

“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.

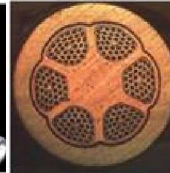
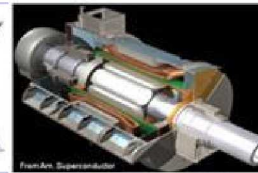
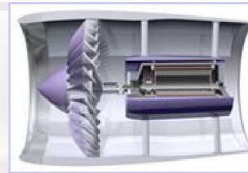


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Materials Aspects of Turboelectric Aircraft Propulsion

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

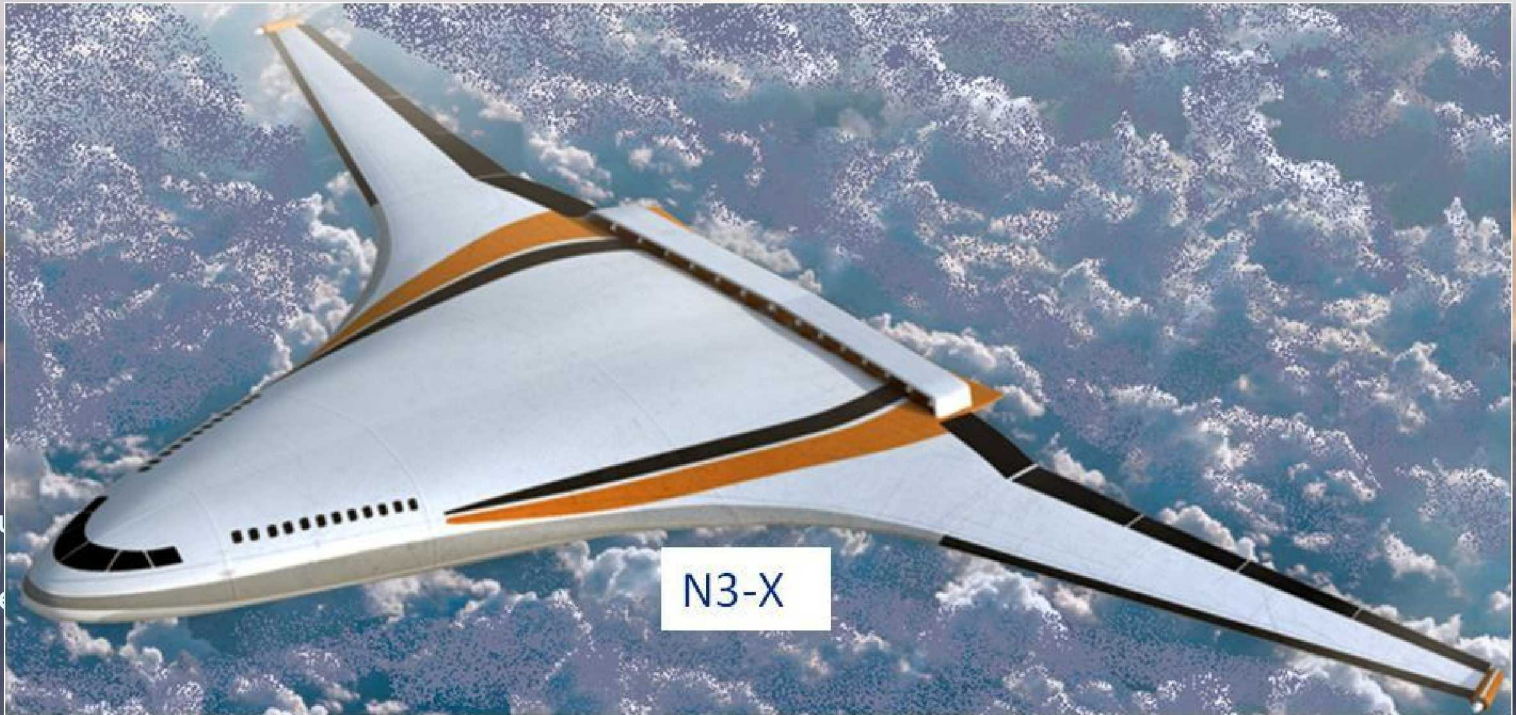
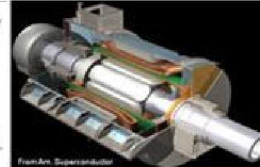
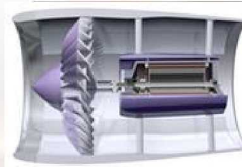


