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Review of Propulsion Technologies for N+3 Subsonic Vehicle Concepts

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Abstract

NASA has set aggressive fuel burn, noise, and emission reduction goals for a new generation (N+3) of aircraft targeting concepts that could be viable in the 2035 timeframe. Several N+3 concepts have been formulated, where the term “N+3” indicate aircraft three generations later than current state-of-the-art aircraft, “N”. Dramatic improvements need to be made in the airframe, propulsion systems, mission design, and the air transportation system in order to meet these N+3 goals. The propulsion system is a key element to achieving these goals due to its major role with reducing emissions, fuel burn, and noise. This report provides an in-depth description and assessment of propulsion systems and technologies considered in the N+3 subsonic vehicle concepts. Recommendations for technologies that merit further research and development are presented based upon their impact on the N+3 goals and likelihood of being operational by 2035.

1.0 Introduction

In a rigorous attempt to meet projected national aviation goals in noise, emissions, and performance, NASA conducted an N+3 case study intended to foster advanced aircraft concepts and technologies projected to enter service in the 2030 to 2035 timeframe. “N+i” is the nomenclature used to describe the sequence of future generations of aircraft, where N specifies the current generation and *i* represents a specific future generation beyond N. Thus, N+1 is defined as one generation beyond N, and so on. Building upon the former case studies examining N+1 and N+2 timeframes, the NASA N+3 study set aggressive performance and environmental goals intended to stimulate more revolutionary concepts than the previous studies produced. The project metrics included a 71dB cumulative (sum of lateral, flyover, and approach noise certification points) reduction in aircraft noise below the FAA Stage 4 noise regulation, a 75 percent reduction in Landing/Takeoff (LTO) NO_x emissions with respect to CAEP 6, and a 70 percent reduction in mission fuel burn relative to a state of the art reference aircraft. Additionally, the study called for investigation into new methods to more effectively utilize existing national aviation infrastructure with a metroplex notion in mind. A metroplex is the idea of reducing the takeoff and landing distance required of large aircraft such that smaller, regional airports can be utilized to ease the traffic at hub airports. These goals are summarized in Table 1.

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TABLE 1.—NASA N+3 SUBSONIC FIXED WING PROJECT METRICS

CORNERS OF THE TRADE SPACE	N+1 (2015) ^{***} Technology Benefits Relative to a Single Aisle Reference Configuration	N+2 (2020) ^{***} Technology Benefits Relative to a Large Twin Aisle Reference Configuration	N+3 (2025) ^{***} Technology Benefits
Noise (cum below Stage 4)	- 32 dB	- 42 dB	- 71 dB
LTO NO _x Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance Aircraft Fuel Burn	-33%**	-50%**	better than -70%
Performance Field Length	-33%	-50%	exploit metroplex* concepts

^{***} Technology Readiness Level for key technologies = 4-6

^{**} Additional gains may be possible through operational improvements

^{*} Concepts that enable optimal use of runways at multiple airports within the metropolitan areas

Once the N+3 metrics were defined, NASA issued a NASA Research Announcement (NRA) for the Subsonic Fixed Wing Project, under the Fundamental Aeronautics Program, to the aerospace community and four teams were selected to participate. Teams were tasked with developing future scenarios to project the state of aircraft operations during the 2030-2035 timeframe. Based on these projections, the teams were to design advanced vehicle concepts addressing the needs of this future scenario. In addition, they were to identify key technologies enabling the advanced airframe and propulsion concepts. Roadmaps were to accompany these technologies, outlining their development during the N+3 timeframe. A risk analysis study of each technology was also conducted, characterizing the relative importance and viability of each technology to achieving the advanced vehicle concept. A sensitivity analysis was completed by many of the teams to show how the application of a technology can affect more than one of the N+3 goals and whether it would have positive or negative influence. In-depth system level studies were then performed, evaluating the effectiveness of the advanced concepts and technologies against a current state-of-the-art baseline aircraft.

The objective of this paper is to review the N+3 aircraft concepts that were evaluated by the contractor teams and provide further analysis of the concepts based on how they affect fuel burn, noise, and LTO NO_x emissions. The metroplex idea was not explored in this review. The focus of the analysis is placed on the specific development of critical propulsion technologies that have a broad application across multiple concepts. The first section provides a top-level discussion of the concepts presented in the N+3 study with the key elements and technologies critical to the viability of the design being introduced. The second section briefly describes the down-selection process using a Quality Function Deployment (QFD) to arrive at a manageable group of technologies within the focus and intent of this project. The next section provides an in-depth description and assessment of each technology considered. The intent of this section is to present pertinent cross-disciplinary information regarding the benefits, challenges, and expected progression of each technology in one central location. Finally, recommendations are made as to which technologies merit further research and development based on both the feasibility of entering service by 2035 and the impact they have on the N+3 goals.

2.0 Summary of Concepts

NASA issued an NRA to the aerospace community, searching for contractors to participate in the N+3 Subsonic Fixed Wing Project. The intent of the NRA is to stimulate industry into focusing on producing more efficient, quiet, greener aircraft. Four contractor teams were selected to take part, as well as a NASA in-house team. Each team produced one or more aircraft concepts that made use of advanced aerospace technology to help them reach the N+3 goals. A brief overview of each of the teams' concepts is provided.

2.1 Boeing

The Boeing Company was one of the team leads on the N+3 project with partners GE Aviation and Georgia Institute of Technology (Ref. 1). During Boeing's research, they developed four different aircraft designs with varying features to help the aircraft reach the N+3 goals. Each of these concepts was given unique names: Refined SUGAR, SUGAR High, SUGAR Ray, and SUGAR Volt (Fig. 1). SUGAR is an acronym for Subsonic Ultra Green Aircraft Research.

Boeing used the 737-800 model with a CFM56 engine as the baseline aircraft, called the SUGAR Free, that all of the following concepts were compared to. The Refined SUGAR is a large aircraft (150 passengers) based on the current Boeing 737 tube and wing aircraft except it was assumed that the technology would make certain progressions throughout the next 20 years. The most significant change would be to the engine. GE developed an advanced turbofan engine (gFan) which would provide a very high bypass ratio, leading to a noise and specific fuel consumption reduction. This engine also incorporates advances in other parts of the engine including the combustor, compressor, and turbines. The SUGAR High is also sized after the 737 and has similar technology to the Refined SUGAR but with significantly more development. The most notable change to the airframe was the addition of a high aspect ratio, strut braced wing with a folding mechanism. The engine was based off of the gFan, with the same architecture but having a higher bypass ratio and more advanced core technologies. This engine was termed the gFan+. Boeing also created a hybrid wing body concept, the SUGAR Ray. The technology in this aircraft is based off of the SUGAR High, except for the blended wing airframe which was selected because of the potential noise reduction benefit due to engine shielding. Boeing's final concept was the SUGAR Volt. The airframe was very similar to the SUGAR High, with a high aspect ratio wings including a folding mechanism. The biggest difference was in the propulsion technology. GE developed an idea for a hybrid electric-gas turbine engine (hFan) that was to use batteries to assist the aircraft during takeoff and cruise.

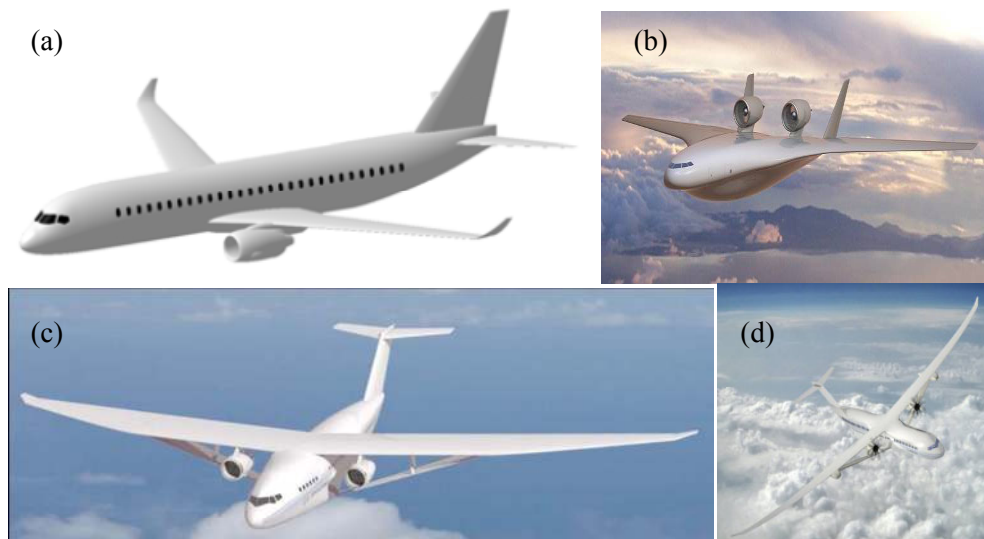


Figure 1.—Boeing N+3 concepts, (a) Refined SUGAR, (b) SUGAR Ray, (c) SUGAR High, and (d) SUGAR Volt.

Despite all of these assumptions in technology advances and new aircraft designs, none of these concepts could completely meet the N+3 goals. The SUGAR Volt aircraft was the closest to meeting the goals with a 63 percent decrease in fuel burn and a 79 percent decrease in LTO NO_x emissions, so it was considered to be the most promising design for the Boeing study. Quantitative noise reductions were not presented in the report. Of their concepts, the Volt had the most far reaching technology ideas, which would help to spur on additional research and development in areas not currently being focused on in the industry but have great potential in reducing noise, fuel burn, and emissions such as electric motors, fuel cells, and batteries.

2.2 Massachusetts Institute of Technology

The Massachusetts Institute of Technology (MIT) was a team lead on the N+3 project, partnering with Aurora Flight Sciences and Pratt & Whitney (Ref. 2). The team developed two N+3 aircraft concepts to address the project goals. They developed both a domestic and international carrier concept, named the D-series “Double Bubble” and the H-series Hybrid Wing Body (HWB), respectively, depicted in Figure 2.

MIT’s Double Bubble is a modified tube and wing configuration, adjoining two traditional fuselages to create an unconventional lifting body (Fig. 3). With rear-mounted engines fixed on top of the fuselage, the design utilizes the benefits of boundary layer ingestion (BLI) for significant fuel burn reduction and noise shielding. The concept also uses natural laminar flow on the wing bottom, an advanced combustor, composite materials, a lifting nose, and pi-tail. Of the two configurations, MIT’s Double Bubble was the closest to achieving the N+3 goals, satisfying the fuel burn, field length, and LTO NO_x with significant reductions in noise. The Boeing 737-800 series was used as a baseline.

The long-range concept, the HWB, employs many of the same technologies as the Double Bubble, but provides greater payloads and increased range. Using a blended wing lifting body configuration, the distributed propulsion system is mounted on top of the fuselage, ingesting large spans of the boundary layer. While this concept was unable to achieve the fuel burn and noise goals, it did meet the NO_x and field length goals. The Boeing 777-200LR series was used as the long range aircraft baseline.



Figure 2.—MIT concepts, Double Bubble and Hybrid Wing Body, respectively.

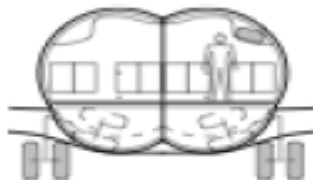


Figure 3.—Two adjoining fuselages of the MIT Double Bubble.



