Distributed Turboelectric Propulsion for Hybrid Wing Body Aircraft

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Abstract

Meeting future goals for aircraft and air traffic system performance will 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. A recently published configuration with 12 small engines partially embedded in a HWB aircraft, reviewed herein, serves as the airframe baseline for the new concept aircraft that is the subject of this paper. To achieve high cruise efficiency, a 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. To improve performance and to reduce noise and environmental impact even further, a drastic change in the propulsion system is proposed in this paper. The new concept adopts the previous baseline cruise-efficient short take-off and landing (CESTOL) airframe but employs a number of superconducting motors to drive the distributed fans rather than using many small conventional engines. The power to drive these electric fans is generated by two remotely located gas-turbine-driven superconducting generators. 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. This paper presents a brief description of the earlier CESTOL vehicle concept and the newly proposed electrically driven fan concept vehicle, using the previous CESTOL vehicle as a baseline.

Nomenclature

AC	alternating current
BLI	boundary layer ingestion
BWB	blended-wing-body
CAEP	Committee on Aviation Environmental Protection
CESTOL	cruise-efficient short take-off and landing
EBPR	effective bypass ratio (ratio of mass flow rate through all fans to rate through engine core)
EIS	entry into service
FAR	Federal Aviation Regulations
HTS	high temperature superconducting
HWB	hybrid wing body
hp	horsepower (1 hp ~ 0.7456 kW)
IBF	internally blown flap
IOC	initial operating capability
LTO	landing and take-off
PAI	propulsion airframe integration
SFW	subsonic fixed wing
STOL	short take-off and landing
TSFC	thrust specific fuel consumption
TOGW	take-off gross weight
USB	upper surface blowing

I. Introduction

According to a number of air traffic forecast studies, the growth in air travel in the United States or world will increase by a factor of 2 to 4 by 2025 (refs. 1 and 2). This continued growth in the passenger and freight air traffic will require better utilization of available airport assets. Large airports with long runways (>10 000 ft, 3050 m) are already heavily utilized while small airports with runways too short (<3000 ft, 910 m) to support large transport class jet aircraft are often underutilized. Table 1 shows a number of metropolitan airports around 15 major U.S. metropolitan areas with at least an intermediate size runway length of 3000 ft (~910 m). Most of these cities have at most one or two large airports handling much of their large transport aircraft traffic, but they also have additional regional airports nearby with shorter runways to accommodate smaller aircraft. For example, the city of Atlanta has one large-capacity, long-runway airport within the city boundary but has four more regional airports with at least 3000 ft runway lengths within 20 miles (~32 km) of the city metropolitan area.

TABLE 1.—NUMBER OF U.S. METROPOLITAN (METRO) AIRPORTS WITH AT LEAST 3000-ft (~915-m) RUNWAY LENGTH AROUND 15 MAJOR METRO AREAS

Metropolitan areas	Number of metro airports within 20 miles (~32.19 km)
Atlanta	5
Charlotte	5
Chicago	5
Houston	9
Las Vegas	4
Los Angeles	11
Minneapolis	6
New York	7
Philadelphia	8
Phoenix	8
San Francisco	4
San Diego	4
Seattle	7
South Florida	
Miami	5
Orlando	4
Tampa	8
Washington-Baltimore	8
Number of U.S. airports in 15 metro areas	108

In order to meet future traffic demand with limited airport access, revolutionary airplane concepts are needed that can utilize these smaller airports. For these new concepts to be successful, they must dramatically reduce take-off and landing noise, due to the urban setting of many of these fields, and yet still carry an economically viable number of passengers and freight over transcontinental distances at current jet transport speeds. At the same time, these new aircraft must dramatically reduce energy consumption and environmental impacts. In response to growing aviation demands and concerns about the environment, NASA's Subsonic Fixed Wing (SFW) project identified four "corners" of the technical trade space—noise, emissions, aircraft fuel burn, and field length—for aircraft design. Table 2 lists these technology goals for three future timeframes, where N+1, N+2, and N+3 represent the years 2015, 2020, and 2030, respectively. Although it may not be feasible to meet all the goals for each timeframe, the multi-objective studies will attempt to identify possible vehicle concepts that have the best potential to meet the combined goals.

One of the vehicle and propulsion concepts that NASA is exploring for N+2 is a synergistic combination of a hybrid wing body (HWB) airframe and a distributed propulsion system. A number of fixed wing aircraft using "distributed propulsion" have been proposed and flown before, although what constitutes distributed propulsion is not clearly defined. Examples include the 1940's YB–49 flying wing aircraft with four completely embedded engines in each side of the wing and the 1960's Hunting H.126 jet flap research aircraft, which diverted almost 60 percent of its thrust across its wing trailing edge to achieve very high lift capability.

