National Aeronautics and Space Administration

Efficient Flight-Weight Electric Systems

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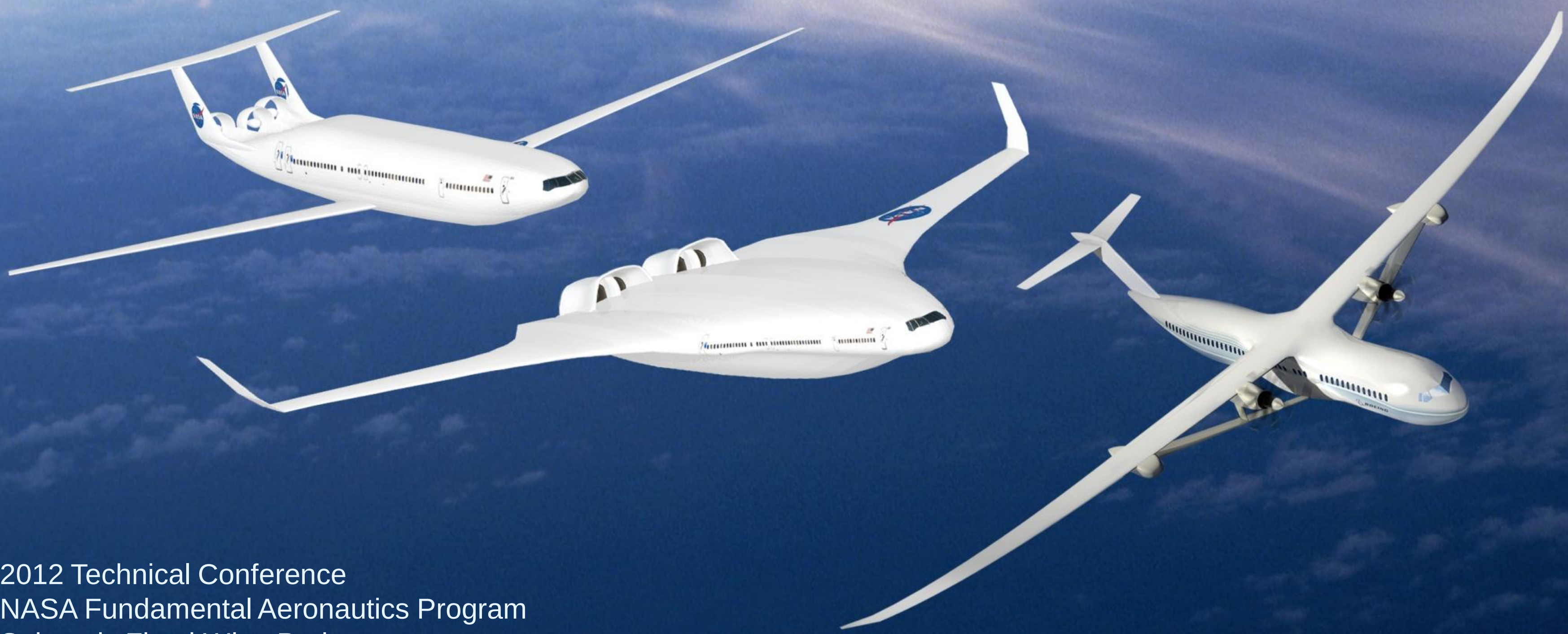

2012 Technical Conference
NASA Fundamental Aeronautics Program
Subsonic Fixed Wing Project
Cleveland, OH, March 13-15, 2012

