firing the afterburners, and the capability of providing stallfree operations. And with the engine running more efficiently thanks to the DEEC, overall engine and aircraft reliability and maintainability were improved as well.[45]

So successful and promising was this program that even before testing was complete the Air Force approved widespread production of the F100 control units for its F-15 and F-16 fighter fleet. Almost at the same time, Pratt & Whitney added the digital control technology in its PW2037 turbofan engines for the then-new Boeing 757 airliner.[46]

With the DEEC program fully opening the door to computer control of key engine functions, and with the continuing understanding of fly-by-wire systems for aircraft control—along with steady improvements in making computers faster, more capable, and smaller—the next logi-

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[44] "The DEEC," NASA TF-2004-03-DFRC (2004).

[45] "Digital Electronic Engine Control (DEEC) Flight Evaluation in an F-15 Airplane," NASA CP-2298 (1984).

[46] Christian Gelzer, "60 Years of Cutting-Edge Flight Research Marked at NASA Dryden," Dryden News Release 06-37 (2006).

cal step was to combine together computer control of engines and flight controls. This was done initially with the Adaptive Engine Control System (ADECS) program accomplished between 1985 and 1989, followed by the Performance Seeking Control (PSC) program that performed 72 flight tests between 1990 and 1993. The PSC system was designed to handle multiple variables in performance, compared with the single-variable control allowed in ADECS. The PSC effort was designed to optimize the engine and flight controls in four modes: minimum fuel flow at constant thrust, minimum turbine temperature at constant thrust, maximum thrust, and minimum thrust.[47]

The next evolution in the combining of computer-controlled flight and engine controls— a legacy of the original DEEC program—was inspired in large part by the 1989 crash in Sioux City, IA, of a DC-10 that had lost all three of its hydraulic systems when there was an uncontained failure of the aircraft's No. 2 engine. With three pilots in the cockpit, no working flight controls, and only the thrust levels available for the two remaining working engines, the crew was able to steer the jet to the airport by using variable thrust. During the landing, the airliner broke apart, killing 111 of the 296 people on board.[48]

Soon thereafter, Dryden managers established a program to thoroughly investigate the idea of a Propulsion Controlled Aircraft (PCA) using variable thrust between engines to maintain safe flight control. Once again, the NASA F-15 was pressed into service to demonstrate the concept. Beginning in 1991 with a general ability to steer, refinements in the procedures were made and tested, allowing for more precise maneuvering. Finally, on April 21, 1993, the flight tests of PCA concluded with a successful landing using only engine power to climb, descend, and maneuver. Research continued using an MD-11 airliner, which successfully demonstrated the technology in 1995.[49]

Numerical Propulsion System Simulation

NASA and its contractor colleagues soon found another use for computers to help improve engine performance. In fact, looking back at the history

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[47] John S. Orne, "Performance Seeking Control Program Overview," NASA 95N33011 (1995), p. 32.

[48] "Aircraft Accident Report: United Airlines Flight 232, McDonnell Douglas DC-10-10, Sioux Gateway Airport, Sioux City, Iowa, July 19, 1989," NTSB AAR-90-06 (1989).

[49] Tom Tucker, *Touchdown: The Development of Propulsion Controlled Aircraft at NASA Dryden* (Washington, DC: NASA, 1999).

A computer system known as Propulsion Controlled Aircraft is tested aboard an MD-11 airliner in 1995 at the Dryden Flight Research Center. NASA.

of NASA's involvement with improving propulsion technology, a trilogy of major categories of advances can be suggested based on the development of the computer and its evolution in the role that electronic thinkers have played in our culture.