NASA funded a 1-year study that evaluated the synergistic benefits of distributed propulsion and airframe integration with respect to cruise efficiency and quiet operation of aircraft

TABLE 2.—NASA'S TECHNOLOGY GOALS FOR FUTURE SUBSONIC FIXED WING (SFW) VEHICLES

Corners of the trade space	N[a]+1 (2015 EIS) Generation Conventional Tube and Wing (relative to B737/CFM56)	N[a]+2 (2020 IOC) Generation Conventional Hybrid Wing Body (relative to B777/GE90)	N[a]+3 (2030–2035 EIS) Advanced Aircraft Concepts
Noise (cumulative below Stage 4)	–32 dB	–42 dB	55 LDN at average airport boundary
LTO NOx Emissions (below CAEP/6)	–60%	–75%	Better than –75%
Performance: Aircraft Fuel Burn	–33%[b]	–40%[b]	Better than –70%
Performance: Field Length	–33%	–50%	Exploit metroplex[c] concepts

[a]"N" represents current state-of-the-art aircraft as stated in parentheses.
[b]An additional reduction of 10 percent may be possible through improved operational capability.
[c]Concepts that enable optimal use of the airports (with shorter runways) within the metropolitan areas.

from regional airports (refs. 3 and 4). The configuration for that study utilized 12 small conventional high-bypass-ratio turbofan engines, each with about 7000 lb (~31 000 N) of thrust at sea level, powering a HWB vehicle. The HWB is the main object of study to meet NASA's N+2 goals. Because the results of that study are newly published, and have not been widely disseminated, they are summarized in the next section for background and provide the baseline for the current study.

Recently, a very low noise "Silent Aircraft," based on the blended-wing body or BWB airframe and on distributed propulsion, was proposed and studied. Its objective was to contain objectionable noise within the airport boundary and to improve vehicle fuel efficiency (ref. 5). This configuration had a number of new technologies, including embedded turbofan engines with each engine core driving three fans through a gear and shaft system, yielding a very high bypass ratio (ref. 6). The increased engine bypass ratio provided both low thrust specific fuel consumption (TSFC) and low engine noise.

To improve vehicle performance enough to meet NASA's N+3 goals, a drastic change in propulsion system is required. A newly proposed vehicle, which is the subject of the present paper, uses the baseline cruise-efficient short take-off and landing (CESTOL) aircraft airframe mentioned above but employs superconducting motors to drive the distributed fans rather than a number of small conventional high bypass ratio engines. The power needed for these electric fans comes from two remotely located gas-turbine-driven superconducting generators through electric power lines. This arrangement allows many small partially embedded fans while retaining the superior efficiency of large core engines. The next section presents a brief description of the baseline CESTOL vehicle and propulsion concept followed by the newly proposed electrically driven fan concept vehicle.

II. Distributed Propulsion Concepts

A number of distributed propulsion vehicle concepts for the HWB platform have been studied recently (refs. 3 to 8). The motivation has been to increase aircraft performance, to lower the noise to the surrounding community, and/or to enable short take-off and landing (STOL) capability. The following possible benefits of distributed propulsion HWB configuration compared to a conventional "tube-and-wing" configuration have been identified:

- Reduction in fuel consumption by ingesting the thick boundary layer flow and by filling in the wake generated by the airframe with the engine thrust stream (refs. 9 to 11).
- High lift via high-aspect-ratio trailing-edge nozzles for vectored thrust providing powered lift, boundary layer control, and/or supercirculation around the wing, all of which enable short take-off capability (refs. 12 and 13).
- Reduction in aircraft noise to the surrounding community through airframe shielding (refs. 3 and 4).
- Improvement in safety through a redundant propulsion system.
- Reduction in aircraft propulsion installation weight through inlet/nozzle/wing structure integration.
- Elimination of aircraft control surfaces through differential and vectoring thrust for pitch, roll, and yaw moments.
- High production rates and easy engine replacement of engines that are small and light.
- Application of nontraditional engine concepts such as the multifan engine or electric fans.

The large available volume in the HWB configuration may facilitate use of hydrogen or other alternative fuels to achieve zero or near zero emissions (refs. 14 and 15).

To address the CESTOL vehicle with low noise characteristics, a CESTOL vehicle configuration was developed jointly by NASA and Boeing to utilize short runways at regional airports and was reported by one of the authors (ref. 3). A brief summary of this concept is described in the first subsection below. Combining that earlier CESTOL vehicle concept with our presently proposed turboelectric propulsion system results in the current conceptual study, which is designated "Turboelectric-Powered CESTOL Concept" and is described in the second subsection below.

