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Revolutionary Propulsion Systems for 21st Century Aviation

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ABSTRACT

The air transportation for the new millennium will require revolutionary solutions to meeting public demand for improving safety, reliability, environmental compatibility, and affordability. NASA's vision for 21st Century Aircraft is to develop propulsion systems that are intelligent, virtually inaudible (outside the airport boundaries), and have near zero harmful emissions (CO_2 and NOx). This vision includes intelligent engines that will be capable of adapting to changing internal and external conditions to optimally accomplish the mission with minimal human intervention. The distributed vectored propulsion will replace two to four wing mounted or fuselage mounted engines by a large number of small, mini, or micro engines. And the electric drive propulsion based on fuel cell power will generate electric power, which in turn will drive propulsors to produce the desired thrust. Such a system will completely eliminate the harmful emissions. This paper reviews future propulsion and power concepts that are currently under development at NASA Glenn Research Center.

INTRODUCTION

The future world economy is envisioned to be truly global, where national boundaries become diffused by interdependent commerce. This vision of the future can only be realized if there is a revolutionary change in transportation systems, enabling greater mobility of people and products with improved timeliness and convenience. Propulsion and power capabilities are the foundation on which future subsonic and supersonic transports will shape the aviation landscape and establish this global conduit of commerce.

Propulsion innovations have been the fundamental driver to progress in air transportation. Enormous advances in propulsion performance and efficiency have made it possible for aircraft to travel at higher speeds over longer ranges while carrying larger payloads. This has increased capacity by orders of magnitude since the advent of air travel. The FAA and commercial sectors are forecasting another dramatic growth in commercial air transportation in the next 10 to 25 years. Commercial air transportation will again seek and rely on advanced propulsion solutions to meet this ever-increasing public demand.

As we approach the centennial celebration of the Wright Brothers' First Flight, the challenge of the new millennium is to develop and deliver innovative, revolutionary solutions to air transport that will meet public demand. Safety, capacity, and environmental concerns remain the theme, vision and challenge for NASA and our industry partners in the 21st Century. We need to travel faster and cheaper, while improving the quality of travel and allowing aviation to expand to meet public demand. The aeropropulsion systems of the future will require operation over a wide range of flight regimes, while providing high levels of safety and reliability. They will need to be much more energy efficient throughout their flight envelope while keeping emissions of atmospheric pollutants and noise to harmless levels. In addition, they will need to be inexpensive to develop, manufacture, and operate.

Advanced aeropropulsion systems and computational research tools, as well as discrete technologies, will be the major contributors to 21st Century air transportation innovation. Revolutionary propulsion systems will enable revolutionary aircraft designs that meet the need and demand of the future.

AEROPROPULSION VISION FOR 21ST CENTURY AVIATION

NASA proposes a phased aeropropulsion research approach triggered by thresholds of technology revolutions and National needs to realize our vision for 21st Century air transportation (Figure 1). NASA will transfer high-risk research and technology from each phase to industry-compatible propulsion configurations. This will be done by compounding innovation successes from the preceding phases to enable new configurations. Revolutionary propulsion ideas will be enabled as we pursue technology research that supports our extended long-term vision with the national research community.

The Gas Turbine Revolution (as characterized by Variable Capacity, Ultra High Bypass Ratio, Intelligent Engines) concentrates on component design and systems operability that result in propulsion systems that are compact, intelligent, and efficient for subsonic and supersonic transports. Adaptive controls and materials will be an integral part of the propulsion system design. The Engine Configuration Revolution (as characterized by Distributed Vectored Propulsion systems) will focus on smart engine operations and distributed vectored propulsion systems. Distributed exhaust and engine concepts will be an integral part of advanced airframe designs.

The Fuel Infrastructure Revolution will make possible the use of alternate fuels such as low carbon fuels, hydrogen and hybrids towards low emissions propulsion concepts. The Alternate Energy Propulsion Revolution will exploit fuel cells and other high-energy power sources towards powering emissionless, non-gas turbine propulsion concepts. Innovative technologies, propulsion components,

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and engine systems will maximize efficiency and performance of the next generations of subsonic and supersonic aircraft while having no adverse impact on our environment.

