PROPULSION TECHNOLOGIES FOR THE FUTURE OF AVIATION

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Abstract

The aircraft engine was critical to enabling powered flight and subsequent advances in aviation. The National Aeronautics and Space Administration (NASA) defined goals that ensure the future health of the aviation industry. Revolutionary aircraft that will enable a new future of aviation and mobility are essential to that industry. This paper presents the objectives that must be achieved to revolutionize the aviation system and breakthrough technology solutions to meet the challenges. The paper highlights research accomplishments at the NASA Glenn Research Center that contribute to these solutions. Accomplishments include technologies that enhance aircraft safety, enable quiet aircraft engines as well as engines with reduced impact on air quality, and enhance the ability to move people and goods.

1 General Introduction

The era of powered flight began with the Wright brothers on December 17, 1903. While they were developing their airplane, the Wrights knew that they needed a vehicle with stability, controllability, and sustainability. They also recognized that propulsion was their most difficult challenge and that the weight of the engine relative to its power was of greatest significance. The Wright Brothers proposed to move their vehicle through the air with engine-driven propellers and computed the required horsepower using drag measured in wind-tunnel tests. For balance, the engine had to weigh about the same as a man. The Wrights decided on a gasoline engine weighing less than 180 pounds and delivering 8 – 9 horsepower with minimum vibration. When it became clear that no off-the-shelf engine with the required power-to-weight ratio was available in the United States and no company was interested in building only one engine, the Wright brothers' mechanic—Charles E. Taylor (Figure 1)—was entrusted with building the engine (Figure 2). It weighed 170 pounds, with accessories, and delivered 12 horsepower at 1025 revolutions per minute. The excess horsepower allowed strengthening of wings, spars and bracing, and the Wrights could have added 150 pounds to the vehicle weight.

Fig. 1. Charles E. Taylor, the Wright Brothers' mechanic

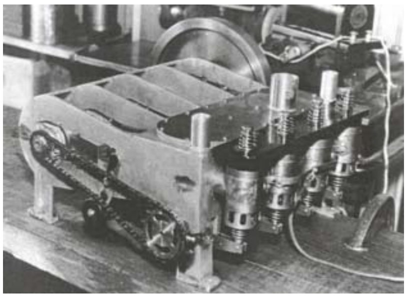


Fig. 2. The Wright Brothers' 1903 engine.

As aviation progressed, engineers began to explore the possibility of developing a jet engine. Sir Frank Whittle, an English aviation engineer and pilot, and Dr. Hans von Ohain, a German airplane designer, both are recognized for their contributions to the jet engine. Each worked separately and knew nothing of the other's work. Whittle was the first to register a patent application for a gas turbine for jet propulsion, in January 1930, having to overcome problems with combustion and turbine blade failure. His first engine, which had a single-stage centrifugal compressor coupled with a single-stage turbine, was successfully bench tested in April 1937. It demonstrated the feasibility of the turbojet concept but was not intended for use in an aircraft. The first flight of Whittle's engine took place on May 15, 1941 in a Gloster E-28/29. The aircraft later achieved a speed of 370 miles per hour with the engine providing 1000 pounds of thrust. The author is shown with a working model of Sir Whittle's W2/700 engine in Figure 3.

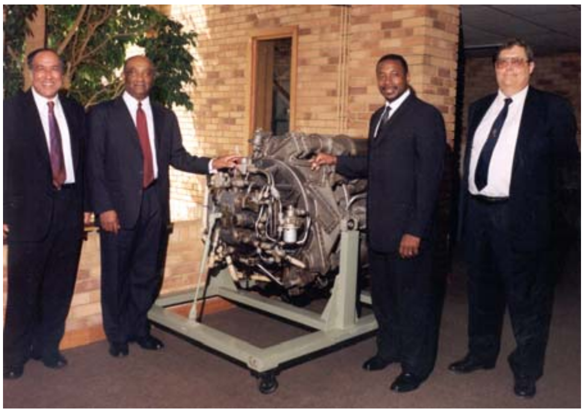
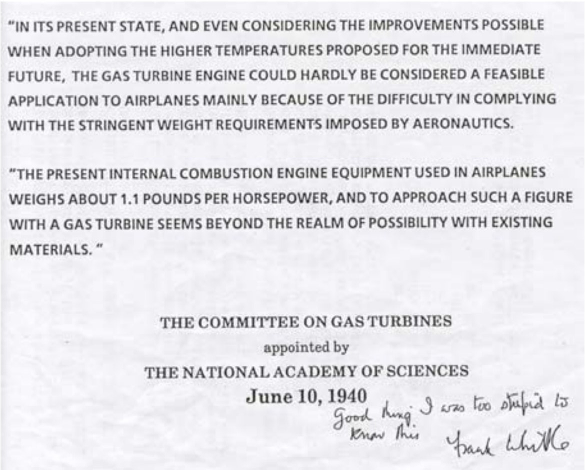


Fig. 3. Professor Riti Singh, Dr. Donald Campbell, Dr. Woodrow Whitlow, Jr., and Professor Phil Hutchinson with Sir Frank's W2/700 engine.

In 1936, Hans van Ohain and Max Han patented a jet engine that Ernst Heinkel Aircraft flew in an HE-178. That aircraft achieved a speed of 400 miles per hour with 1100 pounds of thrust. Sir Frank and von Ohain achieved jet-powered flight despite the doubts of the National Academy of Sciences Committee on Gas Turbines (Figure 4). The handwritten response supposedly is that of Sir Frank himself.



"IN ITS PRESENT STATE, AND EVEN CONSIDERING THE IMPROVEMENTS POSSIBLE WHEN ADOPTING THE HIGHER TEMPERATURES PROPOSED FOR THE IMMEDIATE FUTURE, THE GAS TURBINE ENGINE COULD HARDLY BE CONSIDERED A FEASIBLE APPLICATION TO AIRPLANES MAINLY BECAUSE OF THE DIFFICULTY IN COMPLYING WITH THE STRINGENT WEIGHT REQUIREMENTS IMPOSED BY AERONAUTICS.