Baseline 12-Engine CESTOL Concept

To develop a distributed propulsion CESTOL vehicle configuration, NASA and Boeing performed a joint study, which we summarize in this section. The initial configuration was based on the HWB because of its high cruise efficiency, low noise characteristics, and a large internal volume for integrating embedded distributed propulsion. The preliminary vehicle analysis is reported by Kawai (ref. 16) and summarized in reference 3, and the vehicle configuration is shown in figure 1. The powered lift system was selected because of the high lift efficiency of the internally-blown-flap (IBF) concept. A distributed propulsion system with 12 conventional turbofan engines with approximately 7000 lb (~31 000 N) thrust each would enable high lift by using low pressure fan bypass air that would not have hot duct issues and that would be subsonic to keep the powered lift noise down. The concept here is the use of distributed embedded propulsion for quiet IBF powered lift with substantial engine noise shielding, including some jet noise shielding. The CESTOL concept combines substantial engine noise shielding

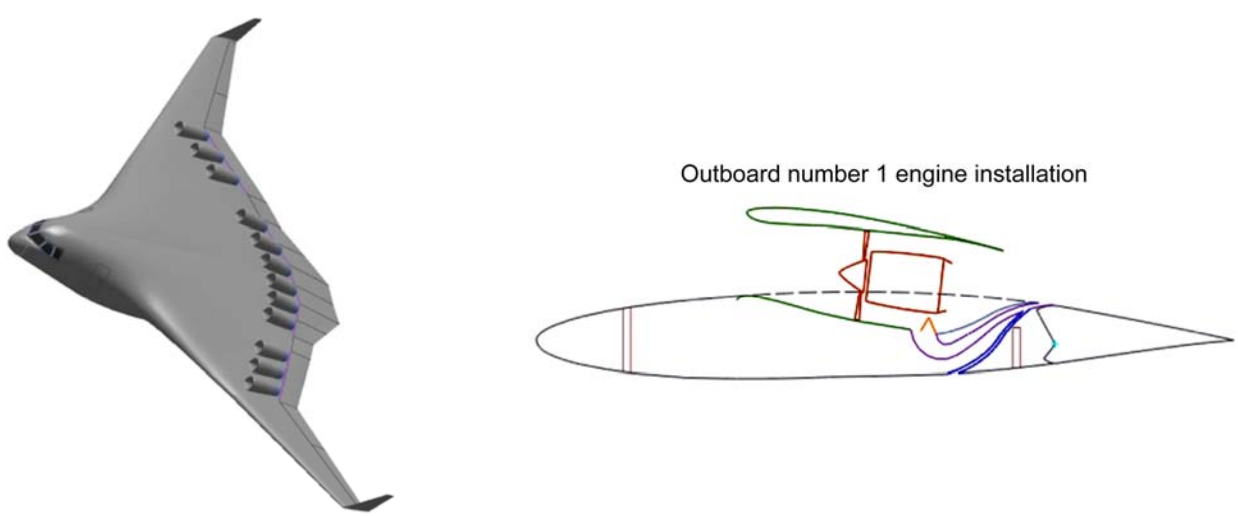

Figure 1.—Cruise-efficient short take-off and landing (CESTOL) vehicle configuration using 12 small conventional high bypass ratio turbofan engines.

with rapid climb out and steep descent to provide a very low noise footprint. The preliminary noise analysis of the vehicle is reported by Stone (refs. 4 and 17).

Based on current trends in air transports and STOL considerations, the following mission requirements were used for the vehicle:

- Payload: 40 000 lb (~18 000 kg)
- Range: 3000 nm (~5.600 km)
- Speed: Mach 0.8 at 30 000 ft (~9000 m)
- Field length: <5000 ft (<1500 m, FAR Part 25)
- Climb at Std + 15 °C
- Landing flare for passenger comfort with a 6° glide slope

With these requirements and using Boeing's WingMOD (ref. 18) multidisciplinary optimization code, an aerodynamically trimmed vehicle configuration was obtained and mission performance data were determined. The following is the set of predicted vehicle and performance parameters:

- Take-off gross weight: 189 140 lb (~85 792 kg)
- Total fuel: 44 098 lb (~20 000 kg)
- Take-off field length: 2452 ft (~747 m)
- Take-off C_{Lmax} = 1.66
- Initial cruise altitude: 39 000 ft (~11 887 m)
- Landing field length: 3477 ft (~1060 m)
- Landing C_{Lmax} = 1.06

The take-off field length is for obstacle clearance with an engine out. However, because many engines (12) were distributed on the wingspan, the engine-out condition did not include lateral control drag because only one engine inoperative (out of 12) would produce no significant yawing moment at a mission-critical stage (mainly at takeoff). Indeed, aircraft with powered-lift distributed-propulsion systems may require a general reexamination of engine-out airworthiness certification regulations because controllability limits are currently based on one engine out. Note that the landing field length is about 3477 ft (~1060 m), which includes the 1.67 factor on stopping distance. It is believed that the use of a variable area nozzle for improved powered lift during approach would enable further reductions in field length.