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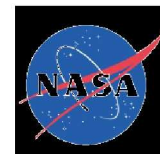
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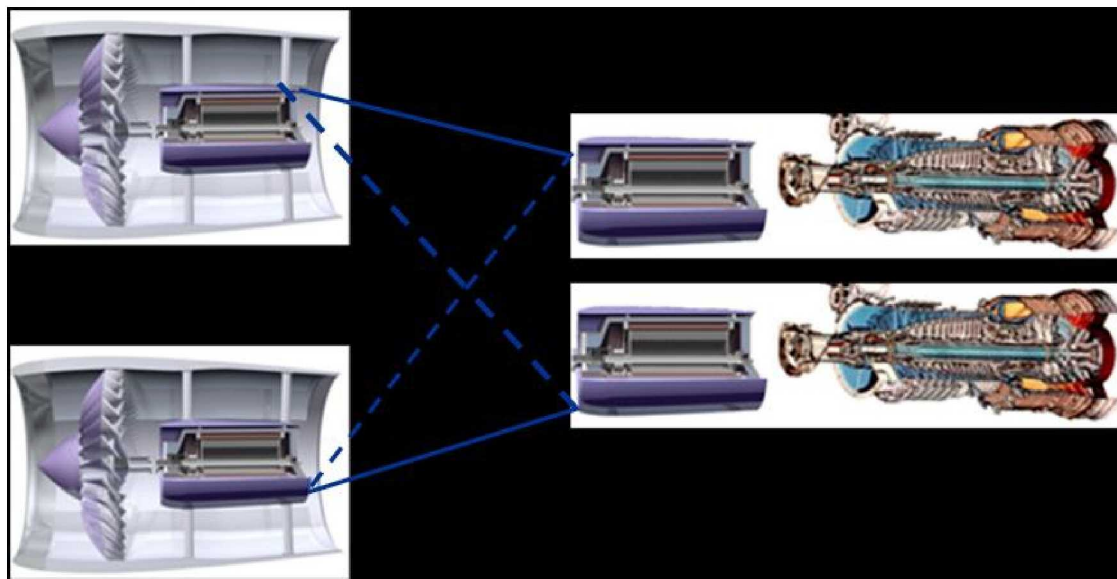
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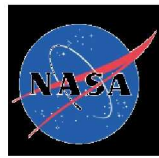