Part one of this story includes all the improvements NASA and its industry partners have made with jet engines before the computer came along. Having arrived at a basic operational design for a turbojet engine—and its relations, the turboprop and turbofan—engineers sought to improve fuel efficiency, reduce noise, decrease wear, and otherwise reduce the cost of maintaining the engines. They did this through such efforts as the Quiet Clean Short Haul Experimental Engine and Aircraft Energy Efficiency program, detailed earlier in this case study. By tinkering with the individual components and testing the engines on the ground and in the air for thousands of hours, incremental advances were made.[50]

Part two of the story introduces the capabilities made available to engineers as computers became powerful enough and small enough to be incorporated into the engine design. Instead of requiring the pilot to manually make occasional adjustments to the engine operation in

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[50] "Propulsion/ACEE," NASA FACTS-93/8-81 (1981).

flight depending on what the instruments read, a small digital computer built into the engine senses thousands of measurements per minute and caused an equal number of adjustments to be made to keep the powerplant performing at peak efficiency. With the Digital Electronic Engine Control, engines designed years before behaved as though they were fresh off the drawing boards, thanks to their increased capabilities.[51]

Having taken engine designs about as far as it was thought possible, the need for even more fuel-efficient, quieter, and capable engines continued. Unfortunately, the cost of developing a new engine from scratch, building it, and testing it in flight can cost millions of dollars and take years to accomplish. What the aerospace industry needed was a way to take advantage of the powerful computers available at the dawn of the 21st century to make the engine development process less expensive and timelier. The result was part three of NASA's overarching story of engine development: the Numerical Propulsion System Simulation (NPSS) program.[52]

Working with the aerospace industry and academia, NASA's Glenn Research Center led the collaborative effort to create the NPSS program, which was funded and operated as part of the High Performance Computing and Communications program. The idea was to use modern simulation techniques and create a virtual engine and test stand within a virtual wind tunnel, where new designs could be tried out, adjustments made, and the refinements exercised again without costly and time-consuming tests in the "real" world. As stated in a 1999 industry review of the program, the NPSS was built around inclusion of three main elements: "Engineering models that enable multi-disciplinary analysis of large subsystems and systems at various levels of detail, a simulation environment that maximizes designer productivity and a cost-effective, high-performance computing platform."[53]

In explaining to the industry the potential value of the program during a 2006 American Society of Mechanical Engineers conference in

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[51] Jennifer L. Baer-Riedhart and Robert J. Landy, "Highly Integrated Digital Electronic Control—Digital Flight Control, Aircraft Model Identification and Adaptive Engine Control," NASA TM-86793 (1987).

[52] John K. Lytle, "The Numerical Propulsion System Simulation: A Multidisciplinary Design System for Aerospace Vehicles," NASA TM-1999-209194 (1999), p. 1.

[53] John Lytle, Greg Follen, Cynthia Naiman, Austin Evans, Joseph Veres, Karl Owen, and Isaac Lopez, "Numerical Propulsion System Simulation (NPSS) 1999 Industry Review," NASA TM-2000-209795 (2000), p. 7.

Spain, a NASA briefer from Glenn suggested that if a standard turbojet development program for the military—such as the F100—took 10 years, $1.5 billion, construction of 14 ground-test engines, 9 flight-test engines, and more than 11,000 hours of engine tests, the NPSS program could realize a:

- 50-percent reduction in tooling cost.
- 33-percent reduction in the average development engine cost.
- 30-percent reduction in the cost of fabricating, assembling, and testing rig hardware.
- 36-percent reduction in the number of development engines.
- 60-percent reduction in total hardware cost.[54]

A key—and groundbreaking—feature of NPSS was its ability to integrate simulated tests of different engine components and features, and run them as a whole, fully modeling all aspects of a turbojet's operation. The program did this through the use of the Common Object Request Broker Architecture (CORBA), which essentially provided a shared language among the objects and disciplines (mechanical, thermodynamics, structures, gas flow, etc.) being tested so the resulting data could be analyzed in an "apples to apples" manner. Through the creation of an NPSS developer's kit, researchers had tools to customize the software for individual needs, share secure data, and distribute the simulations for use on multiple computer operating systems. The kit also provided for the use of CORBA to "zoom" in on the data to see specific information with higher fidelity.[55]

Begun in 1997, the NPSS team consisted of propulsion experts and software engineers from GE, Pratt & Whitney, Boeing, Honeywell, Rolls-Royce, Williams International, Teledyne Ryan Aeronautical, Arnold Engineering Development Center, Wright-Patterson AFB, and NASA's

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[54] Ann K. Sehra, "The Numerical Propulsion System Simulation: A Vision for Virtual Engine Testing," presented at the *American Society of Mechanical Engineers TURBO EXPO, Barcelona, Spain, May 8–11, 2006.*

[55] Cynthia G. Naiman and Gregory J. Follen, "Numerical Propulsion System Simulation—A Common Tool for Aerospace Propulsion Being Developed," Research and Technology Report 2000 (Cleveland: NASA, 2001).