Embedded distributed propulsion enables the use of low-pressure fan-bypass air for an IBF system, wherein a high-aspect-ratio slot nozzle is used in conjunction with a slotted airfoil with the nozzle exhaust pumping through the slot to increase circulation and lift. The small diameter engines with a bypass ratio of 9.4 have forward noise shielding and employ mixer nozzles to increase the jet noise frequency and move the jet noise source locations forward. The forward jet source noise can then be shielded by airframe surfaces to reduce aft and sideline noise. A more complete description of noise analysis methods and results can be found in reference 17.

Turboelectric-Powered CESTOL Concept

To meet the aggressive NASA SFW N+3 goals in table 2, we have begun a study that carries over the baseline CESTOL airframe, but we propose a more radical propulsion system that replaces the discrete turbofan engines. We propose a turboelectric propulsion system with superconducting electric fans powered by two turbine-engine-driven electric generators. A notional vehicle is shown in figure 2. Because this new effort focuses on the propulsion system, the airframe has not been reexamined in light of the new propulsion system. Therefore, an airframe similar to that of the earlier CESTOL configuration was retained as a baseline and the distributed electric propulsion system was applied instead of discrete small turbofan engines.

The initial propulsion system consists of two wing-tip-mounted turboelectric generators and a set of 16 small electric fans. The 35-in.- (~90-cm-) diameter fans are distributed along a large portion of the upper aft wingspan to maximize the benefits of boundary layer ingestion (BLI). The number of fans was chosen on the basis of assumed available span width, nacelle length, and inlet and nozzle geometry constraints. To increase BLI benefits and to minimize interference drag between the fan and external flows, contiguous "mail-slot" inlets, high-aspect-ratio slot nozzles, and span-wise-continuous upper nacelles were adopted. Five outboard low-pressure-ratio fans on each side of the vehicle are used for powered lift and six center fans are used as pitch effectors at take-off rotation. For producing powered lift, upper surface blowing (USB) is deemed to be better than internally blown flap (IBF), because of structural and mechanical simplicity. Based on the baseline 12-engine CESTOL concept thrust requirement, the total shaft power for the vehicle at sea-level static conditions is assumed to be approximately 84 000 hp (horsepower (63 MW)) and the total available shaft power at cruise is assumed to be 25 000 hp (19 MW), which corresponds to approximately 1500 hp (~1.1 MW) for each fan at cruise. The wing-tip-mounted engine-core/turboelectric generator is also analyzed and the estimated effective bypass ratio (EBPR, ratio of mass flow rate through all fans to rate through engine core) for the whole propulsion system is approximately 10, which is higher than that of present turbofan engines (and of the 12-turbofan system), promoting fuel efficiency.

Although this kind of distributed propulsion concept, with a small number of turboelectric generators driving numerous electric fans, could be applied to other vehicle architectures (e.g., conventional tube and wing aircraft), the concept is perhaps most naturally applied to the current CESTOL vehicle configuration to reduce fuel consumption, noise, emissions and field length as noted before. Nevertheless, the following are identified as possible advantages of using a turboelectric drive system on an arbitrary "platform":

Figure 2.—A notional distributed turboelectric propulsion CESTOL vehicle concept using 16 distributed electric fans driven by superconducting motors with power provided by two wing-tip-mounted turboelectric generators.

- Decoupling of the propulsive device from the power-producing device. This is the major departure from the current state-of-art aircraft vehicle/engine design, possibly enabling unprecedented performance and design flexibility of the air vehicles. The turbine-engine-driven generators and the electric-motor-driven fans can be located at their optimum locations in the aircraft to maximize total vehicle performance and operation.
- High fuel efficiency due to high EBPR. EBPR is defined as the ratio of mass flow through all fans to the mass flow through the engine cores.
- Speed of the power turbine shaft in the turbine engine independent of the propulsor shaft speed—the electrical system functions as a gearbox with an arbitrary gear ratio. With the addition of power electronics, the two shaft speeds can change independently, giving the effect of a variable ratio gearbox. This allows the shaft speed of the power turbine in the core engine to be optimized without the usual concern that a low fan pressure ratio requires a low engine shaft speed (because of blade tip speed constraints), which increases the size and weight of the power turbine in direct-drive turbofan engines.
- Minimal engine core jet noise due to maximum energy extraction to provide power to remotely located fans.
- Symmetric thrust in the event of a turbine engine or generator failure. All fan modules could continue operating at a reduced but symmetric thrust with the electric power from the remaining turbogenerator using a common bus network.
- Asymmetric fan thrust available for yaw control because of the fast response electric motors. The fan power, and hence thrust, on one side of the aircraft can be increased and that on the opposite side reduced, keeping the total power from the turboelectric generators constant. Thus, the total thrust can remain constant while yawing the vehicle.
- Use of alternative fuel, for example, hydrogen or electrical power sources such as fuel cells. Cryogenic hydrogen, used as fuel, could provide the required cooling to maintain superconductivity in the electric generators and motors.
- Large electrical power off-take capability for in-flight and ground use.