National Aeronautics and Space Administration

Efficient Flight-Weight Propulsion Electric Systems

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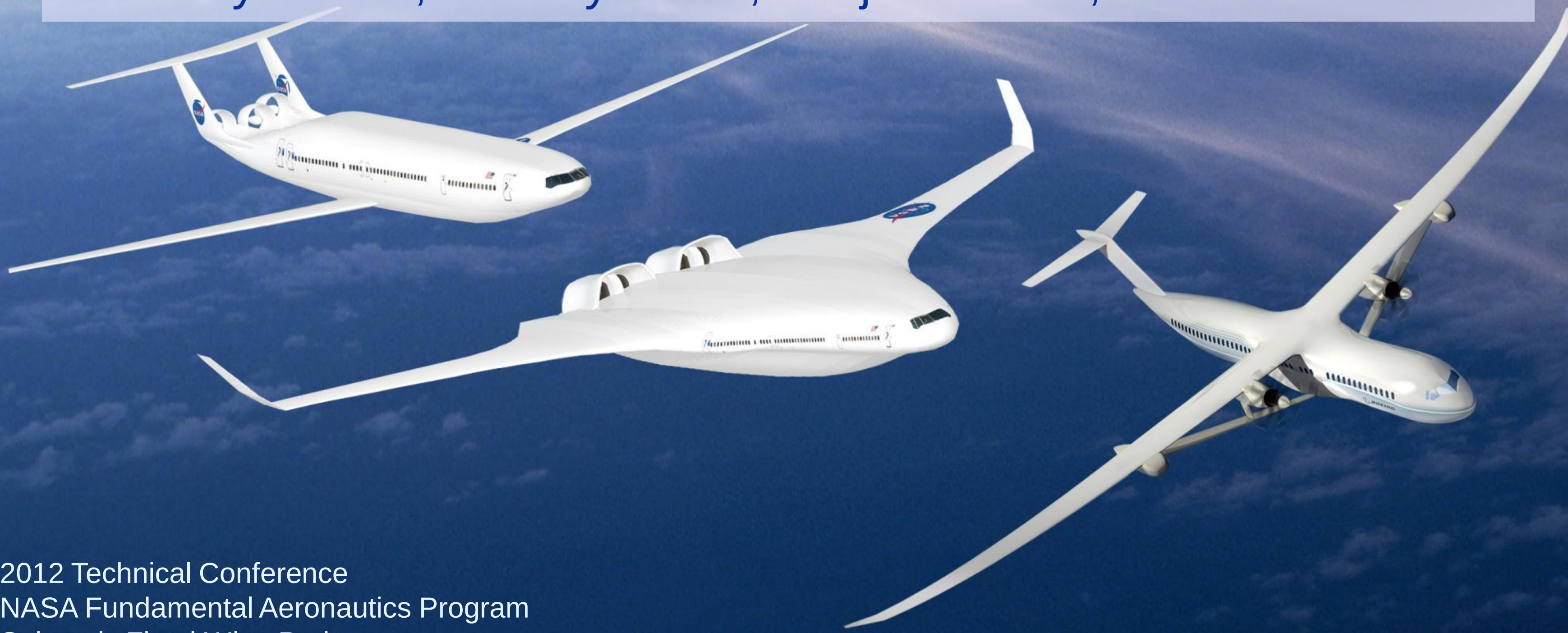

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Outline

- Performance estimates for 3 electric propulsion cases:
  1. Hybrid electric with room temperature components
  2. TeDP* with room temperature components
  3. TeDP* with cryogenic and superconducting components

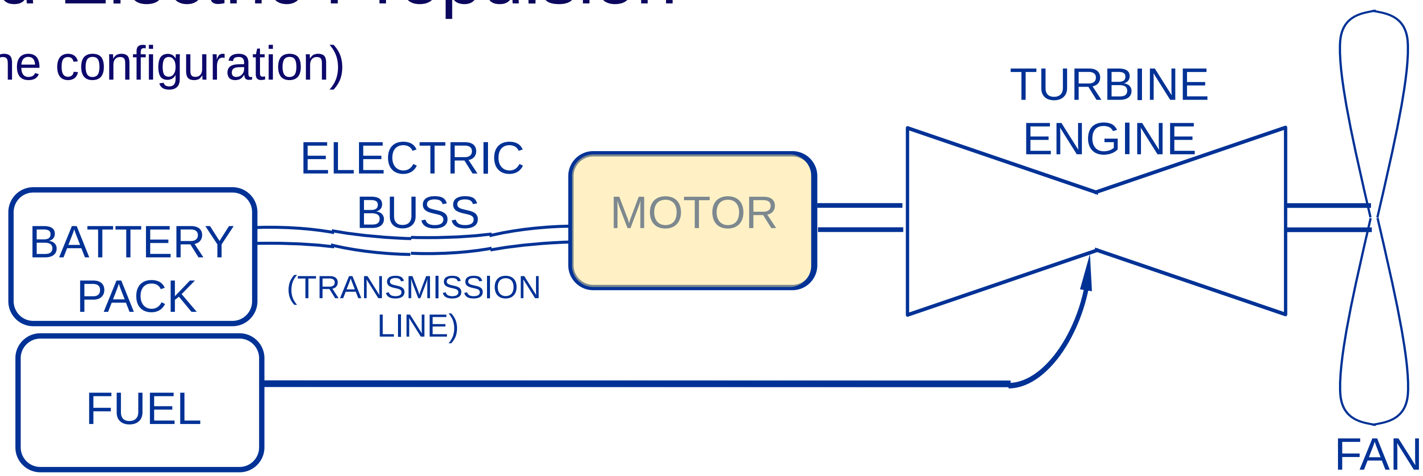
- Technical challenges and program for turboelectric propulsion
  1. Superconducting electric machines
  2. Cryocoolers
  3. Cryogenic Inverters/rectifiers
  4. Overall electric grid system