"THE PRESENT INTERNAL COMBUSTION ENGINE EQUIPMENT USED IN AIRPLANES WEIGHS ABOUT 1.1 POUNDS PER HORSEPOWER, AND TO APPROACH SUCH A FIGURE WITH A GAS TURBINE SEEMS BEYOND THE REALM OF POSSIBILITY WITH EXISTING MATERIALS."

THE COMMITTEE ON GAS TURBINES
appointed by
THE NATIONAL ACADEMY OF SCIENCES
June 10, 1940

Good thing I was too stupid to know this
Frank Whittle

Fig. 4. National Academy of Sciences' evaluation of the possibility of developing a jet engine.

Since the invention of the jet engine, the evolution of propulsion systems has been critical to advances in aviation. Figure 5 shows the contributions of propulsion systems to advances in civil aviation.

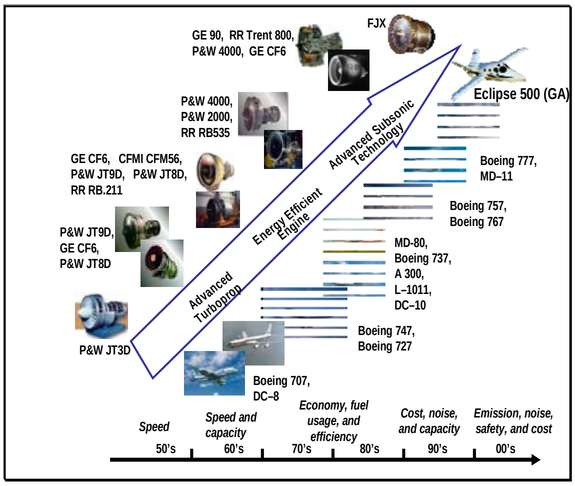


Fig. 5. Contributions of propulsion systems to advances in civil aviation.

In the United States, aviation has become critical to the movement of goods and people. Americans, per capita, use aviation more than the citizens of any other country, and personal trips account for more than 50 percent of U.S. air travel. Sixty percent of all trips over 1000 miles are completed by air, and the number of commercial travelers within the U.S. is expected to double in 10 years and triple in 20 years. This indicates that aviation has become an integral part of everyday American life, and its role will only continue to grow. To enable a safe, environmentally friendly expansion of the air transportation system, the National Aeronautics and Space Administration (NASA) established goals that will help to revolutionize aviation.

One key to revolutionizing aviation is to make the safe air transportation system that we now enjoy even safer. The accident rate for commercial aviation is very low, but that rate has remained constant for more than the past two decades. Even with low accident rates, the anticipated growth in commercial aviation would mean a major accident frequency approaching one per week. NASA has established the objective to introduce technologies that would reduce the accident rate such that, with increased traffic and aging aircraft, the frequency of accidents in the future will be reduced drastically as compared with a baseline period of 1990 to 1996.

Technology solutions that ease the restrictions on the global aviation system must be found. Future advances in aviation will have to address public concerns over noise and emissions, increasing costs associated with high fuel consumption, and the need for faster means of transportation. Environmental issues related to aviation have resulted in imposed limits on aircraft and airport operations worldwide. Community noise restrictions limit the hours of and number of operations at all but the most remote airports. Fifty of the largest airports view noise as their largest concern, and noise concerns are among the major hurdles confronting improvements to the aviation infrastructure such as airport expansion. Significant (and realizable) reductions in aircraft noise levels will be achieved by increased understanding of the physical phenomena that create the noise—unsteady flows, turbulence, shock waves, shear layers, vortical wakes, and their interaction. Because of the effects of aircraft and airport emissions on local air quality, regulations have constrained operations at several airports in the United States and prevented the basing of specific military aircraft within certain areas. Future efforts to address global warming concerns could lead to limitations on the number and type of aircraft flight operations. In order to develop revolutionary, low-emissions concepts—where emissions include nitrogen oxide (NO_X), carbon dioxide (CO_2), water vapor, volatiles, unburned hydrocarbons, particulate matter, and soot—it is essential to understand the physical mechanisms that govern combustion (reaction sets, chemical kinetics, pollutant and soot formation, turbulence interaction) and to develop predictive methodologies that can be used to guide aircraft development. Clearly, noise and emissions issues must be solved to ensure that the air transportation of the future is not constrained and can provide the necessary capacity and accessibility. These advances will occur for aircraft that operate in all speed ranges.

Subsonic, fixed-wing aircraft will require highly improved performance while satisfying the strict environmental constraints. This requires lightweight and strong materials, high-lift concepts, advanced noise prediction and reduction technologies, guidance, navigation, and control systems, and advanced engines with efficient, low-emission combustion systems. Unconventional aircraft such as those with hybrid wing-body planforms promise to be much quieter and more efficient than conventional tube-and-wing concepts.

It will be necessary to improve the competitiveness of rotary wing vehicles, as compared with fixed-wing aircraft, while maintaining their unique benefits. Rotary wing aircraft have the potential to provide point-to-point travel, making routine air travel more accessible to everyone. The potential can be realized only by advancing technologies that increase the range, speed, payload capacity, fuel efficiency, and environmental acceptance (especially noise) of rotorcraft. Advances in materials, aeromechanics, flow control, and propulsion will make this possible. Figure 6 shows an example of flow modeling that could be used in the design of future rotary wing aircraft.

