# Study of Current and Near-Term Technology in Electric Aerospace Propulsion

All units converted to SI units, where possible.

## Introduction

Commercial aerospace is an industry facing: an environmental crisis[1]; the constant pressure to produce planes that can fly farther, on less energy; and the need to reduce development time. This review discusses the future of electric aerospace propulsion by covering the advantages and disadvantages of electric propulsion. It will also cover the direction of the industry along with three different motors and their performance.

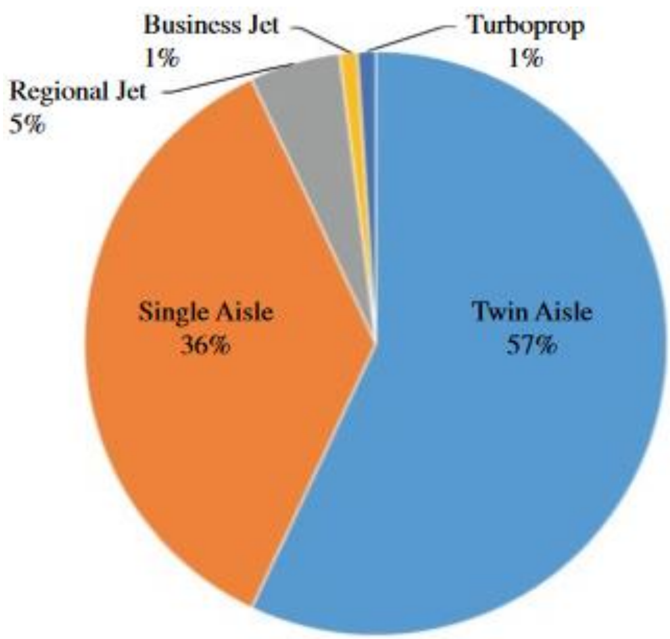


*Figure 1: Worldwide fuel burn by aircraft type. Single and twin-aisle planes are predominantly commercial, from S. Farokhi [1, p. 326]*

Permanent magnet synchronous motors are the dominant choice in electric-aerospace propulsion[2]. This preference is due to the high power to weight ratios possible with high pole or high conductance motors. Permanent magnets do not saturate as quickly as soft-magnetic materials. In one example, replacing a permanent magnet with a soft-magnetic field rotor would require a flux density of 14T[2].

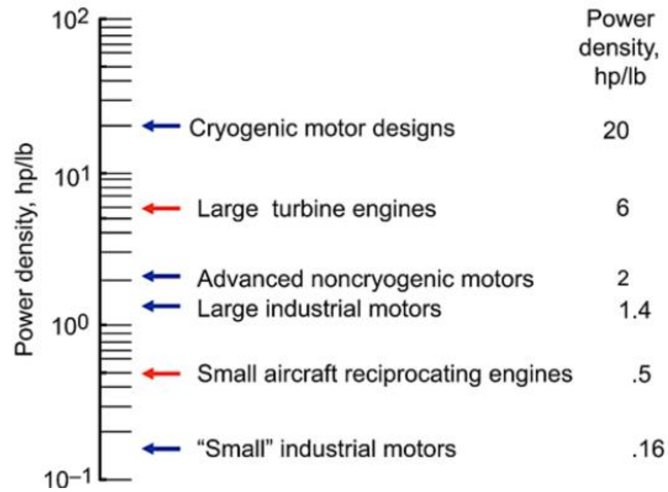


*Figure 2: The state of the motor industry in 2005, from D. Johnson[4]*

A 2005 report from NASA states that the earliest motors capable of meeting commercial aerospace power to weight requirements will be “Cryogenic” or “Superconducting” motors[4]. As the name implies, superconducting motors rely on cooled superconducting materials to improve their performance to weight ratios. These predictions were followed by NASA’s N-3X proposal, a blended wing body proposal that could perform on par with a Boeing 777-200LR using 30% of the energy[5]. To date, superconducting motors have not advanced noticeably since the previously mentioned NASA study and N-3X proposal[6]. Similarly, blended wing body planes have met resistance from manufacturers, their priorities, and industry needs that supersede flight efficiency[3][7].

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[1] Aviation accounts for up to 4% of global anthropogenic greenhouse gas emissions[1, p. 325]

[2] The motors in personal drones and hobbyist planes are excluded from this study.

[3] Blended wing bodies are not scalable. Boeing and Airbus’s preferred method of elongating airframes to provide market flexibility would disappear[7]. Given that aerospace manufacturing facilities are already some of the largest buildings in the world by volume[8], adding more complexity to their manufacturing lines is not an option.

