IEEE/CSC & ESAS European Superconductivity News Forum (ESNF), No. 6, October 2008
(ASC Preprint 2AP01 conforming to IEEE Policy on Electronic Dissemination, Section 8.1.9)

The published version of this manuscript appeared in *IEEE Transactions on Applied Superconductivity* **19**, No. 3, Part 2, 1055 - 1068 (2009)

Next Generation More-Electric Aircraft: A Potential Application for HTS Superconductors

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***Abstract*—Sustainability in the aviation industry calls for aircraft that are significantly quieter and more fuel efficient than today's fleet. Achieving this will require revolutionary new concepts, in particular, electric propulsion. Superconducting machines offer the only viable path to achieve the power densities needed in airborne applications. This paper outlines the main issues involved in using superconductors for aeropropulsion. We review the work done under a 5-year program to investigate the feasibility of superconducting electric propulsion, and to integrate, for the first time, the multiple disciplines and areas of expertise needed to design electric aircraft. It is shown that superconductivity is clearly the enabling technology for the more efficient turbo-electric aircraft of the future.**

***Index Terms*— Aircraft, electric propulsion, superconducting motor**

I. Introduction

RELENTLESS growth in air traffic poses the question of how to achieve a more sustainable way of keeping humankind flying without further environmental damage, and especially in a fuel-efficient manner. This paper discusses the merits and challenges associated with the revolutionary conversion of current day aeropropulsion to novel schemes based on turbo-electric propulsion. Superconducting rotating machines (motors and generators) are destined to play a key role in this conversion as the enabling technology that will allow this conversion to electric propulsion within the very stringent weight and volume constraints imposed by an airborne application. Through our multi-disciplinary collaboration we were able to assess, for the first time, the feasibility of non-conventional aircraft architectures based on superconducting electric propulsion. In the next sections we provide case studies used to assess the prospects of superconductivity on aircraft propulsion and show that superconducting machines have already achieved power densities comparable to turbine engines. To fully enable electric flight however, power densities need to improve even further, which is only possible with all-superconducting machines. We developed design concepts for revolutionary aircraft using superconducting machines for propulsion and showed that with further development in superconducting and cryocooling technologies, all within reach, superconductivity-enabled flight could be a reality within the next 20 years.

Manuscript received August 26, 2008.

This research supported by the NASA Fundamental Aeronautics Program and the Department of Defense Research and Engineering (DDR&E) division under the URETI on Aeropropulsion and Power. Support also received from Florida State University's Center for Advanced Power Systems (CAPS)

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II. Motivation

The major drivers in the design of future aircraft are: 1) reduced airport noise, 2) reduced emissions (both pollutants and greenhouse gasses), and 3) reduced fuel burn. NASA has set performance goals for these corners of design trade space as enumerated in Table I.

TABLE I
NASA Subsonic Airliner Performance Goals*

Corner of the trade space	**N+1 (~ 2015)** **Conventional Tube & Wing** (relative to B737/CFM56)	**N+2 (~2020)** **Unconventional Hybrid Wing Body** (relative to B777/GE90)	**N+3 (~2030)** **Advanced Aircraft Concepts** (relative to user defined reference)
Noise (below Stage 4)	-32 dB	-42 dB	55 LDN at average airport boundary
LTO NOx Emission (ref. CAEP 6)	-60 %	-75 %	Better than -75%
Performance: Aircraft Fuel Burn	-33 %	-40 %	Better than -70%
Performance: Field Length	-33 %	-50 %	Exploit Metroplex Concept (STOL)

* National Aeronautics and Space Administration Headquarters, NASA Research Announcement (NRA): NNH08ZEA001N, Mar. 7, 2008

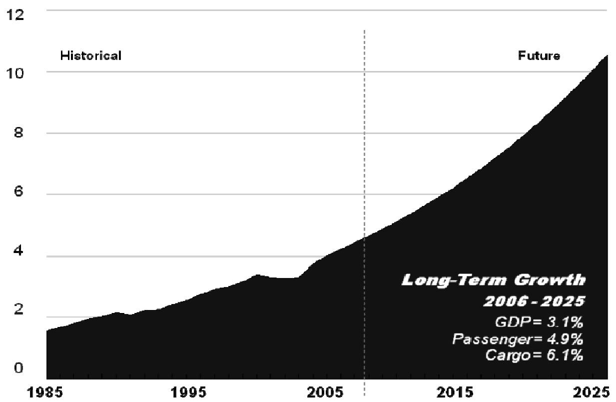


Fig. 1. Air traffic growth (in trillions of passengers-km). (from E. L. Gervais, "Boeing Commercial Airplanes Current Product Overview," presented at San Diego County Regional Airport Authority Advisory Committee Meeting, San Diego, CA, Jul. 12, 2007)

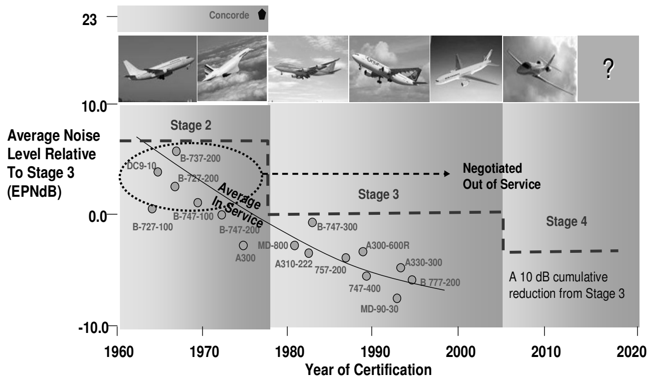


Fig. 2. Aircraft fleet average noise levels continue to decrease. (from F. Collier, E. Zavala, and D. Huff, "Fundamental Aeronautics Program Subsonic Fixed Wing Project Reference Document," NASA)

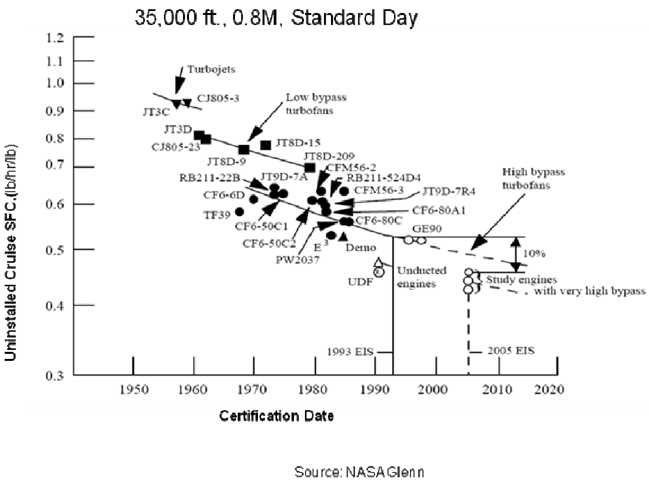


Fig. 3. Specific fuel burn rate (lb/hr of fuel consumption per lb of thrust) has been steadily decreasing since the introduction of jet engines in the 1950s. (from H.D. Kim, J.J. Berton, and S.M. Jones, "Low Noise Cruise Efficient Short Take-Off and Landing Transport Vehicle Study," AIAA-2006-7738, Sept. 2006.)

Future generations of aircraft are designated as N+1, N+2, etc. (with N being today's technology). Note that some of these targets are particularly aggressive, but are driven by the need to achieve sustainable aviation in the face of projected air traffic growth, conservatively predicted to double over the next 20 years (see Fig. 1).

Over the last 50 years the aircraft industry has responded to increased air traffic through a process of technology adoption and improvement that has consistently reduced noise levels and fuel consumption. Fig. 2 shows the decrease in fleet average noise as a result of improvements driven by tighter noise regulations (referred to as "stages"). This tightening of regulations is expected to continue as airports become engulfed by suburban sprawl. Likewise, overall fuel efficiency has steadily improved as evidenced in Fig. 3 showing the fuel consumption per pound of thrust for jet engines since their introduction in the 1950s. Note that fuel efficiency has nearly doubled through the introduction and improvement of high bypass turbo-engines. Note the successive "step changes" in efficiency with the introduction of a new engine type.