WE ATTEMPT TO PROJECT TECHNOLOGY TO THE N+3 TIME FRAME (2025 – 2030)

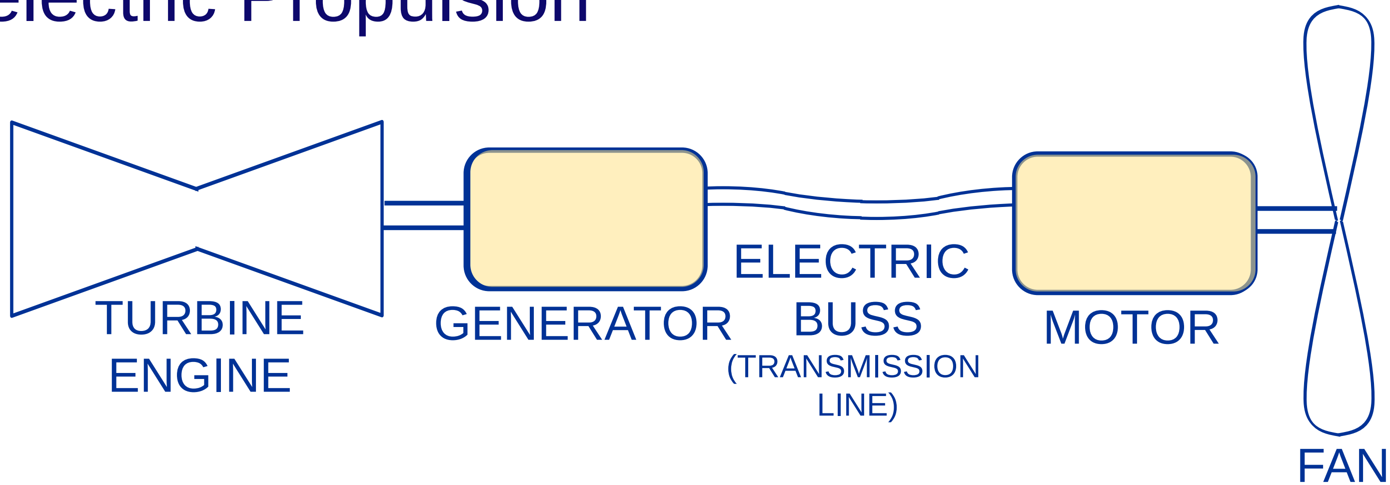
TeDP: Turboelectric Distributed Propulsion

Hybrid Electric Propulsion

(one configuration)