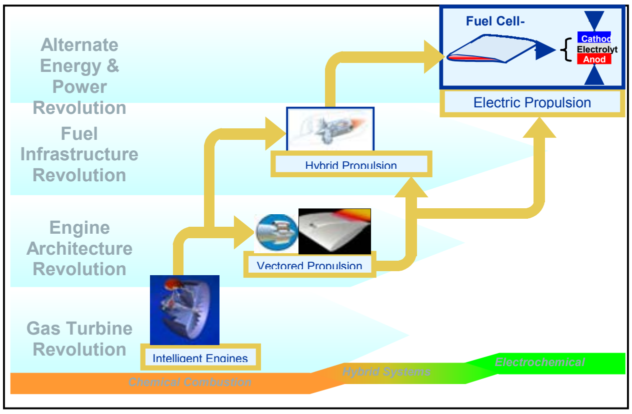

Fig. 1 Propulsion System Revolutions Enabling Mobility

VARIABLE CAPABILITY, ULTRA HIGH BYPASS RATIO INTELLIGENT ENGINES

Advancements in the hydrocarbon-fueled gas turbine engine are rapidly approaching the limits of integration for conventional transport aircraft. Increases in bypass ratio (BPR) enabled by high temperature, high-pressure cores have ushered in a sustained era of quiet, fuel efficient subsonic propulsion. Future improvements in commercial core specific power output are limited by the growing sensitivity to NOx emission impacts and the physical size of the core-powered propulsor (or fan) for any given thrust-class of engine.

Historically, the first generation high bypass turbofan engines prior to about 1985 were designed to meet the energy crisis challenge. These propulsion systems introduced early 3-D aerodynamic and computer aided design, and incorporated the first generation of superalloy materials, ceramic coatings and polymer matrix composites (PMCs). The second-generation aircraft gas turbine engine, prior to about 1995, had continued emphasis on fuel-burn reduction but was also designed to meet emerging noise and emissions challenges. These higher BPR turbofan engines incorporated advanced materials for still higher cycle temperatures and pressures, which realized greater core specific-power and overall efficiency. Aiding these turbine engine advancements was the introduction of multi-bladerow computer analysis and modeling of unsteady flow phenomena, supercomputing advancements, and the introduction of parallel processing. The current generation of turbofan engine technology research focuses on meeting an increasing diversity of applications requirements (civil, fighters, high Mach, high altitude, etc.). This research places emphasis on the environment and affordable performance gains in the wake of lost US market share and declining research budgets. The global economy and ecology are driving more physics-based modeling of the component-integrated propulsion system, with greater emphasis on reduced computational time. This design/analysis capability is presently compounding with fundamental research advancements from traditional disciplines (aerodynamics, materials, controls, etc.) to usher in a next generation of technology innovations.

To further reduce fuel burnt and harmful emissions and noise, the next generation turbine engine(intelligent engine) technologies will be focused in the following three strategic areas:

-Intelligent Computing and Controls strategies.
-Smart Components with active (or passive) control to enhance/ optimize the performance.
-Adaptive Cycles and Systems to optimize the engine performance throughout the entire operation.

Intelligent Computing and Controls

In addition to the current effort on physics based modeling for multi-disciplinary (aero, thermo, and structural) analysis of propulsion systems, the next generation computing process will have several new features. The intelligent computational environment will: provide need based information to individuals from different disciplines; compute the level of uncertainty in the computed results caused by variability in geometry, operating conditions and numerical error (probabilistic methods); select optimum number of processors for computing; and determine the use of appropriate code for desired level of fidelity in the design or analysis process.

NASA Glenn Research Center is currently developing a computational environment for the design and analysis of any conceivable propulsion system (Lytle, 2000), called the Numerical Propulsion System Simulation (NPSS). NPSS (Figure 2) focuses on the integration of multiple disciplines such as thermodynamics, aerodynamics, structures, and heat transfer. It captures the concept of numerical zooming between 0-dimensional to 1-, 2-, and 3-dimensional analysis codes.

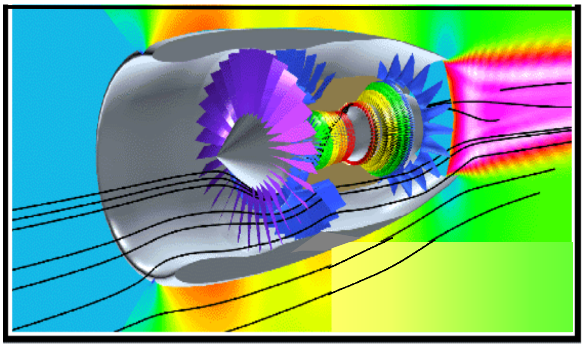

Fig. 2 Numerical Propulsion System Simulation of a Large Commercial Turbofan Engine

The vision for NPSS is to create a "numerical test cell" enabling full engine simulations overnight on cost effective computing platforms. Numerical zooming between NPSS engine simulations and higher fidelity representations of the engine components (fan, compressor, burner, turbines, etc.) has already been demonstrated. Future augmentations will address the above mentioned intelligent computing concepts.

In the area of sensors and controls, future research will also transform recent successes in physics-based multidisciplinary modeling into real-time propulsion health monitoring and management for improved safety and reduced maintenance costs. Further developments in adaptive on-board engine models, advanced component design techniques coupled with material-embedded nano-sensors and evolving information-technology capabilities (computational processing speed, data acquisition and dissemination, etc.) will allow for real-time engine condition monitoring and performance optimization. Such progress will provide several benefits including continuous real-time trending of engine health, synthesized sensor values which can be used in sensor validation logic and estimates of the unmeasurable engine parameters such as thrust and component stability margins which can be used in feedback control logic.