A fair question to ask is whether the required performance goals outlined in Table I can be achieved with the conventional high bypass ratio turbofan engine. The answer to this question may be that new basic propulsion concepts are needed and much of the current research sponsored by NASA is addressing this prospect. Some "new" ideas are not new at all, such as the use of compressor intercooling and recuperation of exhaust heat to pre-heat air into the combustors. These are "old" ideas, but they are worth re-evaluating in light of heat exchanger materials and designs. However, one technology that is definitely new, at least for use in aircraft engines, is a propulsion system design that uses advanced superconducting, cryogenically cooled electric generators and motors to drive a multitude of low noise electric fans. The obvious break-through that must be achieved for this to happen is a marked increase in the power to weight ratio of electric generators and motors.

A brief discussion on the advantages of electric aeropropulsion is presented next. Then to demonstrate the potential of an electric propulsion system based on HTS technology, we present a number of examples for propulsion systems as well as for full aircraft of N+3 generation (first in service circa 2030).

III. Advantages of Electric Aeropropulsion

A. *Present-day high bypass turbofans*

The majority of today's large civil transports are propelled by high bypass ratio engines. This type of engine deploys a large fan mechanically connected and driven by low pressure turbines as illustrated in Fig. 4. Most power produced by the core engine is used to rotate the fan, which in turn will generate most of engine thrust. Turbofans can be very compact with specific power in the range of 3-8 kW/kg. The bypass ratio (BPR), defined as the ratio of the mass flow rate of the stream passing outside the core divided by that of the stream flowing through the core, plays a key design parameter of the engine. A higher BPR, in general, yields lower exhaust speed, which serves to reduce fuel consumption and engine noise at the cost of an increase in weight and fan diameter. In addition, any increases in an engine's BPR must be accompanied by matching improvements in core specific output power so as to maintain fan pressure ratio (the ratio of air pressure in front of the fan to that after it) within a reasonable range. Prodigious advancement in specific power of engine core and material for the past several decades resulted in a significant increase in BPR. Recent engines such as the GE90 turbofan exhibit a BPR of 9:1. Nevertheless, the practical upper limit to increasing the BPR of modern turbofan engines is fettered by the inherent coupling between propulsor operation mechanics and core thermodynamic cycle [1].

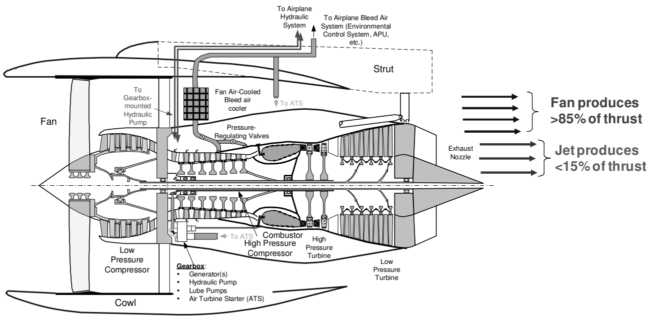


Fig. 4. High bypass ratio turbofan

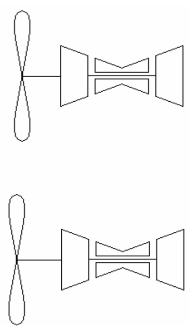
B. *The Case for Electric Propulsion*

In a traditional aero turbine engine, the fan and turbine engine are mounted on the same shaft and rotate at the same speed. The traditional arrangement is shown in Fig. 5a. Turbines naturally exhibit higher efficiency, and are more power-dense, at higher speed; their application to aircraft propulsion greatly limits their rotation speed as the tip of the fan's blades should not go supersonic except for maximum power operations such as take-off when fuel efficiency is not a major driver. This normally means that aero turbine rotation speeds are limited to a few thousand RPM. Moreover, torque and speed are coupled in turbofans, limiting any potential efficiency gain through speed control.

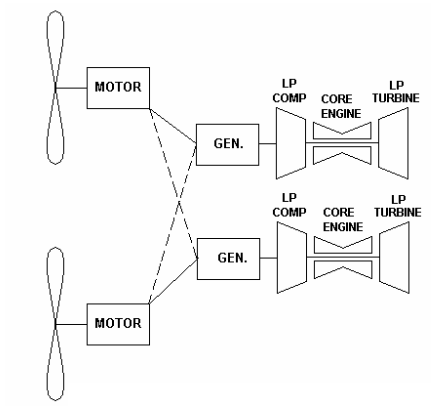
Fig. 5.b illustrates a notional example of how HTS motor technology can help relax this coupling. Each generator is mechanically linked to a corresponding turboshaft, whereas the propulsor (could be a propeller or a fan) is *electrically* connected to the generators through an "electrical gearbox" Decoupling torque and speed would lead to very valuable control flexibility to enable a more favorable trade between on-design and off-design performance. In addition, this architecture is intrinsically compatible with the emerging concept of "distributed propulsion" that produces thrust by means of multiple small propulsors or engines embedded on the wing or fuselage. This revolutionary airframe/propulsion integration concept can be achieved with the proposed architecture by remotely connecting multiple propulsors to a generator. This arrangement is anticipated to surpass other distributed propulsion concepts in many aspects, as will be further discussed in section VII. Furthermore, this type of hybrid architecture is intrinsically well-suited with the emerging and continuing trend towards more electric aircraft; i.e., the replacement of traditionally pneumatically and hydraulically driven functions with electrically powered components [2]. Overall, the electric propulsion scheme opens up the aircraft design space to many new possibilities in which major leaps can be made towards achieving the performance goals specified in Table I.

C. *Electrical Ducted Fan Concept*

In order to take advantage of electrical propulsion, electrical "propulsors" have to be designed. We can take advantage of the high bypass ratio of current engine and replace the engine core with an electrical motor. Thrust would then be generated through the fan rotation only as shown in Fig. 6.



a. Conventional turbine and fan coupled on the same shaft



b. Turbine and fan decoupling through electrical converters

Fig. 5. Comparison of conventional and turbo-electric aeropropulsion

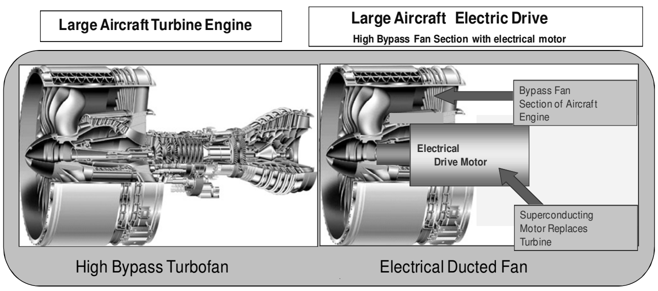


Fig. 6. Electrically driven propulsion system: electrical ducted fan

Such a system is feasible only if electrical motors can be of about the same size or better than aero turbines. Conventional motors exhibit a specific power up to 0.5 kW/kg, too low compared to turbine engine cores. Therefore conventional machines, which are limited by heat generation in copper windings, cannot be used for aircraft propulsion. A new technology has to be considered to lift that specific power limitation. Superconducting machines offer the only hope of ever achieving electrical aeropropulsion.

D. High Temperature Superconductivity as Enabling Technology to Electric Aeropropulsion

Superconductors can carry very high current density with no resistance thus enabling very light machines. High specific power has been demonstrated in superconducting machines since the late 60s. A few low temperature superconducting machines have been built with both the stator and rotor superconducting thanks to the availability of NbTi low AC loss conductors.