Figure 4.—Northrop Grumman SELECT concept.



Figure 5.—General Electric concept.

2.3 Northrop Grumman

Northrop Grumman in partnership with Rolls-Royce, Sensis, Tufts University and Spirit Aerosystems developed the SELECT (Silent Efficient Low-Emissions Commercial Transport) (Ref. 3).

The SELECT is an advanced tube and wing configuration designed for 120 passengers, with a 1600 nm mission and a 0.75 cruise Mach number (Fig. 4). Although the SELECT resembles current aircraft it contains an advanced technology suite that enables projected fuel burn, emissions and noise reduction. Propulsive technologies include a three-shaft turbofan engine (BPR ~18) with compressor intercooling, CMC turbine blades, fuel-cooled cooling air, active compressor clearance control, variable nozzle geometry, advanced inlet acoustic liners, and lean combustor technology. The airframe technologies include: large integrated structures, aeroservoelastic structures, carbon nanotube electric cables, 3-D woven and stitched composites, advanced metallic alloys and swept-wing laminar flow.

The Boeing 737-500 was chosen as the reference vehicle by Northrop Grumman, in contrast to MIT and Boeing who used the newer Boeing 737-800 as their baseline. The predicted performance of the SELECT gives a 63 percent fuel burn reduction when compared to the reference vehicle, a 69.6 EPNdB margin below Stage 4, a 91 percent NO_x reduction below CAEP/6 and a takeoff and landing field length <5000 ft enabling it for metroplex use.

2.4 General Electric

GE aviation in partnership with Cessna and Georgia Tech developed a 20 passenger airliner (Fig. 5) to fit in their 2030-2035 transportation scenario (Ref. 4). The scenario focuses on point-to-point transportation between regional airports, thus avoiding the added distance, time and fuel consumption involved with stops at hub airports.

The key features of the small turboprop include (1) a short range mission (800 nm) with a cruise speed that eliminates compressibility drag (0.6 Mach) and enables the formation of natural laminar flow, (2) advanced turboprop engines with reduced noise and superior fuel economy, (3) an airframe shape that enables low drag through laminar flow and high aspect ratio wings, and (4) a new approach to the application of composite structures that both reduces weight and facilitates the integration of aircraft systems into the airframe structure (Ref. 4).

The GE Cessna concept meets the N+3 goals for noise, fuel burn, emissions, and it is compatible with more than one thousand small community airports. The baseline used is a current technology conceptual aircraft with the same mission as the advanced aircraft.



Figure 6.—NASA Glenn TeDP concept.

2.5 NASA

Two concepts were developed by NASA teams: the TBW-XN Truss-Braced Wing at Langley and the N3-X Turboelectric Distributed Propulsion (TeDP) at Glenn. For this report only the TeDP is considered. The TeDP is a Hybrid Wing Body configuration (Fig. 6) with mission characteristics similar to the baseline Boeing 777-200LR. The N3-X has a 7500 nm range, 0.84 cruise Mach number and a 300 passenger 3-class seating capacity.

The key aspect of the N3-X is its novel propulsion system, which utilizes superconducting electrically driven, distributed low-pressure-ratio (1.35) fans with power provided by two remote superconducting electric generators based on a conventional turbofan core engine design (Ref. 5). Taking advantage of the high degree of flexibility electric power transmission allows, the turbogenerators are located at the wing tips, while the fans are positioned at the rear of the planform where they ingest the boundary layer.

The TeDP preliminary fuel burn estimates show a 72 percent reduction, thus meeting the N+3 fuel burn reduction goal. Further studies are ongoing at NASA to obtain more refined data in terms of vehicle fuel burn, emissions, noise, and field length capabilities.

3.0 Technology Selection

A list of N+3 technologies was compiled after reviewing the reports given by NASA and the aforementioned contractors. While both airframe and propulsion technologies are critical to the system level reductions in the N+3 metrics, only propulsion technologies are discussed in this paper. Quality Function Deployment (QFD), a method for determining how and where priorities are to be assigned in research and development, was used to assess the potential impact of the technologies on both the N+3 goals and aircraft concepts. This analytical tool, shown in Figure 7, is particularly valuable when design trade-offs are necessary to achieve the best overall solution. The QFD was completed over several meetings among field experts with unbiased discussion. The vertical axis contains the project goals and product requirements. The metrics placed here allowed organization and provided criteria for technology evaluation. Notice the second column offers a weighting scheme that was employed to illustrate the relative importance between meeting the goals and the technologies' relevancy to different aircraft configurations. The configurations are simply mediums to achieve better performance with lower emissions. It is much more important to carry out the objective rather than being concept flexible, hence its higher weight. The horizontal axis is where "attributes about the product" are placed. For this study, the propulsion technologies were the attributes. A brief summary of the results according to the technologies' relative weights is shown in Figure 8.

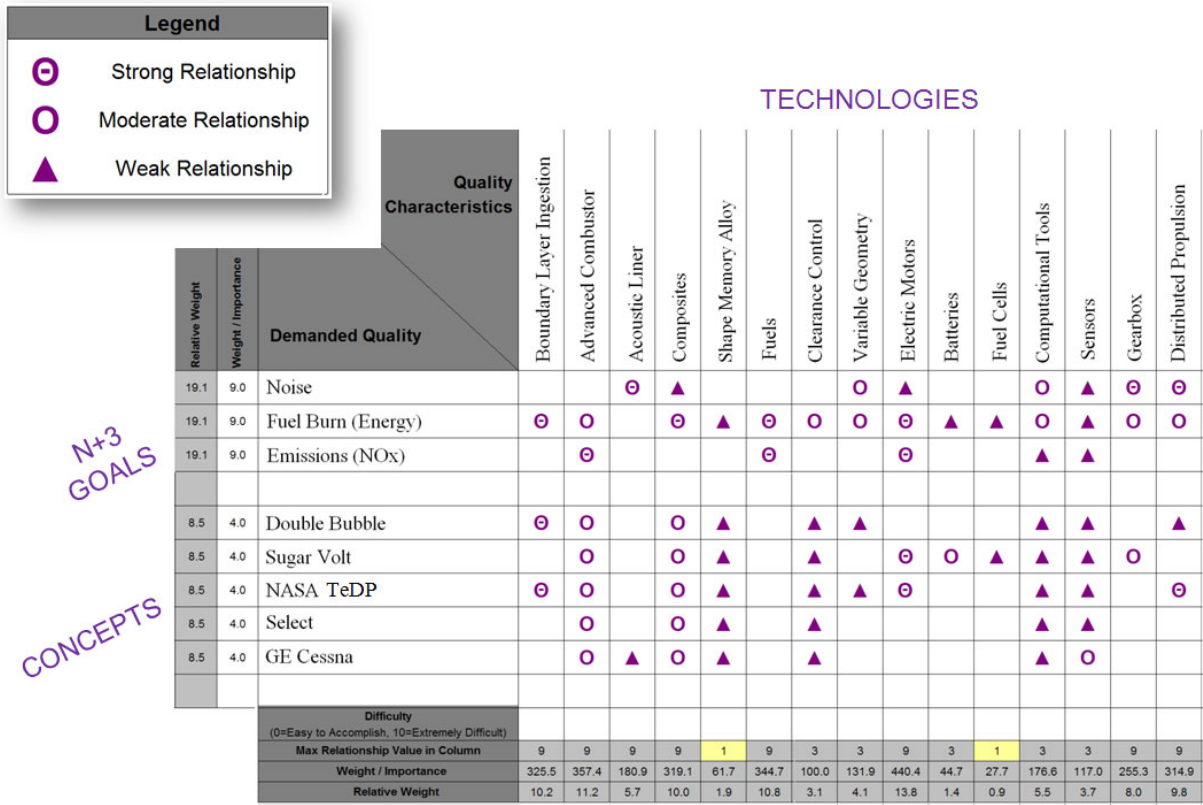


Figure 7.—The completed N+3 propulsion technology QFD.

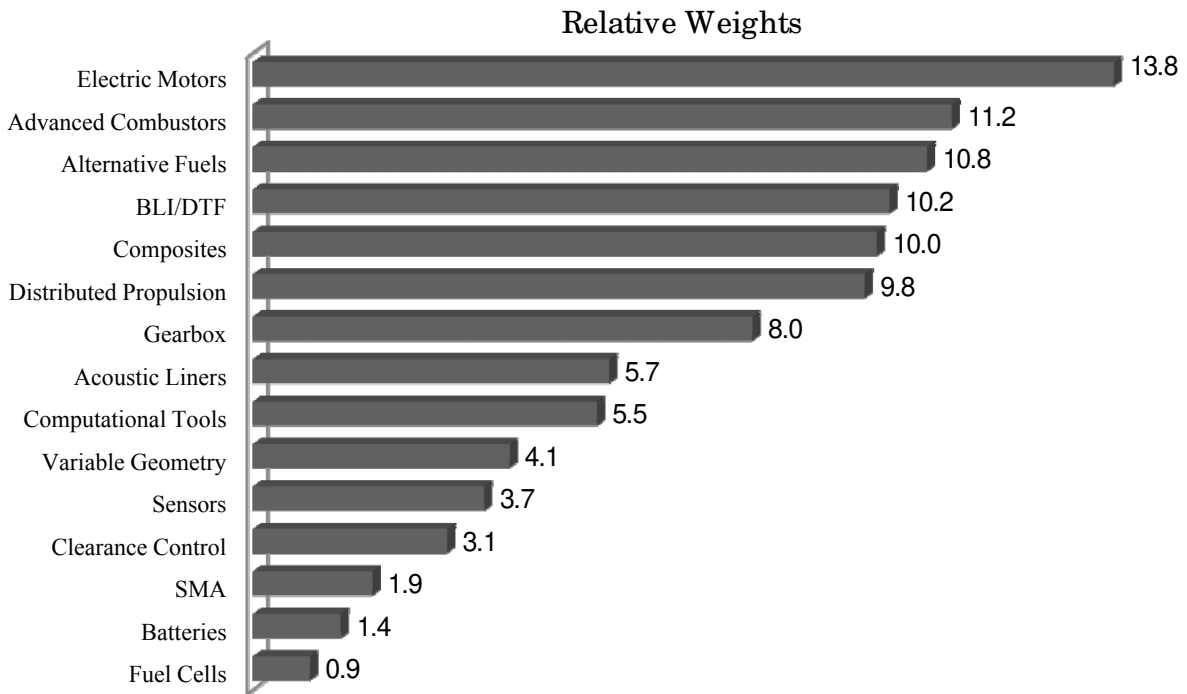


Figure 8.—Relative weights of technologies w.r.t. N+3 goals and concepts.

Electric motors are seen to have the strongest influence on the chosen metrics due to their contributions in reducing fuel burn, emissions, and noise. The Sugar Volt's gas turbine electric motor assist and NASA's TeDP with superconducting electrical motors are two concepts that considered electric motors. A clarification about the relative importance of batteries and fuel cells must be addressed. Fuel burn is the only N+3 metric affected by these energy storage devices and it is a weak relationship due to a potential weight penalty. Traditionally, the onboard fuel mass is decreasing throughout the mission. Fuel cells and batteries will not give such a great change in weight over the mission, but could permit smaller engines given a lower takeoff weight. Dependence on noise and emissions are absent because both technologies do not effect these goals directly. A downside to the QFD was that it did not capture the interdependence between technologies. Electric propulsion viability depends largely on the improvement of storage systems such as fuel cells and batteries. An extension to this study should include a sensitivity analysis showing such relations.