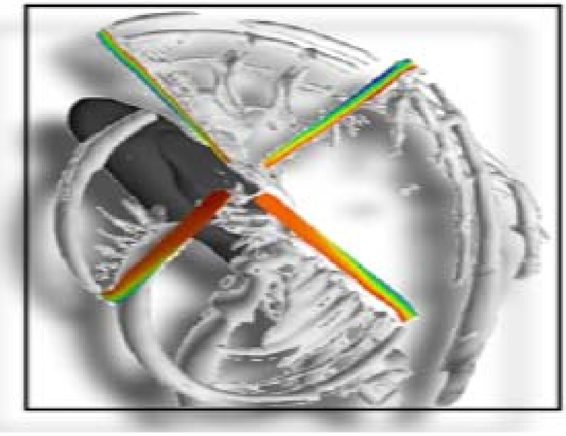


Fig. 6. Modeling of rotary wing flow dynamics.

Advances in cruise efficiency, noise and emissions reductions, and vehicle integration and control could enable routine supersonic transportation. These advances will eliminate environmental and performance barriers that prevent practical supersonic vehicles. Supersonic flight over land will be made possible by reducing the disturbance from sonic booms and by more efficient, environmentally friendly propulsion systems.

Hypersonic aircraft will enable global reach, quick reaction, persistence, and significant payload. In addition, these vehicles can be used as surveillance platforms to augment satellite systems. Development of such aircraft requires advances in high-temperature materials; guidance, navigation, and control; aerothermodynamics; and propulsion systems.

To increase capacity, technology and concepts will have to be implemented to eliminate the potential “exponential growth” in delays that could result at major U. S. airports. Future transports will have at least twice the lift coefficient of today’s aircraft. This will enable shorter take-off and landing field lengths and quicker climb-out and descent maneuvers to improve capacity, reduce noise and open many existing airports to air service. Figure 7, where each blue mark represents an aircraft in flight, illustrates anticipated growth in the congestion of the U. S. national airspace system. Improvements in the terminal and airport domains are necessary to increase the system’s capacity. There is a need to achieve the maximum possible productivity in the combined use of gates, taxiways, runways, terminal airspace, and other airportal resources. Advances in statistical decision theory, data mining, trajectory and wake modeling, applied mathematics for optimization with multiple uncertain variables, and human model development will be critical to enable the development of revolutionary concepts, capabilities and technologies that will enable significant increases in the capacity, efficiency, and flexibility of the airspace system.

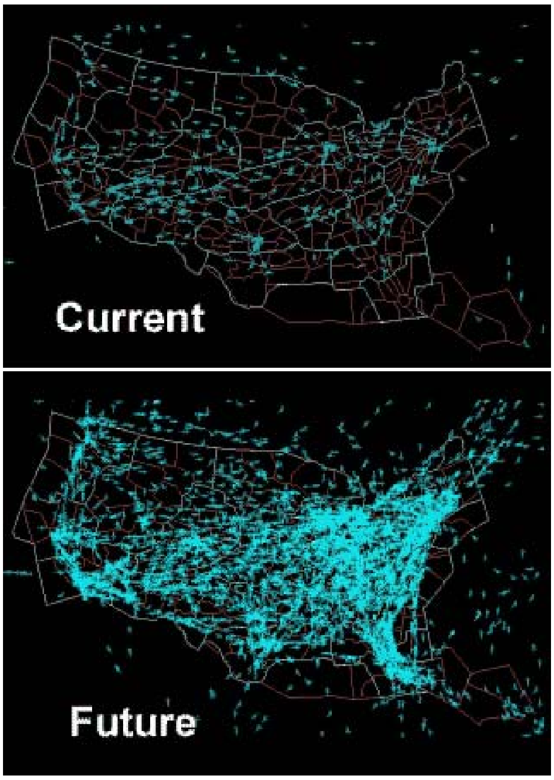


Fig. 7. Anticipated growth in congestion of the U. S. national airspace system.

This paper presents breakthrough technology solutions and research at the NASA Glenn Research Center (GRC) that contribute to the goal of revolutionizing the aviation system. These solutions include propulsion controls and health management methods for aircraft engine performance diagnostics and containment systems for ultra-safe engine operations. Concepts for low-noise fans and nozzles to reduce aircraft engine noise are explored. Technologies for combustors that reduce nitrogen oxide emissions and improve local air quality near airports and that reduce carbon dioxide emissions to reduce aviation’s impact on global air quality are discussed, including advanced combustor and active combustion control concepts. Energy storage devices that could enable all-electric aircraft that are whisper-quiet and pollution-free are discussed. Required advances in aerospace materials and electronics and sensors are presented and, finally, technologies that enhance freedom of movement for inter-city and long-haul travel are presented.

2 Safety

Using accident data from 1996 as a baseline, NASA established an objective to reduce aviation's fatal accident rate by a factor of five within 10 years and by a factor of 10 within 25 years. One key to improving safety is to reduce system and component failures as causal and contributing factors in aircraft accidents and incidents. It will be necessary to develop advanced diagnostic and prognostic capabilities for detection, mitigation, and management of aging-related hazards.

Technologies that decrease the susceptibility of current and next-generation aircraft and onboard systems to premature deterioration will be developed and implemented, greatly improving vehicle safety. This will enable operators to identify aging-related hazards before they become critical, and to incorporate durability and aging mitigation technologies and processes into the design of future aircraft. Highly integrated and complex flight-critical health management technologies and systems will enable nearly continuous on-board situational awareness of the vehicle health state for use by the flight crew, ground crew, and maintenance depot. Improved safety and reliability will be achieved by onboard systems capable of performing self diagnostics and self correction of anomalies that otherwise could go unattended until a critical failure occurs. Advances in areas such as sensors and data mining may lead to self-healing systems. Research in materials will increase our understanding of the aging and durability properties of composites and superalloys. Enhancements in adaptive controls and in crew-vehicle interface technologies will lead to safer aircraft operations.

There is a need to ensure that crew workload and situational awareness are safely optimized and adapted to the future operational environment. Methods to automatically monitor, measure, and assess the state of crew awareness will be incorporated into future vehicles. This will enable system designers to eliminate the safety risk of unintended consequences when introducing new and advanced systems into an operational environment.

Onboard control resilience will be provided to ensure safety in the presence of adverse flight conditions. Specifically, advanced state-of-the-art of adaptive controls as a design option will provide enhanced stability and maneuverability margins.