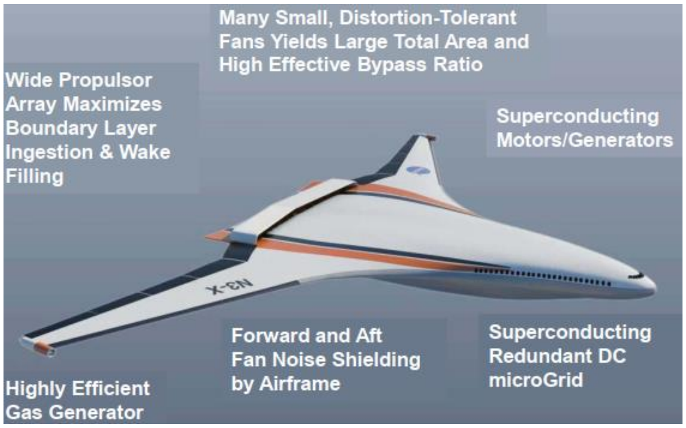


*Figure 3: NASA'S N-3X proposal. This frame geometry is an example of a blended or "hybrid" wing body, from Felder[5]*

# The Future of Electric Aerospace Propulsion

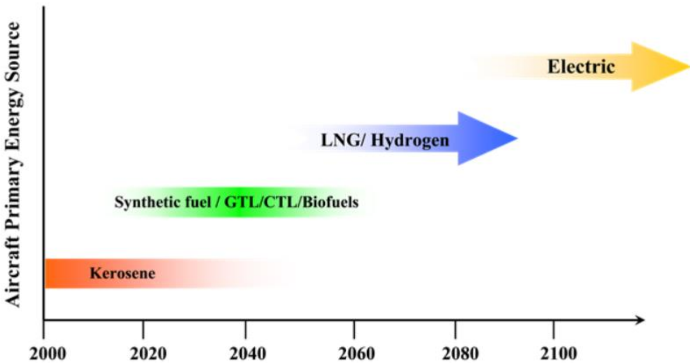


*Figure 4: The anticipated direction of aerospace energy sources for the next century, from RAO, A. G.[9]*

## Advantages to Electric Propulsion

Electric motors have several attractive properties lending them to the aerospace industry. Compared to jet engines, motors are scale independent. The ability of motors to retain their performance over a larger range of sizes than turbofans (jet engines) lends itself very well to manufacturing. The N-3X exploited the ability to run many motors in parallel to exploit aerodynamics in ways that conventional airframes cannot[10]. The efficiency of today's advanced turbofans can reach 75%, whereas reasonable expectations for motor efficiencies are closer to 97%. The thrust to weight ratio of a motor is significantly higher than other turbofan alternatives. Motors retain their efficiency in partial loading by altering the frequency in synchronous motors. The environmental impact of motors is a significant improvement on turbofans; they are quieter and a motor is a zero-emission[4] form of propulsion when connected to a battery[1, p. 325].

## Disadvantages of Electric Propulsion Today

Current energy storage devices have motors at a disadvantage to turbofans. Batteries are not an option for today's commercial aerospace industry and other fuel sources. Kerosene (jet fuel) has 68 times the energy per unit mass of today's best batteries[5] (see Table 1 and Table 2). Current batteries require thermal management to prevent ignition[1, p. 325]. Finally, batteries must be carried through the flight in its entirety whereas fuel is expended through the duration of the flight, leaving the aircraft lighter as it flies.

*Table 1: Anticipated battery density in 10-20 years, from S. Farokhi[1, p. 315]*

| **Battery energy density** | **Wh kg$^{-1}$** |
|---|---|
| Today[a] | 120–200 |
| Boeing (SUGAR Volt) | 750 |
| Rolls-Royce | 750 |
| In 20 yr | 1000 |
| MIT forecast in 10–15 yr | 1000–1500 |

Alternatives to batteries require an intermediary conversion system, an engine and a generator, to convert chemical energy into electromechanical energy. Such systems are assumed to be the next step in the progression from a turbofan-only system to an electric motor-only system as demonstrated by the N-3X and Figure 5[11]. Generators and engines add dry weight to the airframe, cutting into cargo.

[4] Ozone excepted.

[5] There is some hope that those numbers will improve dramatically in the coming decades but the most optimistic solutions remain well below kerosene[1, pp. 314–315]

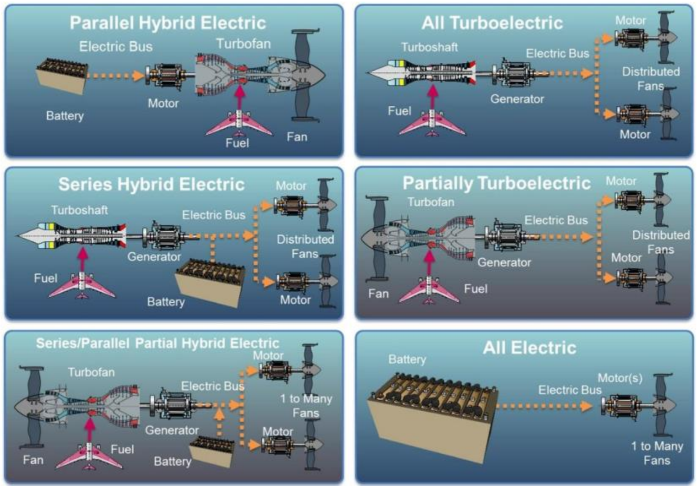


*Figure 5: Alternative electric power train models, proposed by the N-3X team, from Bowman[11]*

Motors demand high voltage transmission for the power and speeds necessary for competitive propulsion[2]. However, breakdown voltages at high altitude[12] will limit the available electric potential to 1000V[2]. Figure 6 highlights a growing trend towards electrification already present in aircraft however, the power supply necessary for aerospace propulsion is of a different order of magnitude, more in line with power engineering than systems that the aerospace is likely to be familiar with. Motors are likely to be mounted to the wings, where fuel is traditionally stored, see Figure 5, meaning that these high power lines will be near fuel storage. The combination of these factors will demand increased attention to power fault prevention and new approaches to aircraft safety.

