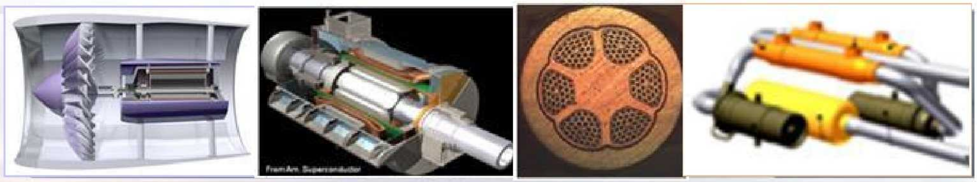
“Materials Aspects of Turboelectric Aircraft Propulsion”

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

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

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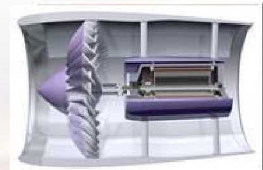

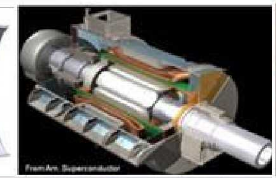

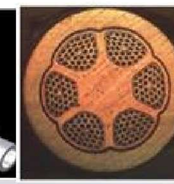

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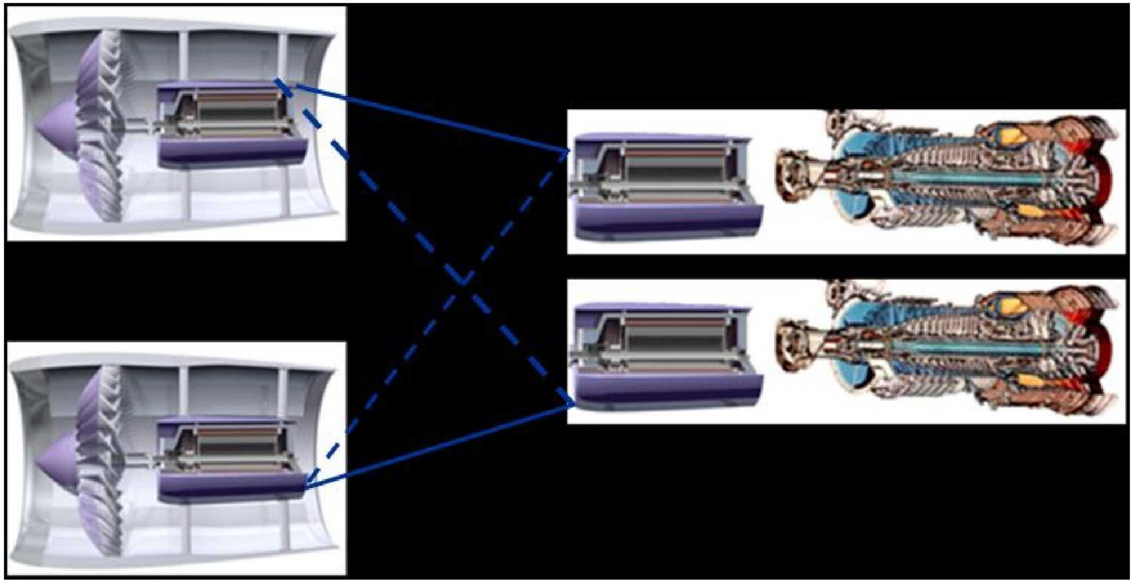
The Turboelectric Approach



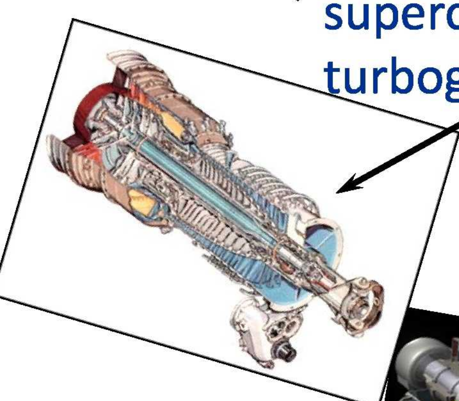
The turboelectric approach does not replace the turbine engines or the fans, rather it enables them to be located and optimized independently for the greatest aircraft benefit.