The Turboelectric Approach

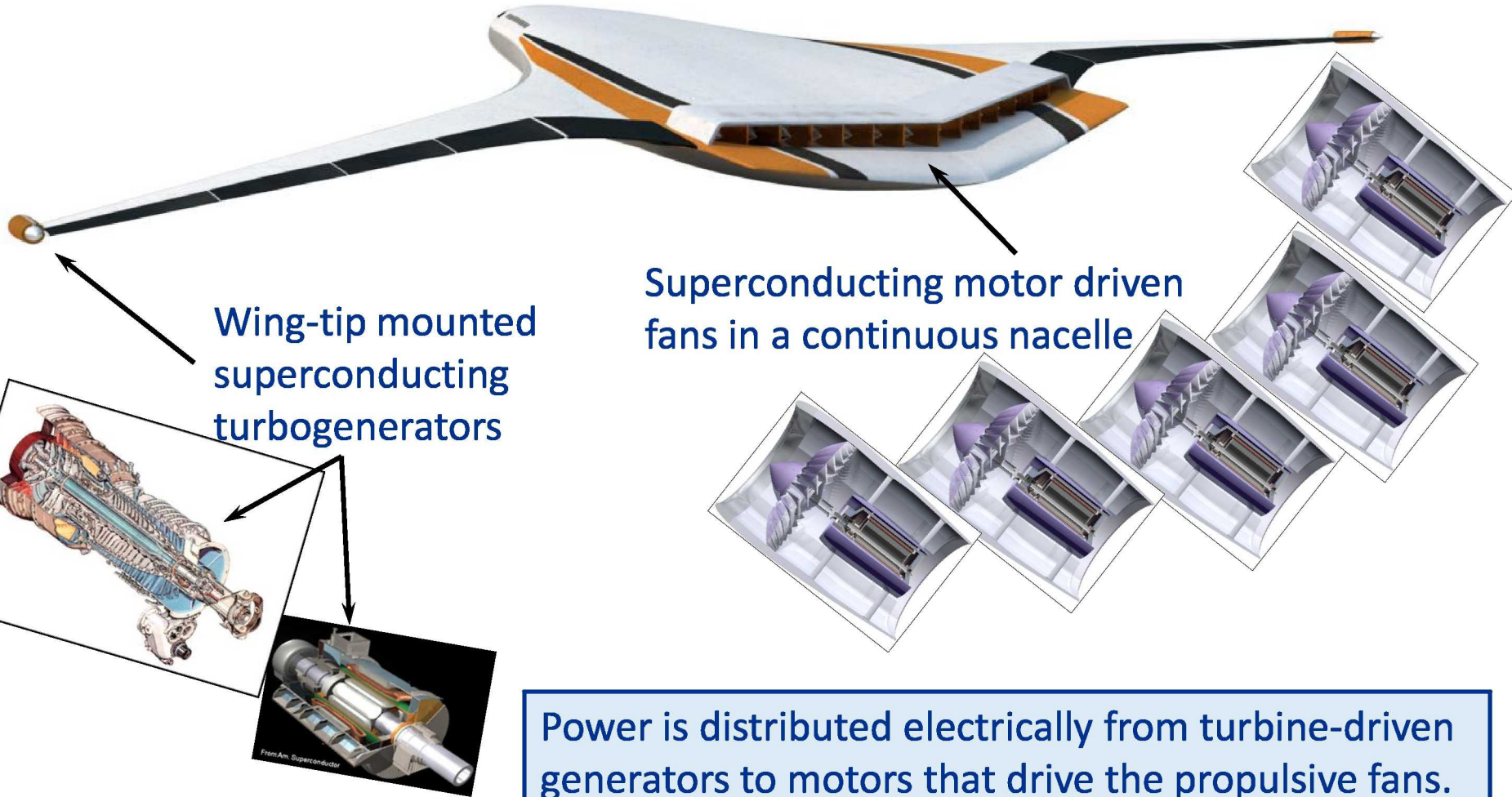


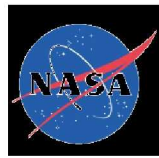
The turboelectric approach does not replace the turbine engines or the fans, rather it enables them to be located and optimized independently for the greatest aircraft benefit.

The incentive for higher thermodynamic and propulsive efficiencies remains.