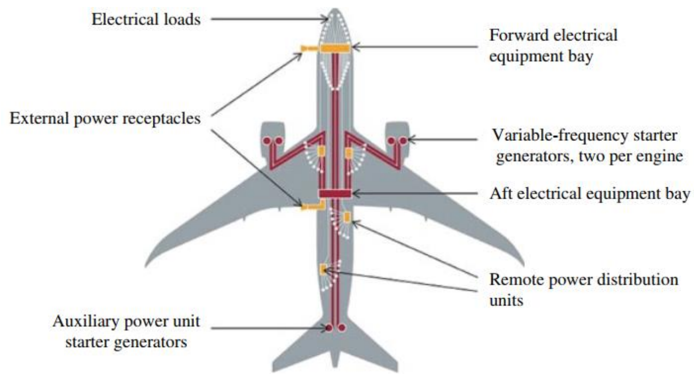


*Figure 6: A high-level electrical layout of the Boeing 787, from Farokhi[1, p. 313]*

## Loss of Traditional Thrust Sources[4]

Turbofans do not produce thrust solely through the fan [1, pp. 69–73]. It is estimated that the ignition of fuel and ejection from the turbine accounts for roughly 20% of the net thrust of today's ultra-high bypass turbofans. It is thought that a motor could overcome this by increasing the power to the fan by 25%[4]. There is no evidence that this has been tried and compelling reasons to think that matching turbofan performance by increasing engine output not be so simple. Propellers and geared turbo-props[6] suffer from performance losses near the supersonic speeds that commercial jet-liners fly as close to as possible[1, p. 94].

## Near Future Path to Electric: Hybrid Paths[1], [5]

*Table 2: Energy densities in terms of mass, JP-4 is jet-fuel, aka kerosene, from S. Farokhi [1, p. 224]*

| Fuel | JP-4 | Propane | Methane | Hydrogen |
|---|---|---|---|---|
| Hydrogen content | 14.5% | 18.8% | 25% | 100% |
| Lower heating value | | | | |
| kcal/g | 10.39 | 11.07 | 11.95 | 28.65 |
| MJ/kg | 43.47 | 46.32 | 49.98 | 119.88 |
| BTU/lbm | 18 703 | 19 933 | 21 506 | 51 581 |

Liquid methane ($LCH_4$) and liquid hydrogen ($LH_2$) are the current favorites for hybrid-electric aerospace applications. Both fuels share certain advantages that lend them an edge against kerosene as a fuel source in hybrid electric applications. In their liquid state $LH_2$ and $LCH_4$ have cryogenic applications, meaning that they can be used to cool superconductive motors instead of solely relying on a refrigerant system[10]. In this scenario, $LH_2$ is

[6] Turbo-fans with a traditional propellers and no direct thrust from the turbine

cold enough to cool the superconductors without any auxiliary refrigerant, whereas the $LCH_4$ will require some refrigerant to meet the critical temperatures of current superconductors.

The energy per unit mass densities of both liquid hydrogen and liquid methane make them desirable fuel sources. $LH_2$ is nearly 3 times as energetic per kilogram than kerosene. The trade-off is that $LH_2$ density per unit volume is ¼$^{th}$ that of kerosene, meaning aircraft will need to be significantly larger to hold the same amount of energy (higher dry weight) even as they require less fuel mass. $LCH_4$ follows a similar, if milder, pattern of higher density per unit mass while requiring more space[1, p. 309].

The storage of both fluids is complicated, requiring constant compression and refrigeration. $LH_2$ is also extremely flammable which may exclude it as an option in any aerospace application, especially when it is being used as a coolant in a high voltage environment. The inherent advantages of LH2 may not overcome the inconvenience of storage, handling, and safety concerns[1, p. 309].

## Comparing the Performance of High-Bypass Turbofans to Electric Motors[4]

To understand where the aerospace industry is in terms of power per unit mass, the GEnx-70B, from the 787-9 [14] will be used as the industry benchmark. Engine power is not traditionally published[7]. The conversion factor of 1.25 $\frac{hp}{lbf_{thrust}}$ listed in D. Johnson to convert from thrust to hp will be used[4]. Figure *7* predicts the max weight of any motor that might feasibly replace the GEnx-70B. The maximum weight of that motor must include any auxiliary equipment that the turbofan did not require; larger generators, inverters, and cooling systems, for example. Table 3 predicts that a motor replacement for the GEnx-70B will have a maximum weight of 2310kg and a performance to weight ratio of 28.2kW/kg.

