

Superconducting Machines and Power Systems for Electric-Drive Aeropropulsion

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ABSTRACT

Societal demands of recent years have increasingly pressured the development of greener technologies in all sectors of the nation's transportation infrastructure, including that of civilian aviation. This study explores the concept of electric-drive aeropropulsion, aided by high-temperature superconducting technology, as an enabler for enhancing the environmental characteristics at the air-vehicle level. Potential improvements in the areas of aircraft noise, emissions, and energy efficiency are discussed in the context of supporting the latest strategic goals of leading governmental organizations.

BACKGROUND

It is generally expected that the projected growth in the future demands for aviation services cannot be met, unless all elements of the air transportation system become more environmentally sensitive via the harnessing of advanced technologies [1]. In the U.S., efforts to lead a complete transformation of the national aviation system are currently being led by the Joint Planning and Development Office (JPDO), which oversees and coordinates those activities within the framework provided by the Next Generation Air Transportation System (NextGen). Such a convergence of aspirations to intertwine technological performance with environmental performance is apparent in one of the six strategic goals of NextGen: "Protect the Environment." [2] Two objectives are rolled under this goal, one of which states: "Reduce noise, emissions, and fuel consumption."

In a tell-tale sign that the future of civilian aeronautics will look vastly different compared to today's standards, NASA has recently announced a new set of technology goals for future subsonic aircraft [3]. Of particular interest here are the environmental metrics specified for the post-NextGen ("N+3") timeframe listed in Table 1. Satisfying such aggressive targets will likely require a holistic, clean-sheet-of-paper approach to combining advanced airframe configurations with a suite of enabling

technologies, for which there are likely to be no unique mappings. Nevertheless, it is undeniable that identifying a revolutionary method of aeropropulsion, which can one day offer breakthrough performance in the areas of noise, emissions, and fuel burn, represents a good starting point toward achieving the N+3 targets.

Table 1: NASA Subsonic Fixed Wing Target Metrics

CORNER OF THE TRADE SPACE	N+3 (EIS 2030-2035) Advanced Aircraft Concepts (relative to user defined reference)
Noise (cum. below Stage 4)	55 LDN at average boundary
LTO NOx Emission (below CAEP 6)	Better than -75%
Performance: Aircraft Fuel Burn	Better than -70%
Performance: Field Length	Exploit metro-plex* concepts

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

EIS = Entry Into Service, IOC = Initial Operating Capability

ELECTRIC-DRIVE AEROPROPULSION SYSTEM

This paper presents one such emerging propulsive arrangement, whose development can be leveraged on some of the latest technological accomplishments outside of the aerospace engineering domain. As a variant of what has been named the "electric-drive" aircraft propulsion system [4], the proposed method of aeropropulsion utilizes a superconducting motor to rotate an aeronautical propulsor [5]. By further endowing the concept with fuel cell technology, it can lead to the elimination of: (a) all environmentally objectionable emissions (excluding water vapor); and (b) the source of engine core noise. There is also the potential for reduced fuel burn, since electric motor and fuel cell technologies

are inherently more energy efficient than their gas turbine-based counterparts.

FUEL CELL SYSTEM ALTERNATIVES

A fuel cell is formally defined as a variant of galvanic cells, which directly convert the chemical Gibbs free energy into electricity [6]. Its reputation as a green technology stems from the fact that the typical base reactants are hydrogen (reductant/fuel) and oxygen (oxidant), and the sole product from this electrochemical reaction is pure water. The rate at which fuel cell technology has advanced during its relatively short history has been remarkable. In the 1990's, a seven-fold increase in specific power (power-to-weight ratio) was reported in five years, a feat that required almost 50 years for the developers of jet engines to achieve.

Thus far, two types of fuel cells have been demonstrated for air-vehicle applications: proton exchange membrane fuel cell (PEMFC) and solid oxide fuel cell (SOFC) technologies. A total of 11 fuel cell powered unmanned aerial vehicles (UAVs) have been test-flown to date, as listed in Table 2.