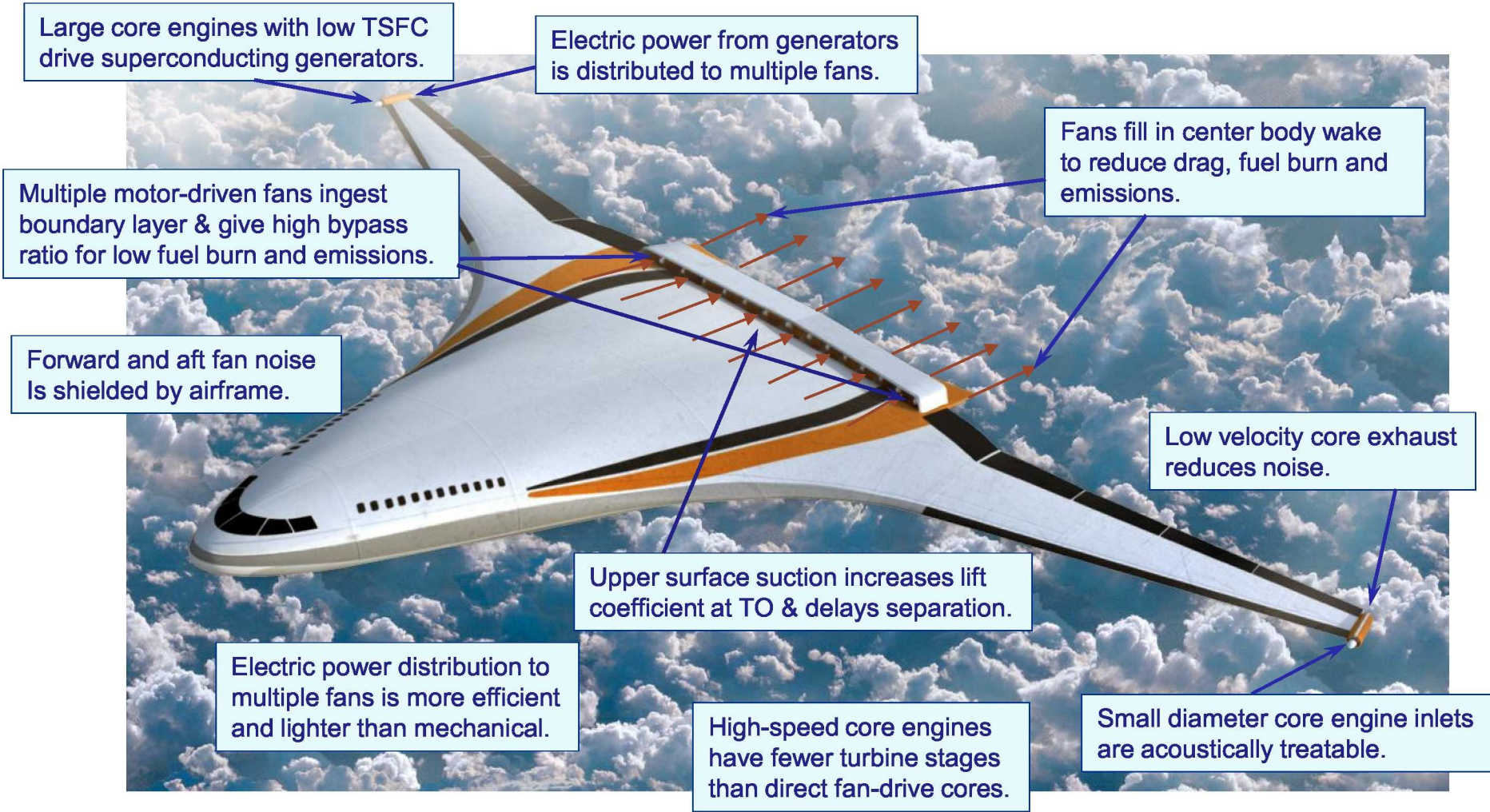


N3-X Distributed Turboelectric Propulsion System





BENEFITS

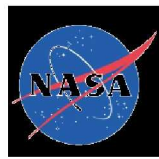


THE TURBOELECTRIC APPROACH CONTRIBUTES TO EVERY CORNER OF THE SFW TRADE SPACE



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



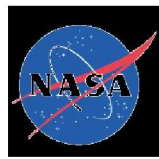
Higher Bypass Ratio & Boundary Layer Ingestion Save Fuel



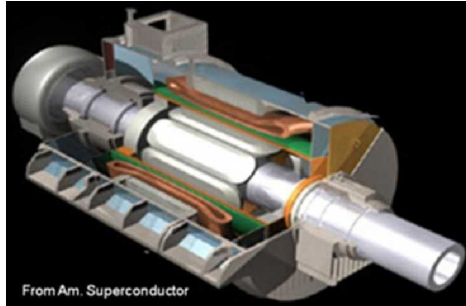
Compared to N2A, N3-X has:

- 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 47th AIAA Aerospace Sciences meeting in Orlando, FL, Jan 7, 2009.