A few technologies were disregarded in the study either for time constraints or are beyond the scope of this paper. First of all, the salient topics of sensors and alternative fuels were not selected for review due to their broad nature and requirement for their own in-depth analysis. Secondly, the gearbox is the contrary, where the weight, lubrication, and reliability are the primary issues which could be improved using mainly other technologies such as new materials. Thirdly, variable geometry (VG) can be accomplished using hydraulic systems; however, such systems are weight inefficient prohibiting a positive performance benefit. Shape Memory Alloys (SMA) are expected to be the driving mechanism for VG. For this reason, a section is not allocated to VG but rather the application of SMA to VG is discussed.

4.0 Technology Description

An in depth analysis of each technology was performed upon completion of the selection and prioritization process. The authors divided the technologies according to their interests and became the lead of the chosen areas. An extensive literature review was conducted to become familiarized with the major issues and concerns for each technology. Several meetings with field engineers and scientists at NASA Glenn Research Center was the next step which provided guidance and discussion about the major roadblocks needing to be conquered in the coming years. This section is intended to deliver the compiled information to shed light on the necessary accomplishments essential to each technology's N+3 success.

4.1 Electric Motors

Electric motors are gaining interest in the aerospace industry as a way to reduce fuel burn, noise, and emissions. However, it has been widely accepted that conventional induction motors will not be able to attain a sufficient Power to Weight Ratio (PWR) to be implemented onto aircraft, so the idea of using superconducting motors is being considered (Refs. 6 to 10). The concept of superconduction is to reduce the temperature of the superconducting wiring in the motor to extremely low values, creating near zero resistive losses and a much higher current density carrying capacity. These superconducting motors will make use of cryocoolers or cryogenic fuels to supply different coolants including liquid helium, neon, hydrogen, and nitrogen. One material that is extensively used for superconductors, Niobium-Titanium, has a critical temperature around 9 K requiring liquid helium to be used to cool it (Fig. 9). More recently, higher temperature superconducting (HTS) materials have been found using Bismuth and Yttrium that have much higher critical temperatures such that liquid nitrogen or hydrogen can be used to cool them (Ref. 6).

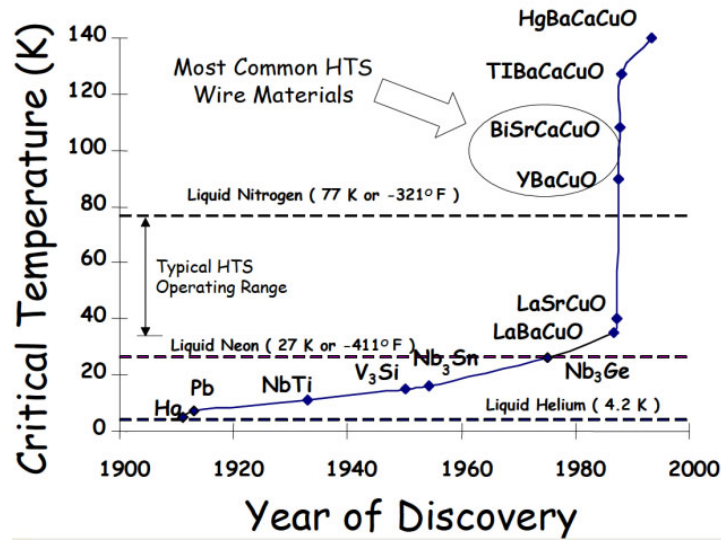


Figure 9.—Advancement of critical temperatures over time for superconducting materials (Ref. 6).

As HTS motors were being developed, a study was carried out based on a 4480 kW HTS motor that was used to quantify the benefits compared to a conventional induction motor. It was found that the full load loss amounted to 40 percent that of the conventional motor which leads to a higher efficiency. The HTS also had a 50 percent volume reduction and it was predicted that the motor weight would be around 70 percent of the conventional motor, which will lead to a much higher power density (Ref. 6). The reduction in volume will correspond to an additional reduction in losses, as there is less material for the current to travel through. There is also a large advantage to using a HTS rather than a low temperature superconductor (LTS). It has been calculated that it takes around 1.2 percent of the rated power of the motor to run the cryocooler for the LTS as opposed to 0.16 percent for the HTS because of the much lower temperatures that must be sustained to reach the LTS critical temperature (Ref. 6).

Superconducting electric motors are extremely important to the success of NASA's N3-X TeDP concept. While aircraft are being studied that would utilize conventional conducting motors, such as Boeing's SUGAR Volt, these aircraft could benefit from the development of superconducting motors. Concepts utilizing distributed propulsion are reliant on the ability to introduce motors that meet strict weight and power requirements that come with being implemented on an aircraft. The advantages to using a superconducting motor are derived from the fact that they will allow the TeDP aircraft to achieve very high bypass ratios resulting in a reduction in fuel burn and noise. This bypass ratio is attainable because the electric motor removes the diameter constraint of a large fan by driving multiple smaller fans instead, ultimately increasing the effective bypass ratio. Using the electric motor will also allow the turbine to be decoupled from the fan, allowing each spool to spin at their optimal speeds, contributing to further fuel burn reduction (Ref. 8). Using an electric motor on an aircraft would give the opportunity to utilize an alternate power source other than gas turbine generators, such as fuel cells or batteries. This would go even further in reducing specific fuel consumption and emissions. The disadvantage to using this superconducting system is the added complexity of the system. Not only would electric motors have to be added, but other technologies such as a cryocooling system, compressor, inverter, and power source would also need to be implemented.

There are still challenges that need to be overcome before this technology will be ready for use on a commercial aircraft. Currently, the greatest barrier to HTS is an insufficient power to weight ratio for the technology to be practical. The cold heads for the cryocooling system are presently at 3 kg/kW-input and the compressor is at around 15 kg/kW-input. It is desirable to reduce the combined cold head and compressor weight to around 3 kg/kW-input (Ref. 10). It has also been estimated that the needed PWR for the motor would be around 25 and 50 kW/kg for the generator (Ref. 8). To put this into perspective, some

turbine engines possess a PWR around 15 to 16 kW/kg (Ref. 10). There is also the issue that the latest generation of HTS wiring is not yet available in long lengths and the first generation wiring is extremely expensive, estimated around 40 percent of the total motor cost (Ref. 6). Another challenge that needs to be addressed is that DC HTS motors meet the low loss requirements, but it has yet to be demonstrated that low loss AC conductors can be developed in the near future, with experts predicting that less than a 10 W/A-m loss is needed (Ref. 10). There are also issues to be solved with the cryogenic cooling system, including cryogenic pipe leakage, the Carnot efficiency (up to 30 percent), and a higher reliability of the system (99.8 percent run time) (Ref. 11). When these challenges are overcome, there is a possibility that electric motors will start being seen in the propulsion systems of aircraft; however, given the way that HTS has progressed throughout the years and the huge jump in PWR needed, substantial development required before this technology is ready for entry into service by 2035.

4.2 Advanced Combustor

The combustor is a major engine component required to convert the chemical energy of the fuel into thermal energy. This is the engine element which has the most potential to dramatically reduce aircraft pollutants such as NO_x . To do this it must burn with the least emission of undesirable chemicals for environmental concerns and without a large pressure loss (due to the turbine's need for a high pressure flowpath to operate efficiently). The key to ultra-low NO_x production is to either burn at the lowest possible flame temperature, or minimize high temperature residence time. This is equivalent to burning as lean as possible and with as uniform a mixture as possible to avoid local stoichiometric zones (Ref. 12). There are a couple kinds of combustors which satisfy the above criteria, the most commendable being the lean-premixed-prevaporized (LPP). The problem in employing these for high pressure/temperature systems is the probability of premature upstream burning. Rich-burn, quick-mix, lean burn (RQL) is used in current aeroengines due to its combination of stability and performance; however, RQL does not give the possibility of large NO_x reductions. Thus, an alternative is essential to meet the stringent N+3 emission goal.

It is desirable to increase the thermal efficiency of the engine to reduce fuel consumption. Increasing the overall pressure ratio (OPR) is a way to increase the efficiency, but it also increases the temperature entering the combustor, T_3 . This will increase NO_x production unless technologies can be developed that simultaneously reduce fuel burn and emissions.

A promising combustor design, lean direct injection (LDI), is capable of providing significant NO_x reduction. As the name implies, a lean burn is executed which decreases the flame temperature. Since NO_x is essentially an exponential function of the flame temperature when burning lean, lower NO_x forms. Direct injection means fuel is injected directly into the flame zone; the reason is to prohibit auto-ignition or flashback (Ref. 13) giving the reaction greater stability. The injection gives little time for the rich-high temperature condition to reside due to rapid turbulent dispersion.

The LDI advanced combustor has been given high hopes in reducing emissions but of course has many challenges similar to other combustors that need to be addressed before implementation. There are four main issues: 1) fuel mixing, 2) combustion instability, 3) liner material, and 4) reduction in all pollutants simultaneously. To reiterate, an LDI combustor lacks a premixing zone which means sending a uniform fuel-air mixture to the combustion zone is not a trivial task. The key is to decrease injector diameter allowing for faster fuel atomization and vaporization. There is a limit to injector diameter when using traditional jet fuels and is approximately 0.02 in. Any further reduction will result in fuel coking clogging the injector. On a side note, alternative fuels drop the minimum diameter by about 50 percent due to their slightly lower viscosity. Since the injector using conventional fuel cannot get much smaller, NASA Glenn (Ref. 12) and others (Ref. 14) started experimenting with a multipoint LDI concept shown in Figure 10 which uses an array of ~25 to 35 injectors to maximize mixing and increase uniformity.



Figure 10.—A multipoint array of lean direct injectors integrated into a sector combustor rig (Ref. 15).

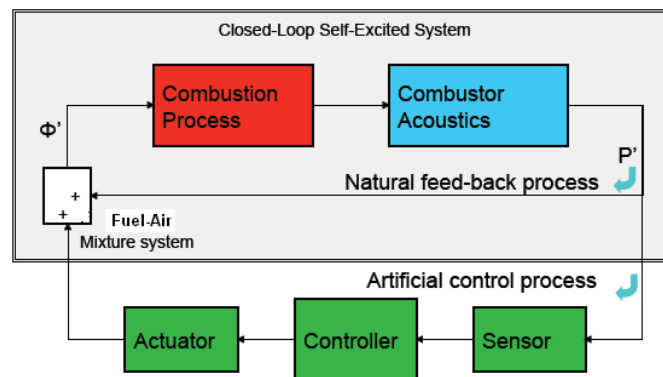


Figure 11.—Combustion instability control strategy (Ref. 8).

