#### "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



#### Materials Aspects of Turboelectric Aircraft Propulsion

Presenter Position Organization Coauthors Gerald V. Brown Senior Research Engineer GRC Structures & Materials Div. Hyun Dae Kim, James Felder



2009 Annual Meeting Fundamental Aeronautics Program Subsonic Fixed Wing Project September 29-October 1, 2009

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### The Turboelectric Approach



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.

### BENEFITS

Electric power from generators

is distributed to multiple fans.



Large core engines with low TSFC drive superconducting generators.

The second

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

Forward and aft fan noise Is shielded by airframe.

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

Low velocity core exhaust reduces noise.

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

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

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

# OUTLINE



- □ 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



# Higher Bypass Ratio & Boundary Layer Ingestion Save Fuel





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. "Turboelectric Distributed Propulsion Engine Cycle Analysis for Hybrid Wing-body Aircraft", James L. Felder, Hyun Dae Kim and Gerald Brown, AIAA-2009-1132, presented at 47<sup>th</sup> AIAA Aerospace Sciences meeting in Orlando, FL, Jan 7, 2009.



Distributed Turboelectric Propulsion System Requires Cryogenic and Superconducting Components for Light Weight



# Fully Superconducting Motor or Generator





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



One of four rotor coil packs



Cross section of four coil packs ready for structural elements

□ <sup>3</sup>7RUTXH□WXEHV´□DUH□UHTXLUHG□WR□WUDQVIHU□ □ Power density of superconducting motors

torgue 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.

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<sub>2</sub> is more easily made with fine filaments and twist but requires lower operating temperature than YBCO\*.
- High resistance matrix is an issue for MgB<sub>2</sub>
- Phase I SBIR made progress (Hyper Tech Research)
- $\Box$  SOA filament diameter : 50 µm. Goal: < 10µm



Low-temperature superconductor - NbTi





- □ 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



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<sub>2</sub> 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<sub>2</sub> temperature

\* "The origin and future of composite aluminum conductors", Oberly, C.E.; Ho, J.C.; IEEE Transactions on Magnetics, Volume 27, Issue 1, Jan 1991 Page(s):458 - 463

- High-purity, fine-filament AI composite conductors were produced by Air Force for use at LH<sub>2</sub> temperature\*
- □ High-frequency performance not pursued
- Matrix alloy (AI-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)





# 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 1/6<sup>th</sup> 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



#### Reverse Brayton refrigeration cycle



Reverse-Brayton warm module (prelim. design)



Reverse-Brayton cold module (prelim. design)



# 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:

- ± /RZHU □ □ <sup>3</sup>RQ □ UHVLVWDQFH' □
- ± 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



SOA numbers:5 W/m loss,10 kg/mTarget numbers:Mass goal:5 kg/mTerminations & interconnects may be issues







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



#### Light-Weight, Conformal Liquid Hydrogen Tanks

#### Three ways LH<sub>2</sub> might be used:

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



Typical LH<sub>2</sub> Tanks



Conformal LH<sub>2</sub> Tanks

- 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<sub>2</sub> permeability data needed.
- Conformal tanks could use of odd-shaped volumes in hybrid wing body
- Available LH<sub>2</sub> would reduce or eliminate cryocooler requirement
- More AC loss can be tolerated in motors and generators

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.

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