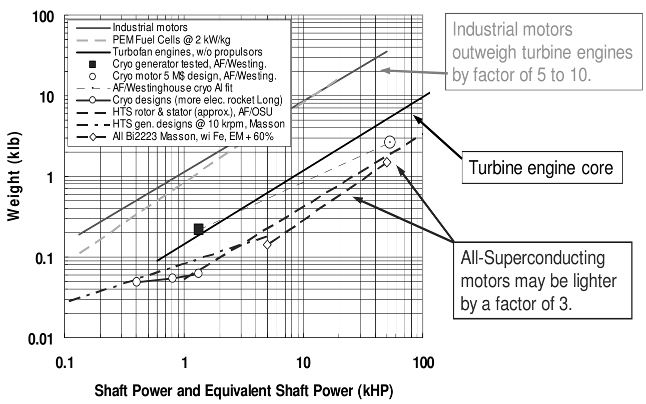


Fig. 7. Specific power of rotating machines compared to turbine engine core

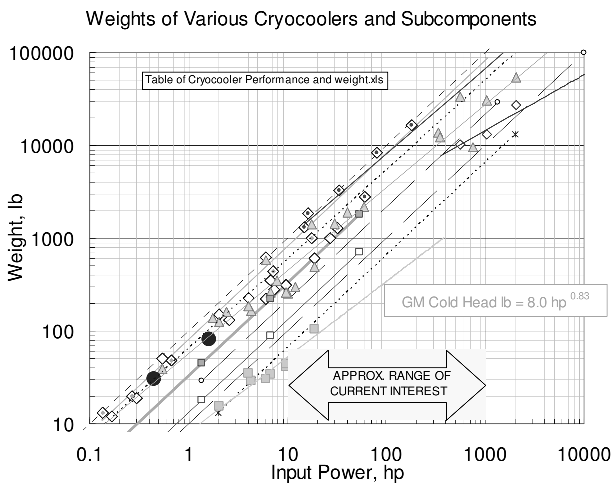


Fig. 8. Specific power of commercially available cryocoolers

Fig. 7 shows a comparison of the weight of electrical machines compared to turbine engine cores as a function of power. As stated, conventional motors are too heavy to even be considered. Current-day superconducting machines (with resistive armature) are comparable with turbine engines in power density, while fully superconducting machines have the potential to be 3 times lighter. HTS can be the enabling technology for turbo-electric aeropropulsion. Unfortunately fully superconducting machines using HTS conductors are not yet practical, until low AC loss HTS conductors are fully developed.

E. Cooling Considerations

Since superconductors require operation at cryogenic temperature, the cooling system is a very important part of the aircraft architecture. The configuration and feasibility of the superconducting machine depends on the cooling system and mostly on the cooling power available.

1) Cryocoolers

Cryocoolers are an obvious choice as they represent an active source of cooling using a close loop of cryogen. Cryocoolers are "plug and play" reliable systems and therefore appropriate for airborne application. However, by today standards, they are still too heavy for use on aircraft.

Off-the-shelf cryocoolers exhibit efficiencies of about 10-15% of Carnot efficiency, which correspond to about 70W/W at 30 K. The lightest cryocoolers today weigh about 5 lb/HP-input (or 3 kg/kW-input) as shown in Fig. 8 (based partially on data from Ref [3]). This is just for the cold head portion, the associated compressors and ancillaries represent an overhead of about 5 times that weight. The use of packaged turbo-compressors may reduce this overhead significantly, and coupled with the development of much lighter cold heads, it may be possible to reach the target of 3 kg/kW-input as overall specific weight for cryocoolers by the time N+3 aircraft come into service (~2030-2035).

2) Cryogen storage

Another possibility (which has not been extensively studied yet) would be to load enough cryogen at the airport for the flight duration including a margin; the cryo-tank would have to be refilled after each landing. This may lead to a minimum weight associated with superconductor cooling. If liquid hydrogen is the cryogen, it could also be used as fuel and burnt in the engine along with jet fuel after cooling the HTS components (e.g., 95% jet fuel, 5% H2).

3) LH_2 as fuel

If LH_2 is available onboard as fuel, either for turbines or fuel cells, then cooling of the superconducting machines is "free" as we need to warm-up the hydrogen before being used as fuel. An excellent synergy is obtained and fully superconducting machines are usable with very liberal limits on the AC losses created. However, dense hydrogen storage is an issue; we may not see LH_2-fueled aircraft in the N+3 time frame (2030-2035), even though extensive studies of such aircraft powered by conventional engines have been performed [4].

IV. Past and Current Development of Superconducting Machines for Airborne Applications

Application of superconductors in propulsion was first introduced in the context of ship propulsion [5], [6]. The first mention of this application for aircraft was done by Oberly in 1976 at the Applied Superconductivity Conference [7]. The main thrust of the Air Force program since then has been for high power density generators in the multi-MW range to power weapons or onboard equipment [8]-[10], very little research has been done until recently on the use of superconducting motors for electric propulsion of aircraft.

A. Superconducting Generators

Having windings rotate above 10,000 RPM is very challenging as large acceleration forces are applied on the conductors. One machine under development by LEI is a 3MVA/15,000 RPM generator pictured in Fig. 9. Both the stator and rotor are operating at cryogenic temperature, but only the excitation coils are superconducting; resistive losses in cryogenic copper being lower than AC losses in HTS conductors at the high operating frequency.

Another development involves a generator with the same requirements as the previous example but based on a different configuration. To address the high rotation speed, General Electric used a bulk piece of magnetic material at the rotor magnetized by a stationary superconducting coil. This configuration provides a very robust rotor able to spin at high RPM. The flux distribution is not optimal but the high rotation speed brings the power density to an impressive 7 kW/kg. A rendering of the machine is shown in Fig. 10.

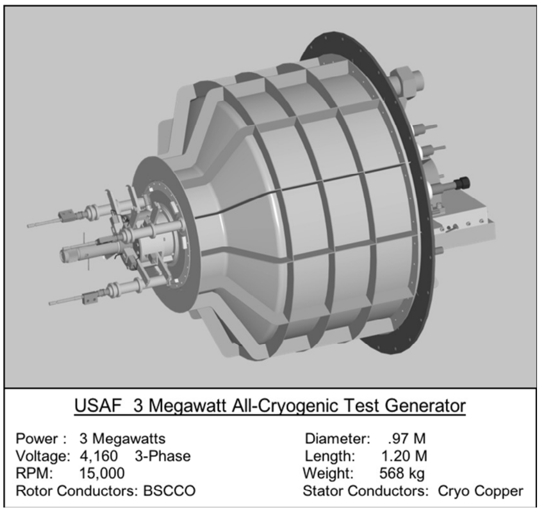


Fig. 9. LEI/AFRL multi-MW superconducting generator

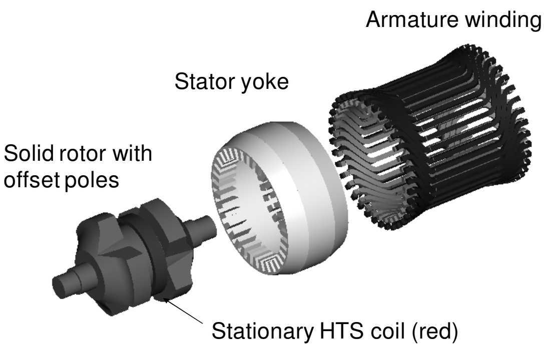


Fig. 10. Homopolar Inductor Alternator from GE/AFRL

Superconducting generators have already been demonstrated to exhibit power densities in the range of turbine engines thus validating the feasibility of future ultra lightweight machines for airborne applications.

B. Superconducting Motors

The case for superconducting electric propulsion of aircraft has been examined in [11]-[17]. In the concept of turbo-electric propulsion presented in Fig. 5, not only ultra-compact generators are needed, but also motors to power the propulsion fans. Motors for propulsion application represent a much more challenging application as rotation speeds are lower than generators and therefore electromagnetic torque needs to be higher. This application was recently investigated as part of our URETI program, results and design examples are presented in next section.

V. NASA-DoD URETI's Superconducting Machines for Airborne Applications

This section briefly reviews our work as part of a 5-year research project sponsored by NASA and DoD: the University Research Engineering and Technology Institute (URETI) on Aeropropulsion and Power [12], [14]. The main objective of this program was to investigate the feasibility of more-electric and all-electric airborne vehicles, and in particular, the possibility of incorporating superconducting machines into electric propulsion schemes for future aircraft. Multiple applications and vehicle configurations were investigated. The first case study is a propeller-driven Cessna 172 type aircraft chosen as a low power application [16]. Increasing power density of small machines is very challenging as they present very little room for coil winding. The first task was then to develop a non-conventional motor topology applicable to low-power machines.