Future vision is to make various engine systems function more autonomously from the cockpit using biologically inspired "intelligent engine" controls akin to the involuntary nervous system. This will enable event or outcome-based decisions from the voluntary cockpit control for safer aircraft operation of increasingly complex aviation systems.

Smart Components for Noise and Emission Reduction

The research effort for smart components is directed at active and passive control strategies to improve performance (increased loading and operability), and reduce noise and harmful emissions. For performance improvement, NASA's research has demonstrated rotating stall and surge instability can be significantly delayed by actively or passively controlling (steady or fluctuating) the compressor bleed. It has also been recently demonstrated that blade loading and efficiency can be significantly enhanced by flow injection/ suction on the airfoil suction surface.

For noise reduction, the key engine components that need to be addressed are Fan, Inlet, and Exhaust Nozzle. Aspirated fans with trailing edge blowing (passive) have shown significant reduction in rotor-stator interaction as well as broad band noise. Inlet and nozzle technologies will focus on noise reduction and propulsion system operability impacts. These advanced modeling techniques will also allow designers to capitalize on natural acoustic phenomena (such as ground reflection/dissipation of noise) to reduce the observable noise footprint of future aircraft to less than that of the surrounding community. Enhanced mixing technologies (such as chevrons and naturally-aspirating ejectors) will be optimized to passively reduce nozzle jet noise without sacrificing performance. Additional active noise suppression (such as pulsating acoustic liners) will also be employed in future inlet and nozzle systems.

While reduction is fuel burn directly translates to CO2 reduction, major advances need to made in the area of combustors to reduce NOx emissions. As the latter requirement becomes more stringent, the combustor designs move towards a "lean" burning solution where the fuel/air mixture is richer in air to allow for complete combustion of the fuel. Active control of fuel/air mixture will help to reduce the NOx emission. Such combustor designs are prone to instability due to thermo-acoustic driven pressure oscillations. Active control of such oscillations will allow for more efficient combustor designs.

Adaptive Cycles and Systems

Adaptive technologies for turbine engines will center on performance and operability, utilizing research in fluidics, structures and material system capabilities, and advanced variable cycle engine configurations. Fundamental fluidic technology will enable "virtual" aerodynamic shapes, providing inlet and nozzle area control and peak compressor and turbine efficiency operation over a wide range of flight speeds. As mentioned in the previous subsection, trailing edge blowing and circulation control for turbomachinery will provide improved loading and efficiency as well as reducing wake-induced acoustics. Similar application of this technology to airfoil leading edges will likewise contribute to virtual camber changes as well as improving operability margins by reducing aerodynamic stall of high-performance, sharp edges.

Flow Control and Management: Active and passive redistribution of boundary layer flows within the engine will have a profound adaptability effect on the overall propulsion performance and weight by minimizing mechanical actuation and associated life and leakage losses. For example, turbine flow area control through fluidics and active seals will enable re-optimization of the engine BPR between takeoff and cruise. This will reconcile design constraints for reduced takeoff emissions and improved cruise fuel-efficiency across the transport aircraft flight envelope. Computational modeling will be extremely taxed for these designs to minimize the losses associated with low Reynolds number flows for fluidics. New propulsion configuration concepts, employing reverse-flow components or concentrically configured flowpaths will benefit most from fluidics, because of the short ducting distance and natural radial migration of flow from the high-pressure core outward. Advancements in ejector design methods will also contribute the fluidic engine adaptability by exploiting natural aerodynamic aspiration rather than active energy-debit pumping of boundary layer control flow. Acoustical fluidic control of inlet and nozzle boundary layers could be teamed with actively pulsed noise attenuating liners, thereby maximizing the dual applicability of a single integrated technology.

Morphing Structures: Mechanical and structural variability will also undergo a revolution with the advent of active/passive shape-memory materials and tailored aeroelastic design capability or "morphing". Similar in effect to the fluidic virtual shape technologies, future shape-memory materials will be employed in a variety of component areas. Inlet lip radius/ sharpness, coupled with anti-icing technology, could be made to change shape between takeoff and cruise, enabling high takeoff airflow without compromising the high cruise efficiency and low drag afforded by a sharper inlet lip. Shape memory inlet and nozzle contraction area variability will improve engine performance and operability without the weight from mechanical actuation. Application of shape-memory materials to turbomachinery will yield camber reshaping (for loading and efficiency optimization and operability) and leading edge sharpness versus operability improvements similar to those described for fluidic virtual shaping. Research in the area of fluidic and shape-memory adaptable airfoils will also be applicable to the aircraft configuration (particularly for viscous drag reduction, trim drag reduction, and circulation control for wings and empenage). The large internal changes in engine temperature environments and speeds readily provide untapped thermal and centrifugal forces from which to team passive, structural shape control. Variable-speed gearboxes are another fertile application of shape-memory materials, providing optimum matching of engine high and low pressure spool speeds throughout the flight envelope, and maximizing the utility of the gearbox.