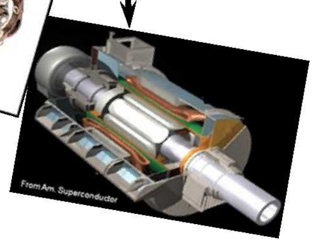
The incentive for higher thermodynamic and propulsive efficiencies remains.

N3-X Distributed Turboelectric Propulsion System

Superconducting motor driven fans in a continuous nacelle

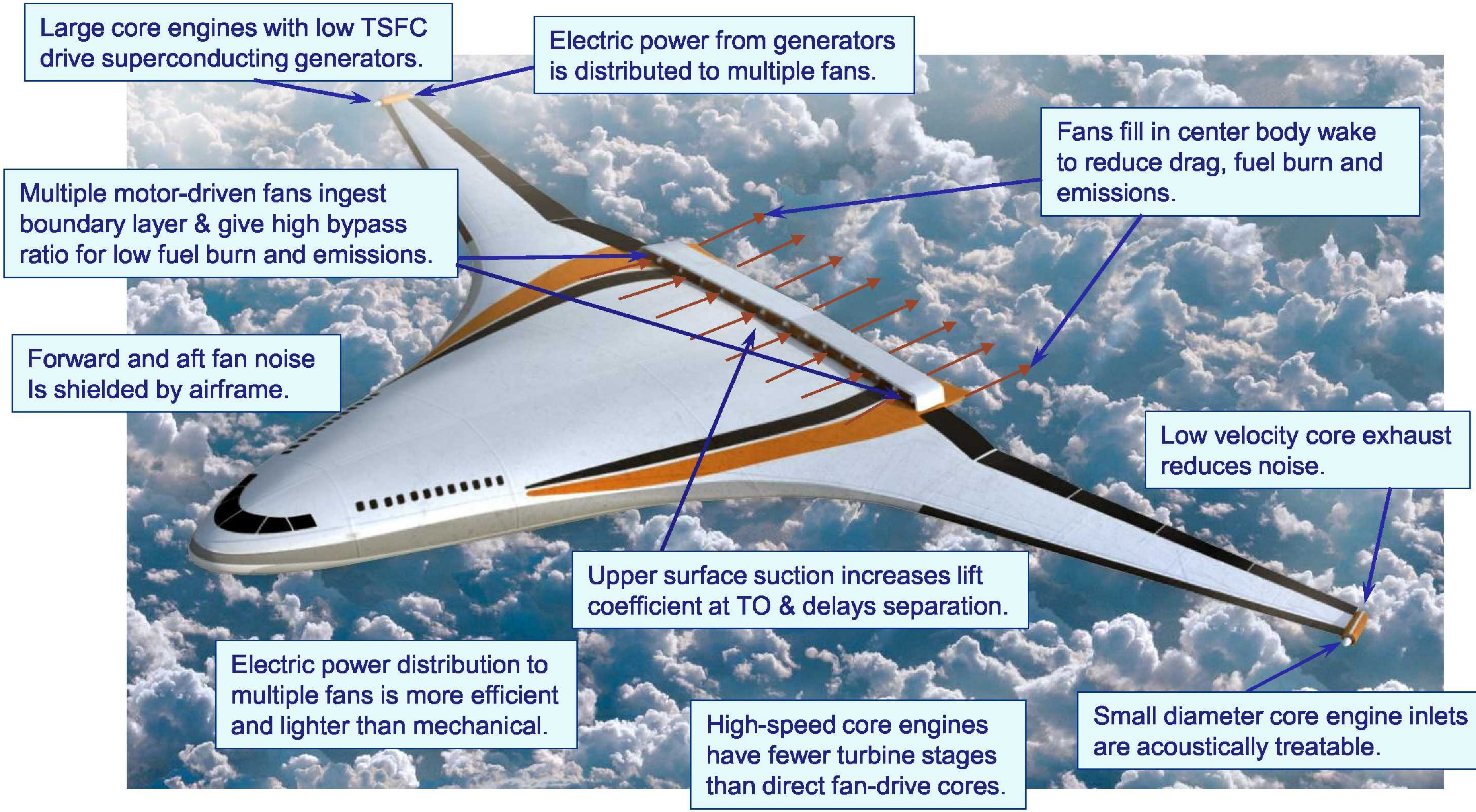
Wing-tip mounted superconducting turbogenerators