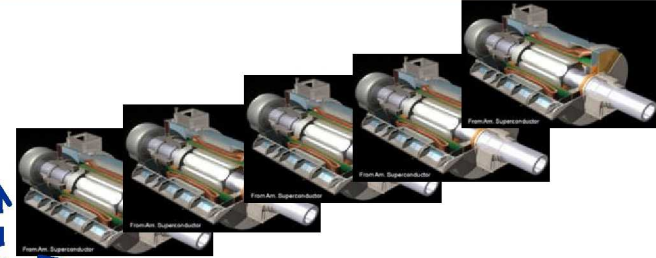
Distributed Turboelectric Propulsion System Requires Cryogenic and Superconducting Components for Light Weight



Turbine engine driven superconducting generator



Superconducting transmission lines between generators and motors



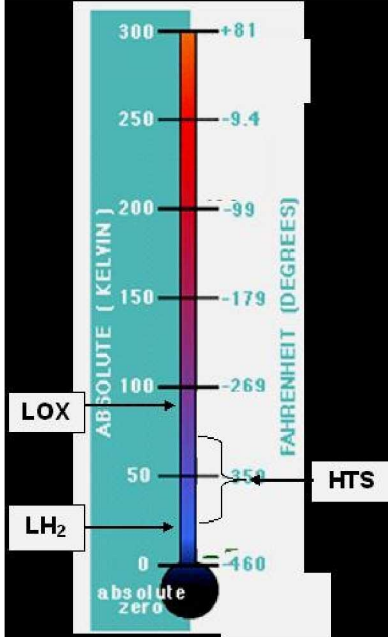
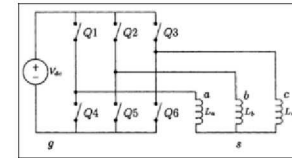
Superconducting motors to drive propulsive fans



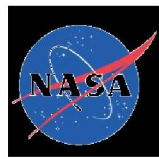
Cryocooler(s) for cryogenic components



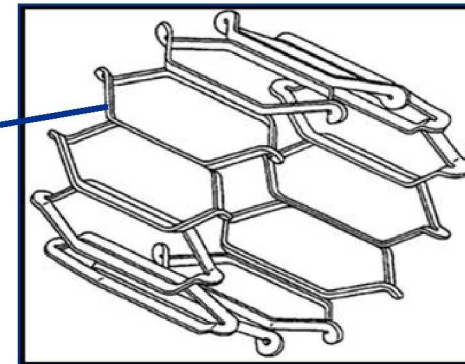
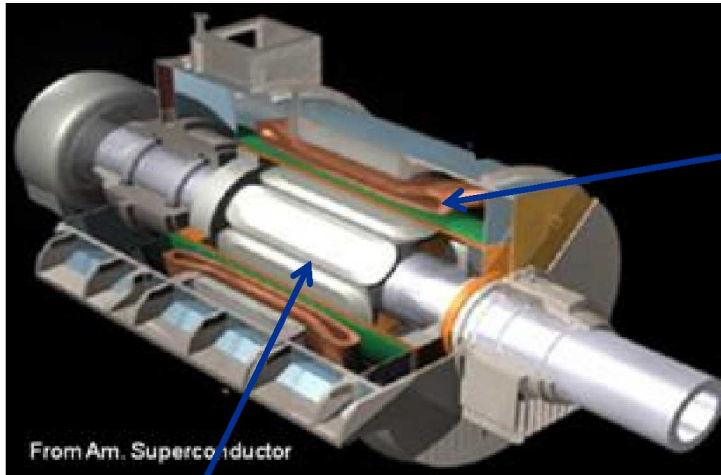
Cryogenic Inverter for variable speed fans



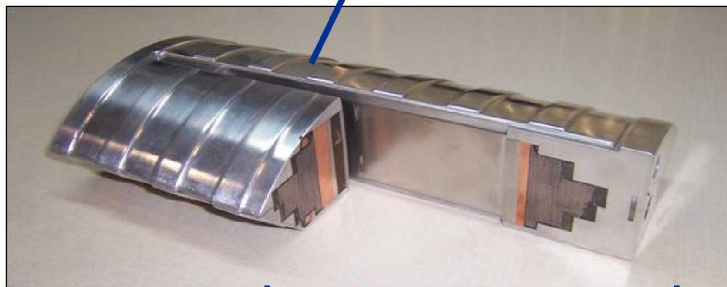
The temperatures needed for superconducting machines and the cryocoolers or LH₂ to produce them are no strangers to the space side of NASA.