Adaptive Materials: Future material systems will not only be designed for their properties but also for their unique functionality. Crystalline grown metallics optimized for their application-specific grain boundary properties may contain lattice-encoded DNA-like properties. These will be capable of changing grain boundary size through active and/or passive stimuli thereby preventing component failures. Similar chemically encoded properties for coatings and compliant layers will passively provide self-healing protection against surface delamination, oxidation, and spalling.

Future matrix fibers (used in MMC, CMC, and PMC materials) will not only provide structural reinforcement but also serve as an embedded conduit for information exchange to and from the intelligent engine control, as described under Fundamentals.

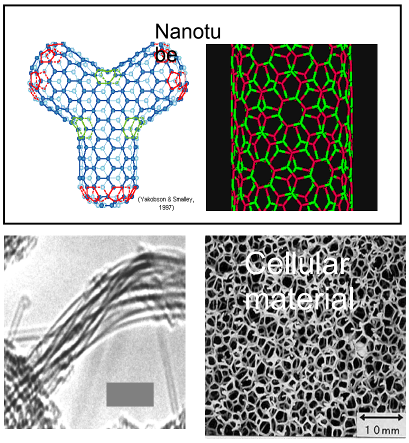

Fig. 3 Nanotechnology Materials

High conductivity fibers such as carbon nano-tubes (Figure 3) will simulate nerve ganglia to passively collect component diagnostic data. These same fibers may also be used to supply messages and adjust the configuration to optimize operating characteristics or to prevent/control component failures.

Adaptive Cycles: Thermodynamic cycle modifications and accompanying structural flowpath changes will also produce propulsion system adaptability. Bladerow by bladerow counter-rotating, concentric spool engines employing blade-on-blade technologies and advanced materials will stretch the limits of the variable cycle engine. These propulsion systems will enable the use of extremely low-weight (strength-compromised) composites by turning the turbomachinery "inside out". This will put the blades in compressive rather than tensile stress. Bladerow counter-rotation will further reduce the required rotational spool speed per turbomachinery loading, enabling acoustically superior tip-shrouded counter-rotating fans. Other modified Brayton cycle adaptations will include off-axis cores powering ultra-high pressure combustion and serving as topping cycles for peak-power takeoff thrust without compromising the optimum cycle operation for cruise. Inter-turbine and even inter-stage turbine combustion configurations are being investigated for their large impacts on cycle adaptability over diverse missions. These modified Brayton cycles also intrinsically offer leaner combustion and reduced emissions, but challenge state-of-the-art stability practices.

DISTRIBUTED VECTORED PROPULSION

With the advent of the high bypass ratio turbofan, research has promoted higher temperature more thermally efficient smaller cores to power larger and larger fans for propulsion. These smaller ultra-efficient cores will someday reach practical economic limits in manufacturing size. Similarly the larger fans will also reach limits in their manufacturability and aircraft integratability. At present the current state-of-the-art design BPR continues to grow, resulting in larger fans (eventually requiring gearing), increased aircraft integration challenges (necessitating high wing aircraft designs, etc.), and growing fan acoustic challenges. To circumvent these eventual limits, technologies affording highly integrated propulsion and airframe configurations must be pursued. Airframe-integrated propulsion and power configurations centered on distributed propulsion and capitalizing on technologies realized through the Gas Turbine Revolution will usher in the future air transportation system. The distributed propulsion concept is based on replacing the conventionally small number of discrete engines with a large number of small, mini, or micro propulsion systems as defined in the following table.

Table 1 Maximum Thrust of Various Engine Class

Engine class	Micro	Mini	Small	Medium	Large
Max Thrust (lb)	<10	10 to <100	100 to <1000	1000 to <10000	10000<

Distributed propulsion broadly describes a variety of configurations that can be classified into three main categories: Distributed Engines (including small, mini, and micro engine systems), Common-Core Multi-Fans/Propulsors, and Distributed Exhaust. In all three categories, the forward thrust delivered by the propulsion system remains as the conventional large engine counterpart (mass flow times exhaust velocity). Strategic distribution of the exhausting mass flow affords direct and indirect propulsion and airframe system performance benefits that can ultimately enable new aircraft missions beyond what is achievable with the state-of-the-art turbofan concepts.