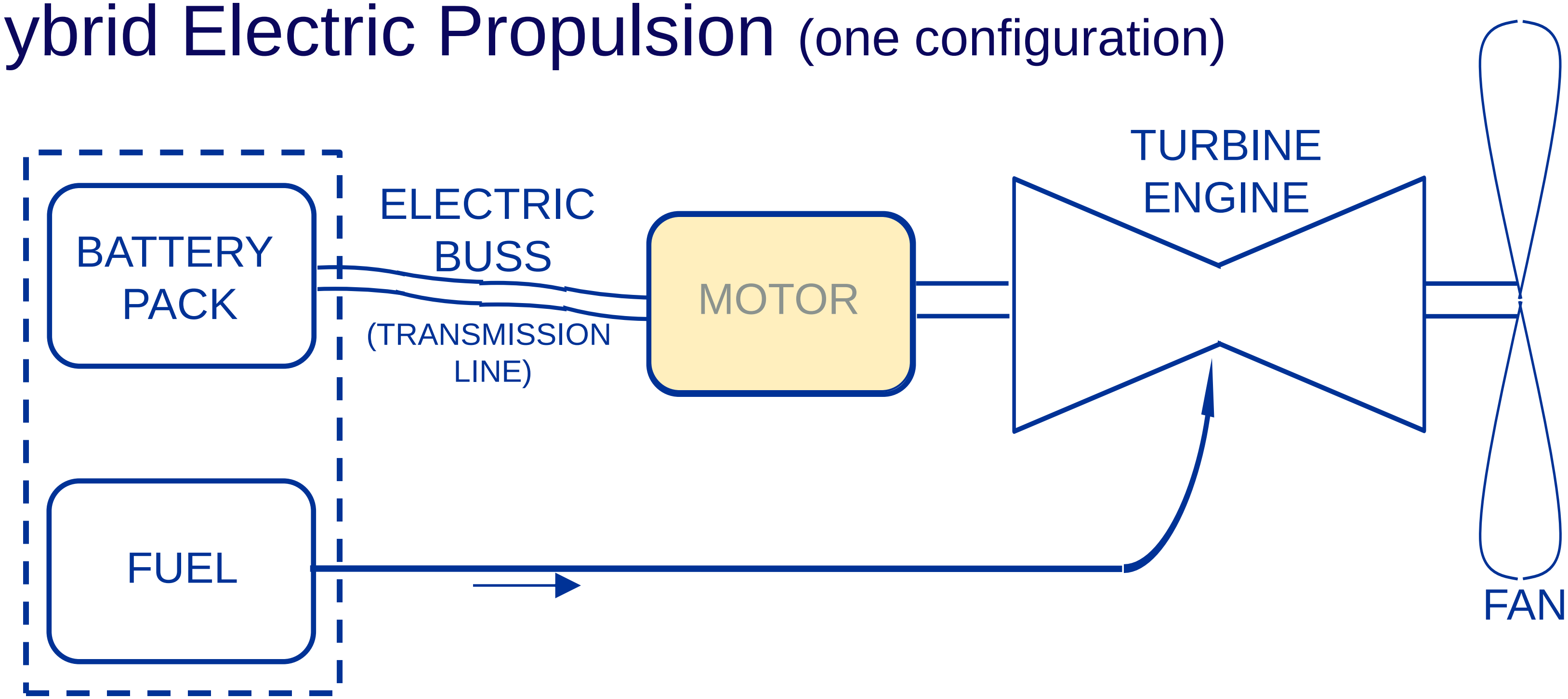


Turboelectric Propulsion



1. Hybrid Electric Propulsion

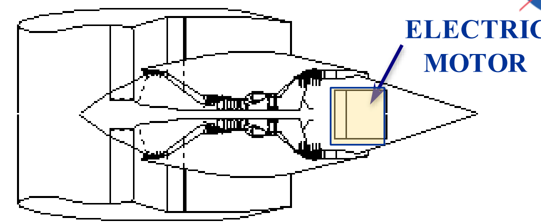
Hybrid Electric Propulsion (one configuration)



- Ratio of electrical to fuel energy varies with flight distance
- Eliminates CO_2 and water vapor emissions at altitude for shorter flights.
- Eliminates ground-generated CO_2 if electricity source is nuclear, solar, wind, hydroelectric, etc.

Some components are not shown (e.g. inverters and thermal management)

Hybrid Electric Propulsion Aircraft NRA: Boeing, GE



hFan Concept from:http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20110011321_2011011863.pdf

- Turbine engines + battery-powered electric motors
- NRA:
  - "SUGAR* Volt" (154 PAX)
  - ~5 MW electric on each of 2 engines
  - Room temperature components
  - Motor & engine each sized for cruise, both used at takeoff
  - Battery pack size depends on range
  - Sensitivity coefficients developed
  - Data development underway

- *<u>S</u>ubsonic <u>U</u>ltra <u>G</u>reen <u>A</u>ircraft <u>R</u>esearch

(PICTURE STOLEN FROM CHEVY VOLT)