Furthermore, the following are identified as possible “vehicle specific” advantages for the currently proposed propulsion concept:

- Lower TSFC with large engines and electrically driven multiple fans than with the multiple small turbofans used in the baseline CESTOL configuration
- Higher propulsive efficiency via continuous spanwide boundary layer flow ingestion and wake fill-in with the fan thrust stream

- Direct powered lift through continuous spanwide USB using low-pressure fan air
- Very low community noise using low-pressure ratio fans and airframe shielding
- Minimal engine rotor blade burst impact on passengers and vehicle structure due to the wing-tip location of the turboelectric generators and the numerous small fans mounted on the rear top side of the vehicle
- Reduction of lift-induced drag and of wake vortices due to the wing-tip location of the engine cores (ref. 19)
- High engine core inlet pressure recovery similar to conventional aircraft podded engine installation
- Lower propulsor nacelle structural weight due to absence of sudden internal pressure rise (hammer shock) from engine core stall
- Use of conventional low-temperature material on thrust vectoring mechanism due to “cold” fan air discharge
- Lower wing structure weight through better load distribution with wing-tip-mounted engine core and distributed span-wide fan installation (ref. 20)
- Low cabin noise due to remote location of engines and propulsors away from the passenger cabin area
- Easier maintenance access to the gas turbine and electric generator than with the embedded engine configuration

However, using a distributed turboelectric propulsion system with superconducting devices may present adverse effects in overall vehicle performance and operation. The following are identified as possible drawbacks of the electrically driven system and of the newly proposed vehicle:

- Weight increase due to core generators, motors, and balance of the superconducting system
- Possible nonlinear aircraft control laws due to interactions between the external aerodynamics and the propulsion system
- System complexity due to additional new technology
- Operational difficulties with superconducting parts and cryogenic fluids
- Ice, snow, rain, etc., ingestion by the upper surface BLI mail-slot inlet

It will be necessary to use superconducting motors and generators rather than conventional motors and generators in the aircraft propulsion system to reduce the weight fraction of the propulsion system. Conventional electric generators and motors are far too heavy to be used on a large transport air vehicle (ref. 21). A description of the superconducting system is presented in the next section.

III. Superconducting Electric Drive System

The use of gas-turbine-driven generators to supply electric power to motor-driven propulsive fans adds considerable flexibility to the propulsion and vehicle architecture. As noted above, the electric components function as a gearbox allowing the turbine engines to run at high speed, independent of the fan-shaft speeds. Beyond functioning as a simple gearbox, the electric components can function as a continuously-variable-ratio gearbox with the addition of a solid-state converter. This would permit the turbine engines to run at the most effective shaft speed regardless of the required changes in the fan-shaft speed as airspeed, altitude and noise limits change. Higher part-load efficiency can thereby be achieved. However, in this initial paper, we consider only a fixed speed ratio, which can be achieved without using a solid-state converter. Figure 3 illustrates the components of a turboelectric propulsion system, including the optional power converters.

Superconducting Motors and Generators

Superconducting materials lose all their electrical resistance below a “critical” temperature and can carry high current in small wires or tapes, leading to light, compact, very efficient motors and generators. The operating temperature required for superconducting windings is somewhere between 20 K (the normal boiling point of liquid hydrogen) and 65 K (somewhat below the normal boiling point of liquid nitrogen). The state-of-the-art of cryogenic and superconducting motors and generators is reviewed in references 22 to 24. Machines as large as 35 MW output (ref. 25) and as fast as 15 000 rpm have been tested or designed. The higher performance machines are intended for military applications, but prototypes for commercial machines are beginning to appear. High-temperature superconducting (HTS) machines for aircraft propulsion have previously been discussed, primarily with “tube-and-wing” aircraft in mind (refs. 21 and 26).