In general, all three categories will produce lower thermal efficiencies using state-of-the-art technology (due principally to reduced component efficiencies from size, increased transmission losses, increased internal nozzle & inlet viscous losses, etc.). Through infusion of innovative propulsion technologies the losses associated with each individual propulsion system thrust will be mitigated and the airframe/mission benefits enabled by distributed propulsion will be fully realized. The most profitable research investment areas to mitigate these losses are those technologies that can only (or most fully) be realized in the small scale (ie, flow/circulation control through micro-turbines, foil/air bearings, concentric engines/core). The most profitable systems benefits are those that result from the airframe configurations that are realized by these propulsion configurations (i.e. tailless propulsion controlled aircraft, noise mitigation, supersonic cruise aircraft weight & drag reductions, etc.).

Distributed Engines

The category of Distributed Engines encompasses decentralized propulsion systems and utilizes separate smaller powerplants strategically deployed over (or embedded) the aircraft. Examples of this type of distributed propulsion might include small or mini engines (Figure 4) deployed across the wingspan and fuselage, and micro-turbine engines (Figures 5) embedded in the aircraft surface for flow/circulation-control and thrust. Severe performance penalties manifest in mini-engine systems are principally due to boundary layer effects of the fluid being on the same geometric scale as the propulsion system. The challenge of manufacturing tolerances that can be economically observed in these engines also severely impacts their performance and cost. Therefore mini and micro engine propulsion must "buy its way on" the aircraft. It must afford greater benefits in other areas, such as noise and drag reduction, or by enabling a superior integrated aircraft/engine system.

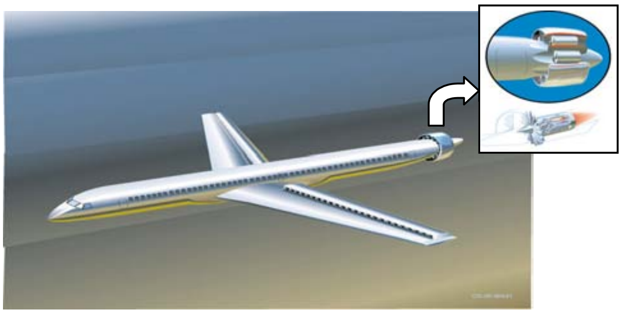

Fig. 4 Distributed Engines embedded in the wing and body

Laterally distributed engines will afford similar aerodynamic and acoustic benefits as those described for the high aspect-ratio wing trailing edge nozzle. Additional aircraft integration of supporting fluidic technologies using distribution engines could provide more dramatic transport mission impacts.

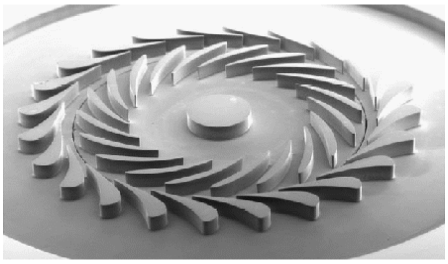

Fig. 5 Radial inflow turbine of a micro engine

As much as 3-5% total aircraft fuel burn reduction might be realized from boundary layer ingestion employing small to mini engine distributed propulsion. This performance benefit may be enhanced in a hybrid system utilizing micro engines to energize the low-momentum boundary layer flow. This benefit can only be realized if the micro engine fuel consumption is low (again scavenging of waste heat would be advantageous as described by the Distributed Exhaust concept). Because of their small size, extremely high specific-strength composite materials may be used in small and mini engines with less statistical failure due to defects. The reduced size allows practical, cost-effective manufacturing of these advanced-material structures. Success of the small and mini engine propulsion deployed laterally across the wing is dependent on exploiting technologies that are best realized in the reduced sized.

Micro engines themselves can provide distributed propulsion and exhibit large thrust to weight potential. Because of their size, low Reynolds number fluid effects, engine manufacturing tolerances and corresponding impacts on seals and clearances, 3-D turbomachinery shapes, and combustion efficiency are primary technical challenges for these propulsion systems. Currently, parts at the micro-scale can only be produced in two dimensions, resembling extruded parts. This efficiency limitation on the rotating components will be overcome with material and manufacturing technologies. These will enable three-dimensional shaping of airfoils and allowing new micro-scale engine configurations with reduced stress concentrations inherent in the current two-dimensional prototypes. Other factors affecting the structural/mechanical design of these micro-engines are the typically high rotational speeds, which may exceed 2 million RPMs. These high speeds are achievable due to reduced-scale inertial loads, but will demand non-lubricated air-bearings to surpass the common modes of failure observed in research prototypes.

Though the physical engine scale is decreased, the chemical reaction times remain constant and will require technology innovation to regain lost combustion efficiency. A very general rule for mini- and micro-engines is that both specific fuel consumption (SFC) and thrust-to-weight ratio increase as thrust and size decrease. To become a viable primary propulsion source, SFC reductions to near current macro-engine levels must accompany the increased thrust-to-weight ratios already achievable in mini and micro engines.