At GRC, the focus is on technologies that improve propulsion system safety. When a propulsion malfunction is involved in an aviation accident or incident, it often is a contributing cause rather than the sole cause for the event. Simon [1] defined propulsion health management (PHM) objectives to develop and validate propulsion system health monitoring technologies. These technologies are designed to prevent engine malfunctions from occurring in flight and to mitigate detrimental effects in the event that such malfunctions occur. The NASA objective is to enhance safety by incorporating PHM technologies such as vibration diagnostics, model-based controls and diagnostics, advanced instrumentation, and general aviation propulsion system health monitoring into aircraft engines.

Uncontained turbine engine rotor failure, an event that results in the escape of debris through the engine nacelle envelope due to a rotating component failure, can result in catastrophic damage to the aircraft structure and systems and/or serious injury or fatalities to passengers and crew. An on-line, automated crack detection system will be capable of detecting turbine rotor disk cracks in the early stages by noninvasive monitoring of vibration measurements. The concept of model-based controls and diagnostics, shown in Figure 8, provides prognostic and diagnostic capability and fault accommodation, preventing or reducing the severity of potential failures [2]. Component health can be diagnosed through interpretation of high-response pressure measurements, and affordable engine crack detection instrumentation is needed for operation within harsh engine environments.

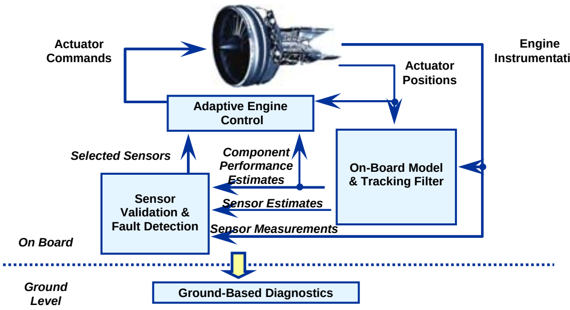


Fig. 8. Model-based controls and diagnostics.

An aircraft engine life-extending control [3] is another method developed at GRC that can improve aviation safety. The controller design utilizes damage models to monitor the damage rate and accumulation for critical engine parts. Required technologies include sensors for crack detection and measurement, stress measurement, and tip clearance measurement. All of these sensors must be capable of operating in harsh engine conditions.

Kobayashi and Simon [4] developed a model-based diagnostic method that used neural networks and genetic algorithms. Neural networks were used to estimate the engine internal health, and genetic algorithms were applied for sensor bias detection and estimation. Results showed that the approach is promising for reliable diagnostics of aircraft engines.

Kobayashi and Simon [5] applied a bank of Kalman filters to aircraft gas turbine engine sensor and actuator fault detection and isolation (FDI) in conjunction with the detection of component faults. Each of the multiple filters is designed to detect a specific or actuator fault, and if a fault does occur, all filters except the one using the correct hypothesis produce large estimation errors, isolating the specific fault. The authors applied the FDI approach to a nonlinear engine simulation for nominal and aged conditions. This approach, which utilizes an on-board engine model, is possible due to the increase of digital computational power. In this work, Kobayashi and Simon demonstrated the ability to successfully detect and isolate sensor and actuator bias errors when faults are caused by foreign object damage, and the method is robust in the presence of engine degradation.

International aviation regulatory agencies require that aircraft turbine engines safely contain fan, compressor, and turbine blades should they be ejected during operation. To achieve this requirement, all commercial turbine engines include an engine blade containment system. In some cases, the system consists of a metal ring that is thick and strong enough to prevent blade penetration. Other systems consist either of relatively light metal or composite rings, a structure to provide stiffness, and a series of layers of impact-resistant dry fabric. In large turbofan engines, metal containment systems can have a mass of over 500 kilograms while fabric systems can have up to 25 percent less mass. Since polymers have yet to achieve the necessary long-term, high-temperature durability, metal systems are necessary for high-temperature applications such as around parts of the compressor and the turbine regions and for fans in supersonic jet engines where conditions are more demanding. For metal containment systems, Revilock and Pereira [6] conducted impact tests in the GRC Impact Dynamics Facility (Figure 9) that showed that Inconel 718 and Titanium-6242 had better impact properties than three other candidate metals at room and at elevated temperatures.

Fig. 9. GRC Ballistic Impact Facility.

Revilock et al. [7] tested five braided fabric containment systems for ballistic impact performance and showed that for the same architecture, Zylon can absorb up to twice the kinetic energy before penetration than other materials (Figure 10), making it the better containment fabric.

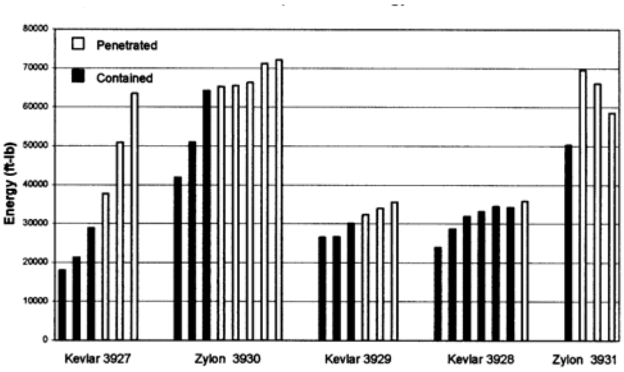


Fig. 10. Fabric impact test energy.

3 Emissions

The International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection is addressing worldwide concerns about local air quality and climate change. While not yet a significant concern at the global level, aircraft emissions already are a major concern in some communities. Some European airports are imposing landing fees based on aircraft emissions and in the United States, some of the busiest commercial airports are unable to increase flight operations because they are located in areas where air pollution levels consistently exceed the national standard. To enable further expansion of airport operations, NO_x emissions from future aircraft engines must be reduced in order to limit the resulting ground-level ozone.