Combustion instability is another challenge which has been a topic of research for some time. Two types arise and are present at different power levels. First of all, at low power settings such as idle, lean blowout issues can occur due to low momentum entering air. The turbulence is not sufficient for mixing causing local extinction. At high power settings, dynamic instability occurs due to the feedback coupling between the two dominant processes, acoustics and heat release, and is referred to as thermoacoustic instability (Ref. 16). Rayleigh described a system with such phenomena will be unstable if the heat release rate from combustion and the acoustic perturbations are in phase (Refs. 16 and 17). An unstable environment affects the equivalence ratio, ϕ , which can cause blowout if an excessive lean mixture is present (Ref. 18), or an emissions increase if near stoichiometric. The equivalence ratio has a very narrow range for proper operation ($\sim 0.35 < \phi < \sim 0.5$) illustrating the need to control these pressure oscillations. In order to achieve 75 percent NO_x reduction, it is necessary to demonstrate the capability to detect and suppress combustor instabilities in order to enable efficient combustor operation at all conditions (Ref. 19). Passive control is currently being used, and is projected to be used even for the N+2 timeframe. However, active control governing fuel injection rates may be implemented to achieve N+3 success. A typical feedback control system for this application is shown in Figure 11. As engine noise sources from the fan and jet are reduced, the combustor noise may become a source that impacts the overall aircraft noise levels. Combustion instabilities need to be controlled for both stable operations and noise. It is possible that lower emission combustors will have even higher noise levels compared to current turbofan engines.

Thermal barrier liner material is another challenge which needs to be conquered in the coming years. As material properties stand today, no alloy or composite has the ability to withstand the temperatures in the combustion chamber. Air cooling systems are employed to create insulation using a thin film of air to keep the surface of the material from melting. However, air is an expensive commodity because it results in a loss of air entering the combustor decreasing turbulent energy thus effecting mixing. Composite materials such as CMCs show great potential for high temperature core components.

Lastly, a tradeoff of pollutants between flight conditions is currently made for RQL combustors because of their inversely proportional dependence. For example, NO_x and smoke are the main problems of high thrust conditions; Carbon Monoxide (CO) and Unburned Hydrocarbons (UHC) are worst during taxi and idling. A long residence time would favor the reduction of CO, UHC, and smoke, but would provide more time for NO_x to form (Ref. 20). LDI decreases residence time by designing the shortest possible combustor chamber (hence, favoring NO_x). Since decreasing all pollutants is fundamentally contradictory, staging should be introduced to allow a variable residence time for different flight regimes. Even though N+3 goals do not specify limits to other emissions, one must be mindful of the tradeoffs.

All aircraft concepts mentioned used some variant of a gas turbine engine with a combustor present. Core size is required to shrink to increase BPR or reduce weight; however, combustors are a limiting factor in size as they need room for the reaction process. The LDI combustor will reduce combustor length decreasing weight due to the lack of a premixing zone. If purely emission considerations are of concern, LTO NO_x will greatly reduce using LDI for all aircraft concepts since it is highly dependent on this propulsive component. MIT² predicted a 100 percent chance of having an LDI at TRL (Technology Readiness Level) 4 by 2025 reducing LTO NO_x emissions to less than 25 percent of the CAEP 6 standards. MIT also predicted a 75 percent chance of attaining a TRL of 6 by 2025.

4.3 Boundary Layer Ingestion

Boundary layer ingestion (BLI) is used by both of the MIT as well as the NASA TeDP aircraft concepts. BLI consists of the propulsive system ingesting or taking in the fuselage boundary layer as its inflow with the purpose of increasing fuel efficiency. Figure 12 illustrates in a simplistic manner the benefit in propulsive efficiency obtained from ingesting the boundary layer. The propulsive efficiency, η_p , is given by

$$\eta_p = \frac{2U_0}{U_j + U_{in}} \quad (1)$$

where U_0 , U_j , and U_{in} are the free stream velocity, jet exit velocity and the inlet velocity, respectively. For the boundary layer ingesting case, $U_{in} < U_0$, the propulsive efficiency is higher compared to the non-ingesting case, $U_{in} = U_0$. This is evident from Equation (1).

A number of earlier studies have assessed the benefits of BLI (Refs. 21 to 24) and depending on the assumptions (level of inlet losses, effect on fan performance) various values of fuel burn reduction ranging from 0 to 16 percent have been found. More recently Plas (Ref. 25) predicted 3 to 4 percent fuel burn reduction for the SAX40, a HWB aircraft similar to the N+3 HWB's. Their work was the first to explicitly consider how the engine or the fan performance interacted with the non-uniformity of the inlet flow. In order to maintain an overall system benefit the losses of fan performance due to its interaction with a non-uniform inflow should not overwhelm the ram drag reduction benefits obtained from ingesting the boundary layer. NASA and United Technologies Research Center (UTRC) have researched technologies capable of obtaining a BLI fan efficiency nearly equal to that of a conventional clean inflow baseline fan by optimization based parametric design of distortion optimized inlets and distortion tolerant fans (Refs. 26 and 27). Wind tunnel experiments to validate the prediction results are planned for 2013. System level analysis showed a 3 to 5 percent fuel burn reduction relative to an advanced baseline, high bypass ratio turbofan engine by use of BLI with optimized inlets and fans.

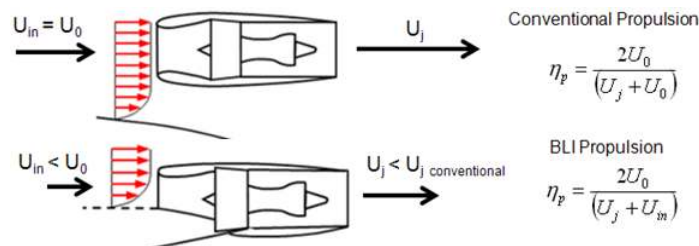


Figure 12.—Conventional propulsion vs. BLI propulsion.

Indications are that the negative impact of a distorted inflow on the fan performance can be overcome. Nevertheless challenges remain that need to be addressed, namely aeromechanical, acoustic and off-design operation. Additional mechanical loads will be experienced by the engine, as the non-uniformity of the inflow will excite cyclic stresses on the fan. This could lead to a heavier fan design with thicker blades. Also, a new noise source will be created due to the interaction of the engine with the non-uniform inlet flow. There is limited data on noise with this type of distortion pattern and the propagation of the noise will be heavily dependent on the engine location on the airframe. It is likely that this new noise source will be shielded by the airframe thus preventing it from propagating to the ground, but the cabin noise is expected to increase. As mentioned above, the loss in fan performance is predicted to be minimized by novel inlet and fan designs, but that is for a specific design point. Reductions in performance for off-design conditions could be significant.

In summary, there is a great deal of further work required for beneficial BLI. Finally, in order to obtain the most benefits from BLI, a significant amount of the aircraft boundary layer needs to be ingested. Therefore large aircraft such as the NASA TeDP with aft-mounted, distributed propulsion offer the largest benefits.

4.4 Composites

Among the technologies implemented in the advanced aircraft and propulsion concepts, one of the most extensively utilized was that of composites. Of these composites, the two main types discussed herein are Polymeric Matrix Composites (PMC) and Ceramic Matrix Composites (CMC). Widely implemented throughout the N+3 concepts, they present extensive weight savings, targeting higher thrust-to-weight properties than their conventional metal super alloy counterparts. While the PMCs pose great weight savings through application into airframe and low-temperature propulsion applications, CMCs are projected to prove beneficial in the propulsion system hot-section. The following sections provide detailed descriptions of the composite technologies, potential benefits, current technological challenges, and past and future projections for the technology.

4.4.1 Polymeric Matrix Composites

Polymeric Matrix Composites consist of plastic matrices with embedded reinforcing fibers, typically either carbon or glass. The leading PMC material for aerospace applications is carbon fiber composites. These have high tensile strength, high stiffness, and the best weight advantages of composite materials, thus making them an attractive candidate for structural aerospace applications. Currently, PMCs are limited to low and moderate temperature applications (approx. -54 to 150 °C) (Ref. 28). Due to their limited thermal capabilities, application of PMCs into the aircraft propulsion system is limited. Current research efforts are working toward moving PMCs into the fan case and the fan.

Due to the relatively limited database of new PMC technologies, analysis methods of damage mechanisms and structural failure modes are not well established compared to that of metallic alternatives. The inability to predict this degradation requires larger safety factors to be employed, decreasing the weight savings benefit. The lack of trustworthy analytic and computational techniques requires expensive and time-consuming engine tests to be mandated when PMC technologies are in question.

Insufficient knowledge into advanced composite constructions currently limits the application of PMC technologies to areas of higher stress and more complex shapes. Research is being conducted into new fiber architectures that can make higher strength applications achievable. Current practices look to the use of braided fiber sheets to deal with difficult geometries not easily lent to traditional fiber layouts. Specific focus is placed on braids where fibers can be shifted. Triaxial braided fiber configurations are utilized for their extreme strength in components with simple geometries.

Further investigation into potential benefits and methods of integrating hybrid structures needs to be performed. Hybrid PMC constructions look to combine several different material technologies into one integrated component, such as the fusion of a high stress and strain material throughout the fan blade structure. Similar philosophies look to the integration of shape memory alloys for potential clearance control or blade profile optimization, resulting in improved efficiency over a broad range of flight regimes. Other concepts look to integrate acoustic liners within the fan blades to cancel some of the dominate fan tones. Concerns with this strategy arise from the perceived inability to repair acoustic liner damaged during operation.

During the 1980's, the main challenge of PMCs was improving performance and cost. The cost margin between PMCs and metallics was enormous, requiring the improved performance capabilities of PMCs to need to “buy their way on” to airplanes. Today, while production costs are higher than that of metallics, lifecycle costs are competitive, if not better than that of their alternatives. PMCs are heavily implemented within the airframe structure, amounting to a 15 percent reduction compared to aluminum in fuselage primary weight. Figure 13 depicts the increased usage of composites over history.

Current and future applications of PMCs within the propulsion system look to replace the traditionally metallic fan blades and casings with PMC compositions. With a low fan section temperature and the continual increase in size of high-bypass ratio fan blades, PMCs offer increased weight savings and allow for the fabrication of more complex airfoil designs (Ref. 28). The main design constraint of PMC fan blades is ensuring the ability to withstand large transient loads, typically dealing with direct impact from bird strike. Also being investigated are PMC fan containment structures. Researchers look to reduce part count by integrating the fan casing and adjacent support structures through a variable PMC architecture.

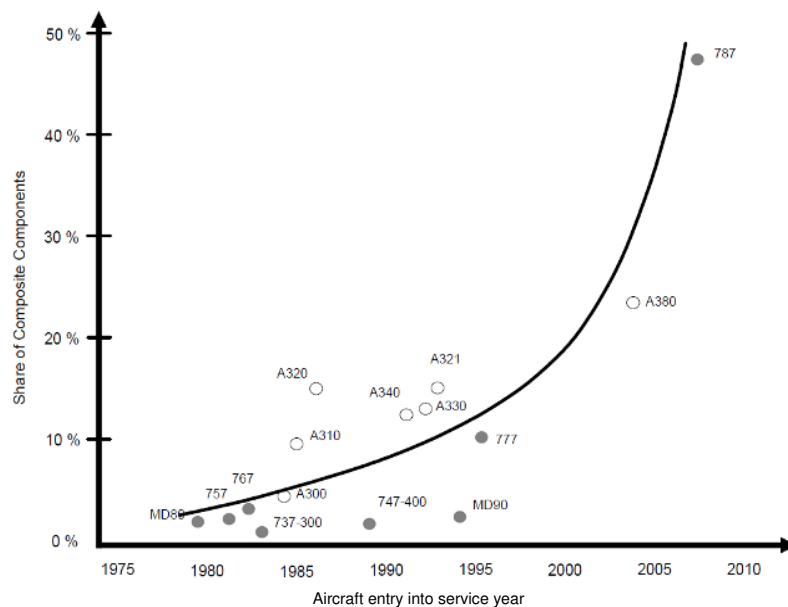


Figure 13.—Percentage of composite components in commercial aircraft (Ref. 28).

