“Materials Aspects of Turboelectric Aircraft Propulsion”
Presenter: Gerald Brown
Coauthors: Hyun Dae Kim and James Felder

Abstract:
The turboelectric distributed propulsion approach for aircraft makes a contribution to all four “corners” of NASA’s Subsonic Fixed Wing trade space, reducing fuel burn, noise, emissions and field length. To achieve the system performance required for the turboelectric approach, a number of advances in materials and structures must occur. These range from improved superconducting composites to structural composites for support windings in superconducting motors at cryogenic temperatures. The rationale for turboelectric distributed propulsion and the materials research and development opportunities that it may offer are outlined.
National Aeronautics and Space Administration

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Presenter: Gerald V. Brown
Position: Senior Research Engineer
Coauthors: Hyun Dae Kim, James Felder

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Materials Aspects of Turboelectric Aircraft Propulsion

Presenter
Gerald V. Brown
Senior Research Engineer
GRC Structures & Materials Div.

Coauthors
Hyun Dae Kim, James Felder
The turboelectric approach does not replace the turbine engines or the fans, rather it enables them to be located and optimized independently for the greatest aircraft benefit.

The incentive for higher thermodynamic and propulsive efficiencies remains.
N3-X Distributed Turboelectric Propulsion System

Wing-tip mounted superconducting turbogenerators

Superconducting motor driven fans in a continuous nacelle

Power is distributed electrically from turbine-driven generators to motors that drive the propulsive fans.
Low velocity core exhaust reduces noise.

Forward and aft fan noise is shielded by airframe.

Multiple motor-driven fans ingest boundary layer & give high bypass ratio for low fuel burn and emissions.

Electric power from generators is distributed to multiple fans.

Fans fill in center body wake to reduce drag, fuel burn and emissions.

Electric power distribution to multiple fans is more efficient and lighter than mechanical.

Upper surface suction increases lift coefficient at TO & delays separation.

High-speed core engines have fewer turbine stages than direct fan-drive cores.

Small diameter core engine inlets are acoustically treatable.

THE TURBOELECTRIC APPROACH CONTRIBUTES TO EVERY CORNER OF THE SFW TRADE SPACE
Rationale for turboelectric distributed propulsion

Turboelectric components

Selected areas of materials needs and opportunities

- Engine materials for high thermodynamic efficiency and light weight—- an ongoing need
  - High-temp disks, blades & coatings, etc
  - Materials to reduce engine weight

- Low-AC-loss conductors for motor and generator stators

- Composite formers, structure and torque tubes for motors and generators

- High-performance cryocoolers

- High-performance cryogenic power converters (inverters)

- Conformal liquid hydrogen tankage

- Flight weight superconducting transmission lines
Compared to N2A, N3-X has:
- Twice the fan area and bypass ratio (BPR 20 vs. 10)
- Ingestion of center body boundary layer
- 10 to 20% lower fuel burn
- Reduced noise from core engine and fans (FPR~1.35)
- Engine-out thrust symmetry
- Lower throttle-dependent pitching moment

*Thrust requirement is 30,000 lbf at aerodynamic design point of 31,000 feet, MN 0.8, ISA.
Thrust requirement is 108,000 lbf at rolling take-off condition at sea level, MN 0.25, and ISA+27.
Distributed Turboelectric Propulsion System Requires Cryogenic and Superconducting Components for Light Weight

Superconducting transmission lines between generators and motors

Superconducting motors to drive propulsive fans

Cryocooler(s) for cryogenic components

Cryogenic Inverter for variable speed fans

The temperatures needed for superconducting machines and the cryocoolers or LH₂ to produce them are no strangers to the space side of NASA.
**Fully Superconducting Motor or Generator**

Superconducting AC stator coils

Superconducting rotor coil packs

Materials needs and opportunities for motors and generators:
- Composite formers and containment for rotor
- Composite torque tubes
- Low-loss super- or normal- conductors for stator windings
Composite Rotor Formers, Structural Support and Torque Tubes

- Lightweight rotor structure, centrifugal containment and torque transfer elements are needed.
- Current technology uses vacuum impregnation of coils in a metallic structure.
- Lower density composite substitutes must have appropriate thermal expansion coefficients and good thermal conductivity.

- Torque tubes are required to transfer torque between cold region and warm parts with low heat leak.
- Composites and titanium compete here. High strength and stiffness but low thermal conductivity is desired for torque tubes.