Fully Superconducting Motor or Generator



Superconducting
AC stator coils



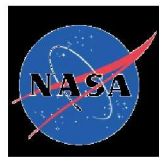
Superconducting rotor coil packs

Materials needs and opportunities for motors and generators:

- Composite formers and containment for rotor

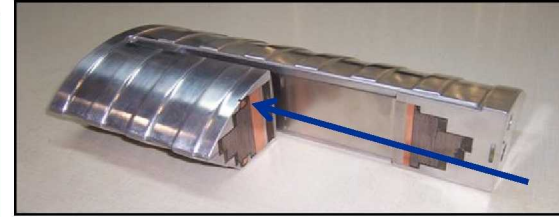
- Composite torque tubes

- Low-loss super- or normal- conductors for stator windings

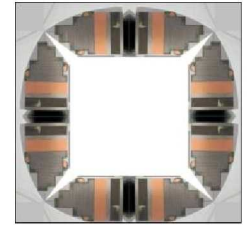


Composite Rotor Formers, Structural Support and Torque Tubes

- 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



One of four rotor coil packs



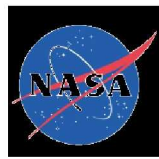
Cross section of four coil packs ready for structural elements

□ ³TRUTXH □ WXEHV' □ DUH □ UHTXLUHG □ WR □ WUDQVIHU □ 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.

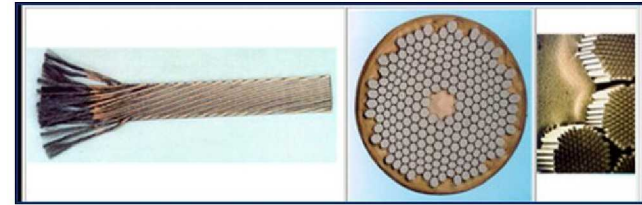
□ Power density of superconducting motors and generators:

SOA: 6 hp/lb
Goal: >30 hp/lb

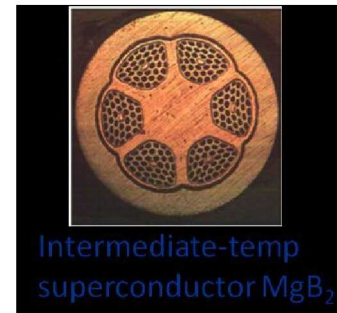


Low-AC-Loss Superconductors

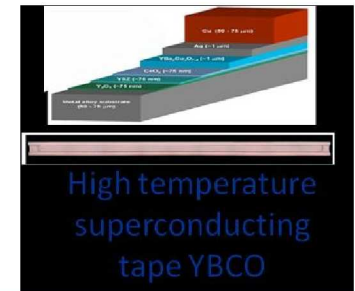
- Must reduce hysteretic, coupling and eddy-current losses
- Superconducting machines require fine, twisted superconductor filaments in a high-resistance matrix to reduce losses
- Complex fine-filament composites were developed for low-temp superconductors including some brittle inter-metallic ones
-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



Low-temperature superconductor - NbTi



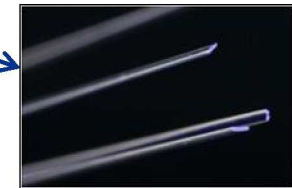
Intermediate-temp superconductor MgB_2



High temperature superconducting tape YBCO

- 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: < 10 μm

- 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)

* Yttrium barium copper oxide

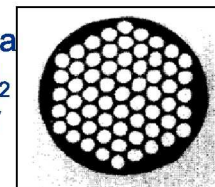


Low-AC-Loss Normal Conductors

- Room temperature resistance of normal Al or Cu is too high but is two orders of magnitude lower near LH₂ 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 LH₂ temperature

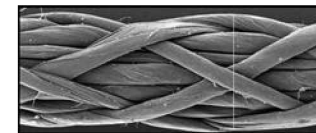
- High-purity, fine-filament Al composite conductors were produced by Air Force for use at LH₂ temperature*
- High-frequency performance not pursued
- Matrix alloy (Al-Fe-Ce) constituents must not diffuse into pure aluminum