Distributed engine concepts will enable a variety of attractive airframe configurations affording both performance and operational benefits. Large engine production rates, lower development cost and cycle time, and line-replaceable-unit elimination of on-the-wing engine maintenance could reduce the life cycle cost by as much as 50%. Aircraft safety will be enhanced through engine redundancy and semi-redundant propulsion control of the aircraft. Dual use of the airframe structure will dramatically reduce the overall system weight, and afford holistic system noise reduction opportunities beyond those attainable with discrete engines. Principle technologies that will afford the greatest potential for realizing micro engine propulsion success include: innovative combustion techniques, processing of SiC and other advanced micro engine material for improved 3D designs, and integral autonomous controls coupled with sub-micro sensors assuring engine array reliability.

Common-Core Multi- Fans/Propulsors

The category of Common-Core Multi-Fans/Propulsors entails the packaging of multiple thrust fans powered by a central engine core (Figure 6). The advantage of these configurations is that they provide ultra high BPR engine with higher propulsive efficiency without necessitating radical airframe changes (such as high wing designs) to accommodate a single large turbofan engine. The principle challenges of this approach are power transmission weight and losses. These challenges may be somewhat mitigated by the variable gearbox technologies previously developed under the Gas Turbine Revolution, or by employing blade-on-blade manifolded tip-turbines on the fans. These challenges could also be circumvented using direct-drive tandem fans (i.e. axially aligned fans with separate inlets for and aft of the common core) rather than the side-by-side configuration. Another potential configuration uses the core exhaust to drive two off-axis turbines that are attached to direct-drive fans. Multi-fan cores will require innovative separate inlets to realize their full BPR and aircraft integration benefit. This will require lightweight structures and possibly flow control to minimize weight and inlet performance losses.

The commonly shared performance challenges associated with all forms of distributed propulsion (low-Reynolds number flows, boundary-layer interactions, and fuel management systems) will be surpassed during this research phase using those technologies and discipline capabilities (aerodynamic, mechanical, materials, structures, manufacturing, etc.) outlined for the Gas Turbine Revolution. The highly integrated Distributed Vectored Propulsion systems for future subsonic and supersonic transports will incorporate V/STOL and Propulsion Controlled Aircraft (PCA) capabilities, and capitalize on intelligent, self-healing properties.

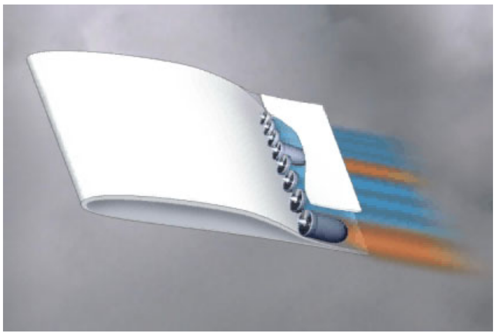

Fig. 6 Common-Core, Multi-Propulsor Engines

Distributed Exhaust

The category of Distributed Exhaust entails using a central engine powerplant with a ducted nozzle(s) for strategic deployment of thrust on the aircraft. Distributed exhaust configurations suffer nozzle viscous losses in performance and will likely only “buy their way on” to aircraft systems exhibiting extreme sensitivity to low-speed lift and/or cruise drag. Therefore, distributed exhaust systems will be better suited to supersonic cruise applications, where noise-sizing for takeoff field length and sustained supersonic cruise drag are the most dominant and least reconcilable constraints (Figure 7).

Fig. 7 Supersonic Airplane with High Aspect Ratio Nozzle

High aspect ratio nozzles for commercial supersonic cruise vehicles promise both noise and nozzle weight reduction potential. The projected sideline noise reduction using a wing trailing edge 2-D mixer/ejector nozzle with comparatively small exhaust height may be as much as 10dB (due to increased ambient jet mixing, improved ejector internal penetration and mixing, and increased liner attenuability resulting from naturally higher frequencies and surface areas). In addition, the high aspect ratio geometrically produces a shorter nozzle for an equal nozzle pressure ratio and provides the potential for shared structural loading with the wing. This will culminate in as much as 50% equivalent nozzle weight reduction and propulsion related cruise drag. Increased low-speed lift via wing trailing edge flap blowing and thrust vectoring will also be achieved through this configuration, and reduce the required takeoff field length and affording community and approach noise reductions.

Hybrid systems incorporating distributed/thrust vectored exhaust and micro-engine for flow control and actuator power are also attractive. To reduce the performance loss of the increased nozzle surface areas and increased internal flow turning, micro-engines can be incorporated for boundary layer control and cooling. This approach might passively utilize waste heat from the nozzle to power the micro-engines rather than active dedicated micro-fuel/combustors. The scavenging of waste heat will reduce the exhaust temperatures as well as increase the effectiveness of the primary distributed propulsion system. The micro engines might also be configured to facilitate virtual shape control through fluidic "reshaping" of the primary nozzles. This reduces or eliminates mechanical actuation while reducing internal viscous losses and waste heat.