Table 2: Timeline of Successful Fuel Cell Powered Flight

Developer	Fuel Cell Powered Aircraft
AeroVironment	Hornet (03/21/2003)
FH-Wiesbaden	Global Observer (05/26/2005)
	Hy-Fly (09/07/2005)
Adaptive Materials	SOFC UAV (2005)
U.S. Naval Research Lab	Spider-Lion (November 2005)
Georgia Tech	Third Prototype (06/14/2006)
California State University, LA	Environmental Research UAV (08/25/2006)
DLR	HyFish (April, 2007)
AeroVironment	Puma Hybrid (June 2007)
California State University, LA and Oklahoma State University	Pterosoar Hybrid (August 2007)
KAIST	UAV (10/09/2007)

It is noteworthy to observe that 10 of these 11 groundbreaking achievements utilized PEMFC-based power plants. Such a proven track record of the technology's maturity, superior specific power (kW/kg), and commercial availability forms a solid basis for extending its application to more advanced concepts.

SUPERCONDUCTING MACHINE ALTERNATIVES

Superconducting machines exhibit unmatched specific torque, typically greater than 20 Nm/kg, due to their unique capability to carry high current. Researchers have considered exploring the design's potential for airborne applications since the 1970s [7]. At that time, however, stringent cooling needs for operation at 4.2 K (-268.95 °C) required over-complicated and high-priced means of

cryogenic cooling. But the breakthrough discovery of high temperature superconductivity in the late 1980s has allowed the construction of superconductors that can operate at more manageable temperature ranges of 20 to 65 K.

To date, several high temperature superconducting (HTS) motors have been built, and successfully tested. Figure 1 shows a comparison between conventional high-torque machines and existing HTS motors or designs. The majority of demonstrated applications are high-torque, low-speed alternatives, consistent with the propulsion requirements of the maritime industry. Nevertheless, more recent design studies by Masson et al (designated as "Conceptual" designs below), have revealed that unconventional topologies of HTS machines could potentially achieve even higher specific power figures, which are comparable to those of gas turbines and orders of magnitude higher than those of conventional copper-based machines.

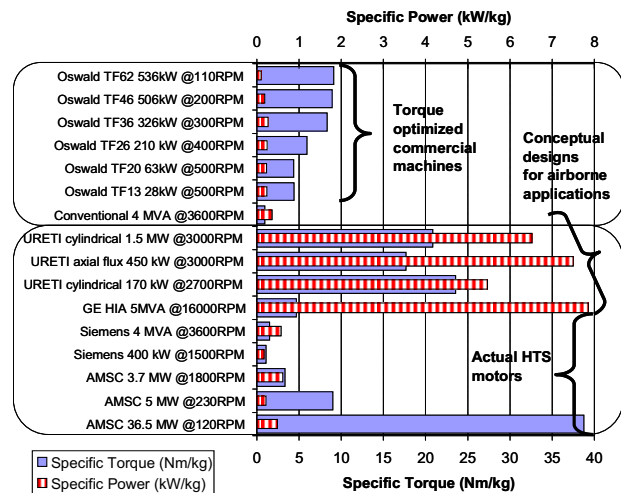


Figure 1: State-of-the-Art in HTS Machine Design [5]

Two types of HTS machines are possible, depending on the amount of cooling power available: fully superconducting and partially superconducting (superconducting rotor and resistive stator) machines. Extracting heat at cryogenic temperatures requires a considerable amount of energy. State-of-the-art cryocoolers exhibit 10-15% Carnot efficiency, which corresponds to requiring 70 W at room temperature to remove 1 W of heat generated at 30 K. Therefore, machine designers tend to minimize losses at cryogenic temperatures by allowing only the rotor to be superconducting. Otherwise, the AC losses in the stator windings, which are made out of copper, would lead to a very large heat load, and, in turn, an oversized cooling system. This would be especially true at high rotational speeds as some of the AC losses depend on the square of the frequency.