To date, the GE 90 and the GENx are the only commercial turbofans with composite fan blades, consisting of a carbon fiber composite with a toughened epoxy matrix. The GENx engine also has a composite fan casing. Temperature limitations limit further application PMCs within the turbine engine.

4.4.2 Ceramic Matrix Composites

Contrary to PMCs, ceramic matrix composites can be used for higher temperature applications associated with engine cores. Ceramics, having high thermal resistance, low density, and high specific strength, pose great potential for hot temperature applications. Despite their high specific strength, ceramics must overcome inherent characteristics of low fracture toughness. To achieve this, continuous fibers are embedded within the ceramic matrix to improve their strain capabilities and brittle characteristics. Sensitive to surface flaws commonly resulting in catastrophic failure, the fibers protected by a ceramic matrix allow CMCs to be more ductile. The ability to toughen ceramics through reinforcing fibers enables CMC technologies to become a viable technology in areas of high thermal and mechanical stresses.

State-of-the-art CMCs typically utilize either a SiC fiber-reinforced Si-based matrix composite (SiC/SiC) or an oxide fiber-reinforced oxide matrix composite (Ox/Ox) construction (Ref. 30). Properties of silicon carbide are typically more applicable to higher temperature regimes (>1100 °C), but lack sufficient corrosion resistance and have higher production costs. At lower temperatures (<1100 °C), Ox/Ox are typically sufficient, since they are cheaper to produce. The ability for oxides to resist corrosion of harsh operating conditions such as exposure to combustion gases and fuel make oxides a prime base for Environmental Barrier Coatings (EBC). Thin EBCs (5 to 10 mils) are deposited on SiC/SiC CMC component surfaces in order to shield the more thermally resistive SiC/SiC CMCs from the harsh environment, also acting as a thermal insulator due to the low thermal conductivity of oxides. Figure 14 depicts the thermostructural capability of SiC/SiC CMCs compared to competing materials.

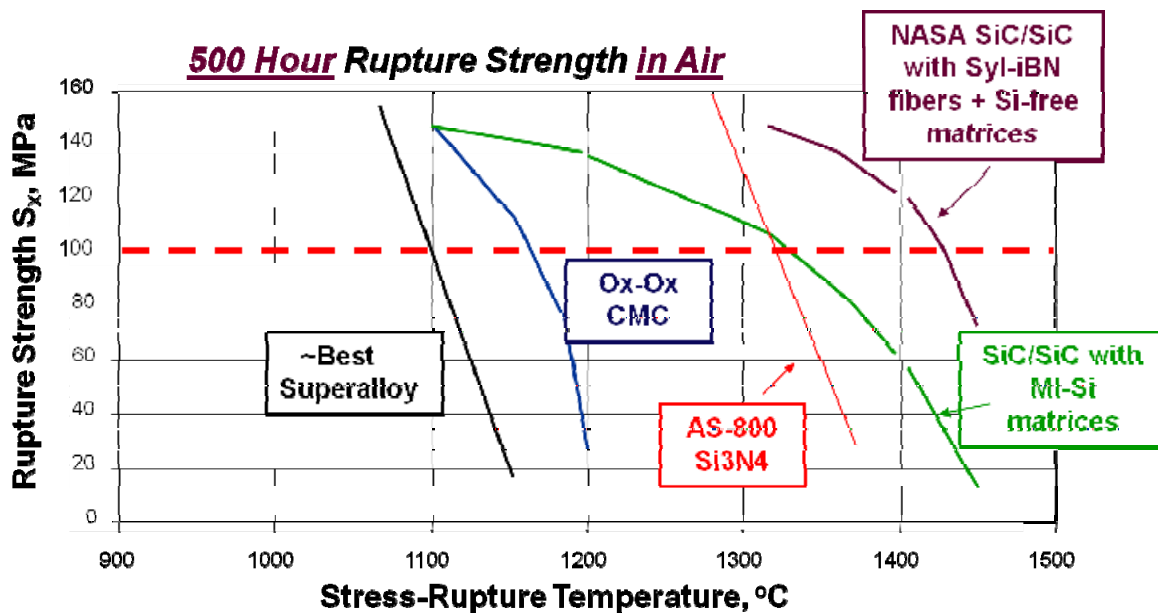


Figure 14.—In-plane 500-hr rupture strength in air for NASA CVI-MI SiC/SiC versus competing materials. The dashed red line indicates the required strength of ~ 100 MPa for static CMC engine components. NASA SiC/SiC systems display higher thermostructural capability than competing materials (Ref. 33).

Potential benefits of CMCs include low density, high thermal resistance, high specific strength and low thermal expansion. Compared to their superalloy counterparts, they are approximately 1/3 the density of the lightest metallic alternative. Additionally, CMCs have higher thermal resistance than superalloys. If implementable in the propulsion system's blades, vanes, combustion liners and nozzles, required cooling bleed air can be reduced. While there is varying debate in the level of cooling air reduction CMCs are able to achieve, substantial TSFC (Thrust Specific Fuel Consumption) improvements can still be made with higher temperature CMC components. Studies show that the implementation of components capable of achieving temperatures between 1200 to 1450 °C could provide 2.5 to 3 percent improvements in TSFC. More aggressive predictions project a 4.25 percent improvement in TSFC with the elimination of all turbine cooling air (Ref. 32).

While attempts to implement CMCs within a gas turbine engine have been on-going for at least 20 years, several key challenges hinder CMCs (Ref. 30). The major challenges facing their implementation are insufficient fiber thermal stability, high procurement costs, limited design techniques, and understanding of CMC properties.

Increasing the temperature stability of CMC components require finding the best fiber, fiber coating, and matrix. To date, demonstrations of specific materials have shown the ability to survive in harsh operating conditions for approximately 2,500 hr at temperatures between 1100 to 1200 °C. Better understanding of the chemistry and properties of both oxide and non-oxide CMCs needs to be established, providing a knowledge base to develop higher-temperature fibers, coatings, and matrix materials (Ref. 31).

Environmental barrier coatings (EBC) have been shown to improve the temperature stability of CMCs, while also forming a barrier from the harsh environmental operating conditions. Interactions with combustion fuel and moisture created in the high pressure conditions plus thermal cycling place considerable erosion and stress conditions on the EBC. Additionally, oxide-based EBCs require high thermal shock characteristics to serve as a long-term environmental protector and thermal insulator for the internal CMC materials, increasing the life and decreasing the required temperature capabilities of the inner SiC materials. Without prime reliant EBCs capable of withstanding these harsh operating conditions over the lifetime of the system, SiC CMC compositions will be unfit for application within the combustion chamber. To date, EBCs have been able to extend the life of CMC industrial gas turbine combustor liners up to ~1260 °C (Ref. 30). Further work into the composition and application methods of EBCs needs to be done to improve the temperature stability of these components to 1200 to 1500 °C.

Another problem facing CMC's is applying the technology to complex blade and component design, such as high-pressure turbine blades seen in the hot section of gas turbine engines. Extensive consideration must be placed into the architecture of the CMC fibers, allowing for the highest fraction of fibers to exist in areas of high tensile stress. This high concentration of fibers is crucial, since the fibers are the primary means of damage tolerance (Ref. 31). CMC constructions can consist of either a simple fiber fabric construction or a more complex three-dimensional weave (Fig. 15). While the 2D layering of fabric is less complicated, these fiber constructions provide low stress capabilities through the thickness of the component. For this reason, three-dimensional fiber geometries are necessary to provide sufficient strength characteristics. Current research is examining the optimal architectures to withstand the stresses induced on rotating components within a gas turbine hot section. Additionally, the component design needs to be optimized to reduce induced component stresses as much as possible.

Due to the lack of maturity of CMC technologies, procurement and production costs of components are still very high. Associated component costs should be reduced substantially with increased production volume and manufacturing scale-up. Additionally, the application of SiC/SiC CMC into other commercial venues has potential to further reduce costs and increase experience base. CMCs have potential application in military hardware and nuclear power, where SiC-based materials can provide more efficient energy conversion through higher operating temperatures and demonstrate high stability under radiation conditions (Ref. 30).

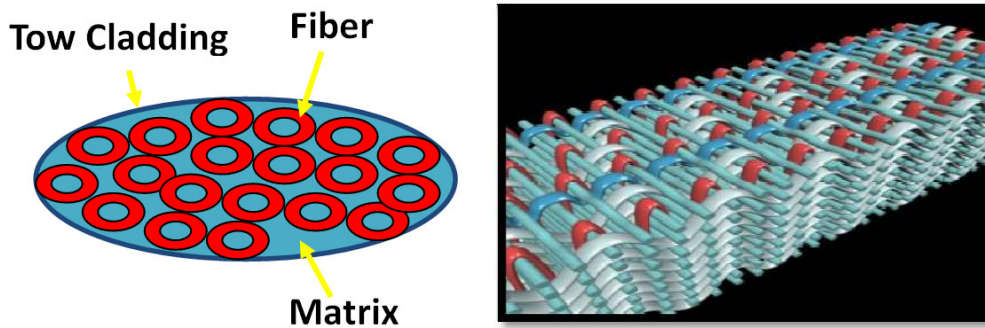


Figure 15.—CMC fiber reinforcement in tow and 3D constructions (Ref. 34).

There are varying opinions about CMC technology, the largest being the potential achievable temperature capability of the materials. Variation in expert opinion ranges from a top achievable temperature of ~ 1500 °C to the ability to run the turbine hot section without any cooling air at ~ 1650 °C. Additionally, there are varying opinions as to the level of implementation CMCs will reach in the N+3 timeframe. The practicality of CMCs in static structures is less disputed relative to rotational machinery, given their higher operating stresses and temperatures.

4.5 Distributed Propulsion

Using multiple engines is not a new concept in fact most early aircraft had multiple engines (Refs. 35 and 36). For the last 50 years conventional subsonic transport aircraft have favored two to four engines with under-wing installations. All these aircraft can be considered to have distributed propulsion as they have more than one propulsor; however, what is meant here by distributed propulsion is similar to the definition used by Kim (Ref. 35): distributed propulsion is the span-wise distribution of the propulsive stream and/or the integration of these propulsors with the airframe in such a way that the overall vehicle benefits from maximized aerodynamic, propulsive, structural, and/or other efficiencies. Both the MIT and NASA TeDP concepts qualify as distributed propulsion vehicles.

There are numerous advantages in using distributed propulsion some of which are related to scalability effects as a greater number of smaller engines would be used (Refs. 35 and 37). Distributed propulsion has the potential to: lower structural load by distributing propulsion units, lower engine installation drag, increased aircraft configurational freedom, lower noise by airframe shielding and increased area for acoustic treatment. As well as lower fuel consumption by enabling boundary layer ingestion, differential and thrust vectoring that could augment control capabilities and greatly reduce engine out asymmetric thrust risks, and finally mass production cost advantages as smaller engines may find a wider application for transport aircraft of various sizes, business jets and UAV's, which would increase production efficiency and spread development cost (Ref. 37).