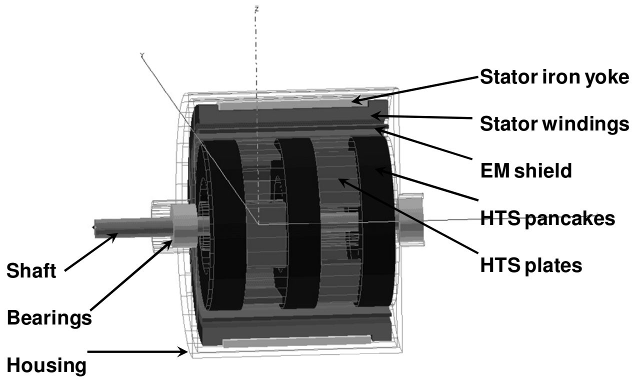


Fig. 11. Diagram of the superconducting motor

A. General aviation aircraft

For small aircraft, motors based on trapped flux may be applicable. Design requirements were those of a Cessna 172: 120 kW of power at 2700 RPM. Because of the low power level, a novel motor configuration was developed. A diagram of the motor is shown in Fig. 11. The machine is composed of Bi2223 pancake coils placed on the same axis and fed with opposite currents. YBCO plates are evenly distributed around the axis and are used to trapped magnetic flux and concentrate flux lines. Since the machine is expected to be conduction cooled, the superconducting inductor is stationary and the outside copper air gap armature is rotating. The machine can be small enough to fit inside a propeller hub, allowing the blades to be directly attached to its rotating armature, which collectively save the aircraft's internal volume.

1) Principle of operation

The generation of the eight pole excitation field is based on a 2-stage cooling system; the time evolution of the current in the pancake coils is shown in Fig. 12 [17].

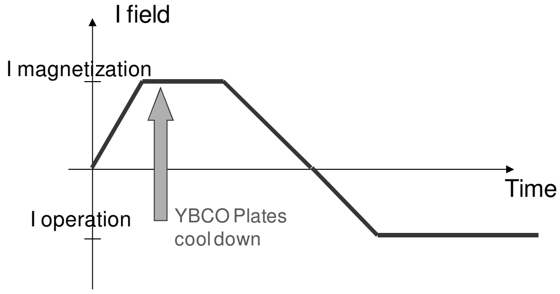


Fig. 12. Time evolution of the current on the pancake coils.

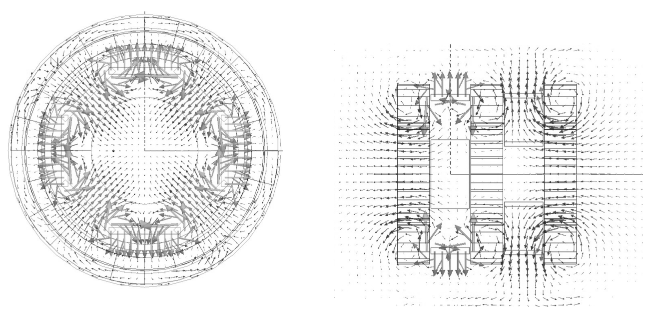


Fig. 13. Flux distribution in the machine.

TABLE II
SUMMARY OF GENERAL AVIATION HTS MOTOR

Total length	160 mm
External diameter	220 mm
Number of poles	8
Rotation speed	2700 RPM
Power	160 kW
Total mass (including conduction cooling apparatus)	30 kg
Power density	5 kW/kg
Heat load of superconducting part	< 10W
Operating temperature	30 K

The whole system is cooled down to about 90 K when heaters are activated to maintain the YBCO plates above critical temperature, but the rest of the motor (including the coils) continue to cool down to about 30K. The current in the coils is then ramped up and a radial flux penetrates the YBCO plates (which are non-superconducting at this time). Once the current achieved its nominal value, the heaters are shut down and the YBCO plates are allowed to cool down and thermally equilibrate with the rest of the machine, thus trapping the applied field. The current is then ramped down and reversed, the YBCO plates will keep their magnetic flux constant by means of undamped induced currents and the reversed flux from the pancake coils is then concentrated between the plates giving a flux distribution such as that of Fig. 13, creating an 8-pole machine. The machine operates synchronously and exhibits the performance outlined in Table II.

The presented topology is very promising and exhibits a predicted power density in the same range as gas turbines despite the low power level. The low power density of potential generation options (e.g., fuel cells) and cryocooler overhead negates most weight gains and makes this concept not practical yet.

2) Experimental validation

Since the feasibility of the proposed inductor is based on the 2-stage cooling system, a full-size thermal mock-up of the inductor was constructed to experimentally validate the cooling procedure [18]. The major challenge is to keep the YBCO plate above 90 K while the coils operate at full current around 30 K. The large temperature gradient is handled by a 1 mm gap between the two parts placed in a vacuum cryostat. Fig. 14 shows the thermal mock-up before MLI wrapping.

Preliminary results obtained with a low power cryocooler show that at least a 40K temperature difference between the Bi2223 coils and the YBCO plates can be achieved in steady state allowing the possibility of 2-stage cooling (Fig. 15). Further experiments (with a larger cryocooler) will be done to also validate steady-state gradients.

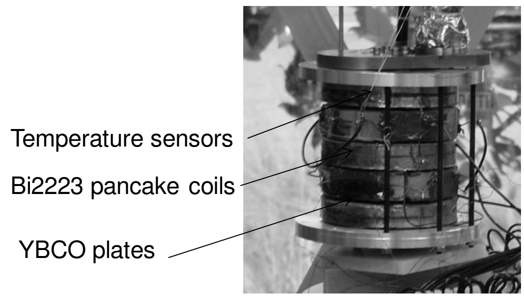


Fig. 14. Thermal mock-up of the inductor

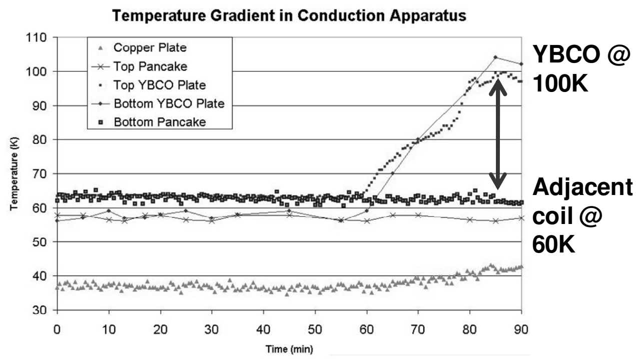


Fig. 15. Experimental validation of the 2-stage cooling system

B. *Safety Torque Generation*

On a single-engine airplane of course the issue of safety and reliability is paramount, and we studied design options in case of a superconductor quench or loss of cooling [19]. Of the options studied, the most promising is pictured in Fig. 16, consisting of adding a squirrel cage to the inductor so that the motor reverts from a synchronous motor to an induction machine in case of failure.

In case of a quench (failure) the propulsion motor does not have to provide full power, the airplane is able to maneuver to the nearest airport and land on only a fraction of the power (typically 35-45%). The concept of Fig. 16 allows to generate about 35% of full power with a decrease in overall power density of about 35%.

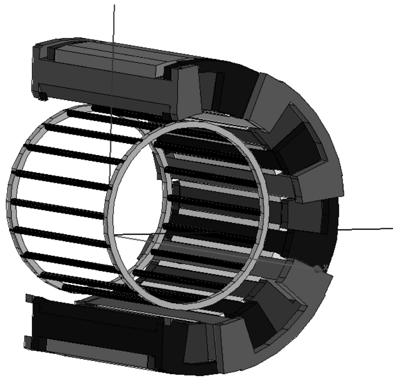


Fig. 16. Squirrel cage concept to provide safety torque in case of failure

C. *Small Engine Study*

The second case study was to see if the motor topology described above could be scaled up to a larger engine. The turbine engines in a typical small business jet are about 1.5 MW. The concept described above is modular, and more HTS coils/YBCO plates can be stacked axially to increase power. The power density of this system was estimated to be 6.6 kW/kg, comparable to that of state-of-the-art turbines [20].

D. *High Altitude Long Endurance Aircraft*

The final case study is concerned with a High-Altitude, Long-Endurance (HALE) air vehicle (e.g., a hurricane tracker). This would be an unmanned aircraft, fully electric, able to fly and loiter for up to 14 days without refueling or returning to base. For maximum efficiency, the superconducting motor for the propulsor needs to be both extremely light and compact, but also have very low losses. We chose a lead-less axial flux configuration (allowing for higher trapped flux for compactness). The design concept, described in [21] and shown in Fig. 17, is projected to achieve an impressive power density of 7.4 kW/kg using conventional HTS materials available today.