For turboelectric aircraft propulsion, motors and generators with HTS windings on both the rotors and the stators are envisioned. In most state-of-the-art machines that are called superconducting today, only the rotor windings are superconducting. The stator windings, which are the high-power windings where most of the losses occur, are made of copper and operate at room temperature. As of this writing, only a few small experimental machines have been made with superconducting stators. The reason is that, whereas the rotor carries direct current and dissipates little power, the stator carries alternating current (AC) and has losses that depend on the fineness of the filaments in the superconducting composite wire in the winding. Reducing those losses requires some technology development. It appears reasonable that the AC losses in a superconducting stator can be reduced to less than 0.1 percent of the machine’s output power, with a developmental goal as low as 0.01 percent.

The electric power would be carried from the generators to the motors by HTS transmission lines. Such lines are presently being tested in the electric grids of congested urban areas. They can carry hundreds of megawatts of power with less than 10 kg/m of mass and only a few W/m of loss (ref. 27).

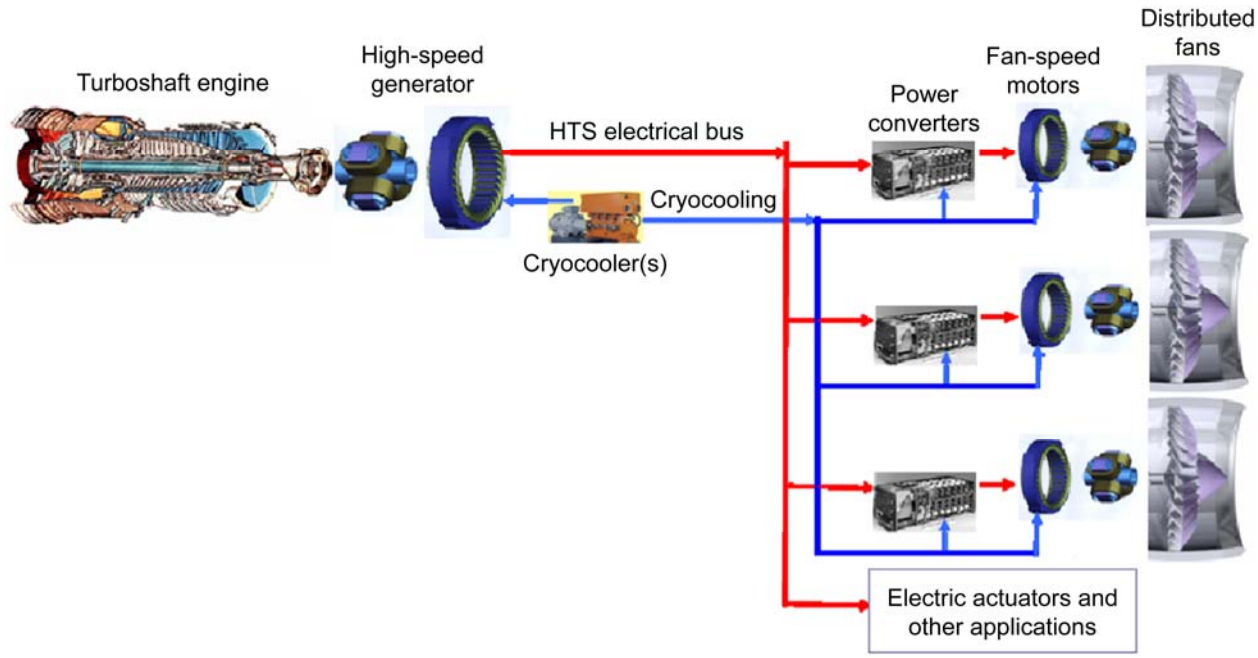

Figure 3.—Components in a turboelectric propulsion system, schematically illustrated (not to scale). Motor and generator rotors and stators are axially displaced for clarity.

Refrigeration Options

The low temperatures required for the electrical components can be viewed as analogous to the lubrication required for a gearbox. Both are required to remove waste heat from the power transferring components. In the electrical case, this removal might be achieved in three different ways. If future aircraft are liquid hydrogen fueled, that fuel can cool the electrical components before being burned in the turbine engines. That refrigeration mode entails minimal weight or efficiency penalty and could enable turboelectric propulsion even with motors and generators that employ cryogenic, but nonsuperconducting, pure-metal conductors in their stators. On a purely jet-fueled aircraft, refrigerators must be used. They may be major components, depending on the efficiencies and on the weight per input power of the refrigerator. As discussed below, reasonable technology developments are required to make the refrigeration system manageable. An alternative for primarily jet-fueled aircraft is to carry only enough liquid hydrogen (with a reserve) to cool the electric system and then to use the hydrogen as fuel, so it would contribute to the aircraft's total fuel complement. The stored liquid hydrogen would represent less than 10 percent of the total fuel heating value on the aircraft, if the electrical losses are reasonably low.