- Power density of superconducting motors and generators:
  - SOA: 6 hp/lb
  - Goal: >30 hp/lb
Low-AC-Loss Superconductors

- Must reduce hysteretic, coupling and eddy-current losses
- Superconducting machines require fine, twisted superconductor filaments in a high-resistance matrix to reduce losses
- Complex fine-filament composites were developed for low-temp superconductors including some brittle inter-metallic ones
- Critical current improvement always sought from flux pinning improvements

- MgB$_2$ is more easily made with fine filaments and twist but requires lower operating temperature than YBCO*
- High resistance matrix is an issue for MgB$_2$
- Phase I SBIR made progress (Hyper Tech Research)
- SOA filament diameter: 50 µm. Goal: < 10µm

- YBCO ribbon has high AC losses
- Air Force striated ribbon reduced loss, but not enough for our need
- New ORNL wrap-around YBCO wire may have promise

* Yttrium barium copper oxide

ORNL Structural, Single-crystal, Faceted Fibers (SSIFFS) (2009 IR-100 Award)
Low-AC-Loss Normal Conductors

- Room temperature resistance of normal Al or Cu is too high but is two orders of magnitude lower near LH$_2$ temperature
- But the AC losses can be nearly as bad as for superconductors
- As for superconductors, fine, twisted filaments and a high resistance matrix are required for Al or Cu operating at LH$_2$ temperature

- High-purity, fine-filament Al composite conductors were produced by Air Force for use at LH$_2$ temperature
- High-frequency performance not pursued
- Matrix alloy (Al-Fe-Ce) constituents must not diffuse into pure aluminum

Conductor with 61 pure Al filaments in a high-resistance Al-Fe-Ce matrix for LH$_2$ operation (AFRL). Precursor strand for conductor with 2989 filaments.

- Nanotube conductors at room temperature are under study for aircraft wiring applications, but present DC resistivity is over two orders of magnitude too high for motors

Carbon nanotube multifilament conductor for high frequency applications at room temperature, (SBIR for Air Force)

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State-of-the-Art-Breaking Cryocooler

Reverse-Brayton, Stirling and pulse-tube coolers are candidates

Phase I SBIR produced preliminary design of reverse Brayton cryocooler with 1/6th the weight of existing coolers and no loss in efficiency (Creare)

High performance recuperator is required

Light-weight turbo-compressor is required

Cooler SOA is 30 lb/hp-input.

Goal is 5 lb/hp-input.

Recuperator needs high lateral thermal conduction and low longitudinal conduction. Opportunity for nanotube mats, etc?

Recuperator stack

Recuperator plate

"A Recuperative Heat Exchanger for Space-Borne Turbo-Brayton Cryocoolers",
R. W. Hill, M. G. Izenson, W. B. Chen and M. V. Zagarola
Cryogenic Power Converter (Inverter)

- Changes DC electrical power to AC power for variable speed motor drive
- Room temp inverters are 95% efficient with power density up to 10 hp/lb
- 99.8% efficiency expected at cryogenic temperatures
- Power density goal: 20 hp/lb or more

- Some cryogenic inverter work has been done
- 2 kW unit to be delivered to NASA (by MTECH Laboratories, Inc.)
- Semiconductor parts for cryogenic use are selected from standard parts

Higher efficiency at low temp from:
- Lower on resistance
- Faster switching

High heat transfer to cryo fluids is possible
New semiconductors especially for cryo temperatures
Passive components can be greatly improved
Expansion coefficient compatibility important to avoid brittle failure
Flight-Weight Superconducting Transmission Lines

Superconducting transmission lines for ground-based electric grid should be further developed for flight weight.

SOA numbers: 5 W/m loss, 10 kg/m
Target numbers: Mass goal: 5 kg/m
Terminations & interconnects may be issues
**Light-Weight, Conformal Liquid Hydrogen Tanks**

### Three ways LH$_2$ might be used:

- **Jet-fueled aircraft (1)** - Replace cryocoolers with tanked LH$_2$. Use GH$_2$ as fuel (LH$_2$: ~8% of total fuel energy)
- **Jet-fueled aircraft (2)** - Size cryocoolers for cruise. Tanked LH$_2$ for excess cooling at TO (LH$_2$ < 1% of total fuel energy)
- **LH$_2$-fueled aircraft** - Portion of fuel cools cryogenic components before being burned. (Zero CO$_2$ aircraft)

- No current NASA activity for aircraft in this area
- NASA carbon-fabric-reinforced composites for composite tanks reduced tank permeability to He by 70%. H$_2$ permeability data needed.

- Conformal tanks could use of odd-shaped volumes in hybrid wing body
- Available LH$_2$ would reduce or eliminate cryocooler requirement
- More AC loss can be tolerated in motors and generators
- Use of pure normal conductors and/or MgB$_2$ becomes more favorable with LH$_2$

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**N.B.** The use of LH$_2$ is only a possible option. It is NOT required to implement turboelectric propulsion!
Ships, Trains & Cars Already Benefit From Hybrid Electric Power Systems

Why not Airplanes?

Advances in materials can help make this possible.
References