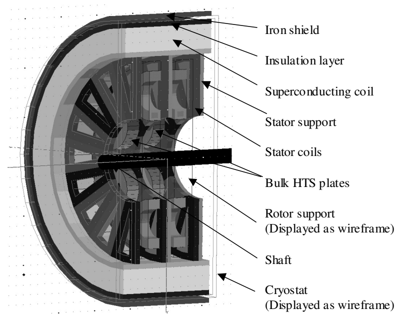


Fig. 17. Axial flux configuration for HALE aircraft

E. *HTS Machines for Aircraft: Summary Conclusions*

The results from the URETI work demonstrate that superconducting motors and generators can be designed using today's materials to match the power density of turbine engines. As Fig. 18 shows, the superconducting machines considered in the URETI program, as well as others, can reach much higher power densities than conventional machines, even at relatively low power levels.

This is a very promising result that opens the possibility of superconducting aeropropulsion. However, to fully replace turbofans, the power density of the electrical components needs to be even higher, which can only be achieved with fully superconducting machines (inductor and armature). The next section describes a physics-based model developed to predict and optimize the weight of fully superconducting machines as way of projecting what power densities are needed to achieve airworthiness.

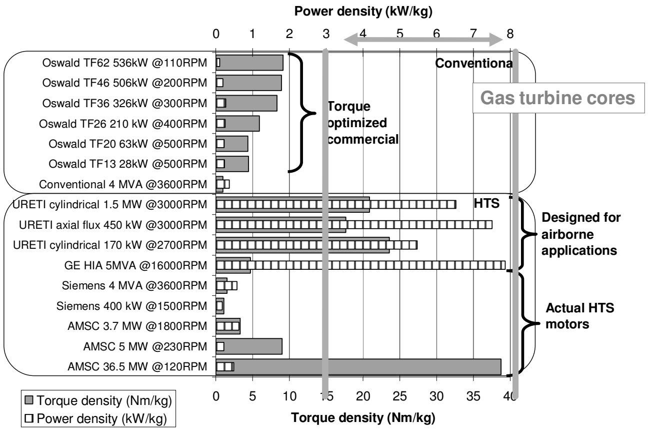


Fig. 18. Comparison of concept designs and existing HTS machines with respect to conventional motors and turbine engines in terms of power density

VI. PHYSICS-BASED SIZING MODELS FOR THE MORE/ALL-ELECTRIC AIRCRAFT DESIGN

Of particular importance in the URETI program was the development of physics-based models for superconducting machines for integration into existing aircraft design tools (i.e., realistic size and weight models for superconducting components to use in aircraft system design studies).

A. *Aircraft Design Based on New Propulsion Technology*

Integrating a single disciplinary technology into aircraft systems often results in an array of cross-disciplinary effects. This is particularly true in the case of the HTS machinery technology, because it will entail fundamental changes in not only the propulsion system but also the subsystem architecture and airframe design. Such complex nature of aircraft systems integration may disqualify a premature technology evaluation made solely relying upon its component level metrics such as power density and efficiencies [22], [23].

In addition, the introduction of the HTS motor drive power system will usher in an uncharted design space that encompasses revolutionary propulsion system architectures, alternative energy sources and storage, and a myriad of options to integrate them into an airframe. For instance, the generators and gas turbine engines in Fig. 5b can be potentially replaced with any electric power source such as fuel cells, high performance electric batteries, or ultra capacitors. Although they are not readily applicable to high power systems due to their low power and/or energy density, those technologies, providing a supplemental power, may serve to facilitate the integration of a HTS motor drive propulsion system.

Therefore, the true value of airborne HTS applications need be evaluated at the air-vehicle integration level at least in light of the benefits from a synergistic integration of facilitating technologies. To this end, various combinations of aircraft configurations, technologies, and missions must be assessed in terms of vehicle-level metrics such as aircraft weight, field length, fuel burn, emissions, and noise through an aircraft sizing and synthesis process at the appropriate level of fidelity and engineering realism. Nevertheless, such revolutionary concepts are very likely to substantially deviate from a historical trend, thereby necessitating the development of physics-based analysis capabilities (illustrated in Fig. 19).

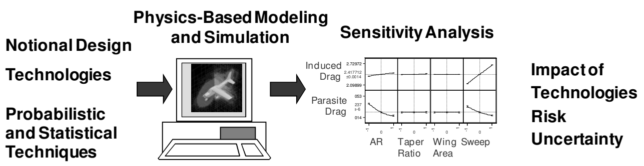


Fig. 19. Block diagram representing a physics-based model approach to aircraft design and optimization

Addressing this deficit, a joint effort [24], [25] under the URETI program has indentified and developed key enabling capabilities for electric aeropropulsion and aircraft modeling and simulation, including revolutionary propulsion architecture modeling focusing on fuel cells [26], energy-based aircraft sizing and synthesis [27], and volumetric sizing methods [28]. The addition of probabilistic methods such as reliability-based design optimization [29], [30] and stage-based recourse programming [26] allows the effect of uncertainty to be embraced, resulting in a reliable and robust solution for rapidly advancing technologies.

B. *Fully Superconducting Machine Sizing Model*

An integrated electromagnetic/thermal model of superconducting rotating machines has been developed to be integrated into aeropropulsion system design/analysis tools developed at Georgia Institute of Technology and NASA Glenn Research Center [31]. The model is composed of an analytical electromagnetic model and a lump-parameter thermal model [32]. The model architecture is shown in Fig. 20.

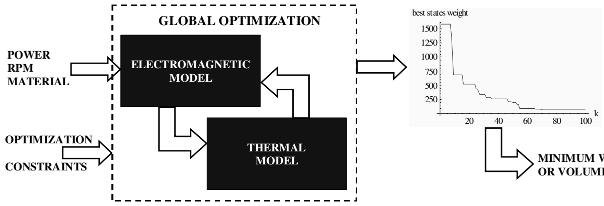


Fig. 20. Block diagram of a fully integrated electromagnetic-thermal model of a superconducting machine tied to an optimizer to achieve minimum volume or weight

1) *Machine Configurations*

Several machine configurations are possible such as radial flux machines or trapped flux magnet excited machines. For this study, we will limit the configuration of the superconducting machines to radial flux and distributed windings. The windings are usually made of racetrack coils that will be considered as continuous current distributions in a first approximation. Flux density in the backiron is limited to 1.7T and the J(B) operating point of the conductor is calculated.

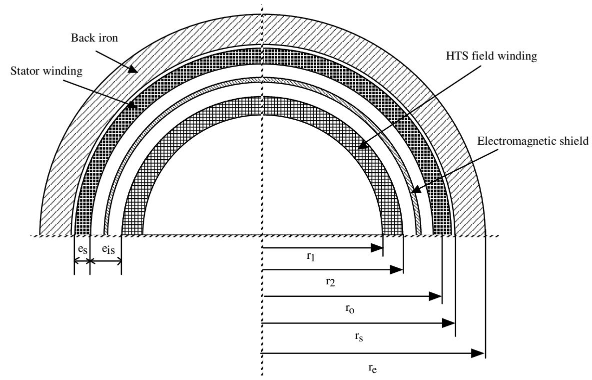


Fig. 21. Generic superconducting machine configuration

2) *Electromagnetic Model*

For this particular model only Bi2223 and YBCO conductors are considered, their properties have been determined from data available in literature. The following equation shown the relation used to represent the YBCO coated conductors and Fig. 22 shows the characteristic of Bi2223 considered for the simulations.

$$J_e(B,T) = \frac{J_e(0T,77\,K)}{1-\dfrac{77}{T_c}}\left(1-\frac{T}{T_c}\right)e^{-\frac{B}{90\left(1-\frac{T}{T_B}\right)}} \qquad (1)$$

With T_c =92 K and T_B =80 K

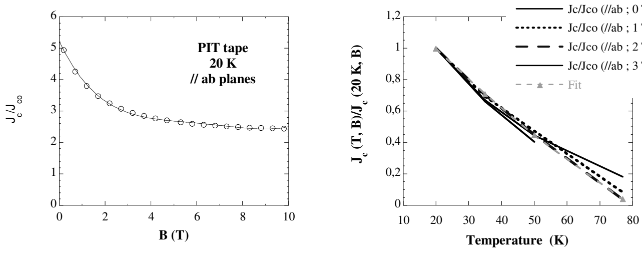


Fig. 22. Critical current density of Bi2223 tapes (from AMSC)

The sizing of the machine is performed based on power and speed requirements; from speed Ω and power *P*, the electromagnetic torque *T* can be obtained using equation 2.