The weights and efficiencies of the electrical components of a turboelectric propulsion system will depend strongly on the level of technology development over the next 20 years or so (especially with respect to cryogenic refrigerators and AC tolerant superconductors). While there is reasonable basis to expect that the assumed technology development can be achieved, it is by no means assured. Inadequate developments of lightweight cryogenic refrigerators would make tanked liquid hydrogen the preferred cooling option. If superconductors with sufficient AC tolerance are not developed, then turboelectric propulsion could still be an option on liquid-hydrogen-fueled aircraft.

Preliminary Weight, Efficiency, and Performance Estimates

In spite of uncertainty of the future level of refrigerator and AC superconductor technology, we present some weight and efficiency estimates that are based on the level of development that we expect for all-superconducting generators and motors. Weights as a function of power, based on electromagnetic and loss analyses from references 28 to 30 and structural weight estimates, are shown in figure 4. Optimization was performed to minimize motor (or generator) weight plus refrigerator weight. The refrigerator, with our assumptions, weighs ~70 percent as much as the motor or generator that it cools. Efficiencies, including the refrigerator power, are at least 99.4 percent. Figure 4 shows that 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 3 among three propulsion systems: a 16-fan turboelectric propulsion system, 16 independent small turbofan engines, and 2 large conventional turbofans. The core engine and generator in the turboelectric system were uprated 0.9 percent to 42 380 hp to compensate for the 1 percent loss in the electric system at

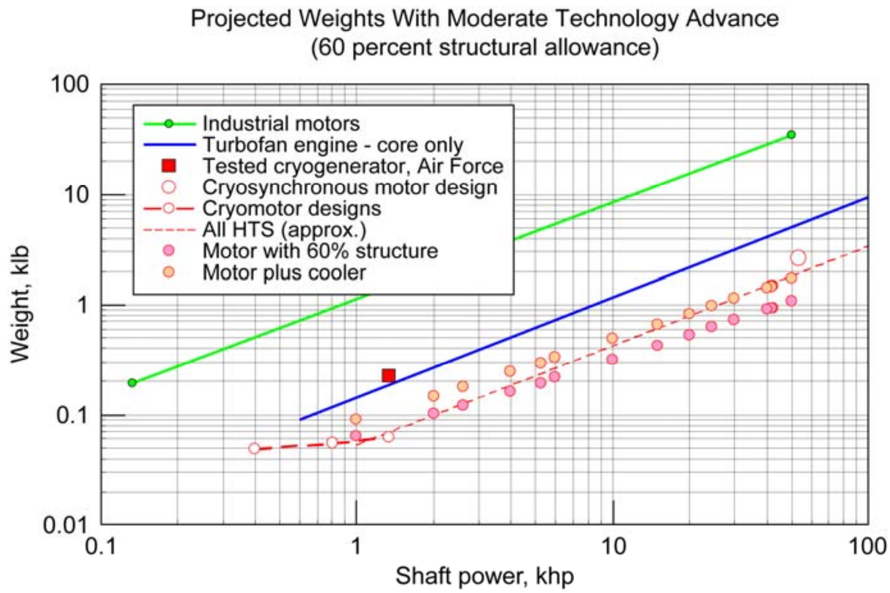

Figure 4.—Weights of turbine engine cores and various types of motors and generators as functions of power. Assumed cryorefrigerator mass is 3 kg/kW-input and superconductor characteristic dimension for alternating current loss computation is 12 µm.

take-off conditions, but the core weight estimate was reduced (from the value typical for a turbofan engine) because of an assumed one-third reduction in low-pressure shaft and power turbine weight due to higher shaft speed and a shorter power shaft. The turboelectric system weighs 5000 lb (2300 kg) more than the 16-engine system but has 9 percent lower TSFC including the 1 percent electrical and refrigeration loss at takeoff. (The electrical loss at cruise would be lower, due to much lower required refrigerator power at cruise, but the take-off efficiency is used to make the estimates that follow.)

Table 3 shows a comparison of different propulsion systems (16 turboelectric distributed fans with 2 cooling options, 16 conventional small turbofan engines, and 2 conventional large turbofan engines) with the same thrust requirement. Weights exclude propulsors (fans), which would have similar total weights in all systems. TSFC values shown in table 3 are based on best present-day values for the engine size. Refrigerator weight is based on 5 lb per hp input and 30 percent efficiency and HTS AC losses on a 12-µm filament characteristic dimension.