Even with today's best technology improvements, NO_x and CO_2 emissions from aircraft are projected to increase by 400 percent and 300 percent, respectively, by 2050. NASA established the objective to reduce NO_x emissions from aircraft by 70 percent within 10 years and by 80 percent within 25 years (using the 1996 ICAO standard as the baseline) and to reduce aircraft CO_2 emissions by 25 percent and by 50 percent in the same timeframes (using 1997 subsonic aircraft technology as the baseline). Reduction of NO_x will require advanced combustion technology, and CO_2 emissions reduction can be accomplished by reducing fuel burn through increased performance and efficiency. Meeting this objective requires overall engine pressure ratios as high as 55:1 – 60:1 and turbine inlet temperatures exceeding 1700ºC.

Demands for decreased emissions while increasing performance have resulted in advanced combustor designs that are dependent on effective fuel-air mixing and lean operation. Lean-burning, low-emissions combustors are susceptible to combustion instabilities that typically are caused by the interaction of the fluctuating heat release from the combustion process with naturally occurring acoustic resonances [8]. Due to non-uniformities in the fuel-air mixing and in the combustion process, hot areas that can be zones of increased NO_x formation exist in the combustor exit plane. Elimination of the hot streaks—reduction in pattern factor—can contribute to emissions reduction. It also is desirable to maintain a combustion zone fuel-air mixture ratio near stoichiometric to minimize the formation of carbon monoxide (CO) and unburned hydrocarbons (UHCs). However, mixture ratios near stoichiometric result in high flame temperatures and increased NO_x production. Control of the fuel-air ratio is required to minimize the production of CO, UHCs, and NO_x.

Active combustion control research at GRC includes combustion instability control, burner pattern factor control, and emission minimizing control [9]. A neural network-based control approach, shown in Figure 11, was developed to attenuate thermo-acoustic instabilities observed in a lean premix-prevaporize (LPP) combustor flame tube.

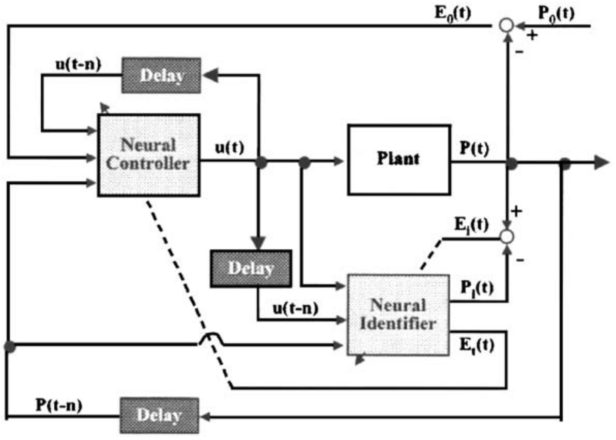


Fig. 11. Neural combustion instability control approach.

A burner-pattern-factor control system that is capable of producing a more uniform combustor exit temperature has been developed [9]. The active distribution system delivers the required total fuel flow and, based on feedback from temperature sensors at the combustor exit plane, the control system sends signals to redistribute the total fuel inside the combustor. This results in as uniform a temperature distribution at the exit plane as possible. Preliminary testing showed that this method produced up to 52-percent reduction in pattern factor and up to 7-percent NO_x reduction. At some engine operating conditions, slight increases in CO (1 percent) and UHC (2 percent) were observed.

LPP has been used to demonstrate extremely low NO_x emissions in ground power applications. However, for higher pressure and temperature aircraft applications, LPP is susceptible to autoignition and flashback. An alternative to LPP systems is lean-direct injection (LDI) combustion in which the fuel is injected directly into the flame zone. While the potential for either auto-ignition or flashback is not present, it is important to achieve fine atomization and mixing of the fuel and air quickly and uniformly. This results in low flame temperatures and NO_x levels near those of LPP systems. Tacina et al. [10] developed a lean-direct-wall-injection combustor concept in which fuel is injected into a swirling airflow from a fuel injector located on the combustor wall or mixer wall. The basic configuration is shown in Figure 12.

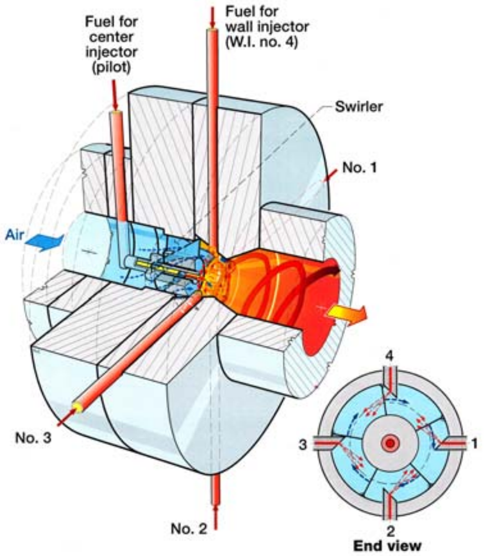


Fig. 12. Lean-direct-wall-injection combustor concept.

A 75-percent NO_x reduction from the 1996 ICAO standard was demonstrated in flame tube tests using this technology over a range of engine pressure ratios.

Tacina et al. [11] demonstrated multipoint, lean-direct injection concepts that had 25 and 36 fuel injectors in the size of a conventional single fuel injector. An integrated-module approach was used for the construction where photo-chemically etched laminates, diffusion bonded together, combine the fuel injectors, air swirlers, and fuel manifold into a single element (Figure 13).

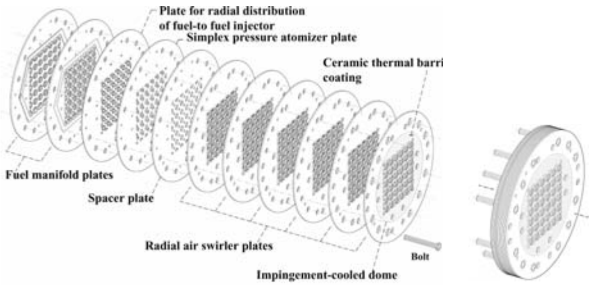


Fig. 13. Multipoint integrated module.