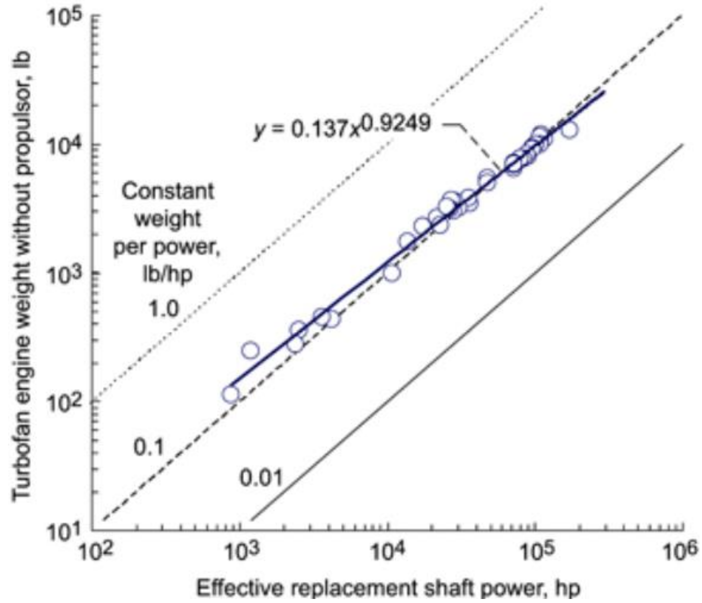


Figure 7: A predictive model for turbofan replacement requirements. Courtesy of: *D. Johnson, [4, p. 3]*

*Table 3: Turbofan to motor replacement for a 787-9 turbofan (the GEnx-70B). All values derived from Norris, et al[14]*

| | **US Customary** | | **Metric** | |
|---|---|---|---|---|
| Thrust | 69800 | lbf | 310 | kN |
| Power Equivalent | 87300 | hp | 65100 | kW |
| Mass Replacement | 5090 | lb | 2310 | kg |
| Power to Weight/Mass Ratio | 17.2 | $\frac{hp}{lb}$ | 28.2 | $\frac{kW}{kg}$ |

## Conventional, Non-Cryogenic, Motors

Barring a dramatic change in their relative performance, it is unlikely that the commercial aerospace industry will ever adopt conventional motors over superconducting motors. The theoretical power to weight potential of superconducting motors exceeds the inconvenience of cooling superconducting materials. However, increasingly competitive power in conventional motor designs indicates that they may see use in personal and short-range aircraft. Furthermore, there are several novel conventional motors designs at the personal aircraft size that have escaped the notice of teams designing superconducting motors.

As discussed in the introduction, aerospace designs exclusively use permanent magnet synchronous

[7]Listed weights include hardware that motors would require (fan blades) and report their output in static thrust at sea level, not power.

motors[15]. These motors all have relatively high pole quantities, researchers suggest that designers start with 14 to 18 poles and refine from there[8]. Atypical slot and phase numbers are not unheard of, one example had 14 poles, 15 slots, and 5 phases, see Figure 8 and Figure 9[16]. There are advantages to high pole quantities that extend beyond performance. Increasing pole and slot quantities reduces flux weakening and improves fault tolerance[9][10].

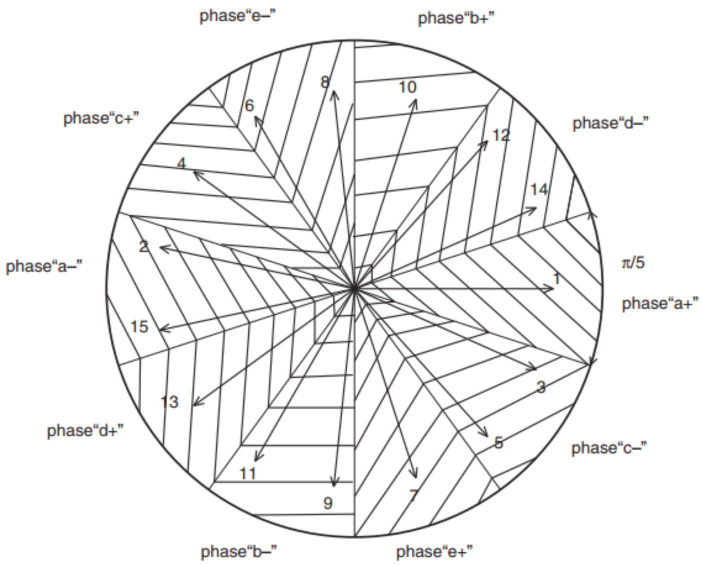


*Figure 8: Star diagram of a 14 pole, 15 slot, and 5 phase motor, from I. Bouzidi[16]*