Glenn Research Center. By the end of the 2000 fiscal year, the NPSS team had released Version 1.0.0 on schedule. According to a summary of the program produced that year:

> (The new software) can be used as an aero-thermodynamic zero-dimensional cycle simulation tool. The capabilities include text-based input syntax, a sophisticated solver, steady-state and transient operation, report generation, a built-in object-oriented programming language for user-definable components and functions, support for distributed running of external codes via CORBA, test data reduction, interactive debug capability and customer deck generation.[56]

Additional capabilities were added in 2001, including the ability to support development of space transportation technologies. At the same time, the initial NPSS software quickly found applications in aviation safety, ground-based power, and alternative energy devices, such as fuel cells. Moreover, project officials at the time suggested that with the further development of the software, other applications could be found for the program in the areas of nuclear power, water treatment, biomedicine, chemical processing, and marine propulsion. NPSS proved to be so capable and promising of future applications that NASA designated the program a cowinner of the NASA Software of the Year Award for 2001.[57]

Work to improve the capabilities and expand the applications of the software continued, and, in 2008, NASA transferred NPSS to a consortium of industry partners, and, through a Space Act Agreement, it is currently offered commercially by Wolverine Ventures, Inc., of Jupiter, FL. Now at Version 1.6.5, NPSS's features include the ability to model all types of complex systems, plug-and-play interfaces for fluid properties, built-in plotting package, interface to higher fidelity legacy codes, multiple model views, command language interpreter with language sensitive text editor, comprehensive component solver, and variable setup controls. It also can operate on Linux, Windows, and UNIX platforms.[58]

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[56] Ibid.

[57] Laurel J. Strauber and Cynthia G. Naiman, "Numerical Propulsion System Simulation (NPSS): An Award Winning Propulsion System Simulation Tool," Research and Technology Report 2001 (Cleveland: NASA, 2002).

[58] "NPSS User Guide, Software Release: NPSS 1.6.5," *NASA NPSS-User* (2008), pp. 1-1 to 1-2.

Originally begun as a virtual tool for designing new turbojet engines, NPSS has since found uses in testing rocket engines, fuel cells, analog controls, combined cycle engines, thermal management systems, airframe vehicles preliminary design, and commercial and military engines.[59]

Ultra Efficient Engine Technology Program

With the NPSS tool firmly in place and some four decades of experience incrementally improving the design, operation, and maintenance of the jet engine, it was time to go for broke and assemble an ultra-bright team of engineers to come up with nothing short of the best jet engine possible.

Building on the success of technology development programs such as the Quiet Clean Short Haul Experimental Engine and Energy Efficient Engine project—all of which led directly to the improvements and production of turbojet engines now propelling today's commercial airliners—NASA approached the start of the 21st century with plans to take jet engine design to accomplish even more impressive feats. In 1999, the Aeronautics Directorate of NASA began the Ultra Efficient Engine Technology (UEET) program—a 5-year, $300-million effort—with two primary goals. The first was to find ways that would enable further improvements in engine efficiency to reduce fuel burn and, as a result, carbon dioxide emissions by yet another 15 percent. The second was to continue developing new materials and configuration schemes in the engine's combustor to reduce emissions of nitrogen oxides (NOx) during takeoff and landings by 70 percent relative to the standards detailed in 1996 by the International Civil Aviation Organization.[60]

NASA's Glenn Research Center led the program, with participation from three other NASA Centers: Ames, Langley, and the Goddard Space Flight Center in Greenbelt, MD. Also involved were GE, Pratt & Whitney, Honeywell, Allison/Rolls-Royce, Williams International, Boeing, and Lockheed Martin.[61]

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[59] Edward J. Hall, Joseph Rasche, Todd A. Simons, and Daniel Hoyniak, "NPSS Multidisciplinary Integration and Analysis," NASA CR-2006-213890 (2006).