ALTERNATE ENERGY PROPULSION

While the timing remains debatable, the 21st Century will almost assuredly see the emergence of an all-electric economy. In this era, electricity will be the common currency. It will be produced, stored, converted and consumed as other exchange medium are today. Preceding this inevitable end is the likelihood of the hydrogen-fuel economy. The ever-increasing global energy consumption rate for electric ground power and the transportation industries will continue to drain global reserves of crude oil which will have even greater environmental emissions impacts. Depletion of crude oil reserves and the associated $/barrel price increase will invoke the economic practicality of refining new oil resources (from shale oil for example). This will sustain the hydrocarbon fuel economy well into the 21st Century but at a significantly more tenuous economic level. Global environmental impacts from hydrocarbon emissions (predominantly the greenhouse gas CO_2) will likely accelerate the introduction of cleaner alternative energy sources and more efficient utilization systems for both the ground power and transportation industries.

While nuclear energy seemingly remains the next ground power alternative, the transportation industry must practically constrain itself to other alternatives in maintaining a safe public-access environment. The transportation industry energy alternative will include low-carbon fuels and additives, hydrogen fuel, stored electrochemical, and electromechanical energy sources. Future 21st Century aeropropulsion systems and aviation systems must align to best utilize these future available energy sources. The cost associated with infrastructure changes and the sustained use of legacy aviation systems logically demands a transition period as new energy sources are introduced. Hybrid propulsion systems will be required in order to meet the challenges of transition and timely introduction of fledgling new power systems.

A global hydrogen consumption rate for future power demands a practical, cost effective production rate. This implies hydrogen production from water, using a net-positive (and as yet undetermined) energy means. Safety issues (whether real or perceived) will also govern the production, distribution, and storage of hydrogen. Complexities associated with hydrogen production and densification compounded by safety issues will likely result in centralized "refineries". These will be similar to present-day hydrocarbon fuel refineries, despite the global availability of water. Furthermore, energy storage and consumption by the majority of the non-aviation transportation industry (e.g. automotive) will likely be from distributed electricity rather than directly from hydrogen. The aviation transportation segment is the only possible exception to the electric currency model. This is due to large takeoff power requirements favoring hydrogen combustion systems over fledgling electrochemical systems on a per weight basis. Airports may therefore require on-site handling of hydrogen. Early acceptance of hydrogen at controlled-access airport facilities will also promote the introduction of hybrid combustion/electric propulsion such as the gas-turbine/fuel-cell.

Recent advances in fuel cell technology and electrical component power densities, promoted by automotive and other transportation sectors, will eventually displace combustion-based propulsion in the aviation industry. In summary, the 21st Century will see an environmental-inspired revolution in the transportation system from hydrocarbon combustion power to electric power. Possibly hydrogen fuel and hybrid combustion/electric systems may bridge the transitions.

Fuel Cells

Fuel cells are becoming a viable option for small aircraft propulsion and Auxiliary Power Units (APUs) and hold future promise for large-scale commercial aircraft (Figure 8). Doubling of fuel cell power densities can be achieved in the next five years. This would make electrically powered light general aviation aircraft possible with no performance penalties compared to their conventionally powered counterparts. Preliminary results from a recent NASA study (Berton, et. al. 2003) indicate that flight is possible using off-the-shelf fuel cell and power management technology levels, albeit at reduced speed, climb rate, range, and payload-carrying capability. Aircraft performance appears sufficient to fly a technology demonstration, proof-of-concept type vehicle using today's automotive-derived fuel cell and power systems. Only light aircraft are anticipated to be feasible with near-term technology due to their relatively low, automobile-like power requirements.

The increase in power density would also make fuel cell APUs for larger aircraft viable. NASA is working with Boeing to explore a possibility of development and demonstration of a Solid Oxide Fuel Cell (SOFC) APU for a large transport by building on DOE's successes in SOFC. The current gas turbine APUs operate at about 14% load cycle efficiency contributing 20% of the airport ground based emissions. A fuel cell APU will lead to near zero emissions, lower noise, and could reduce aircraft fuel consumption. A full time, integrated power unit will improve operational effectiveness by replacing multiple secondary power systems with a single "sold-state" device. A five-fold increase in fuel cell power density would enable electrically powered regional/commuter size aircraft. A ten-fold increase would enable electrically powered large commercial passenger aircraft. Advanced fuel cell and power management technologies will be needed to achieve comparable aircraft performance and utility and to enable the design of larger electric aircraft.