Flame tube tests of the 25-point configuration resulted in greater than 80 percent reduction in NO_x emissions from the 1996 ICAO standard. A 15-degree combustor sector test of the LDI concept using 36 injectors spaced farther apart

(Figure 14) demonstrated a 70-percent NO_x reduction [12]. The sector represented a realistic full annular combustor, including cooled liner.

Fig. 14. 36-point, integrated module, 15º sector.

An LDI concept that is a multiplex fuel injector concept (Figure 15) manufactured using conventional machining methods and containing multipoint fuel injection tips and multi-burning zones was developed to reduce NO_x emissions from advanced high-pressure aircraft gas turbine engines at all power conditions [13]. Flame tube tests of the multiplex LDI concept with 49 equally spaced injector tips in the size of a conventional, single-fuel injector demonstrated NO_x levels that are the same as the 25-point method developed by Tacina et al. [12] but slightly more than those obtained using the 36-point method reported in the same reference. This indicates that interaction effects are important in NO_x reduction and may represent a practical limit on the number of fuel injector sites.

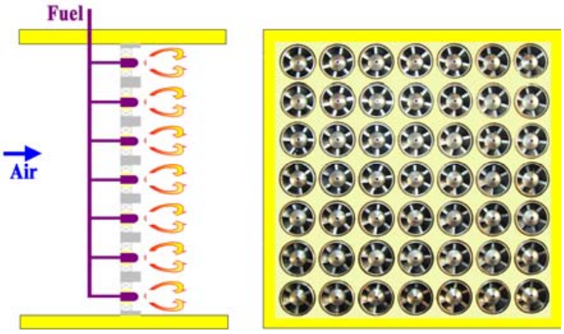


Fig. 15. Multiplex fuel injector module.

3.1 Materials Challenges

Advanced high-temperature materials that lead to reduced NO_x and CO_2 emissions were developed as part of NASA's Ultra Efficient Engine Technology Program [14]. Meeting these goals requires overall engine pressure ratios as high as 60:1 and turbine inlet temperatures exceeding 1700ºC. Achieving an overall engine pressure ratio of up to 60:1 requires high-temperature disk alloys with temperature capabilities in the 700ºC – 760ºC range. Researchers from NASA, General Electric Aircraft Engines, and Pratt & Whitney developed a nickel-based powder disk superalloy for commercial and military engines that can withstand temperatures over 700ºC, an 80ºC increase over production disk alloys. The alloy was scaled up successfully to produce forgings typical of Boeing 737 aircraft engines (Figure 16), and over one million hours of testing demonstrated that the alloy has a balanced set of material properties that far exceeds state-of-the-art production material.

Fig. 16. Boeing 737-size disk forging from new alloy.

The strategy for increasing turbine inlet temperature is to improve the capabilities of single-crystal nickel-based alloys and thermal barrier coatings (TBCs). An advanced, single-crystal nickel-base alloy with a 40ºC increase in temperature capability over the state-of-the-art alloy has been developed [14]. One goal is to develop computational tools using multiscale models for the design of single crystal nickel-base alloys. Researchers at GRC and the Ohio Aerospace Institute have developed computational tools to design alloys at the atomistic level [15]. Thermal barrier coatings that will provide capability for a 165ºC increase in temperature gradient across the coating and surface temperature as compared to state-of-the-art yttria stabilized zirconia (YSZ) TBCs are under development. The approach is to develop low-thermal conductivity ceramic coatings that would be stable at higher surface temperatures and under large thermal gradients. Preliminary experiments showed that the thermal conductivity of YSZ could be lowered by up to 66 percent by adding various alloying oxides.

Silicon carbide (SiC) fiber reinforced silicon carbide (SiC/SiC) ceramic matrix composite (CMC) materials for combustor liners allow for higher temperature operation capability for gas turbine engines. Elimination or reduction of film cooling of the liner results in lower NO_x emissions [16] and reduces compressor bleed-air requirements, improving aerodynamic efficiency. A CMC system with 1480ºC temperature capability has been developed in the Ultra Efficient Engine Technology Program. The system includes a CMC with 1315ºC temperature capability and an environmental barrier coating with 1480ºC capability and a 165ºC gradient across the coating [14]. Efforts to develop a coating with 1480ºC capability are underway. Use of SiC nanotubes as reinforcement for CMCs is being explored to develop a CMC system with 1650ºC capability. Vapor phase growth of SiC nanotubes by chemical vapor deposition and functionalizing the surface of carbon nanotubes to form SiC are being pursued as methods to produce SiC nanotubes.

3.2 Alternate Power

GRC researchers have investigated electric power and propulsion technologies to reduce emissions from aircraft. Concepts that have been studied include airbreathing fuel cells to produce environmentally benign, competitively priced, and durable systems for aircraft power and propulsion. Technologies such as cell chemistries, advanced materials, and novel cell, stack, component and systems designs were investigated.

Solar cells have been used to produce electric power to run propeller motors during the day for an ultralight flying wing aircraft [17]. Because there is no energy storage system aboard the aircraft to provide power in absence of sunlight, the planes are forced to glide back to earth at night. Regenerative fuel cell energy storage systems would produce reactants via electrolysis during the day using solar array power and, at night, use those reactants in a fuel cell to produce power to maintain the solar in flight. This would allow the aircraft to fly indefinitely. The energy storage system for such an airplane has been projected to require an energy density of at least 400 W-hr/kg [17], making regenerative fuel cell energy storage systems viable candidates.