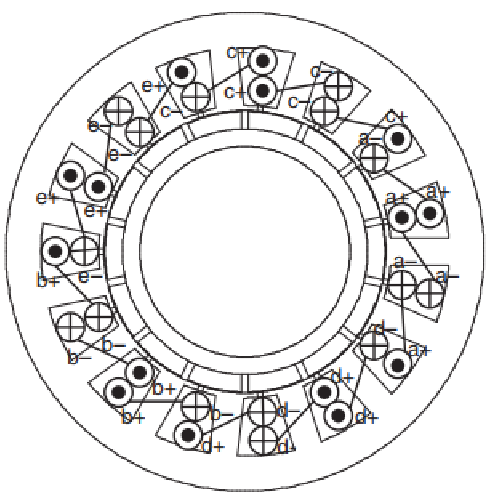

*Figure 9: 2D distribution drawing of a 14 pole, 15 slot, and 5 phase motor from I. Bouzidi[16]*

## Examples:

### Siemens, for the DA 36 E-Star 2 Motor Glider:

Siemens released a report describing a 5 kW/kg motor, gearbox and inverter inclusive, in 2015. This established the then highest power density for any motor in the world (Figure 10)[17]. This motor is rated to 260kW and weighs 24.4kg. Siemens believes it can be easily scaled to 1MW.

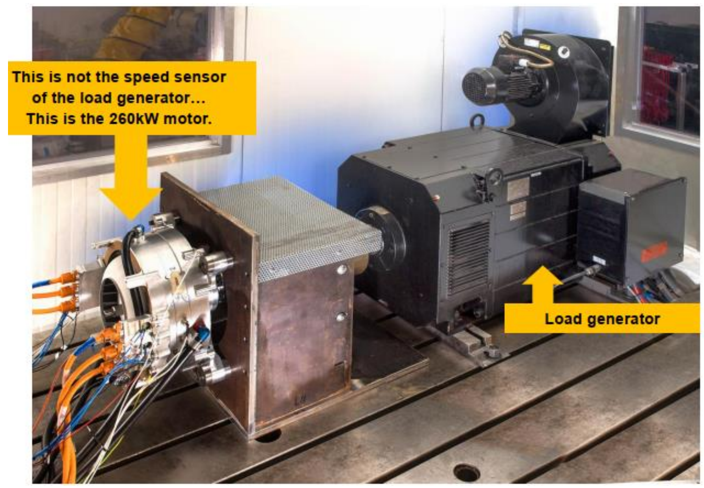


*Figure 10: At 5kW/kg, the engineers on the team lost a sense of perspective, from K. Petermaier[17]*

There are plans for a 7kW/kg motor with a rated output of 170kW. Both motors rely on high-performance permanent magnetic materials, utilize high electric frequency, and flat wire windings to attain their performance. Higher coolant temperatures, 90-100° C, are utilized to minimize cooler size and weight. Structural optimization and composites are essential to weight reduction[15].

[8] These pole quantities lend these motors a functional similarity to radial engines that is not explored.

[9] This approach to reducing flux weakening has been overlooked by current superconducting motor research

[10] By addressing fault tolerance these motors overcome an obstacle to the adoption of electric aerospace propulsion

*Figure 11: A 7kW/kg motor proposed by Siemens, from Petermaier[17]*

## Engineers at the University of Sfax, Tunisia and the University of Padova, Italy[15]

An FEA analysis was performed based on the 14 pole, 15 slot, and 5 phase motor shown above. This analysis reported a power to weight ratio of 3.6 kW/kg achieved using an electric frequency of 240hz and the geometry shown in Table 4. There is a significant degree of torque ripple, oscillating between 200-240Nm.

*Table 4: Parameters and Geometry of the 14 Pole, 15 slot, 5 phase motor, from I. Bouzidi [15]*

| | | |
|---|---|---|
| number of pole pairs | $p$ | 9 |
| number of phases | $m$ | 5 |
| number of series conductors per slot | $n_c$ | 10 |
| number of slots | $Q$ | 20 |
| width of the stator tooth | $w_t$ | 12mm |
| slot opening | $w_{so}$ | 3mm |
| slot height | $h_s$ | 38mm |
| slot opening height | $h_{so}$ | 2mm |
| width of the insulating paper | $ins$ | 0.3mm |
| fill factor | $k_{fill}$ | 0.4 |
| stator/rotor back iron height | $h_{bi}$ | 10mm |
| air-gap | $g$ | 0.5mm |
| thickness of the magnet | $h_{pm}$ | 10mm |
| space opening between two magnets | $w_{ro}$ | 2mm |
| cage height | $h_{cage}$ | 5mm |
| air layer (separator: cage/stator back iron) | $f_r$ | 0.03mm |

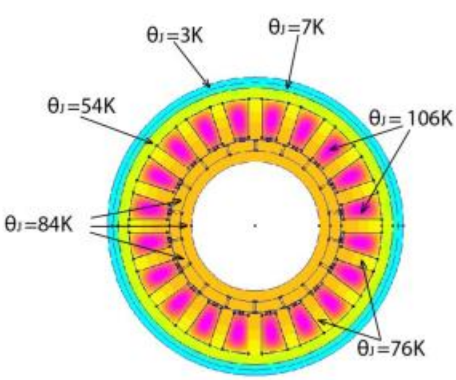


*Figure 12: Temperature distribution for the design, before optimization, from I. Bouzidi [15]*

Special attention was paid to temperature variation within the motor, which ranged from ambient to +100°C before optimization. The max permissible temperature in the permanent magnets was not to exceed +155°C to prevent demagnetization. Optimizations were suggested that reduced stack height by 25mm and allowed for higher current to be passed through the armature winding. This reduced the net weight by 23%.