[60] Joe Shaw, "Ultra-Efficient Engine Technology Project Continued to Contribute to Breakthrough Technologies," Research and Technology Report 2002 (Cleveland: NASA, 2003).

[61] Lori A. Manthey, "NASA Glenn Research Center UEET (Ultra-Efficient Engine Technology) Program: Agenda and Abstracts," NASA RTOP-714-01-4A (2001).

The program was comprised of seven major projects, each of which addressed particular technology needs and exploitation opportunities.[62] The Propulsion Systems Integration and Assessment project examined overall component technology issues relevant to the UEET program to help furnish overall program guidance and identify technology shortfalls.[63] The Emissions Reduction project sought to significantly reduce NOx and other emissions, using new combustor concepts and technologies such as lean burning combustors with advanced controls and high-temperature ceramic matrix composite materials.[64] The Highly Loaded Turbomachinery project sought to design lighter-weight, reduced-stage cores, low-pressure spools and propulsors for more efficient and environmentally friendly engines, and advanced fan concepts for quieter, lighter, and more efficient fans.[65] The Materials and Structures for High Performance project sought to develop and demonstrate high-temperature material concepts such as ceramic matrix composite combustor liners and turbine vanes, advanced disk alloys, turbine airfoil material systems, high-temperature polymer matrix composites, and innovative lightweight materials and structures for static engine structures.[66] The Propulsion-Airframe Integration project studied propulsion systems and engine locations that could furnish improved engine and environmental benefits without compromising the aerodynamic performance of the airplane; lowering aircraft drag itself constituted a highly desirable means of reducing fuel burn, and, hence, CO2 emissions will develop advanced technologies to yield lower drag propulsion system integration with the airframe for a wide range of vehicle classes. Decreasing drag improves air vehicle performance and efficiency, which

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[62] Manthey, "Ultra-Efficient Engine Technology (UEET) Program," Research and Technology Report 2001 (NASA, 2002).

[63] Ronald C. Plybon, Allan VanDeWall, Rajiv Sampath, Mahadevan Balasubramaniam, Ramakrishna Mallina, and Rohinton Irani, "High Fidelity System Simulation of Multiple Components in Support of the UEET Program," NASA CR-2006-214230 (2006).

[64] Kathleen M. Tacina and Changlie Wey, "NASA Glenn High Pressure Low NOx Emissions Research," NASA TM-2008-214974 (2008).

[65] Michael T. Tong and Scott M. Jones, "An Updated Assessment of NASA Ultra-Efficient Engine Technologies," presented at *17th International Symposium on Airbreathing Engines, Munich, Germany, Sept. 4–9, 2006*.

[66] James A. DiCarlo, Hee Mann Yun, Gregory N. Morscher, and Ramakrishna T. Bhatt, "High-Performance SiC/SiC Ceramic Composite Systems Developed for 1315 C (2400 F) Engine Components," Research and Technology Report 2003 (Cleveland: NASA, 2004).

reduces fuel burn to accomplish a particular mission, thereby reducing the CO2 emissions.[67] The Intelligent Propulsion Controls Project sought to capitalize upon breakthroughs in electronic control technology to improve propulsion system life and enhance flight safety via integrating information, propulsion, and integrated flight propulsion control technologies.[68] Finally, the Integrated Component Technology Demonstrations project sought to evaluate the benefits of off-the-shelf propulsion systems integration on NASA, Department of Defense, and aeropropulsion industry partnership efforts, including both the UEET and the military's Integrated High Performance Turbine Engine Technology (IHPTET) programs.[69]

By 2003, the 7 project areas had come up with 10 specific technology areas that UEET would investigate and incorporate into an engine that would meet the program's goals for reducing pollution and increasing fuel burn efficiency. The technology goals included:

1. Advanced low-NOx combustor design that would feature a lean burning concept.
2. A highly loaded compressor that would lower system weight, improve overall performance, and result in lower fuel burn and carbon dioxide emissions.
3. A highly loaded, high-pressure turbine that could allow a reduction in the number of high-pressure stages, parts count, and cooling requirements, all of which could improve fuel burn and lower carbon dioxide emissions.
4. A highly loaded, low-pressure turbine and aggressive transition duct that would use flow control techniques that would reduce the number of low-pressure stages within the engine.
5. Use of a ceramic matrix composite turbine vane that would allow high-pressure vanes to operate at a higher

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[67] Cecile M. Burg, Geoffrey A. Hill, Sherilyn A. Brown, and Karl A. Geiselhart, "Propulsion Airframe Aeroacoustics Technology Evaluation and Selection Using a Multi-Attribute Decision Making Process and Non-Deterministic Design," AIAA Paper 2004-4436 (2004).

[68] Sanjay Garg, "NASA Glenn Research in Controls and Diagnostics for Intelligent Aerospace Propulsion Systems," presented at the *Integrated Condition Management 2006 Conference, Anaheim, CA, Nov. 14–16, 2006*.

[69] Mary Jo Long-Davis, "Integrated Components Technology Demonstrations Overview," NTRS Document ID 200.502.14062 (2001).

inlet temperature, which would reduce the amount of engine cooling necessary and result in lower carbon dioxide emissions.

6. The same ceramic matrix composite material would be used to line the combustor walls so it could operate at a higher temperature and reduce NOx emissions.
7. Coat the turbine airfoils with a ceramic thermal barrier material to allow the turbines to operate at a higher temperature and thus reduce carbon dioxide emissions.
8. Use advanced materials in the construction of the turbine airfoil and disk. Specifically, use a lightweight single crystal superalloy to allow the turbine blades and vanes to operate at a higher temperature and reduce carbon dioxide emissions, as well as a dual microstructure nickel-base superalloy to manufacture turbine disks tailored to meet the demands of the higher-temperature environment.
9. Determine advanced materials and structural concepts for an improved, lighter-weight impact damage tolerance and noise-reducing fan containment case.
10. Develop active tip clearance control technology for use in the fan, compressor, and turbine to improve each component's efficiency and reduce carbon dioxide emissions.[70]

In 2003, the UEET program was integrated into NASA's Vehicle Systems program to enable the enginework to be coordinated with research into improving other areas of overall aircraft technology. But in the wake of policy changes associated with the 2004 decision to redirect NASA's space program to retire the Space Shuttle and return humans to the Moon, the Agency was forced to redirect some of its funding to Exploration, forcing the Aeronautics Directorate to give up the $21.6 million budgeted for UEET in fiscal year 2005, effectively canceling the biggest and most complicate jet engine research program ever attempted. At the same time, NASA was directed to realign its jet engine research to concentrate on further reducing noise.[71]

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[70] Michael T. Tong and Scott M. Jones, "An Updated Assessment of NASA Ultra-Efficient Engine Technologies," ISABE-2005-1163 (2005), p. 3.

[71] John W. Douglass, "NASA Aeronautics Research Funding: The Wrong Direction," *Space News*, Mar. 28, 2005, opinion page.

Nevertheless, results from tests of UEET hardware showed promise that a large, subsonic aircraft equipped with some of the technologies detailed above would have a "very high probability" of achieving the program goals laid out for reducing emissions of carbon dioxide and other pollutants. The data remain for application to future aircraft and engine schemes.[72]

Damage-Tolerant Fan Casing

While most eyes were on the big picture of making major engine advancements through the years, some very specific problems were addressed with programs that are just as interesting to consider as the larger research endeavors. The casings that surround the jet engine's turbomachinery are a case in point.

With the 1989 crash of United Airlines Flight 232 at Sioux City, IA, aviation safety officials became more interested in finding new materials capable of containing the resulting shrapnel created when a jet engine's blade or other component breaks free. In the case of the DC-10 involved in this particular crash, the fan disk of the No. 2 engine—the one located in the tail—separated from the engine and caused the powerplant to explode, creating a rain of shrapnel that could not be contained within the engine casing. The sharp metal fragments pierced the body of the aircraft and cut lines in all three of the aircraft's hydraulic systems. As previously mentioned in this case study, the pilots on the DC-10 were able to steer their aircraft to a nearly controlled landing. The incident inspired NASA pilots to refine the idea of using only jet thrust to maneuver an airplane and undertake the Propulsion Controlled Aircraft program, which took full advantage of the earlier Digital Electronic Engine Control research. The Iowa accident also sent structures and materials experts off on a hunt to find a way to prevent accidents like this in the future.