Solid oxide fuel cells (SOFCs) have been explored as an alternate means of producing power. Current gas turbine auxiliary power units (APUs) contribute 20 percent of airport ground-based emissions, and a fuel cell APU will lead to near zero emissions, lower noise, and could reduce aircraft fuel consumption. SOFCs are simpler in concept; their solid construction alleviates corrosion problems and gas crossover associated with liquid-electrolyte-based cells. Hydrogen and light hydrocarbons are suitable fuels and stack operating temperatures are compatible with fuel reforming techniques. To enable near-term application of SOFCs to aircraft power systems, efforts were initiated to identify and characterize promising candidate hydrocarbon fuels. Fuel desulfurization techniques and sulfur-tolerant anodes are being developed to increase the durability of SOFC systems operating with sulfur-containing jet fuels. For aircraft operations, fuel cell power densities are required to be at least an order of magnitude greater than current state of the art. Current efforts include reducing anode thickness by a factor of 10 – 15, developing advanced interconnect and electrolyte materials to increase SOFC operating temperature, and developing durable high-temperature seals.

Kahout and Schmitz [18] presented the results of a first-order feasibility study for an all-electric personal air vehicle utilizing a fuel cell-powered propulsion system. They considered the following configurations: a proton exchange membrane (PEM) fuel cell with liquid hydrogen storage; a direct methanol PEM fuel cell; and a direct internal reforming solid oxide fuel cell (SOFC)/turbine hybrid system using liquid methane fuel. The SOFC/hybrid system appears to offer the most potential in terms of achieving an acceptable range and take-off weight.

3.3 High-Temperature Electronics and Sensors

In order for future aeronautics engines to meet the increasing requirements for reduced emissions, reduced fuel burn, and increased safety, it is necessary to include intelligence in the engine design and operation. This implies the development of sensors, actuators, control logic, signal conditioning, communications, and packaging that will be able to operate under the harsh environments present in an engine. This requires technology advancements in four areas: high-temperature electronics, sensors, packaging of harsh environment devices, and silicon carbide (SiC) electronic materials.

SiC appears to be the strongest candidate semiconductor for near-term implementation of 500ºC – 600ºC integrated electronics [19]. Discrete SiC devices such as pn junction diodes, Junction Field Effect Transistors (JFETs), and Metal Oxide-Semiconductor Field Effect Transistors (MOSFETs) have demonstrated excellent electrical functionality at 600ºC, but only for short periods. For such electronics to be useful in turbine engine applications, much longer 600ºC harsh-environment lifetimes must be realized. The operational lifetime of SiC-based transistors at 600ºC is governed primarily by the reliability and stability of various interfaces with the SiC crystal surface. Junction-based transistors without gate insulators appear more feasible in the near term. Hunter et al. [19] reported that the pn junction gate JFET is closest to demonstrating long-term operation at 600ºC.

SiC-based pressure sensors have a much wider temperature range than standard sensors and can have high-temperature SiC electronics integrated with the sensor. However, improvements in micromachining and packaging for operating in harsh environments are required. Reactive ion etching to form well-defined diaphragm structures has been developed by Beheim and Salupo [20], and a novel packaging strategy that decouples thermomechanical interactions between the sensors and packaging components has been demonstrated. A chip-level electronic package was designed, fabricated, and assembled for high-temperature, harsh-environment microelectronic systems using ceramic substrates and gold, thick-film metallization. This packaging system has been tested successfully at 500ºC in an oxidizing environment for over 5000 hours.

To advance SiC electronic materials, improved SiC starting material should significantly enhance the development of electronics and sensor technologies. Research by Powell et al. [21] was aimed at improving the quality of the SiC starting material on which devices are fabricated. Eliminating the defects and growing step-free SiC surfaces are used to improve the starting material. They reported the formation of SiC mesa surfaces as large as 0.2 x 0.2 millimeters completely free of a single atomic step. Further work needs to be done to characterize these new material growth mechanisms and to realize the advantages in device properties that the uses of these new materials can provide.

4 Noise

Airports once built in remote areas now are located closer to sprawling communities, and noise typically is the primary objection to airport and runway expansion. Airports are subject to an increasing number of noise restrictions affecting their operation and the operations of aircraft. Since 1980, the number of airports operating under noise restrictions worldwide has grown to several hundred. To address this issue, NASA established the objective to reduce the perceived noise levels of future aircraft by a factor of 2 (10 decibels) within 10 years and by a factor of 4 (20 decibels) within 25 years, using 1997 subsonic aircraft technology as the baseline. Reducing perceived noise levels by 20-decibels, in most cases, will contain objectionable aircraft noise within airport boundaries.

Quieting aircraft propulsion systems will provide significant progress towards meeting the noise objective. With the advent of high-bypass-ratio turbofan engines, the fan has become a major source of noise from modern commercial aircraft propulsion systems. At takeoff and on approach, fan and jet noise tends to dominate the engine total flyover noise signature even when noise suppression due to acoustic liners is included. Figure 17 shows representative flyover noise levels, on a component basis, for several types of aircraft using turbofan engines representative of 1992 technology [22].

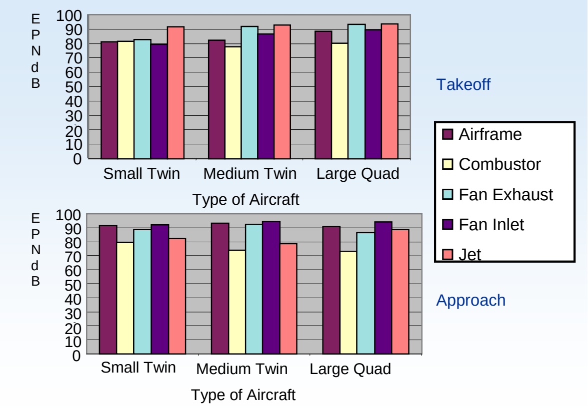


Fig. 17. Representative flyover noise levels.

The anticipated increase in engine bypass ratio to improve thermodynamic efficiency is likely to increase the importance of fan noise, making controlling and reducing this component of engine noise even more important.