In contrast, the availability of on-board cryogenic hydrogen makes the fully superconducting alternative attractive. All losses in the stator windings, on the order of up to several kilo-watts, can be removed by bleeding some of the fuel (liquid hydrogen) off as coolant. Fully

superconducting designs can exhibit specific torque values above 100 Nm/kg, in addition to very high specific-power. A comparison of the two topologies is shown in Figure 2.

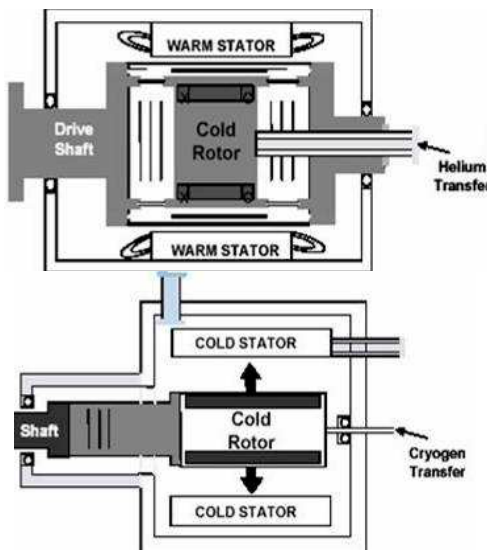


Figure 2: Representative Configurations of Partially (top) and Fully Superconducting (bottom) Machines [8]

Typical HTS machines are ironless because high flux densities can be generated by the superconducting coils in the rotor. However, different topologies can be considered, as shown in Figure 3. Iron can still be used as part of the stator, rotor or both, depending on the requirements for rotation speeds, power levels, efficiencies, cost, etc. While iron can be removed in superconducting machines due to the lack of electrical resistance and the resultant availability of *free* amp-turn, the current density in the superconductor is limited by the magnitude of the external flux density. By using iron, the on-wire flux density can be reduced, and the amount of superconductor can be greatly decreased, but only at the expense of extra weight. The magnetic configuration depends entirely on the application requirements.

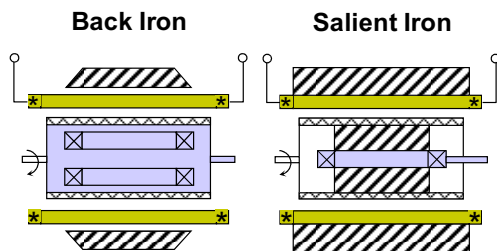


Figure 3: Alternative HTS Machine Topologies [8]

Fully superconducting machine topologies depend on the application of interest and mostly on the frequency, as shown in Figure 4. If desired, iron can be used in high-speed applications to keep the excitation coils stationary. Nevertheless, high rotational speeds present the most stringent technical challenges, since the conductors experience heavy acceleration. If the frequency is very

high then a non-magnetic shield can be used; eddy currents are created to shield the flux from the outside.

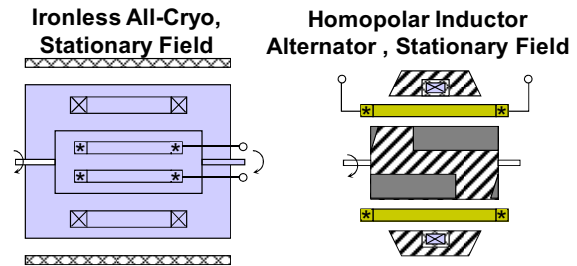


Figure 4: Fully Superconducting Machine Topologies [8]

PRIMARY ENERGY STORAGE ALTERNATIVES

All fuel cell types, with the exception of direct methanol fuel cell, must be supplied with hydrogen – in one form of another – to carry out the two-part redox (reduction, or the gain of electron, and oxidation, or the liberation of electron) process. The main obstacle in adapting hydrogen as an aviation fuel is its low energy density. Hydrogen possesses nearly three times as much energy as petroleum-derived liquid fuels on a gravimetric basis. But for the same volume, its energy content becomes less than half of conventional aviation fuels, making hydrogen a double-edged sword. The ideal hydrogen storage device would allow the containment of as much hydrogen as possible on a per volume basis, while being structurally light enough to be carried on a flying vehicle.