Power is distributed electrically from turbine-driven generators to motors that drive the propulsive fans.

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

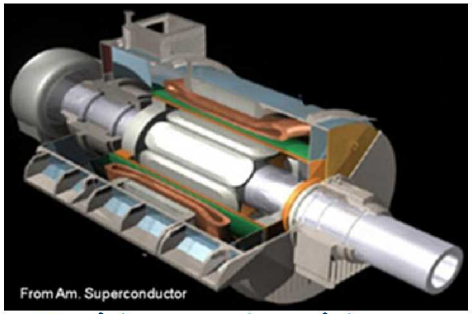
Higher Bypass Ratio & Boundary Layer Ingestion Save Fuel

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

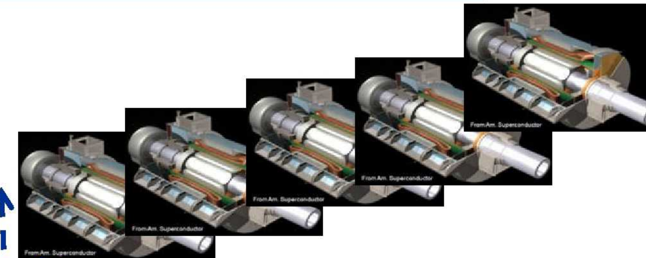
* Thrust requirement is 30,000 lbf at aerodynamic design point of 31,000 feet, MN 0.8, ISA.
Thrust requirement is 108,000 lbf at rolling take-off condition at sea level, MN 0.25, and ISA+27.
"Turboelectric Distributed Propulsion Engine Cycle Analysis for Hybrid Wing-body Aircraft", James L. Felder, Hyun 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



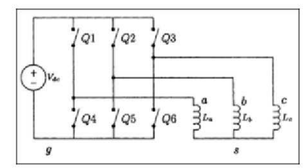
Turbine engine driven superconducting generator