There are challenges with smaller engines as they have reduced compressor and turbine efficiencies compared to larger engines with the same technology level. The increased number of engines and their location can lead to higher maintenance costs. Also, losses and complexity need to be minimized with the thrust distribution system. Furthermore, the coupling between the aircraft aerodynamics and the propulsion system is a difficult design integration issue requiring consideration right from the conceptual design stage (Refs. 35 and 38).

In terms of the N+3 goals, distributed propulsion vehicles have the potential of greatly reducing fuel burn and noise; however, their viability in the N+3 timeframe is intimately related to the development of many of the technologies described in this paper, some of which include: boundary layer ingestion, advance simulations capabilities that will permit propulsion airframe integration, composite materials in the engine, superconducting electric motor/generators that will eliminate mechanical connections to distribute the power.

4.6 Acoustic Liners

Acoustic liners are noise suppression mechanisms used to attenuate engine noise. These liners are designed to provide a desired acoustic impedance boundary condition that reduces the propagation of noise in an engine nacelle (Ref. 39). Innovative ideas enhancing these liners such as multiple layers, 2DOF, and even variable depth have been offered to provide a wider bandwidth of suppression (Ref. 40). Turbomachinery such as the fan, compressor, and turbine produce acoustic modes that can propagate normal to the engine axis causing community disturbance. Acoustic treatment inside the nacelle has been effective for sound waves that propagate directly into the liner (Ref. 40). However, with the advent of the high-bypass ratio turbofan, the L/D (the ratio of engine length to diameter) and fan speed has decreased. This is reducing acoustic treatment area and also causing broadband noise to dominate rather than tones (Ref. 41). Additionally, core-noise is increasing at all engine thrust levels due to higher power density and better performance. Performance trends include an increase in OPR and T_4 generating more noise from the combustor. Also, highly loaded LPT blades as well as a projected stage spacing reduction will increase tone-noise source strength and complexity (Ref. 41). Thus, the demand is high for new innovative engine noise reduction techniques.

It is established that engine noise shielding (Refs. 42 to 44) by the fuselage is paramount to N+3 success and is estimated to give as much as 10 EPNdB cumulative reduction in overall noise (Refs. 45 to 47). It also allows other technologies to be applied such as boundary layer ingestion. Placing acoustic treatment outside the engine nacelle such as on the fuselage, elevons, wings, or other empennage adjacent to the engine is being considered (Ref. 41). Acoustic propagation through the cabin will also be reduced which is imperative to passenger comfort given some aircraft could have embedded engines along with composite skins allowing for easier transmission (both acoustic and structural). In any case, a performance/noise tradeoff should be completed to understand how drag increases due to the perforate liners. However, initial tests have shown that this concept is plausible.

N+3 aircraft are calling for complete configuration changes which greatly affect the relative impact of noise sources. For example, if noise shielding is introduced as previously described, a complex nacelle liner decreasing tones may not be necessary. However, on a traditional tube and wing, several dB reduction could be substantial enough to justify the increase in liner complexity. Another example can be seen on the TeDP which is likely to have higher shaft speeds due to the addition of an electric generator. Higher shaft speeds result in higher frequency tones that may be easier to attenuate with acoustic liners. Therefore, uncertainty is present until the different configurations are investigated. For this reason, it is necessary to review N+1 and N+2 liner concepts and how their applications may be different for N+3 vehicles.

A few promising ideas in the engine/nacelle for N+1 and N+2 are over the rotor treatment (OTR), soft vane, multi-segmented liners, and active tunable liners (Fig. 16). OTR is designed to reduce the noise associated with the fan rotor. Soft vanes are designed to reduce rotor-stator interaction noise. It is a hollow vane that has several implanted Helmholtz resonators, each of which is sized to mitigate a particular frequency of the vane surface unsteady pressure spectrum (Ref. 45). Segmented liners can be applied to mitigate aft noise. This is an important concept for over the wing installed engines because they are usually mounted or embedded as far back as possible where aft shielding is poor. The goal is to reduce rearward propagating rotor-stator interaction tones using axial scattering varying the impedance boundary condition between liner segments (Ref. 48). Lastly, active tunable liners allow a wide bandwidth without penalizing the amount of sound being absorbed for a given frequency as opposed to multi-layer passive liners. Research has suggested this be implemented using a compliant face sheet (Ref. 49), or even using a

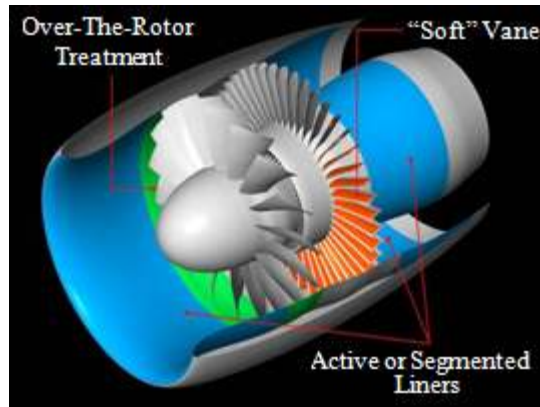


Figure 16.—Promising noise reduction technologies (Adapted from Ref. 45).

self-powered tunable electromechanical Helmholtz resonator (EMHR) (Refs. 50 to 55). Some of these technologies might have too low a benefit to cost ratio for their intended application; however, different airframe configurations could make implementation possible.

4.7 Computational Tools

The use of high fidelity simulations and Multidisciplinary Design Analysis and Optimization (MDAO) early in the design process is imperative in order to facilitate the development of aircraft capable of meeting the N+3 goals. The use of advanced MDAO tools will be especially beneficial for the non-conventional configurations (most of the N+3 concepts) because of the highly coupled nature of these designs and of the limitation of current design tools in their ability to accurately model non tube and wing configurations. These new design tools will need to make use of first principles, instead of empirical relations and curve fits used by current system analysis tools (Ref. 2).

Improvements need to be made in the ability to accurately predict aeroacoustic, aeroelastic, aerodynamic, aerothermodynamic, and structural behavior to meet noise, fuel burn and emissions requirements. In addition to integrated advanced system design tools, computational tools with the capability of aiding the understanding of the underlying physical phenomena are needed.

Many of the key features present in the N+3 concepts will be made possible and achieved only with the help of novel computational tools. These tools will aid in the design of low loss boundary layer ingesting inlets, distortion tolerant fans, propulsion integration with the airframe, advanced combustors, etc. Therefore it is imperative for simulation capabilities to continue rapid development. In this section the capability to perform a high fidelity fully coupled engine simulation is used as a reference to determine how simulations capabilities will develop into the N+3 time frame and their potential benefits.

There have been numerous research efforts to perform a full engine simulation (Ref. 56). The most computational intensive simulation was carried out at Stanford as part of the ASC program (Ref. 57). The simulation used Reynolds Average Navier Stokes (RANS) for the turbomachinery and Large Eddy Simulation (LES) for the combustor. An average run on 700 computer nodes of a 20 degree annular section of the engine took 2 weeks. Currently there are also more practical engineering application simulations available (Refs. 58 to 60) that can run in one day on ~100 nodes. Nevertheless these times are prohibitive to be considered useful design tools, but progress has been made given that one decade ago full engine simulations were considered mere demonstrations. The rate of advance in computing technology and multidisciplinary tools makes it likely that high-fidelity simulations of complete gas turbines will be routine for the N+3 timeframe (Ref. 56). However, in order to obtain performance benefits on the final design it is essential to move beyond flow simulation to a capability for aerodynamic shape optimization and ultimately multidisciplinary system optimization (Ref. 61).

Besides allowing for better designs, the main benefits of advance simulations will come from reducing development time and cost (Ref. 62). It is important to recognize that in current practice the setup time and cost of simulations substantially exceed the solution's time and cost; therefore, going forward it is essential to remove this bottleneck. Finally, all N+3 concepts will benefit from better engines achieved through advance simulations and the idea of "virtual" engine testing. The Numerical Propulsion System Simulation (NPSS) (Ref. 63) is a good example of a system simulation tool with multidisciplinary capability and varying levels of fidelity. NPSS is used routinely by industry and has helped them reduce their engine analysis time and cost throughout the product life cycle by about 50 percent (Ref. 64).

4.8 Active Tip Clearance Control

Tip clearance control in turbomachinery is used to close the gap between the rotating blades and shrouds of the fan, compressor, and turbines of gas turbine engines, which will improve the efficiency of these stages by reducing air leakage through the clearance between the blades and casings. Tip clearance issues come from the fact that the engines are designed to have enough operational clearance subject to varying loads. This means that clearance cannot be optimized for cruise where minimized leakages will have the largest impact on mission fuel burn. Active and passive clearance control are both being investigated as potential solutions. Several current engines use thermal growth of the case that is activated by engine bleed air to control the tip clearances. Active control could also include using a system of sensors and actuators to shrink or grow the cases surrounding each stage. New concepts make use of Shape Memory Alloy (SMA) material which are thermally triggered to change shape at different segments of flight, such as cruise and takeoff, but is still in the development stage (Ref. 65).

Each of the four NRA contractors for the N+3 study utilized active clearance control technology in the core of their engines. The advantage to using this technology is to achieve a decrease in fuel burn. For every 10 mils (0.01 in.) of excess clearance in the compressor stages there is a 1 percent specific fuel consumption increase (Ref. 66). Another advantage to tighter tip clearances is a reduction in noise resulting from tip flows off the fan blades interacting with downstream blade rows. The disadvantages to using an active clearance control system are the added weight and complexity. An active control system includes using sensors, actuators, control logic, and wireless telemetry for instrumentation.

The goal of the active clearance control system is to provide a fast acting system using direct sensor feedback that can handle unanticipated changes (Ref. 65). One challenge holding back the use of this technology is sensor capability. Current sensors do not have the desired accuracy or reliability needed to meet the compressor and turbine applications (Ref. 65). The material of the sensors will also have to be improved to withstand the high temperatures in the core of the engines. Another challenge to incorporating this system is the ability to make a dynamic model of the clearance phenomenon to better understand how to make the system function correctly.

Despite these challenges, it is feasible that active clearance control will be developed sufficiently by 2035 to be incorporated into the N+3 era aircraft. Sensors have progressed quickly throughout the years and materials have made steady advances in the temperatures they can withstand. Much research has been focused on increasing the accuracy with which complex dynamic modeling can be computed. A tradeoff analysis should be conducted to understand if the benefits will be worth the added complexity and cost given to the engine for a small decrease in fuel burn and emissions.

4.9 Shape Memory Alloy

Shape memory alloys (SMAs) are metallic alloys that undergo solid-to-solid phase transformations induced by appropriate temperature and/or stress changes and can recover seemingly permanent strains (Ref. 68). This solid-state phase transformation occurs between a low-temperature martensite phase and a high-temperature austenite phase (Refs. 69 to 71), giving these alloys unique characteristics such as: high energy output, high strain, and the ability to be used in many forms (axial, bending, torsion, radial, and

other actuation). However, only a few alloys based on the binary NiTi alloy system are currently being used in the aerospace industry today and include the alloys Ni-Ti45, Ni-Ti43, and Ni-Ti4 (Ref. 72).