The high-pressure tank embodies the simplest method of hydrogen storage. Gaseous hydrogen is pressurized to maximize both the gravimetric and volumetric storage efficiency. Hydrogen storage tanks rated at 5,000 and 10,000 psi have already been certified according to a number of safety standards, such as ISO 11439 (Europe) and NGV2 (U.S.), and are commercially available to be integrated into ground vehicles [9]. However, compressed hydrogen tanks are relatively low-capacity alternatives from a storage-efficiency point of view. State-of-the-art mass and volume fractions of hydrogen stored in 5,000-psi tanks are 5.7% and 1.5%, respectively. Doubling the storage pressure to 10,000-psi improves the volumetric capacity to 2.5%, but at the cost of gravimetric storage efficiency, which is reduced to 2.4%. The figures are metrics measured with the tank, hydrogen, and all support equipment, and not just with respect to the tank itself.

The cryogenic hydrogen storage tank is an insulated, strongly reinforced vacuum flask. It represents the most efficient method of storing hydrogen, in terms of volumetric capacity. By cryogenically cooling hydrogen to its liquid state at around 22 K, it is possible to significantly increase the density of hydrogen, which is 0.084 kg/m³ at STP, to 71 kg/m³. State-of-the-art liquid hydrogen tanks are reported to have a volumetric storage capacity of 3.6%, which is more than double the efficiency of 5,000-psi tanks, and a gravimetric capacity greater than that of 10,000-psi tanks [9]. Even with proper insulation, however, liquid hydrogen cannot

remain permanently stored. The hydrogen inside the tank will begin to boil off; that is, slowly evaporate, thus raising the internal pressure of the containment vessel. This is perceived as one of the major technical challenges for adapting liquid hydrogen storage for vehicular applications, as the build-up of hydrogen gas must be periodically vented and the storage subsystem must always be oversized to compensate for the boil off.

Hydrides are compounds that are formed by bonding with the negative ion of hydrogen. Metal hydrides thus refer to a class of metals or metallic alloys that enable the absorption and release of hydrogen gas. Such reactions are entirely chemical in nature, and do not require any additional support systems other than the connecting valves to a fuel cell system. A spent hydride cartridge can be refilled with hydrogen in a manner similar to that of a high-pressure storage cylinder. Despite their inherent simplicity, metal hydrides are gravimetrically inefficient storage methods – less than 1% hydrogen by mass. Metal hydrides are, however, quite efficient in terms volumetric capacity, approaching the levels attainable with cryogenic tanks.

Hydrogen can also be stored in spheres of glass engineered with a diameter on the order of micrometers. The tiny spheres have the property of becoming permeable to hydrogen when heated and impermeable when cooled, thusly allowing themselves to be amenable as hydrogen storage devices. Although glass microspheres release hydrogen endothermically, similar to metal hydrides, the level of heat that must be supplied for a practical flow rate of hydrogen excludes them from being compatible with a low-temperature system like PEMFCs. For instance, in order to expedite the purge rate that is on the order of thousands of hours at room temperature, the spheres are required to be heated up to 300 °C for a still miserly period of 15 minutes [10].

Carbon nanofibres are perhaps the most exotic methods of hydrogen storage one can be considered. These are fibrous carbon materials that are synthesized in a nanoscale environment. By making carbon filaments at the nanometer scale, the structure can be made to have greater surface area and porosity that allow practical amounts of hydrogen absorption, and thus storage, near ambient conditions. The initial craze on carbon nanofibres as the future of hydrogen storage began after the seminal work of Chambers et al, who reported measuring gravimetric storage capacity of 67% in graphitic nanofibres around 50 to 1000 nm in length and 5 to 100 nm in diameter [11]. Since then, researchers in this field experimented with single-walled nanotube and multi-walled nanotube designs. It is unfortunate that widely varying reports of experimental results, some of which were declared irreproducible, have caused much debate on the efficacy of carbon nanofibres as a reliable medium for hydrogen storage [12].