A major source of engine noise comes from the interaction of the rotor viscous wake with the stators. Traditional methods of reducing this interaction noise have been to select blade/stator ratios to satisfy the cut-off criterion for propagation of the fundamental rotor tone and increased axial spacing between the rotor and stator. Increased rotor-stator axial spacing may degrade fan aerodynamic performance and increase engine weight.

NASA tested an advanced high-bypass-ratio fan with swept and leaned stators, shown in Figure 18, and demonstrated the benefits of this technology in reducing fan noise [23].

Fig. 18. Partially assembled fan stage showing swept and leaned stators.

The results clearly showed that incorporation of either sweep and lean or sweep only could significantly reduce rotor-stator tone levels beyond what is achieved by relocating the conventional radial stator to the downstream location. When scaled to a two-engine aircraft, the results suggest that this technology could be used to achieve a significant portion of the NASA noise objective.

Testing at takeoff and approach flight conditions showed that acoustics benefits similar to those obtained for low-speed fans might be achieved for higher-tip-speed fans with similar stator sweep and lean [24].

Rotor trailing edge blowing where the velocity deficit from the viscous wake of rotor blades is reduced by injecting air into the wake from a trailing edge slot was demonstrated for low-speed fan noise reduction [25]. Figure 19 shows a model of a composite hollow rotor blade with the pressure side skin removed to show the internal flow passages. The passages are designed to deliver the injected flow at the design pressure and flow rate to fill the wake momentum deficit. Substantial reduction in the fan tone levels was achieved by filling the viscous wakes at a blowing rate of 1.6 percent – 1.8 percent of the fan mass flow rate. Figure 20 shows a typical result in which trailing edge blowing caused a more uniform mean flow profile. The inset shows that the wake harmonic amplitudes were reduced by more than a factor of two for the first four harmonics. This indicates the potential for significant noise level reductions using wake management technology.

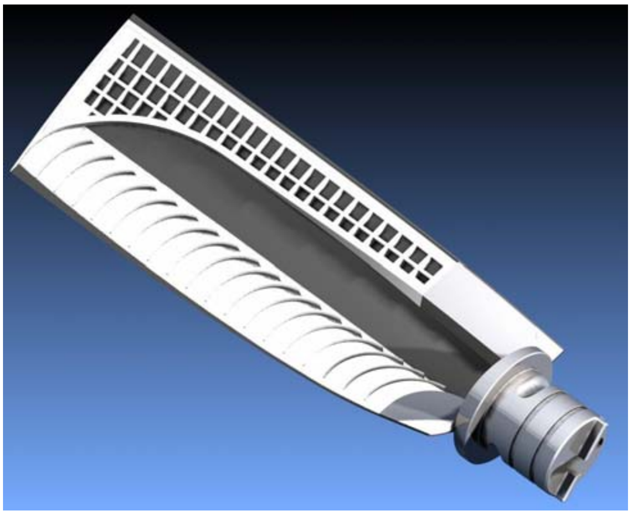


Fig. 19. Internal flow passages for hollow fan blade, tested on low-speed fan rig.

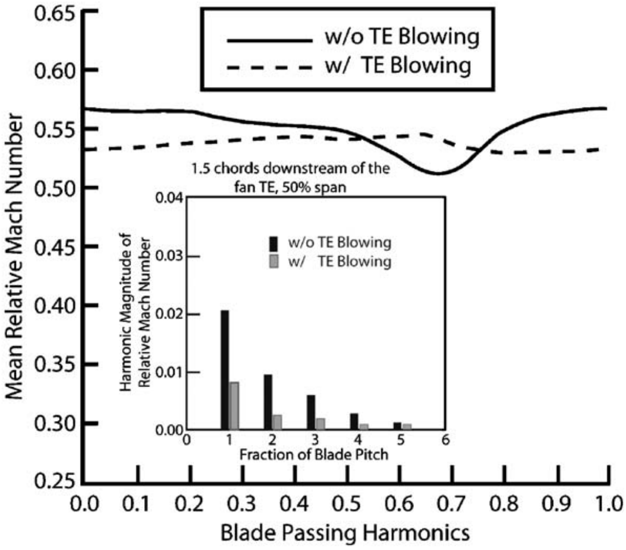


Fig. 20. Effect of fan trailing edge blowing on mean flow profile in fan wake.

5 Capacity

The essence of freedom of movement hinges on aviation, and improving mobility by reducing travel time for long and short journeys requires a wide range of innovations and improvements. In response to these needs, NASA established an objective to reduce intercity door-to-door time by half in 10 years and by two-thirds in 25 years and reduce long-haul transcontinental travel time by half within 25 years.

For long journeys, affordable supersonic travel will be essential, but the technological challenges are significant. NASA is developing technologies to resolve problems that include engine emissions. The section on materials challenges in this paper contains technology solutions that could address engine emissions issues for supersonic transports.

NASA researchers developed technology that would reduce the cost of operating short-haul regional jets. Foil air bearings (Figure 21) [26] and a high-temperature, shaft coating could replace ball bearings and lubricating oil found in conventional gas turbine engines [27]. The coating is used to reduce friction and wear of the air bearings during start-up and shut down when sliding occurs and prior to the formation a lubricating air film. The coating technology allowed the bearings to operate successfully at temperatures up to 650°C. Studies have shown that for a 50-passenger jet, oil-free technology can reduce direct operating costs by 8 percent.

Fig. 21. Photograph of foil air bearing.

6 Concluding Remarks

Since aviation has become an integral part of everyday life, NASA has defined a goal to revolutionize aviation. This will ensure the health of the air transportation industry by enabling a safe, environmentally friendly expansion of aviation. Revolutionary aircraft are required to reach the goals, and propulsion systems are a critical part of the strategy. Significant progress has been made in developing technology solutions that enhance the safety of aircraft engines, and that reduce their noise and emissions. Technologies that enable people and goods to be moved farther and faster to anywhere at any time have been demonstrated. As the technologies critical to the advancement of aircraft propulsion systems continue to be developed, the goal of a safe, environmentally friendly air transportation will become closer to reality.

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