Superconducting transmission lines between generators and motors

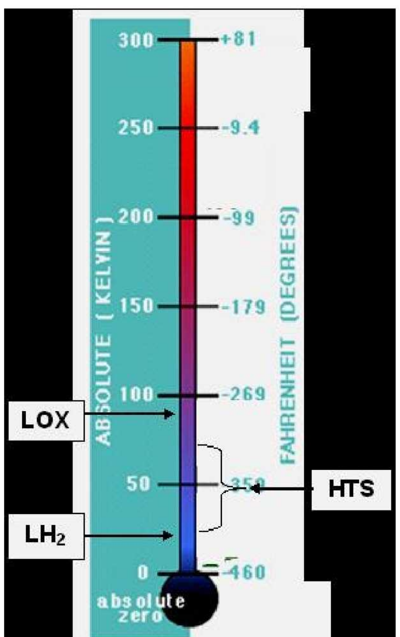


Superconducting motors to drive propulsive fans

Cryocooler(s) for cryogenic components

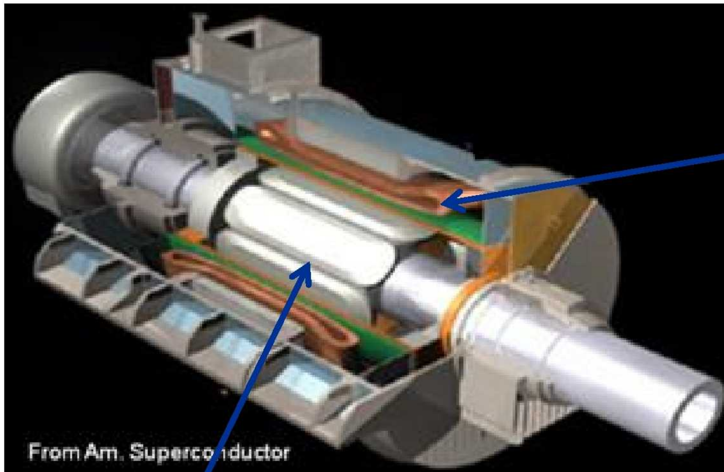


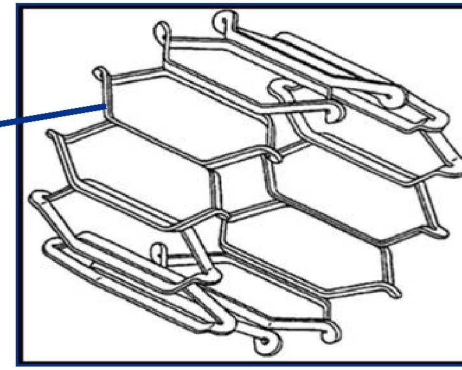
Cryogenic Inverter for variable speed fans



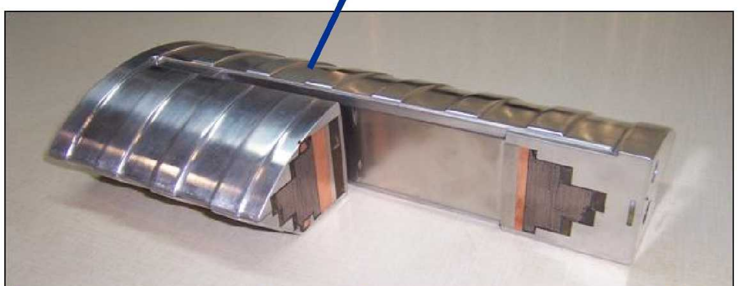
The temperatures needed for superconducting machines and the cryocoolers or LH_2 to produce them are no strangers to the space side of NASA.

Fully Superconducting Motor or Generator





Superconducting
AC stator coils



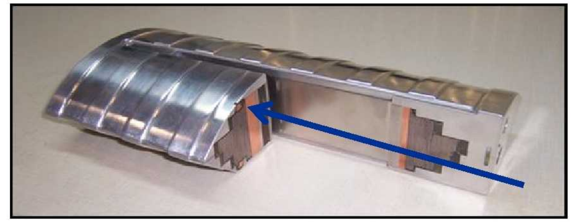
Superconducting rotor coil packs

Materials needs and opportunities for motors and generators:

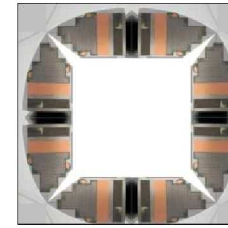
- Composite formers and containment for rotor
- Composite torque tubes
- Low-loss super- or normal- conductors for stator windings

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

□ ³7RUTXH□WXEHV´□DUH□UHTXLUHG□WR□WUDQVIHU□ torque between cold region and warm parts with low heat leak.

□ Composites and titanium compete here

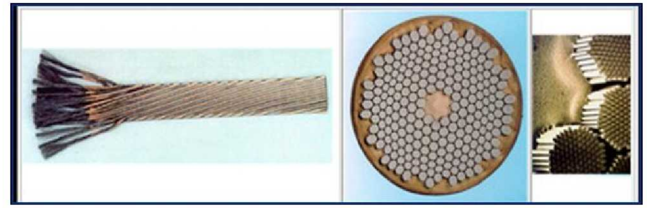
□ High strength and stiffness but low thermal conductivity is desired for torque tubes.