*Table 5: Operating optimizations suggested by the design team, $L_{min}$ is stack height, from I. Bouzidi [15]*

| $L_{min}$ (mm) | $\hat{I}$ (A) | $T_{em}$ (N.m) | $\theta_J$ (K) |
|---|---|---|---|
| 86 | 240 | 216 | 155 |

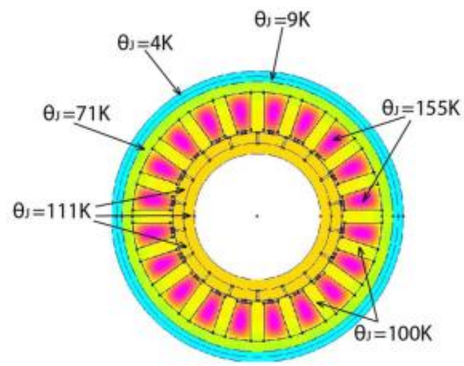


*Figure 13: The temperature distribution after optimization, from I. Bouzidi [15]*

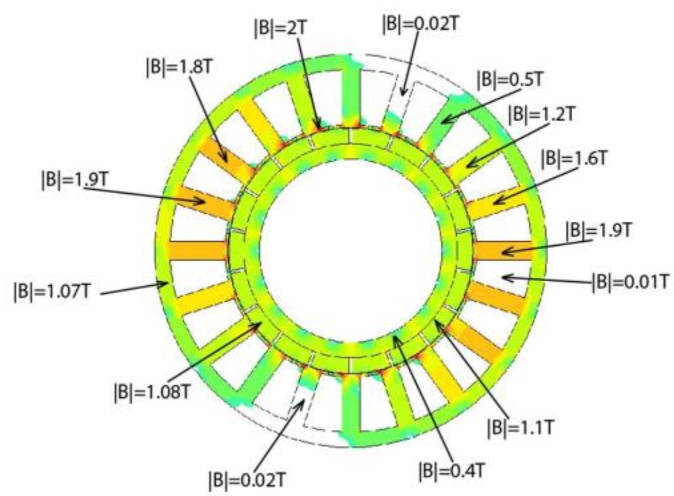


*Figure 14: Flux density of the designed 14-pole, non-superconducting motor, from I. Bouzidi [15]*

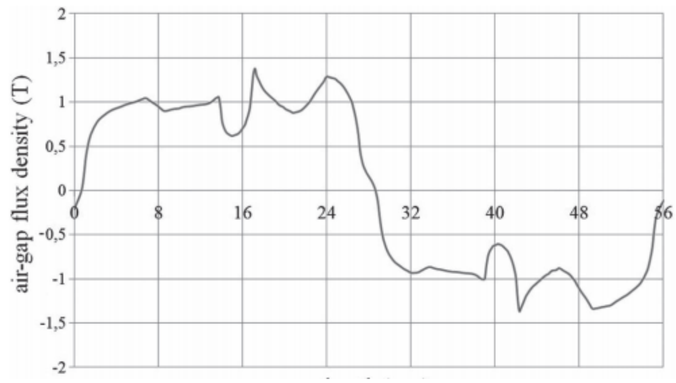


*Figure 15, Air-gap flux density waveform for the 14-pole motor at a current of 187A and a stack length of 111mm, from I. Bouzidi[15]*

To date, these advanced permanent magnet synchronous motors have improved significantly since 2005 in terms of power density, however, their performance remains nowhere near the 28kW/kg necessary power to weight ratio for a GEnx-70B replacement.

## Cryo-synchronous motors, aka superconducting motors[2]

In 2005, NASA released a report containing Figure 2 stating that 32.9 kW/kg was considered a feasible power to weight ratio at the time[4]. It is not clear where this example was found, there is the possibility that it was a rough estimate based on the best conventional motors of the time. Since that report, there has been at least one FEA analysis of a superconducting motor by a UK-based team, performed jointly between the University of Manchester, the University of Lorraine, and Rolls-Royce, shown in Figure 16.