In summary, none of the identified hydrogen storage methods are without drawbacks. Each presents its own set of technical challenges that must be addressed

before the technology becomes viable for aeropropulsion applications. Carbon nanofibres and glass microspheres could be excluded without much contention on the basis that these are yet highly speculative technologies, allowing the high-pressure tank, cryogenic tank, and metal hydrides to emerge as the main contenders. Among these three alternatives, the liquid hydrogen option is the most well-balanced storage technology, in terms of gravimetric storage efficiency, volumetric capacity, and technical maturity. The reported success of AeroVironment's Global Observer program [13] is an especially encouraging development that paves the way for ultimately resolving the concern over sufficient insulation and boil-off compensation at high altitudes.

AUXILIARY ENERGY STORAGE ALTERNATIVES

Fuel cells in general, and the direct hydrogen types in particular, are inherently good load followers [14], capable of keeping up with variable power demands without long transients between steady states. But for transportation applications, there would be instances when an abrupt change in the load demand exceeds the response time of the fuel cell system, potentially leading to catastrophic consequences. Incorporating an auxiliary energy source, which can serve as an *energy buffer* between the fuel cells and near-instantaneous load fluctuations, into the system would not only increase system reliability, but also provide a supplementary power source capable of augmenting propulsion in short bursts; e.g., acceleration during turbulence due to wind gusts, etc. In an electric-drive aeropropulsion system, an auxiliary energy source is likely to play all of the above roles, in addition to serving as the energy source for meeting the engine thrust or power transient requirements stipulated in the Federal Aviation Regulations (FARs). In this regard, the ideal auxiliary energy source for a PEMFC power plant would be a device with a fast load-response time, high specific power, but not necessarily high specific energy.

BALANCE OF PLANT ALTERNATIVES

In the fuel cell literature, the term balance of plant (BOP) is a reference to all ancillary components of a fuel cell power plant; i.e., everything else besides the fuel cells. Different fuel cell types impose different thermomechanical needs on the subsystem level, impacting the final architectural composition of the entire system. For example, various amounts of fluids and gases, including air, must be circulated throughout the system to serve several different purposes.

Air delivery is a critical function in all but the smallest of fuel cell systems, and one without which fuel cells cannot generate power. For PEMFCs, air must be continually supplied to a cell's cathode to sustain the electrochemical reaction. This supply rate should also be controllable, so that the fuel cells are able to respond to variable loads. Additionally, the fuel cell stack would often need to be pressurized for optimal electrochemical performance. Stack pressurization would, nonetheless,

In this regard, compressor technology represents an excellent means for achieving both air delivery and pressurization. Among the alternatives that are often mentioned as possibilities for PEMFC-based systems, the centrifugal (radial) compressor appears to be singularly capable of delivering the range of flow rates and back pressures that would be required for in-flight operations. All other compressor types either lack the ranges of pressure boost at typical flight altitudes (roots), flow rates (Lysholm), or efficiency (axial flow).

POWER MANAGEMENT AND DISTRIBUTION SYSTEM ALTERNATIVES

The function of DC power regulation can be fulfilled by designing the appropriate electric circuits capable of stepping up or down DC voltage. Electronic switches, which can connect or disconnect a current path from the power source to the load at set frequencies, thus become critical components in circuit regulation. When used in conjunction with inductors, capacitors and diodes, a switch can form a regulating circuit, also known as the buck-boost regulator.

The operating current in power converters is limited by the temperature of the semiconductor junctions. If hydrogen is used as fuel and stored cryogenically on-board the aircraft, then a flow of hydrogen can be used to extract heat from the converters and, in turn, increase their operating current density and power output. Typically, a 3-fold specific power gain can be obtained with cryogenic cooling. Low temperatures also enable high-frequency operations, which will not only improve the power quality, but also allow the downsizing of bulky filtering elements composed of capacitors and inductors. The specific power of PMAD systems is still very low compared to that of superconducting motors, as shown in Figure 5 below.



The subsystem-level choices per each technology category resulted in the candidate system architecture depicted in Figure 6.