□ Power density of superconducting motors and generators:

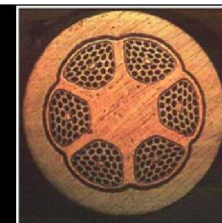
SOA:	6 hp/lb
Goal:	>30 hp/lb

Low-AC-Loss Superconductors

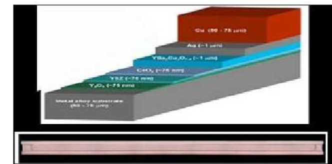
- Must reduce hysteretic, coupling and eddy-current losses
- Superconducting machines require fine, twisted superconductor filaments in a high-resistance matrix to reduce losses
- Complex fine-filament composites were developed for low-temp superconductors including some brittle inter-metallic ones
-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



Low-temperature superconductor - NbTi



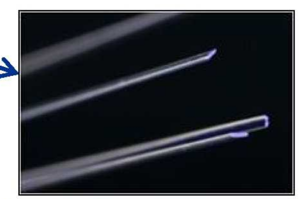
Intermediate-temp superconductor MgB_2



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: < 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



ORNL Structural, Single-crystal, Faceted Fibers (SSIFFS) (2009 IR-100 Award)

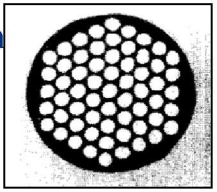
* Yttrium barium copper oxide

Low-AC-Loss Normal Conductors

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

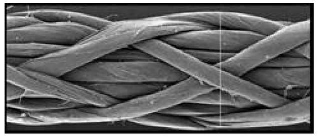
- High-purity, fine-filament Al composite conductors were produced by Air Force for use at LH_2 temperature*
- High-frequency performance not pursued
- Matrix alloy (Al-Fe-Ce) constituents must not diffuse into pure aluminum

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

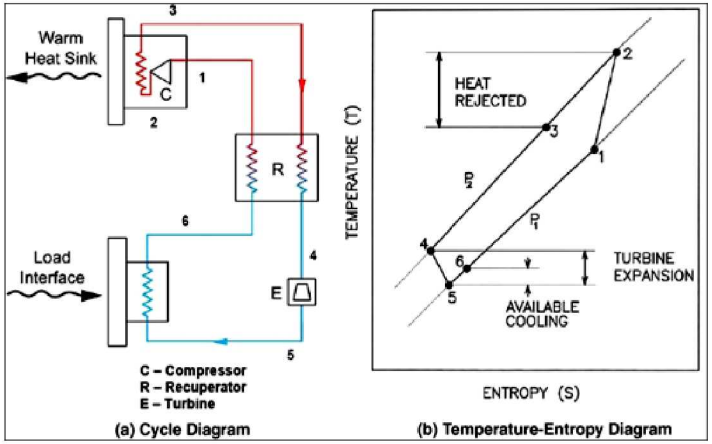
Carbon nanotube multifilament conductor for high frequency applications at room temperature, (SBIR for Air Force)



*"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

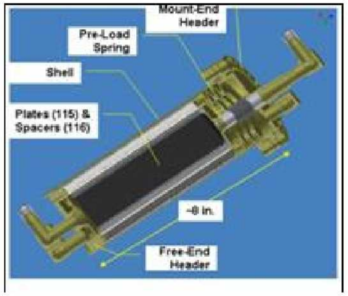
State-of-the-Art-Breaking Cryocooler

- 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.