Conductor with 61 pure Al filaments in a high-resistance Al-Fe-Ce matrix for LH₂ 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)



*"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

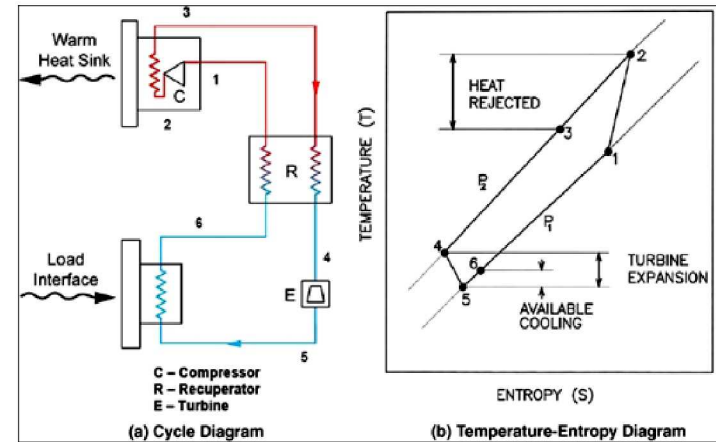


State-of-the-Art-Breaking Cryocooler

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

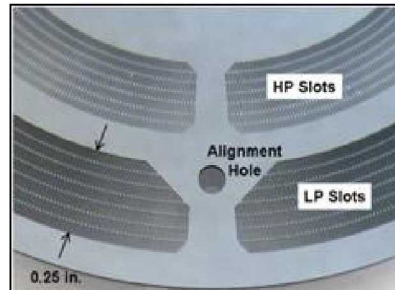
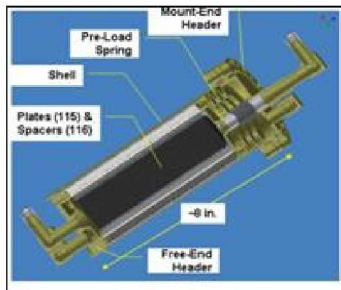
Phase I SBIR produced preliminary design of reverse Brayton cryocooler with 1/6th the weight of existing coolers and no loss in efficiency (Creare)

High performance recuperator is required
 Light-weight turbo-compressor is required
 Cooler SOA is 30 lb/hp-input.
 Goal is 5 lb/hp-input.



Reverse Brayton refrigeration cycle

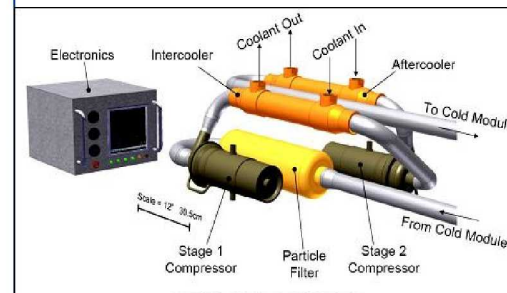
Recuperator needs high lateral thermal conduction and low longitudinal conduction.
 Opportunity for nanotube mats, etc?



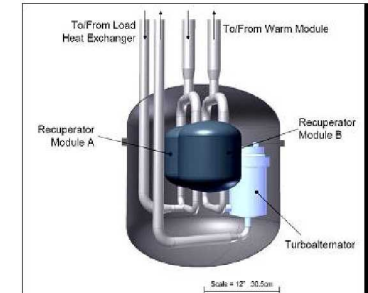
Recuperator stack*

Recuperator plate*

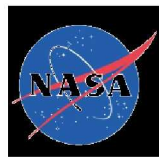
* "A Recuperative Heat Exchanger for Space-Borne Turbo-Brayton Cryocoolers", R. W. Hill, M. G. Izenson, W. B. Chen and M. V. Zagarola



Reverse-Brayton warm module (prelim. design)