$$T = \frac{P}{\Omega} \qquad (2)$$

From the electromagnetic torque, the no-load field B_r^0 can be determined as follows:

$$B_r^0 = \frac{T}{\sqrt{2}\, K_S \pi r_0^3 \left(\frac{L_a}{r_0} \right)} \qquad (3)$$

With K_S the electrical loading defined in equation 4, r_0 the mean armature radius (cf. Fig. 21), and L_a / r_0 the aspect ratio of the machine.

$$K_s = \frac{3 N_s k_d I_s}{\pi r_0} \qquad (4)$$

The thickness of the armature winding can be determined from the value of K_s and the thickness of the rotor windings can be obtained from the value of B_r^0 using the following equation.

$$B_r^0 = \frac{2\mu_0}{\pi} \frac{J_f r_2 \sin\frac{\beta}{2}}{p+2} \left(\frac{r_2}{r_0}\right)^{p+1} \left(1 - \left(\frac{r_1}{r_2}\right)^{p+2}\right) \left(1 + \left(\frac{r_0}{r_s}\right)^{2p}\right) \qquad (5)$$

where J_f is the rotor current density, β is the winding aperture, *p* the number of pair of poles and μ_0 the permeability of vacuum. The weight and volume of the machine can then be computed together with the cryostat, torque tubes, mechanical structure, shaft, etc. The synchronous reactance that gives important information about the dynamic behavior of the machine can also be calculated.

3) AC Losses

For a fully superconducting machine, AC losses represent the major part of the heat load. It is important to have a good approximation of the AC losses. They can be separated into three categories: the magnetization losses, transport current losses and the coupling losses in the matrix. The dominance of one type of losses over the others depends on the frequency of current and applied field. In a first approximation, we have limited the losses computation to magnetization losses as we think they will be dominant in a rotating machine application. They can be calculated using equation 6.

$$P_{AC} \approx \frac{8}{3\pi} J_c\, d\, f\, B_r^0 V_{sc} \qquad (6)$$

where J_c is the critical current density of the conductor, d the dimension of superconductor that faces the flux (filament size for Bi2223), f the frequency and V_{sc} the volume of superconductor.

4) Thermal Model

For both superconducting and conventional machines, the limit of power output comes from the amount of heat generated in the conductors. In the case of conventional superconducting machines where only the rotor is superconducting, the limiting factors are the critical current curve for the superconductor, and the maximum allowed temperature of the armature windings and thus the amount of Joule heating in the copper. Therefore, accurate estimation of the maximum temperature of the armature winding is an important part of the machine design. Such calculation can be done using an equivalent lumped parameter circuit model as shown in Fig. 23.

For a fully superconducting machine, the AC losses in the armature winding need to be removed by the cooling system. Depending on the cooling available, thermal transients can occur. An equivalent lumped parameter model including AC losses can be used to simulate the thermal transient response of the superconducting armature winding and assess the minimum amount of cooling power required for stable operation.

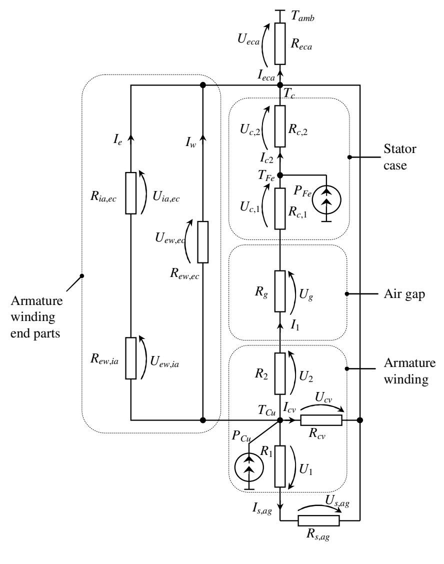


Fig. 23. Example of lumped parameter thermal model used to calculate the resistive armature maximum temperature

5) Optimization

For a given power (or torque), an optimization method is used to minimize the weight or volume based on the coupled electromagnetic and thermal models (using appropriate physical constraints) to make sure that the output sizing is realistic. Simulated annealing method is used to avoid local minima and cover the entire design space.

VII. Aircraft Design Examples

A. Application of Superconducting Machine Models to Aircraft Design

Electric propulsion systems with superconducting technology can potentially be applied to any future aircraft, manned or unmanned. But to have the maximum impact on the critical issues of the environment, electric propulsion must be introduced into subsonic transport aircraft designs of the future. Two potential transport aircraft with electric propulsion are discussed in this section: 1) a small regional transport aircraft with a design having a conventional arrangement of fuselage and high aspect ratio wing, and 2) a large transcontinental or intercontinental transport having hybrid-wing-body (HWB) design and short takeoff and landing (STOL) capabilities. For both designs, electric power production is obtained with turbine engines driving superconducting generators, and propulsive thrust is distributed on the lifting surfaces with multiple electric motors driving single-stage fans.

B. Small Regional Jet

As described earlier, NASA has defined several future time-frames in which technology measured by noise level, emissions and mission fuel burn is successively reduced from levels of current technology (see Table I). A study is now being conducted to design short-field regional subsonic transport aircraft having a full payload of nominally 100 passengers [33]. These aircraft are for the N+2 time frame, and the study has been extended to include a design having a superconducting electric propulsion system (for possible N+3 introduction).

In this design, two advanced turboshaft engines are buried within the lower fuselage each with direct drive to an electric generator. Electric power is transmitted to multiple motors each with direct drive to a single stage fan (see Fig. 24). Both generators and motors are assumed to be fully superconducting. The fan-motor sets are mounted above and toward the wing trailing edge in individual nacelles with a total of ten (10) sets – five per wing. The turboshaft engines are relatively near term and the development of the fans will not require a major new development although they may require either variable pitch blades or a variable area nozzle. Thus it is the development of the superconducting generators and motors that will enable and pace the future introduction of such an aircraft. It should be noted that electric propulsion offers a level of safety in the event of the loss of an engine not available in current transport aircraft. Albeit at reduced power, all ten fan-motor sets can be run with a single turboshaft engine. In fact, this may be a desirable mode of routine operation in some segments of the standard aircraft mission such as descent and landing.

The engine, generator, motors and fans shown in the figure are to scale, and, as can be seen, the integration of the propulsion system into the aircraft does not pose any significant problems. The generator is placed in front of the engine to avoid having to insulate it from the hot exhaust gas, and, as a result, an off-set inlet is required to duct the intake air to the engine. Electric cables transfer energy to the fan motors, and there would be cross cabling to the other side of the aircraft to complete an electrical bus so that all motors can draw from both generators.

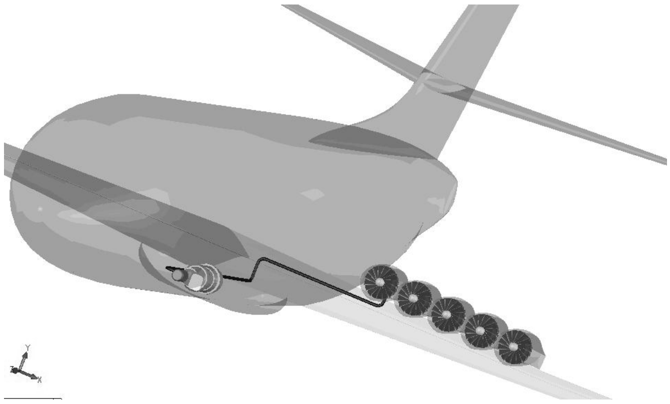


Fig. 24. Super-Conducting Electric Propulsion

Noise from the buried turboshaft engine will easily be attenuated, and the jet noise from these engines is essentially non-existent. Tip speed for the fans is low and this noise from the fans is partially shielded from the ground by the wings. Although a full noise study for this aircraft has not been completed, it is expected to be very quiet and meet the N+2 targets of Table I.

The engine design is patterned after that of the General Electric T700 turboshaft engine with a single spool compressor having multiple axial stages followed by a single centrifugal stage. The major technology in this propulsion system is obviously with the superconducting generator. The generator is designed using the methodology outlined in this paper, and the result is truly remarkable. The diameter of the generator at 10.24 inches is half that of the maximum engine diameter, and the light weight of the fully superconducting generator yields a power to weight ratio of 40 HP/lb (66 kW/kg). The generator rotates at engine rotational speed resulting in reduced torque and very light weight (335 lb each generator, with each turbine engine at 894 lb).