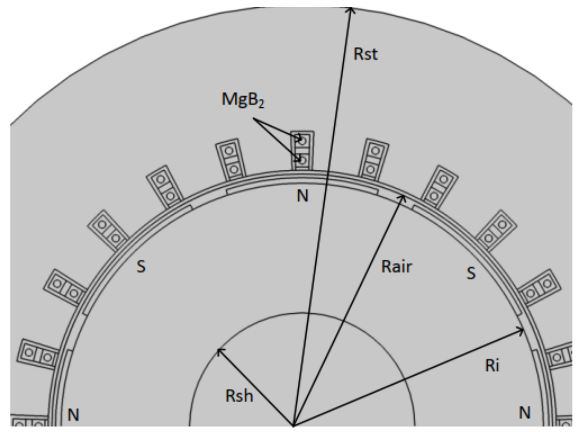


*Figure 16: The generalized model of the PM Synchronous motor used for this study, C. D. Manolopoulos [2]*

*Table 6: Shared Design Parameters, from C. D. Manolopoulos [2]*

DESIGN PARAMETERS OF THE AC SUPERCONDUCTING MACHINE

| Quantity | Value | Quantity | Value |
|---|---|---|---|
| Machine power | 1 MW | Number of slots | 24 |
| Mechanical speed | 12,000 rpm | Axial length | 0.3 m |
| Pole pairs | 4 | Shaft radius *Rsh* | 0.07 m |
| Rated Torque | 800 Nm | Rotor iron radius *Ri* | 0.15 m |
| Phase voltage | 800 Vrms | Airgap radius *Rair* | 0.1557 m |
| Phase current | 560 Arms | Outer radius *Rst* | 0.26 m |
| Current per coil[a] | 140 Arms | Turns per coil[a] | 5 |

[a]The rated emf is achieved by using 5 turns per stator coil, with two coils in series and four groups in parallel.

*Table 7: A summary of the superconducting coil used, from C. D. Manolopoulos [2]*

SPECIFICATIONS OF THE $MgB_2$ WIRE USED IN ARMATURE

| | |
|---|---|
| Manufacturer | HyperTech Inc. |
| Superconducting Material | Mono-core $MgB_2$ |
| Critical current density (20 K, 1.37 T) | 1.5 kA/mm$^2$ |
| Voltage criterion $E_0$ | 1 μV/cm |
| Index of power law $n$ | 30 |
| Sheath material | Stainless Steel |
| Resistivity of sheath | 540 nΩm |
| Filament diameter | 0.18 mm |
| Total diameter | 0.36 mm |

Some restrictions for this motor design were outlined immediately. Phase voltage was not to exceed 1000V to prevent breakdown and $800V_{rms}$ was selected as an appropriate compromise to meet this need. The rotor is magnetized out of necessity. It was suggested that a soft-magnetic material rotor would require a field density of 14T to meet the performance requirements of this system[11]. The need for a permanent magnet rotor establishes a pattern seen in all of the aerospace motor designs examined thus far.

[11] This is probably a joke given that they immediately emphasize that the stator conductors never exceed an anticipated flux density of 1.37T in this model.

The entire focus of this study was on the stator. There was no adjustment made to the rotor design. No net mass is listed for the rotor leaving the power to weight ratio of this design an open question. The team acknowledged that there were limits to a standard rotor, stating that in practice a rotor would have to be designed for every permutation of the motor configuration.

*Table 8: Performance of Stator Coils in Different Motor Designs, from C. D. Manolopoulos[2]*

STATOR SUPERCONDUCTING LOSSES FOR DIFFERENT MACHINE DESIGNS

| Superconducting losses[1] | 4-Pole Designs | | 8-Pole Designs | | | |
|---|---|---|---|---|---|---|
| | $AC_4$ | $FD_4$ | $AC_8$ | $FD_8$ | $TFD_8$ | $MS_8$ |
| Outer layer coil (W/m) | 259 | 239 | 269 | 196 | 161 | 13 |
| Inner layer coil (W/m) | 665 | 569 | 478 | 404 | 290 | 43 |
| Total stator loss (active length) (W) | 6653 | 5818 | 5378 | 4320 | 3247 | 403 |

Key: AC-Air core, FD-Flux diverter (2mm), TFD-Thick flux diverter (4mm), MS-magnetic stator, the subscript is the pole number.
[1]All the designs have 1 T magnetic loading and the same electrical loading.

*Table 9: Performance of Different Motor Designs, from C. D. Manolopoulos [2]*

STATOR EFFICIENCY AND WEIGHT FOR DIFFERENT MACHINE DESIGNS

| Design Parameter[1] | 4-Pole Designs | | 8-Pole Designs | | | |
|---|---|---|---|---|---|---|
| | $AC_4$ | $FD_4$ | $AC_8$ | $FD_8$ | $TFD_8$ | $MS_8$ |
| Output Power (kW) | 925.9 | 925.9 | 850.7 | 909.8 | 967.6 | 1173.7 |
| Mean torque (Nm) | 736 | 736 | 677 | 724 | 770 | 934 |
| Torque ripple (%) | 41 | 150 | 14 | 336 | 430 | 26 |
| Remanent Flux (T) | 27.5 | 25 | 11.5 | 10 | 8.2 | 2 |
| Screening (%) | 0 | 21.4 | 0 | 30.8 | 54.4 | 87.5 |
| St. iron loss (W) | 0 | 1161 | 0 | 3391 | 5598 | 7037 |
| St. $MgB_2$ loss (W) | 6653 | 5818 | 5378 | 4320 | 3247 | 403 |
| St. 'cold' inefficiency[2] (%) | 0.72 | 0.63 | 0.63 | 0.47 | 0.33 | 0.034 |
| St. efficiency (%) | 99.29 | 99.25 | 99.37 | 99.16 | 99.09 | 99.37 |
| St. weight (kg) | 0.5 | 7.7 | 0.5 | 7.7 | 16 | 308 |

Key: AC-Air core, FD-Flux diverter (2mm), TFD-Thick flux diverter (4mm), MS-magnetic stator , the subscript is the pole number, St-Stator active length.
[1]All the designs have 1 T magnetic loading and the same electrical loading.
[2]This is defined as the armature superconducting losses in the cryogenic system as a percentage of the machine output power [6].