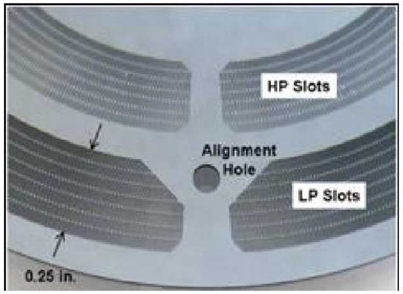


Reverse Brayton refrigeration cycle

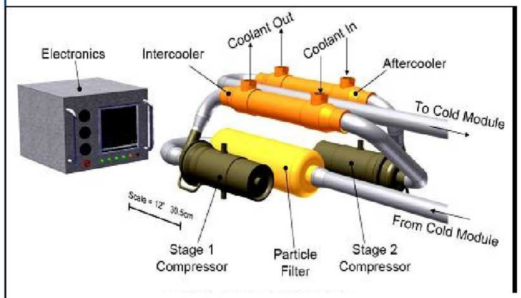
Recuperator needs high lateral thermal conduction and low longitudinal conduction. Opportunity for nanotube mats, etc?



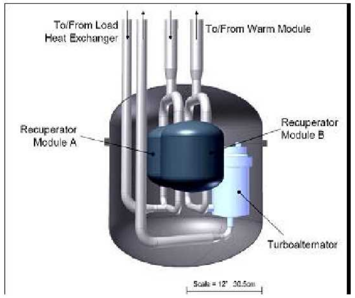
Recuperator stack*



Recuperator plate*



Reverse-Brayton warm module (prelim. design)

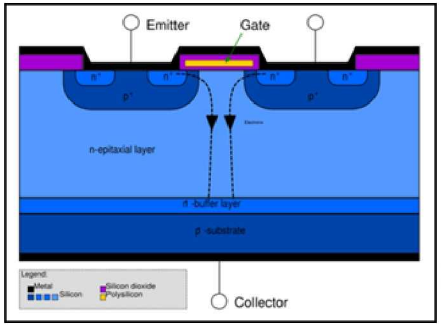


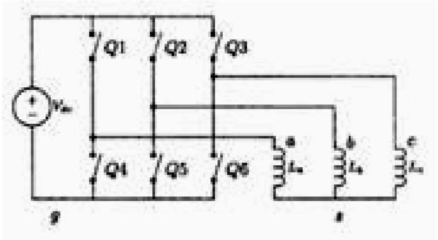
Reverse-Brayton cold module (prelim. design)

* "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:

± /RZHU□□³RQ□UHVLVWDQFH´□

± Faster switching

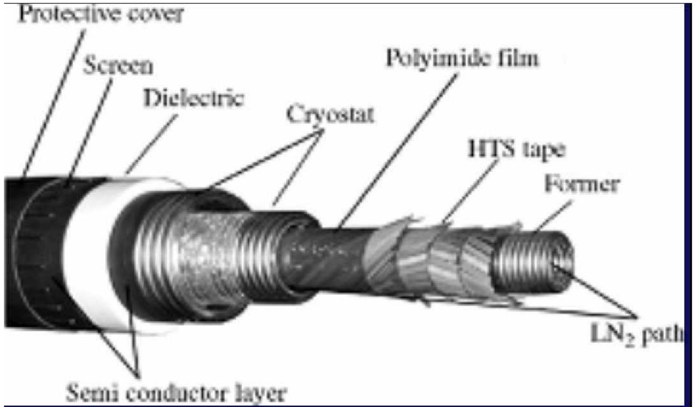
High heat transfer to cryo fluids is possible

New semiconductors especially for cryo temperatures

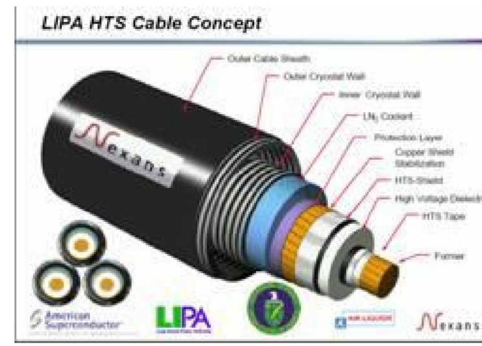
Passive components can be greatly improved