Current propulsion systems are not optimized across the various flight conditions and speed regimes. Sensitivity studies must be carried out to design for performance tradeoffs to optimize the flight as a whole. In the future, SMAs could provide variable geometry using passive and/or active control for better overall aircraft performance. As an example, variable area nozzle (VAN) concepts are being developed to provide at least 15 percent area change using a SMA-actuated torque tube [personal communication] (Ref. 73). This can be accomplished either passively (using a temperature actuated bypass nozzle (Ref. 1)) or actively (controlled supplemental heat). As an alternate to the torque tube approach, a different study was performed utilizing SMA ‘cables’ wrapped circumferentially around the aft portion of the fan cowl of a high-bypass nozzle (Refs. 68 and 74). The idea was to optimize fan efficiency throughout all flight conditions. Inlet geometry variations could help control inlet flow separation (Ref. 75) for the various Mach regimes, or increase the operating range of scarfed inlets (Ref. 76). The former could provide a well-rounded lip for static conditions or a sharpened lip for high speed flow, while the latter could enable fan noise shielding by protruding the lower edge of the inlet. In any case, benefits are expected with some form of variable geometry in both the inlet and nozzle. Passive chevrons are also being looked at for jet noise attenuation but affect performance during cruise due to their intrusive nature. However, a variable-geometry chevron (VGC) could be designed to reduce jet engine noise during takeoff while maintaining efficiency in cruise (Ref. 77). Lastly, camber changing fan blades seem to be the most ambitious SMA application and could possibly be introduced in 2035 aircraft.

There are several concerns with incorporating these SMA ideas into aircraft. The main issues that need to be resolved are dimensional stability, temperature capabilities, overall knowledge, and design tool maturation. Dimensional stability is of utmost importance, since a permanent change in the shape of the material or a shift in transformation temperatures during cyclic loading may render the SMA inoperable and necessitate the replacement of the actuator (Ref. 77). Temperature is also a limiting factor for implementation because the transformation temperature of binary NiTi is low, affording the possibility of accidental actuation. Figure 17 depicts how research has confirmed the capability of increasing temperature. Today, commercial NiTi alloys are limited to -100 to 100 °C (Ref. 78) and cannot be used safely in aerospace applications. However, $\text{Ni}_{30}\text{Pt}_{20}\text{Ti}_{50}$ alloy (referred to as 20Pt) with transformation temperatures above 230 °C and $\text{Ni}_{20}\text{Pt}_{30}\text{Ti}_{50}$ alloy (30Pt) with transformation temperatures above 530 °C have been demonstrated in a lab based setting (Ref. 79).

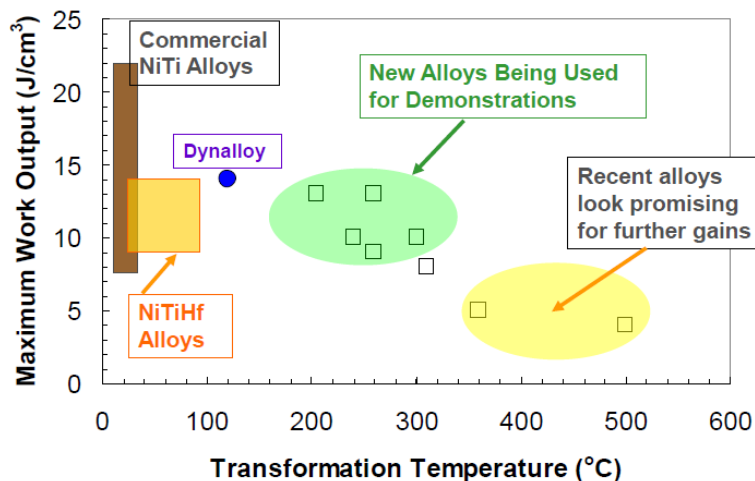


Figure 17.—SMA present and future temperature capabilities (Ref. 78).

SMA are relatively immature given the lack of overall knowledge of their properties. Their durability, fatigue rates, and response time are being investigated, but need further review for a complete understanding. Current response time, i.e., the time it takes to fully actuate upon heating, is on the order of one second, hindering active control applications unless the signal frequency is much less. Also, thermal cycling must be performed to “train” the SMA to actuate a specified amount, thus stabilizing its response. This is time consuming, so improvements need to be made in either the material or the training methods to minimize production costs.

As the knowledge of SMA are being matured, so too will the design tools, both experimentally and computationally. Design tools can enhance life and damage prediction, training, transient behavior, and the understanding of multi-axial deformation. The latter will allow for the development of variable camber fan blades. By 2035, SMA are expected to be mature enough for use in VAN, VGC, variable inlet, and possibly fan blades. Notice these ideas change shape with flight conditions rather than small perturbations requiring quick response active control systems. This is again due to the slow response time, which is not likely to improve enough by this timeframe. Also, the core engine components are not expected to be replaced by SMA materials on N+3 aircraft due to their inferior transformation temperatures.

4.10 Batteries

With the introduction of alternative propulsion system concepts and advanced superconducting motors for distributed propulsion, the need for powerful environmentally-conscious energy sources is evident. While traditional systems may still be applicable, emission regulations drive researchers to pursue alternative energy sources. One such energy device is the battery. A battery is an electrochemical device that converts stored chemical energy into usable electrical energy and has been extensively researched since their invention in the 1800s. Batteries are composed of one or more voltaic cells, which contain two electrodes (positive cathode, negative anode) and an ionically conducting electrolyte that facilitates the flow of ions between the polarized electrodes. This flow of ions creates electrical energy used for power. With the recent push for the electrification of automobiles, emphasis has been placed on the development of highly energy dense batteries that are safe and have an acceptable lifetime.

There are several advantages to using batteries toward achieving the N+3 goals, with reduced emissions being the most significant. Batteries integrated within an aircraft propulsion system would emit no in-flight emissions, where toxins are the most harmful to the ozone. This design would also make use of cheaper land-based energy resources, reducing flight operation costs. Consequently, the benefits of these systems could permit N+3 concepts, such as Boeing’s SUGAR Volt, to be a viable alternative to current aircraft. In this concept, batteries would power an electric motor, acting as an “electric assist” for the advanced gas turbine. This alternative electric system would be used during ground taxiing and takeoff when emissions, noise and fuel flow are at their highest.

There are many challenges associated with the use of batteries in commercial aircraft propulsion systems. Their current energy density is low, with the state-of-the-art lithium ion batteries achieving between 150 to 250 Wh/kg. In order to accomplish range and efficiency requirements, Boeing determined the specific energy density of these systems would need to be 750 Wh/kg or greater. To increase present energy capacity, scientists are continuously looking for new chemistries than can achieve the extreme power-to-weight requirements of commercial aircraft. Other challenges include safety, reliability, life cycle, cost, and recharge rate.

Lithium-air is one of the new chemistries being considered for its potential to provide energy densities of 1700 Wh/kg for automobiles, equivalent to that of gasoline. Figure 18 depicts the gravimetric energy densities of various types of rechargeable batteries. While the theoretical energy density of gasoline is 13000 Wh/kg, accounting for an average tank-to-wheel efficiency of US automobiles (12.6 percent), the practical energy density of gasoline in automobile applications is 1700 Wh/kg. On the other hand, the oxidation of 1 kg of lithium metal releases 11680 Wh/kg (Ref. 80). Compared to the practical energy density of gasoline, the efficiency of Lithium-air batteries would need to be 14.5 percent

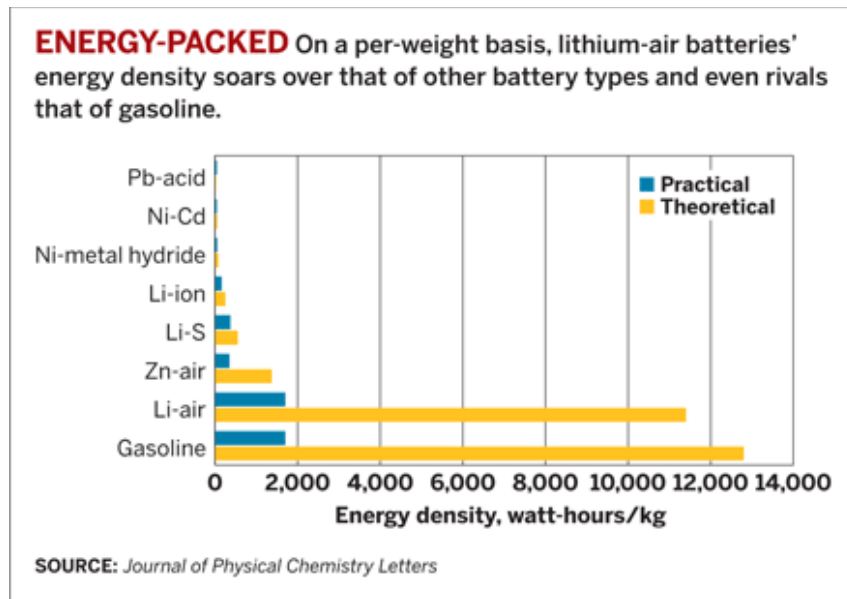


Figure 18.—Theoretical and practical energy densities of battery types in automobile applications (Ref. 80).

of the theoretical energy content of lithium metal. While this is much lower than the practical energy density of existing zinc metal-air batteries (40 to 50 percent), a lower efficiency for developed lithium-air batteries is expected, as the overhead of the battery will have a much larger impact on the lighter lithium (Ref. 80). It is important to note that these calculations are relevant to automobiles and not commercial aircraft. The graph is presented to show the vast differences in energy densities between current batteries and gasoline.

Lithium-air technology is still in the early developmental stages, with practical results falling far short of theoretical calculations. The best reported lab cell has achieved a specific energy of only 363 Wh/kg (Ref. 81). Lithium-air technology is immature and extensive chemistry issues must be resolved to address the general challenges of batteries discussed above.

After 35 years of research and development, Lithium-ion chemistries are just beginning to phase out their predecessor, the nickel metal hydride battery (Ref. 80). Based upon past developmental cycles, it is unlikely that new chemistries such as Lithium-air will be available for 2035 advanced concepts.

There are also several promising technologies that focus on the further refinement of currently viable battery chemistries. Two such concepts look to replace the graphite anode of a lithium-ion cell with either a silicon nanowire or nanoparticle construction. Silicon, having the highest energy density of any element, has energy storage capabilities ten times that of graphite (Ref. 82). Through the use of porous nano constructions, researchers hope to mitigate swelling issues associated with silicon during ion insertion. Amprius, a startup company developing nanowire anodes promises to deliver batteries with four times the energy density of current technologies (Ref. 83).

A radically new approach to the design of batteries, the Semi-Solid Flow Cell, is a current research topic. Researchers at MIT have developed a revolutionary architecture that combines rechargeable batteries with fuel cells that could allow current battery technologies to be “refueled” similar to that of gasoline vehicles. The design merges the active electrode through suspension into a liquid electrolyte, creating slurry that can be pumped through the battery (Ref. 84). While the concept has been demonstrated using current Lithium-ion technologies, it is not linked to any particular chemistry and can be applied to newly developed materials (Ref. 85). If producible, this architecture could have a great impact on aviation. Coupled with other research efforts, this “redefined” flow cell could permit batteries to be refueled similar to conventional gasoline vehicles, with spent slurry sent to a processing facility to be recharged for subsequent use.

Considering the development of past battery chemistries, it appears unlikely that technologies such as lithium-air will not reach an acceptable maturity by the N+3 timeframe. However, innovative technologies built upon currently proven chemistries may reach maturity by this timeframe. While these technologies will not rival energy densities of petroleum-based fuels, they may permit alternative electric assist concepts such as the SUGAR Volt to become reality.