The United Flight 232 example notwithstanding, the challenge for structures engineers is to design an engine casing that will contain a failed fan blade within the engine so that it has no chance to pierce the passenger compartment wall and threaten the safety of passengers or cause a catastrophic tear in the aircraft wall. Moreover, not only does the casing have to be strong enough to withstand any blade or shrapnel impacts, it must not lose its structural integrity during an emergency

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[72] Tong and Jones, "An Updated Assessment of NASA Ultra-Efficient Engine Technologies," p. 1.

engine shutdown in flight. A damaged engine can take some 15 seconds to shut down, during which time cracks from the initial blade impacts can propagate in the fan case. Should the fan case totally fail, the resulting breakup of the already compromised turbomachinery could be catastrophic to the aircraft and all aboard.[73]

As engineers considered the use of composite materials, two methods for containing blade damage within the engine casing were now available: the new softwall and the traditional hardwall. In the softwall concept, the casing was made of a sandwich-type aluminum structure overwound with dry aramid fibers. (Aramid fibers were introduced commercially by DuPont during the early 1960s and were known by the trade name Nomex.) The design allows broken blades and other shrapnel to pass through the "soft" aluminum and be stopped and contained within the aramid fiber wrap. In the hardwall approach, the casing is made of aluminum only and is built as a rigid wall to reflect blade bits and other collateral damage back into the casing interior. Of course that vastly increases the risk that the shrapnel will be ingested through the engine and cause even greater damage, perhaps catastrophic. While that risk exists with the softwall design, it is not as substantial. Another benefit of the hardwall is that it maintains its structural soundness, or ductility, during a breakup of an engine. A softwall also features some amount of ductility, but the energy-absorbing properties of the aramid fibers is the major draw.[74]

In 1994, NASA engineers at the Lewis Research Center began looking into better understanding engine fan case structures and conducted impact tests as part of the Enabling Propulsion Materials program. Various metallic materials and new ideas for lightweight fan containment structures were studied. By 1998, the research expanded to include investigations into use of polymer composites for engine fan casings. As additional composite materials were made available, NASA researchers sought to understand their properties and the appropriateness of those materials in terms of containment capability, damage tolerance, commercial viability, and understanding any potential risk not yet identified for their use on jet engines.[75]

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[73] C.L. Stotler and A.P. Coppa, "Containment of Composite Fan Blades," NASA CR-159544 (1979).

[74] Bob Griffiths, "Composite Fan Blade Containment Case: Innovative Use of Carbon-Fiber Braid Yields a Ductile Structure that Resists Blade Impact," *High Performance Composites* (May 1, 2005).

[75] Ibid.

In 2001, NASA awarded a Small Business Innovation Research (SBIR) grant to A&P Technology, Inc., of Cincinnati to develop a damage-tolerant fan casing for a jet engine. Long before composites came along, the company's expertise was in braiding materials together, such as clotheslines and candlewicks. A&P—working together with the FAA, Ohio State University, and the University of Akron—was able to rapidly develop a prototype composite fan case that could be compared to the metal fan case. Computer simulations were key to the effort and serendipitously provided an opportunity to grow the industry's understanding and ability to use those very same simulation capabilities. First, well understood metallic casings undergoing a blade-out scenario were modeled, and the computer tested the resulting codes to reproduce the already-known results. Then came the trick of introducing code that would represent A&P's composite casing and its reaction to a blade-out situation. The process was repeated for a composite material wrapped with a braided fiber material, and results were very promising.[76]

The composite casing proposed by A&P used a triaxial carbon braid, which has a toughness superior to aluminum but is lighter, which helps ease fuel consumption. In tests of debris impact, the braided laminate performed better than the metal casing, because in some cases, the composite structure absorbed the energy of the impact as the debris bounced off the wall, and in other cases where the shrapnel penetrated the material, the damage to the wall was isolated to the impact point and did not spread. In a metal casing that was pierced, the resulting hole would instigate several cracks that would continue to propagate along the casing wall, appearing much like the spiderweb of cracks that appear on an automobile windshield when it is hit with a small stone on the freeway.