Expansion coefficient compatibility important to avoid brittle failure

Flight-Weight Superconducting Transmission Lines



70 MW HTS TRANSMISSION LINE
(Wt: 20 lb/m, Loss: 5 W/m)



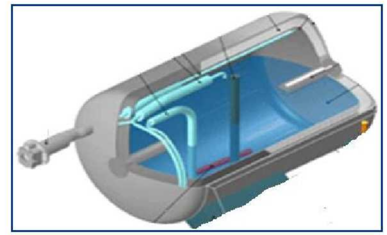
SOA numbers: 5 W/m loss, 10 kg/m
Target numbers: Mass goal: 5 kg/m
Terminations & interconnects may be issues

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

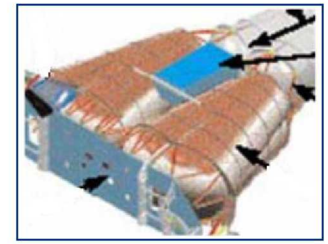
Light-Weight, Conformal Liquid Hydrogen Tanks

Three ways 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)



Typical LH_2 Tanks



Conformal LH_2 Tanks

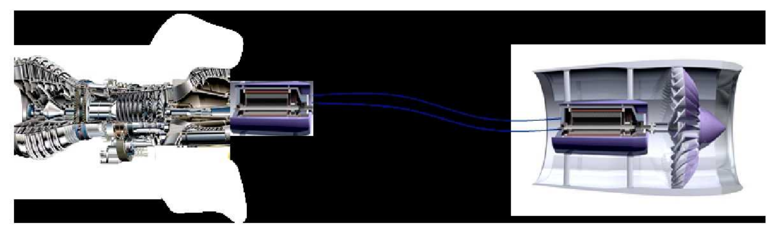
- No current NASA activity for aircraft in this area
- NASA carbon-fabric-reinforced composites for composite tanks reduced tank permeability to He by 70%. H_2 permeability data needed.

- 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

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

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13. ³$□5HFXSHUDWLYH□+HDW□([FKDQJHU□IRU□8VH□LQ□5HYHUVH-Brayton Turbo-%UD\WRQ□&U\RFRROHUV□³□□5□□:□□+LOO□□0□□*□□,]HQVRQ□□gariola, □□%□□&KHQ□DQG□(... Cryocoolers 14, edited by S.D. Miller and R.G. Ross, Jr., International Cryocooler Conference, Inc., Boulder, CO, 2007, pg 525 - 533.
14. ³&KLQD¶V□□m, 35 kV/2 N$□+76□DF□SRZHU□FDEOH¶V□RSHUDWLRQ□LQ□SRZHU□JULG´□□+□;□□;L□□:□=□□*RQJ□□Wen, B. Hou, □<□)□□%L□□ and Y. Xin,, Physica C 445±448 (2006) 1054±1057.
15. ³3UHGLFWLRQ□RI□:LQGDJH□3RZHU□/RVV□LQ□$OWHUQDWRUV´□□9UDQFLV□□□□□□,QWHUQDO□□□□1$6$□71□'... 4849, Oct. 1968.
16. ³(QJLQHHULQJ□$QDO\VLV□6WXGLHV□IRU□3UHOLPLQDU\□'HVLJQ□RI□/LJKWZHLJKW□&U\RJHQLF□+\GURJHQ□7DQN□LQ□8$9□$SSOLFDWL... Sullivan, Joseph L. Palko, Robert T. Tornabene, Brett A. Bednarcyk and Lynn M. Powers, Subodh K. Mital, Lizalyn M. Smith, Xiao-Yen J. Wang, and James E. Hunter, NASA/TP² 2006-214094, May 2006.