Five fans per wing are installed above the wing with the exhaust nozzle near the trailing edge. This nozzle is a two-dimensional variable area design to match energy and flow requirements at both takeoff and cruise. Light weight, wide chord composite fan blades are assumed using the technology of current high bypass ratio turbofan engines. Advanced technology is assumed in the low value of hub-tip ratio at the entrance of the fans and high inlet Mach number at the fan entrance annulus. These parameters are selected to reduce fan diameter.

As with the generators, major new technology is applied to the superconducting motors. The fully superconducting motor outside diameter at 7.24 inches is an excellent match with the hub diameter of the fan exit, and the light weight of the motors is based on a power to weight ratio of 24.6 HP/lb (40 kW/kg), a lower power density that the generators. The motors rotate at fan rotational speed, and the torque-power ratio is somewhat higher in this case. Nonetheless, these light weight motors contribute to a very light weight propulsion system. Each motor weighs 110 lb, and with cables included, the total turboelectric propulsion system weighs slightly more than 5100 lbs.

The NASA aircraft design study of [33] is continuing, and a preliminary comparison of the aircraft described in this section has been made with a similar aircraft designed with high bypass ratio turbofan engines. These turbofan engines are assumed to be an advanced version of the new geared turbofan (GTF) engine now under development by Pratt and Whitney Aircraft. The design point bypass ratio of the engine is nominally 10 with a fan pressure ratio in the 1.45-1.5 range. The engines for this aircraft are placed above the wing to provide shielding to reduce noise. One can consider that the electric propulsion system also represents a very high bypass ratio engine with the fan (bypass) flow displaced from the core flow through the turboshaft engines. In the design presented above, the equivalent bypass ratio is approximately 13.

A preliminary comparison of the two aircraft is given in Table III. Both aircraft are designed for short-field operation, and, as a result, they have relatively high total takeoff thrust to gross weight ratios. To accommodate the multiple fans, the aircraft with the electric propulsion system is designed with a larger and higher aspect ratio wing. The result is a much shorter field length capability for this aircraft.

The gross weight of the electric powered aircraft is approximately 5% lower than the turbofan powered aircraft primarily due to a reduction in the propulsion system weight, but no comparison of the range of each aircraft has been made yet. However, the electric powered aircraft does have higher parasite drag due to the added surface area of the fan nacelles, and this will have an effect on cruise aerodynamics and thus on range capability. Also, note that the thrust specific fuel consumption of the electric propulsion system is slightly greater than that of the high bypass ratio turbofan propulsion system. With the proper engine cycle for the turboshaft engine, it is expected that the specific fuel consumption at cruise will be comparable for both aircraft. A complete evaluation of range will include operation of the aircraft. It is anticipated that aircraft with an electric propulsion system will be able to operate with a single engine operating at high efficiency through the descent phase of the mission thus offering further fuel savings.

TABLE III

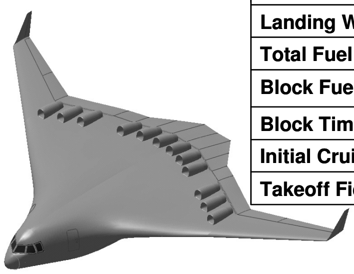
COMPARISON OF AIRCRAFT PERFORMANCE

N+2	Characteristic	N+3
0.80	Cruise Speed (Mach)	0.80
36,000	Cruise Altitude (ft)	36,000
83.33	Wingspan (ft)	100
9.29	Aspect Ratio	10.36
81,650	Takeoff Gross Weight (lbs)	77,311
109	Takeoff Wing Loading (psf)	80
0.46	Takeoff Thrust-to-Weight Ratio	0.42
4,644	Takeoff Field Length (ft)	2,415
3,132	Landing Field Length (ft)	1,755

C. Distributed Turboelectric Propulsion for Hybrid Wing Body Aircraft

Meeting future goals for aircraft and air traffic system performance may well require new airframes with more highly integrated propulsion. Previous studies have evaluated hybrid wing body (HWB) configurations with various numbers of engines and with increasing degrees of propulsion-airframe integration. One recently published configuration [11] with 12 small conventional engines partially embedded in a HWB aircraft (shown in Fig. 25) served as the airframe baseline for the turboelectric concept aircraft described below.

To achieve high cruise efficiency, this high lift-to-drag ratio HWB was adopted as the baseline airframe along with boundary layer ingestion inlets and distributed thrust nozzles to fill in the wakes generated by the vehicle. The distributed powered-lift propulsion concept for the baseline vehicle used a simple, high-lift-capable internally blown flap or jet flap system with a number of small high bypass ratio turbofan engines in the airframe. In that concept, the engine flow path from the inlet to the nozzle is direct and does not involve complicated internal ducts through the airframe to redistribute the engine flow. In addition, partially embedded engines, distributed along the upper surface of the HWB airframe, provide noise reduction through airframe shielding and promote jet flow mixing with the ambient airflow.



Range (nm)	**3,000**
Payload (lb)	**40,000**
Takeoff Gross Weight (lb)	**189,000**
Landing Weight (lb)	**152,000**
Total Fuel (lb)	**44,100**
Block Fuel (lb)	**37,700**
Block Time (h)	**6.92**
Initial Cruise Altitude (ft)	**39,000**
Takeoff Field Length (ft)	**2,450**

Fig. 25. Hybrid Wing Body Aircraft used as baseline airframe for turboelectric HWB.

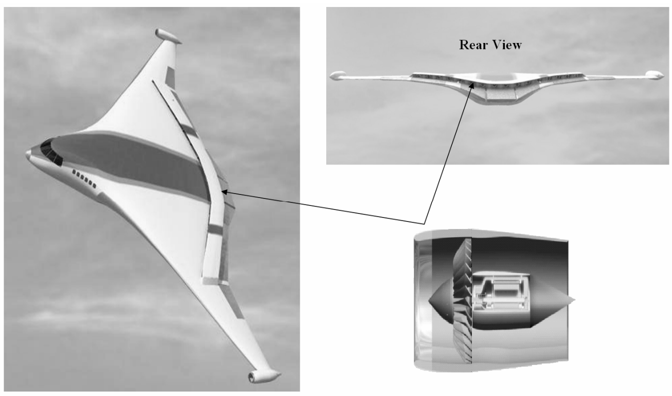


Fig. 26. Two views of a sixteen-fan hybrid wing body aircraft and a cross section of one of the superconducting-motor-driven fans in its duct.

To improve performance and to reduce noise and environmental impact even further, a turboelectric propulsion system was proposed for that vehicle. The turboelectric concept aircraft [13] shown in Fig. 26 uses essentially the same airframe but employs a number of superconducting motors to drive the distributed fans rather than many small conventional turbofan engines. The power to drive the electric fans is generated by two remotely located gas-turbine-driven superconducting generators (at each wing-tip). This arrangement allows many small partially embedded fans while retaining the superior efficiency of large core engines, which are physically separated but connected through electric power lines to the fans. Descriptions of the vehicle, the superconducting system, and the propulsion system are described in [13] with some "zeroth-order" weight and efficiency comparisons to the multiple turbofan system. Preliminary analysis suggests that fuel savings might be greater than six percent for a turboelectric propulsion system compared to the same frame with distributed discrete turbofans.

Beyond fuel savings related only to the propulsion system, however, turboelectric propulsion introduces a very high degree of aircraft design and operational flexibility as a result of decoupling power production from power consumption, as has been noted earlier in this paper. Lightweight superconducting generators, motors and power cables allow a small number of efficient large turbo-generators to power an arbitrary number of propulsor units. Either can be placed practically anywhere and in various orientations on the vehicle. This flexibility opens up design possibilities not obtainable with discrete large turbofans or with distributed propulsion systems that employ mechanical power distribution by gearboxes and shafts. Fuel savings resulting from this design freedom may be book-kept as drag reduction rather than under thrust production. Remembering that thrust must equal drag in steady level flight, we may further note that there is only a limited amount of fuel saving to be gained by engine improvement whereas fuel saving from drag reduction is more open ended. Large engines already extract half or more of the fuel energy, very close to the thermodynamic limit. Drag reduction by boundary layer ingestion and wake filling are yet to be fully analyzed and exploited and will require engine/airframe integration and a distributed propulsion approach to be realized.