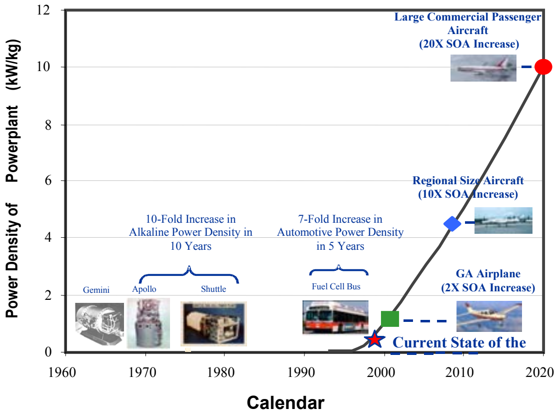

Fig. 8 Potential Fuel Cell Evolution Towards Meeting Future Aircraft Transportation Needs

The benefits of fuel cell powered aircraft are very low to zero emissions, simpler more reliable power and propulsion systems providing increased safety and lower maintenance costs; and greatly reduced noise from the power generator portion of the propulsion systems. Some of the critical challenges are fuel cell and power management system weight and hydrogen fuel system volume. Heat management is critical to the practical operation of any fuel cell-powered application and requires more rigorous modeling. An efficient, safe airport hydrogen fueling infrastructure also must be in place if electric aircraft are to be economically viable. A global hydrogen economy also remains elusive.

Capitalizing on the micro-manufacturing technologies characterized for Distributed Vectored Propulsion, micro-fuel cells and other electrochemical and pure electric storage devices (such as super batteries and capacitors) will be made small enough and in sufficient quantity as to allow viable all-electric propulsion. These devices will be integrated within the aircraft, taking full advantage of structural load sharing and dual-functioning systems (e.g. distributed propulsion and controls). These and other electrical components (such as high-temperature superconductors) will benefit from the ever-improving electronics industry in terms of their capability and affordability. Further superconductivity advancements in the later 21st Century may introduce propulsion-controlled flowfield capability, enabling practical high field-strength magnets and use of unseeded-MHD for aircraft propulsion lift/thrust.

The electrically-powered subsonic transports of the future will likely be powered by small, distributed motors and fans (Figure 9). Similar in configuration to the wing-span distributed engines, these configurations will utilize remote fans and motors to achieve forward propulsion, and may be coupled with blown wing/flaps for high lift at takeoff. The primary advantage of these configurations is the use of a centralized, highly efficient core power unit. This may be in the form of fuel cells or centralized gas turbine APUs. Electric power transmission to the remote fans is a safer more efficient approach than independent distributed fuel delivery systems (as would be utilized by the distributed engines). In the case of the APU configuration, the excess APU power could also be used in flight to meet the increasing passenger/aircraft demand for electric power and communications. In the case of multiple side-by-side fans sharing a common 2D wing integrated inlet, the benefits of boundary layer ingestion (previously discussed) may also be realized. The primary challenges for this type of propulsion will be the motor weight (many small motors with independent structures (inefficient power conversion density) versus fewer, larger heavy motors).

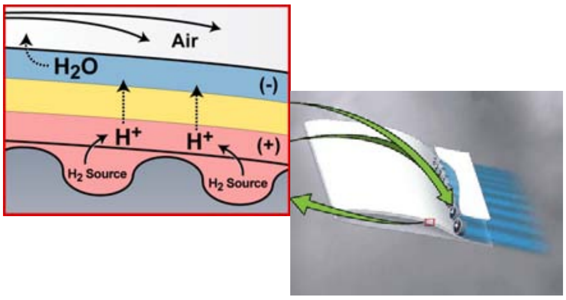

Fig. 9 Fuel Cell Wing with Distributed Propulsors

Variable speed motors, leveraging the adaptive engine and controls from the Gas Turbine Revolution and the distributed fans from the Engine Configuration Revolution, will be produced from lightweight superconducting technologies born of the Alternate Energy & Power Revolution. The culmination of these and other contributing technologies in a single adaptive system will power a variety of future transport aircraft, while assuring safe environmental 24-hour operation.

SUMMARY

Propulsion system advances have been the fundamental drivers toward the progress made in air transportation and will continue into the 21st Century. Enormous advances in propulsion performance, emissions and efficiency have made it possible for aircraft to travel at higher speeds safely over longer ranges. Over the last ten years NASA, working with other federal agencies and industry partners, have developed aeropropulsion technologies that when fully implemented will reduce aircraft emissions by 70%, engine noise levels by 6 dB and improved fuel consumption by 15%. To continue this trend and each the ultimate goal of an emissionless, silent aircraft, NASA has identified a series of propulsion system technology revolutions that will be essential to meet the challenge of 21st Century commercial air transportation. Future propulsion systems have been presented including intelligent engines, distributed vectored propulsion systems based on mini/micro engines, and fuel cell powered mini-fans. These advanced propulsion systems hold the potential to enable continued improvements in performance and emissions required to achieve the vision of an affordable, emissionless, and silent aircraft.

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