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 percent, or 3000 lb (1400 kg) less mission fuel. Thus, the slightly heavier turboelectric aircraft would have a net fuel savings of roughly 7 percent on each flight, compared to the baseline aircraft powered by 16 small engines. This estimate

TABLE 3.—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[a]	**0.63**
Conventional large nondistributed turbofans	Two 42 000-hp engine cores	**8700 (4000)**	----	**0.57**

[a]Relative to 42 000-hp engine core at 0.57 thrust specific fuel consumption.

will be refined as the study progresses with a detailed mission analysis. Known omissions in the weight estimates of the electric system include the superconducting transmission lines (estimated at only 3 percent of the turboelectric system weight) and other power management and distribution components.

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 percent (calculated from the efficiency advantage of the large engines, without accounting for the replacement of jet fuel energy with liquid hydrogen energy), and TOGW drops by 560 lb (255 kg). This estimate does not include corrections for the weight of the liquid hydrogen (which would provide about 5 percent 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.)

A comparison between the turboelectric case and two large (presumably podded) turbine engines can be made based on the numbers in table 3. 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 percent 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 STOL capability and only limited noise reduction, two important corners of the trade space, and none of the other potential benefits and capabilities mentioned above.

IV. Further Study and Research Directions

As previously mentioned, the distributed electric propulsion concept is not limited only to HWB aircraft but also could easily be applied to other vehicle configurations such as traditional tube and wing aircraft and tilt rotor aircraft. However, in order to achieve maximum benefits, it will be necessary to design an aircraft with greater emphasis on propulsion airframe integration right from the conceptual design stage. Moreover, to achieve all the benefits described in the above sections, a diligent research and development effort is required on the superconducting system for aircraft application. Besides additional modeling and analytical refinement of the electromagnetic, structural, and thermal aspects of the superconducting motors and generators, development is required on subsystems and auxiliary systems. The largest potential technology development payoff is in reducing the AC losses in HTS motors and generators. Those losses must be well below 1 percent in each machine to keep the required refrigeration reasonable. (Note that large generators already exceed 99 percent efficiency, even at room temperature.) The several types of AC losses that occur in HTS materials can be reduced by reducing the size of HTS filaments in the composite conductor and twisting them. An order of magnitude or more decrease in size from present practice is required. Such dimensions (and smaller) have been achieved in the older low-temperature superconductors, indicating promising approaches for the newer HTS materials. In addition, the required refrigeration is proportional to the above losses, as is the required input power to drive the refrigerator and hence the refrigerator weight. Present cryogenic refrigerators of the required capacity have not been designed with low weight as an objective and must reach significantly lower weight per input power to be acceptable on aircraft. A factor of 3 to 6 reduction from the present best machines is desired. Improvements in refrigerator mechanical efficiency would also be effective but may be more difficult to achieve. As noted above, no refrigerators would be required on liquid-hydrogen-fueled aircraft or on ones carrying enough liquid hydrogen inventory to cool the electric components.

A wide range of analyses and system studies would be beneficial. To determine the optimal fan pressure ratio and other propulsion system parameters, a detailed mission analysis is needed, which would include optimizing both the fan propulsor modules and the thermodynamic cycle of the engine. Other propulsor options, such as ducted-propeller systems, should be examined. In addition, the basic mission profile needs to be examined to determine the impact of cruise Mach number on mission fuel burn, block times, and direct operating costs for different fuel prices. The unique flexibility of the turboelectric propulsion system is well suited to the examination of a wide range of propulsion and mission options.

V. Concluding Remarks

Two novel transport vehicle concepts based on hybrid wing body configurations have been proposed under NASA's Subsonic Fixed Wing project to achieve low-noise and cruise-efficient short take-off and landing (CESTOL). The first vehicle concept was a high subsonic short take-off and landing (STOL) capable hybrid wing body airframe with multiple, small, partially embedded conventional engines. The vehicle characteristics and performance data of that aerodynamically trimmed and low-noise concept vehicle were briefly reviewed in this paper. The present proposed vehicle is similar to the first but uses distributed superconducting electric fans, powered by two wing-tip-mounted turboelectric generators, to lower the fuel consumption, noise, and emissions even further, as suggested by NASA's SFW N+3 goals. Descriptions of the vehicle, the superconducting system, and the propulsion system were presented with some zeroth-order weight and efficiency comparisons to the multiple turbofan system. Preliminary analysis suggests that fuel savings may be greater than 6 percent for a turboelectric propulsion system compared to distributed discrete turbofans. Beyond fuel savings, however, turboelectric propulsion systems introduce a very high degree of aircraft design and operational flexibility as a result of decoupling power production from power consumption. Lightweight superconducting generators, motors and power cables allow a small number of 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 turbofans or with distributed propulsion systems that employ mechanical power distribution by gearboxes and shafts.

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