In spite of uncertainty of the future level of refrigerator and AC superconductor technology, we summarize some weight and efficiency estimates from [13] that are based on the level of development that we expect for all-superconducting generators and motors. A sizing code [34] for fully superconducting motors and generators was used. Optimization was performed to minimize motor (or generator) weight plus refrigerator weight. The refrigerator, even with our aggressive 2030 assumptions, weighs ~70% as much as the motor or generator that it cools. Efficiencies, including the refrigerator power, are at least 99.4%. The expected weight of a motor or generator with its cooler is considerably less than the weight of a turbine engine core for equal power. Weight and efficiency comparisons are made in Table IV among three propulsion systems: a 16-fan turboelectric propulsion system, 16 independent small turbofan engines, and 2 large conventional turbofans. The turboelectric system weighs 5000 lb (2300 kg) more than the 16-engine system but has 9% lower TSFC (Thrust Specific Fuel Consumption) including the 1% electrical and refrigeration loss at takeoff. Weights exclude propulsors (fans), which would have similar total weights in all systems. TSFC values shown in Table IV are based on best present-day values for the engine size. Refrigerator weight is based on 5 lb/HP-input (3 kg/kW-input) and 30% efficiency, and HTS AC losses corresponding to a 12-μm filament. As noted above, even with this optimistic assumption (about equal to the weight of just the cold head in today's cryocoolers), the weight overhead of the refrigeration is such that the optimizer pushes the operating temperature of the superconducting components to a relatively high 49K (at the expense of having larger and heavier electric machines) to reduce refrigeration needs.

To compare the turboelectric system with the 16-turbofan system, by balancing out the opposite effects of lower SFC and higher weight of the turboelectric system, the Breguet range equation, sufficient to determine relative ranking, is applied to both systems, with the requirement of equal aircraft range and approximating the entire flight as cruise. Solving for the required change in fuel weight between the 16-engine case and the turboelectric case, we find that the turboelectric aircraft would require 7%, or 3000 lb (1400 kg) less mission fuel. Thus, the slightly heavier turboelectric aircraft would have a net fuel savings of roughly 7% on each flight, compared to the baseline aircraft powered by 16 small engines. This estimate must be refined by a detailed mission analysis. Known omissions in the weight estimates of the electric system include the superconducting transmission lines (estimated at only 3% of the turboelectric system weight) and other power management and distribution components.

A comparison between the turboelectric case and two large (presumably podded) turbine engines can also be made based on the numbers in Table IV. One can see that the entire refrigerated turboelectric system weighs 6300 lb (2900 kg) more than two large turbofan engine cores of 42,000 HP each (with no weight allowance for podding) and would be ~1% less efficient at takeoff because of the electrical losses. A liquid-hydrogen-cooled turboelectric system would weigh 3600 lb (1600 kg) more than the large turbofan engine cores. Thus, the propulsion system weight for an HWB using podded engines would be significantly less than either of the two turboelectric systems discussed, with consequent accompanying reductions in fuel burn. However, the use of two separate podded engines would provide no short take-off capability and only limited noise reduction, no drag reduction and none of the other potential benefits and capabilities that have been mentioned above. It is therefore still very advantageous to switch to turboelectric propulsion, even with the slight weight penalty.

TABLE IV

COMPARISON OF DIFFERENT PROPULSION SYSTEMS

Propulsion System	Components	Weight, lb (kg)	Efficiency, %	TSFC, hr^{-1}
Turboelectric distributed fans (refrigerated)	Two 42 380 hp engine cores	7300 (3300)	----	0.57
	Two 42 380 hp electric generators (including refrigerators)	3000 (1300)	99.7	----
	Sixteen 5250-hp motors (including refrigerator)	4700 (2100)	99.4	----
	Total	**15 000 (6800)**	**99.1**	----
Turboelectric distributed fans (LH_2 cooled)	Two 42 080-hp engine cores	7300 (3300)	----	0.57
	Two 42 080-hp electric generators (LH_2 cooled)	1900 (860)	99.9+	----
	Sixteen 5250- hp motors (LH_2 cooled)	3100 (1400)	99.9+	----
	Total	**12 300 (5600)**	**99.9**	----
Conventional small distributed turbofans	Sixteen 5250-hp engine cores	**10 000 (4500)**	91*	**0.63**
Conventional large nondistributed turbofans	Two 42 000-hp engine cores	**8700 (4000)**	----	**0.57**

* Relative to 42,000-HP engine core at 0.57 thrust specific fuel consumption.

If the motors and generators were cooled by liquid hydrogen (with only enough carried on the aircraft to provide refrigeration) rather than refrigerators, then the turboelectric system would weigh 2300 lb (1000 kg) more than the 16-engine system, and the required jet fuel is reduced by 4000 lb (1800 kg), or 9% (calculated from the efficiency advantage of the large engines, without accounting for the replacement of jet fuel energy with liquid hydrogen energy), and TOGW (Take-Off Gross Weight) drops by 560 lb (255 kg). This estimate does not include corrections for the weight of the liquid hydrogen (which would provide about 5% of the aircraft's fuel energy) and its tankage and accessories, compared to the corresponding weight reduction of the jet fuel, tankage, and components. (It may be noted that, for the same energy, liquid hydrogen has almost 4 times the volume but only one-third the weight of jet fuel.)

VIII. CONCLUSIONS AND RESEARCH DIRECTIONS

Electric aircraft have long been considered due to a number of operational and environmental benefits that could be derived from such transition. Electric aeropropulsion would offer tremendous benefits in the design of aircraft, ushering in the possibility of revolutionary concepts that are quieter and much more energy efficient, thus enabling sustainable aviation. Conventional electric machines are too heavy to ever be considered for this extremely weight sensitive application, thereby warranting the need to investigate the feasibility of superconducting machines as an alternative: motors to drive propulsion fans, and generators to power such load.

The authors reviewed numerous case studies concerning the application of superconducting rotating machines to aircraft. Detailed design studies for HTS propulsion motors supported by experimental validation have convinced us that superconducting rotating machines today can achieve power densities comparable with that of turbine engines (3-8 kW/kg). This remarkable achievement, however, is still not enough for deployment into commercial aircraft. Electrically-propelled airliner aircraft would become feasible when power densities approach 25 kW/kg for motors and 50 kW/kg for generators, which appears to be achievable with fully superconducting machines (both inductor and armature).

The design examples of HTS motor-drive aircraft that were studied indicate that turbo-electric propulsion using superconducting machines can substantially contribute towards achieving the aggressive goals set for overall fuel efficiency. This is primarily due to the separation of power generation devices and propulsors, which offers an unprecedented level of design freedom facilitating the integration of short take-off capabilities into aerodynamically efficient body shapes (i.e, very high lift/drag ratio).

This promising new application cannot come to fruition without further research and development on HTS superconducting materials and refrigeration technology. A development roadmap includes:

- Develop and demonstrate fully superconducting rotating machines in the range of 25-40 kW/kg for motors, and 40-80 kW/kg for high rotation speed generators (up to 15,000 RPM)
- Develop low AC loss HTS conductors (<10 W/A-m @ 500Hz, equivalent to 10 μm filament) for fully superconducting machines
- Develop cryocoolers capable of 30% of carnot efficiency and weighing less than 3 kg/kW-input (or alternative lightweight refrigeration schemes)
- Refine the physics-based models for superconducting machines and ancillaries to continue exploration of aircraft design space and alternative concepts

It is important to consider that safety and reliability are primary considerations in the aircraft industry, so that no new technology will be introduced without a solid track record of implementation and test. Even though the concepts discussed here may be slated for first service in 20-25 years, the superconducting machines to power them need to be a somewhat mature and tested technology 15-20 years from now. This is an instance in which the market pull will be strong, but the technology has to be ready before the pull is fully expressed. It means that funding and effort for the developments outlined above need to start soon, and be sustained for the next decade or more. It should be pointed out that the development of ultra-compact superconducting generators and motors, and the associated lightweight cryocooling, could also be applied to other mass-market transportation applications such as trucks, busses, or even cars if compact enough. Realization of these applications could be the next big opportunity for superconductivity to fully realize its game-changing potential.

ACKNOWLEDGMENT

The authors thank Dr. Danielle Soban of ASDL/Georgia Tech for the helpful discussions on aircraft design, and Prof. Pascal Tixador of Grenoble INP for his work on the sizing models.

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