NASA continues to study the use of composite casings to better understand the potential effects of aging and/or degradation following the constant temperature, vibration, and pressure cycles a jet engine experiences during each flight. There also is interest in studying the effects of higher operating temperatures on the casing structure for possible use on future supersonic jets. (The effect of composite fan blades on casing containment also has been studied.)[77]

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[76] "Damage-Tolerant Fan Casings for Jet Engines," *Spinoff 2006* (Washington, DC: NASA, 2006), p. 14.

[77] C.L. Stotler and A.P. Coppa, "Containment of Composite Fan Blades," NASA CR-159544 (1979).

A General Electric GEnx engine with a composite damage-tolerant fan casing is checked out before eventual installation on the new Boeing 787. General Electric.

While composites have found many uses in commercial and military aviation, the first use of an all-composite engine casing, provided by A&P, is set to be used on GE's GEnx turbojet designed for the Boeing 787. The braided casing weighs 350 pounds less per engine, and, when other engine installation hardware to handle the lighter powerplants is considered, the 787 should weigh 800 pounds less than a similarly equipped airliner using aluminum casings. The weight reduction also should provide a savings in fuel cost, increased payload, and/or a greater range for the aircraft.[78]

Conclusion and a Look Ahead

For more than 50 years now, NASA has methodically and, for the most part, quietly advanced the state of art of propulsion technology. With the basic design of the jet engine unchanged since it was invented during World War II, modern jet engines incorporate every lesson learned during NASA's past five decades of research. As a result, jet engines are

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[78] "Damage-Tolerant Fan Casings for Jet Engines."

now quieter, safer, more fuel-efficient, less expensive to operate, and less polluting, while being easier to maintain. And thanks to advancements in computers and simulations, new engines can be tested for thousands of hours at a time without ever bending one piece of aluminum or braiding a square yard of composite material.

So what's in store for propulsion technology during the next few decades? More improvements with every possible variable of engine operations are still possible, with future advances more closely linked to new aircraft designs, such as the blended wing and body in which the engines may be more fully integrated into the structure of the aircraft.

In a feature story written in April 2009 for NASA's Aeronautics Research Mission Directorate Web site, this author interviewed several key Agency officials who are considering what the future holds for engine development and making plans for what the Agency's approach will be for managing the effort. Here is that look ahead.

NASA Researchers Work to Reduce Noise in Future Aircraft Design

It's a noisy world out there, especially around the Nation's busiest airports, so NASA is pioneering new technologies and aircraft designs that could help quiet things down a bit. Every source of aircraft noise, from takeoff to touchdown, is being studied for ways to reduce the racket, which is expected to get worse as officials predict that air traffic will double in the next decade or so.

"It's always too noisy. You have to always work on making it quieter," said Edmane Envia, an aerospace engineer at NASA's Glenn Research Center in Cleveland. "You always have to stay a step ahead to fulfill the needs and demands of the next generation of air travel."[79]

Noise reduction research is part of a broader effort by NASA's Aeronautics Research Mission Directorate in Washington to lay a technological foundation for a new generation of airplanes that are not as noisy, fly farther on less fuel, and may operate out of airports with much shorter runways than exist today. There are no clear solutions yet to these tough challenges, neither is there a shortage of ideas from NASA researchers who are confident positive results eventually will come.[80]

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[79] Interview of Envia by Jim Banke, Cape Canaveral, Feb. 4, 2009.

[80] Jeffrey J. Berton, Envia, and Casey L. Burley, "An Analytical Assessment of NASA's N1 Subsonic Fixed Wing Project Noise Goal," NASA LF99-8609 (2009).

“Our goal is to have the technologies researched and ready, but ultimately it’s the aircraft industry, driven by the market, that makes the decision when to introduce a particular generation of aircraft,” Envia said.