4.11 Fuel Cell

A fuel cell is an electrochemical device that converts the free energy of a chemical reaction into electrical energy; the byproducts being dependent on the reactants used (Ref. 86). The three main parts of a fuel cell are the anode, cathode, and electrolyte. An electrolyte is any substance containing free ions that makes the material electrically conductive. The anode is an electrode through which electric current flows into a polarized electrical device. Lastly, the cathode is an electrode through which electric current flows out of a polarized device (Ref. 86).

There are multiple types of fuel cells that are differentiated by the type of electrolyte that is used, two examples being Proton Exchange Membrane Fuel Cell (PEMFC) and Solid Oxide Fuel Cell (SOFC). These two fuel cells are the most relevant to aerospace applications. PEM fuel cells are typically being used in automotive and stationary power applications, but there have been tests conducted using PEMs for small aircraft propulsion. There has been a large focus on using SOFCs in future propulsion technologies because they operate at a much higher temperature (800 °C) and they do not use platinum as the catalyst, which is an increasingly rare and expensive metal to purchase (Ref. 89). Solid Oxide Fuel Cells are also extremely efficient, with values being found as high as 65 percent (Ref. 87).

There are many advantages to using fuel cells that help to achieve the N+3 goals. The process of producing electricity with a fuel cell has no combustion stage, which in turn means that there will be no NO_x emissions created. The high efficiency of SOFCs could help to reduce the fuel burn of the aircraft. They have the ability to use different types of fuel, including methane, hydrogen, fossil fuels, and carbon monoxide. The most common fuel is hydrogen. If hydrogen is used, the only byproducts being produced from the process would be water and heat. Some carbon dioxide would be emitted from the production of the hydrogen using hydrocarbons, but this emission would be greatly decreased compared to conventional means of powering an aircraft.

A fuel cell could be used to help make the SUGAR Volt a reality. In this concept, the fuel cell would allow this aircraft to achieve the fuel burn reduction and emission goals that Boeing predicted they could attain using the hfan engine. In a hybrid application, the heat being emitted from the fuel cell could be rerouted into the combustor and the water could be collected and used for onboard utilities, such as the sinks and toilets (Ref. 90).

There are many challenges that must be faced before the use of fuel cells on commercial aircraft propulsion systems can be utilized. The power to weight ratio for fuel cells is extremely low, with the current ratio for SOFC stacks being around 0.3 kW/kg (Ref. 90). A balance of plant is all of the additional equipment and machinery that is required to support and operate the fuel cell. When the balance of plant is added, the ratio goes down even further, to between 0.15 to 0.2 kW/kg. To put into perspective how far the fuel cell's power to weight ratio must be improved, studies have shown that just to power an aircraft's on board APU, the power to weight must increase to around 1 kW/kg (Ref. 88). Other challenges to using fuel cells in an aircraft include reliability, life cycle, fuel leakage, and fuel processing. Fuel leakage occurs because of the difficulty to keep the cell stack sealed at the high temperatures that SOFCs run at (800 °C). Fuel processing to extract sulfur must be extremely rigorous, as sulfur is "poisonous" to fuel cells and any contamination will make the cell stack experience a severe degradation (Ref. 87).

The history of fuel cells dates back to the mid-1800s and they have continued to be improved and further developed throughout the last two centuries. Fuel cells have been successfully demonstrated in automobiles and small aircraft (Ref. 92), as well as being used for large stationary power applications. These trends show that fuel cells will continue to be developed in the future, but a significant increase in

the power to weight ratio is needed. It looks as though it will be very difficult for fuel cells to be ready for use in powering the propulsion systems on large aircraft by the year 2035 without a major breakthrough (Ref. 91). It is more likely that fuel cells will be used to augment a primary power source.

5.0 N+3 Technology Assessment

The potential readiness of the propulsion technologies and their benefits discussed in this paper are summarized in Figure 19. These results are based on the authors' opinion through the combination of a literature review and consultation with experts. It captures the probable benefit each technology has in attaining the N+3 goals and the likeliness of them being ready for implementation in the 2035 timeframe. The color scheme is for illustrative purposes where green has the highest combination of likelihood and benefit, yellow is a cautionary color where either metric is lower than desired, and red where both metrics need thorough improvements. On a systems level, if several technologies utilized by a specific aircraft concept are in the upper right corner, that concept is plausible. Conversely, if several are in red, the concept is likely to need further review.

Promising technologies with a green rating include: electric motors, advanced combustors, distributed propulsion and computational tools. Note that computational tools do not directly contribute to the goals, but can reduce the risk so the goals can be met in the N+3 timeframe. Currently all of these technologies are receiving extensive attention not only by NASA, but also from industry and academia which will likely help the technologies succeed. Technologies with a yellow rating and with applications in other fields besides aeronautics will have the necessary push for continuing development; these technologies include composites, shape memory alloys and batteries. The substantial fuel burn benefit from boundary layer ingestion supports continued research and development for this concept. Acoustic liners are well developed for current aircraft, but what remains to be seen is if they can be deployed in new areas on novel airframe configurations. Active tip clearance control and fuel cells have a red rating. Clearance control is not as beneficial on a system level as the other technologies considered in this review. Fuel cells won't be ready for use as the only aircraft power source for N+3 vehicles, but they are very promising and research in this area should continue in order to make them available for N+4 vehicles.

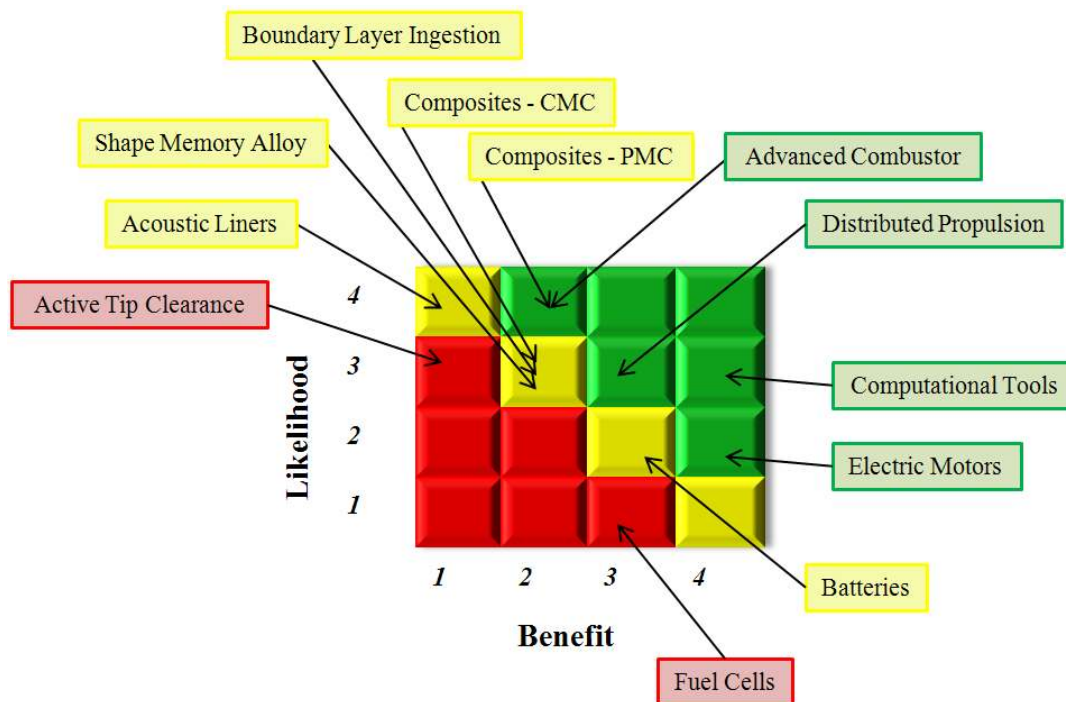


Figure 19.—Technology assessment matrix.

TABLE 2.—TECHNOLOGIES WITH KEY CHALLENGES WHICH NEED TO BE OVERCOME BEFORE IMPLEMENTATION

Technology	Challenges
Electric Motor	- Power to Weight Ratio - Decrease AC losses
Advanced Combustor	- Fuel Mixing - Combustion Instability - Liner Material
Boundary Layer Ingestion	- Fan/Inlet Losses - Acoustic and Aeromechanical Issues - Off Design Operation
Composites	- Material Composition/Properties - Design Architecture
Distributed Propulsion	- Integration Complexity - Maintenance Cost - Minimal Loss Power Distribution
Acoustic Liners	- Determine Location and Applicability - Higher Bandwidth Attenuation
Computational Tools	- Setup Times - Validation - Greater MDAO
Active Tip Clearance Control	- Sensor Capabilities - Dynamic Modeling Accuracy - System Complexity
Shape Memory Alloys	- Dimensional Stability - Fatigue/Durability - Higher Temperature Capabilities
Batteries	- Energy Density - Lifecycle
Fuel Cells	- Power to Weight Ratio - Fuel Leakage/Processing - Deterioration/Lifecycle

Independent of each technology's status given above, all have well defined areas where progress is needed. Table 2 summarizes the major challenges which need to be overcome to permit N+3 implementation. These represent the authors' opinions on where research and development should be concentrated.

6.0 Conclusions and Recommendations

Major technologies critical to the N+3 concepts have been identified and ranked against a qualitative selection tool, identifying the key propulsion technologies requiring further examination. These technologies were studied in extensive detail through a combination of literature review and meetings with experts. They were evaluated based upon opinion gathered during the review, and are sorted through an assessment matrix (Fig. 19) using criteria of likelihood and benefit. Technologies that received a green rating appear to be beneficial and within the scope of the N+3 timeframe. Those that received a rating of green include electric motors, advanced combustors, distributed propulsion and computational tools. Technologies receiving a yellow rating show promise toward achieving the goals, but increased attention is needed for their development to reach an acceptable maturity. These technologies include composites, shape memory alloys, acoustic liners, boundary layer ingestion and batteries. Those receiving a rating of red either fall outside of the N+3 timeframe, or were not perceived to provide substantial benefits. Key challenges that need to be overcome to enable the implementation of all of the technologies discussed herein have been extensively reviewed, and are presented in Table 2.

Going forward, it is important to remember that the propulsion system, although an important component to the N+3 concepts, is only one constituent needed to achieve the aggressive N+3 goals. Therefore, companion review should be conducted to assess airframe technologies and mission design. These studies are critical to the evaluation and assessment of N+3 concepts from a systems level outlook. A systems level sensitivity analysis should also be conducted at the propulsion and airframe level, documenting overall reductions toward the N+3 study goals.

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14. ABSTRACT NASA has set aggressive fuel burn, noise, and emission reduction goals for a new generation (N+3) of aircraft targeting concepts that could be viable in the 2035 timeframe. Several N+3 concepts have been formulated, where the term "N+3" indicate aircraft three generations later than current state-of-the-art aircraft, "N". Dramatic improvements need to be made in the airframe, propulsion systems, mission design, and the air transportation system in order to meet these N+3 goals. The propulsion system is a key element to achieving these goals due to its major role with reducing emissions, fuel burn, and noise. This report provides an in-depth description and assessment of propulsion systems and technologies considered in the N+3 subsonic vehicle concepts. Recommendations for technologies that merit further research and development are presented based upon their impact on the N+3 goals and likelihood of being operational by 2035.					
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