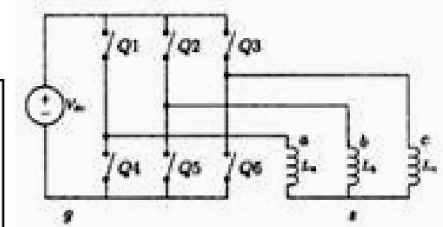
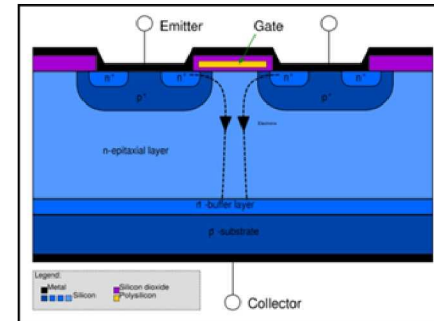


Reverse-Brayton cold module (prelim. design)



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:

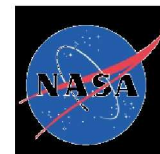
- ± /RZHU□□³RQ□UHVLVWDQFH'□
- ± Faster switching

High heat transfer to cryo fluids is possible

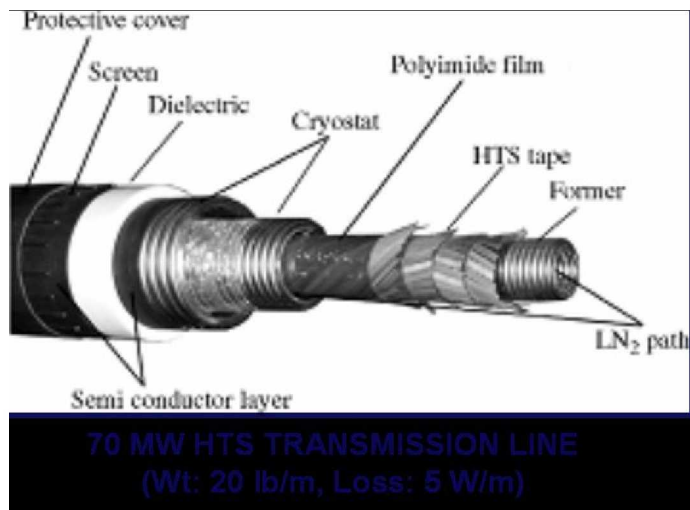
New semiconductors especially for cryo temperatures

Passive components can be greatly improved

Expansion coefficient compatibility important to avoid brittle failure



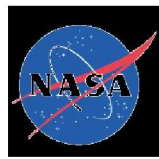
Flight-Weight Superconducting Transmission Lines



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



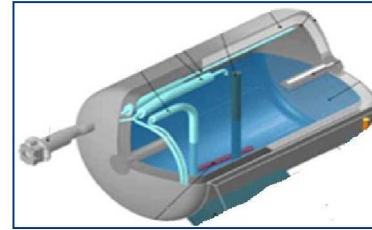
Superconducting transmission lines for ground-based electric grid should be further developed for flight weight.



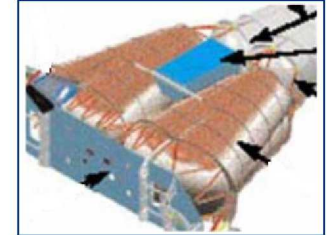
Light-Weight, Conformal Liquid Hydrogen Tanks

Three ways LH₂ might be used:

- Jet-fueled aircraft (1) - - Replace cryocoolers with tanked LH₂ . Use GH₂ as fuel (LH₂: ~8% of total fuel energy)
- Jet-fueled aircraft (2) - - Size cryocoolers for cruise. Tanked LH₂ for excess cooling at TO (LH₂ < 1% of total fuel energy)
- LH₂-fueled aircraft - - Portion of fuel cools cryogenic components before being burned. (Zero CO₂ aircraft)



Typical LH₂ Tanks

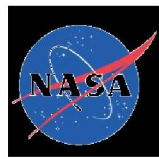


Conformal LH₂ Tanks

- No current NASA activity for aircraft in this area
- NASA carbon-fabric-reinforced composites for composite tanks reduced tank permeability to He by 70%. H₂ permeability data needed.

- Conformal tanks could use of odd-shaped volumes in hybrid wing body
- Available LH₂ would reduce or eliminate cryocooler requirement
- More AC loss can be tolerated in motors and generators
- Use of pure normal conductors and/or MgB₂ becomes more favorable with LH₂

N.B. The use of LH₂ 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.