NASA organized its research to look three generations into the future, with conceptual aircraft designs that could be introduced 10, 20, or 30 years from now. The generations are called N+1, N+2, and N+3. Each generation represents a design intended to be flown a decade or so later than the one before it and is to feature increasingly sophisticated methods for delivering quieter aircraft and jet engines.[81]

“Think of the Boeing 787 Dreamliner as N and the N+1 as the next generation aircraft after that,” Envia said.

The N+1 is an aircraft with familiar parts, including a conventional tube-shaped body, wings, and a tail. Its jet engines still are attached to the wings, as with an N aircraft, but those engines might be on top of the wings, not underneath. Conceptual N+2 designs throw out convention and basically begin with a blank computer screen, with design engineers blending the line between the body, wing, and engines into a more seamless, hybrid look. What an N+3 aircraft might look like is anyone’s guess right now. But with its debut still 30 years away, NASA is sponsoring research that will produce a host of ideas for consideration. The Federal Aviation Administration’s current guidelines for overall aircraft noise footprints constitute the design baseline for all of NASA’s N aircraft concepts. That footprint summarizes in a single number, expressed as a decibel, the noise heard on the ground as an airplane lands, takes off, and then cuts back on power for noise abatement. The noise footprint extends ahead and behind the aircraft and to a certain distance on either side. NASA’s design goal is to make each new aircraft generation quieter than today’s airplanes by a set number of decibels. The N+1 goal is 32 decibels quieter than a fully noise compliant Boeing 737, while the N+2 goal is 42 decibels quieter than a Boeing 777. So far, the decibel goal for the N+1 aircraft has been elusive.[82]

“What makes our job very hard is that we are asked to reduce noise but in ways that do not adversely impact how high, far or fast an airplane is capable of flying,” Envia said.

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[81] Envia, “Progress Toward SFW N+1 Noise Goal,” presented at the *NASA Fundamental Aeronautics Program 2nd Annual Meeting, Atlanta, Oct. 7, 2008*.

[82] Beth Dickey, “NASA Awards Future Vehicle Aircraft Research Contracts,” NASA Contract Release C08-60 (2008).

NASA researchers have studied changes in the operation, shape, or materials from which key noise contributors are made. The known suspects include the airframe, wing flaps, and slats, along with components of the jet engine, such as the fan, turbine, and exhaust nozzle. While some reductions in noise can be realized with some design changes in these components, the overall impact still falls short of the N+1 goal by about 6 decibels. Envia said that additional work with design and operation of the jet engine's core may make up the difference, but that a lot more work needs to be done in the years to come. Meanwhile, reaching the N+2 goals may or may not prove easier to achieve.[83]

"We're starting from a different aircraft configuration, from a clean sheet, that gives you the promise of achieving even more aggressive goals," said Russell Thomas, an aerospace engineer at Langley Research Center. "But it also means that a lot of your prior experience is not directly applicable, so the problem gets a lot harder from that point of view. You may have to investigate new areas that have not been researched heavily in the past."[84]

Efforts to reduce noise in the N+2 aircraft have focused on the airframe, which blends the wing and fuselage together, greatly reducing the number of parts that extend into the airflow to cause noise. Also, according to Thomas, the early thinking on the N+2 aircraft is that the jet engines will be on top of the vehicle, using the airplane body to shield most of the noise from reaching the ground.

"We're on course to do much more thorough research to get higher quality numbers, better experiments, and better prediction methods so we can really understand the acoustics of this new aircraft configuration," Thomas said.

As for the N+3 aircraft, it remains too early to say how NASA researchers will use technology not yet invented to reduce noise levels to their lowest ever.

"Clearly significant progress has been made over the years and airplanes are much quieter than they were 20 years ago," Envia said, noting that further reductions in noise will require whole new approaches to aircraft design. "It is a complicated problem and so it is a worthy challenge to rise up to."

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[83] Don Weir, ed., "Engine Validation of Noise and Emission Reduction Technology Phase 1," NASA CR-2008-215225 (2008).

[84] Interview of Russell Thomas by Banke, Cape Canaveral, Feb. 4, 2009.

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