There are some interesting conclusions to be made from Table 8 and Table 9. 4-pole systems are not lighter than 8 pole systems but higher pole quantity does impact output power negatively. This decrease in output power does not necessarily correlate with a decrease in efficiency. The team dedicated much of its focus to analyzing stator losses in the superconducting materials. These losses were primarily inductance losses in the stator coils. Flux diverters (steel placed in the air gap) did reduce the exposure to the magnetic flux of the rotor. However, they also reduce the specific performance of the motor and losses in these shielding methods result in reduced net efficiency.

Conclusions from this report are not optimistic about the feasibility of motors with current technology. The magnetized stator has a power to mass ratio less than 4 kW/kg, underperforming conventional motors *before* including rotor mass. The team suggests further research avenues to reduce losses to AC fields: Higher temperature superconductors, improving winding techniques from the five coil and nine strand method, and reducing electric frequency[12].

These suggestions do not reflect familiarity with the high-performance conventional motors of today. The motors built and designed by Siemens and engineers at the University of Sfax, Tunisia/the University of Padova, Italy are universally high-pole, high frequency, and high-phase. There are no compelling reasons to think that such motors would perform poorly when constructed with superconducting material given the simulated results(Table 8 and Table 9). High pole motors suffered some performance losses (8%) offset by;

- increased efficiency
- no changes to their net mass
- significant reductions in stator losses (19%)
- persisting stator heating could be absorbed by $LH_2$ and $LCH_4$ cooling

Johnson[4] estimated that a well-engineered superconducting motor could have a kW/kg performance ratio 10 times that of an advanced conventional motor. Extrapolating, there is some hope that a current technology superconducting motor could incorporate the lessons learned from advanced conventional motors and exceed the 28.2kW/kg ratio estimated in Table 3.

[12] The simulated frequency was omitted from their report. While this value can be derived, it's absence suggests the significance of frequency was overlooked.

# The State of Superconductors Today and Future Research

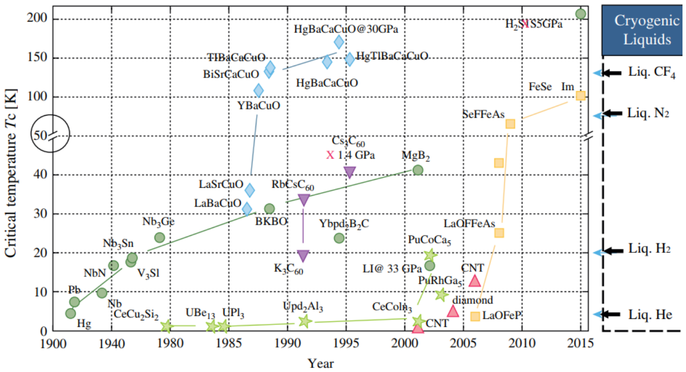

*Figure 17: A timeline of superconductor discoveries, their critical temperature, and the boiling points of significant liquids to the right, from S. Farokhi [1, p. 379]*

The selection of superconductors for a given application is not always clear. Manopolous suggests that their preference for $MgB_2$ was a result of available material data from HyperTech Inc[2]. By contrast, BSCCO (in Figure 17 as BiSrCaCuO) is a popular alternative to $MgB_2$, with a critical temperature[13] above liquid nitrogen. Given how near the BSCCO critical temperature is to $LCH_4$, $MgB_2$ may fall out of favor once superconducting motor designs cease to be theoretical and must be integrated into a broader structure.

There are also newer superconductive materials not discussed in any of the materials covered. FeSe is a recently discovered compound of comparatively abundant materials and has many promising, high temp properties[16]. Carbon nanotubes and graphene have been discussed as superconductors for several years. However, we currently cannot explain the superconductivity of either, discouraging widespread implementation[18].

## Conclusion

There are compelling reasons not to expect commercial all-electric flight in the near-term. Many of the most visible proposals hinge on non-traditional airframes that will struggle in a manufacturing environment. The energy density of batteries remains nowhere near that of kerosene and will remain uncompetitive even in the most optimistic forecasts. Superconducting motors have not visibly advanced since 2005 and the field appears to have been nearly forgotten.

However, there are some hopes that this could change. Innovations in traditional motor designs demonstrate that electric aerospace has a future. There is evidence to believe that superconducting motors could benefit from the lessons of top-performing conventional motors. Current conventional motors are sufficiently advanced to encourage revisiting superconducting motors with a reasonable chance of outperforming current turbofans.


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