Room Temperature Hybrid Electric (generic example)

(Assume 11,000 hp total from 2 motors)

BATTERY

TRANSMISSION LINE

0.1%

Wt: 1 klb

INVERTER

3%

10 hp/lb

Wt: 1.1 klb

MOTOR

3%

3 hp/lb

Wt: 3.7 klb

Cum. loss

6%

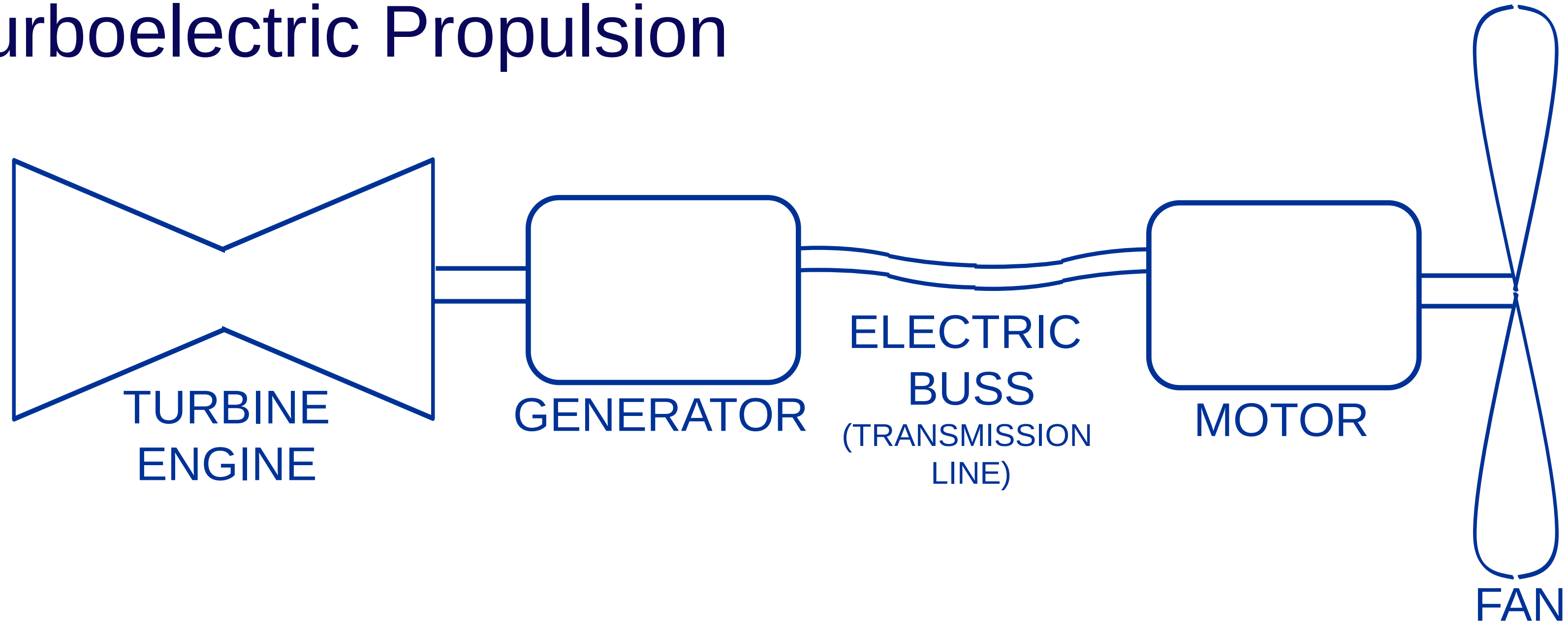
Aircraft mean weight (150 PAX)	~150 klb	
Electric component total weight: (not incl. batteries)	6 klb	(4% of aircraft wt.)
Battery pack weight:	~ 30 klb	(20% of aircraft wt.)
Battery over-sizing for 6% electrical loss:	6%	(before iterating)
Battery over-sizing for 6 klb added weight:	4%	(before iterating)
Total battery size penalties:	10%	(before iterating)

But CO_2 and H_2O emissions are reduced and are nearly eliminated for short missions. Superconductors could help; CNTs* might one day.

*CNTs: Carbon nanotubes

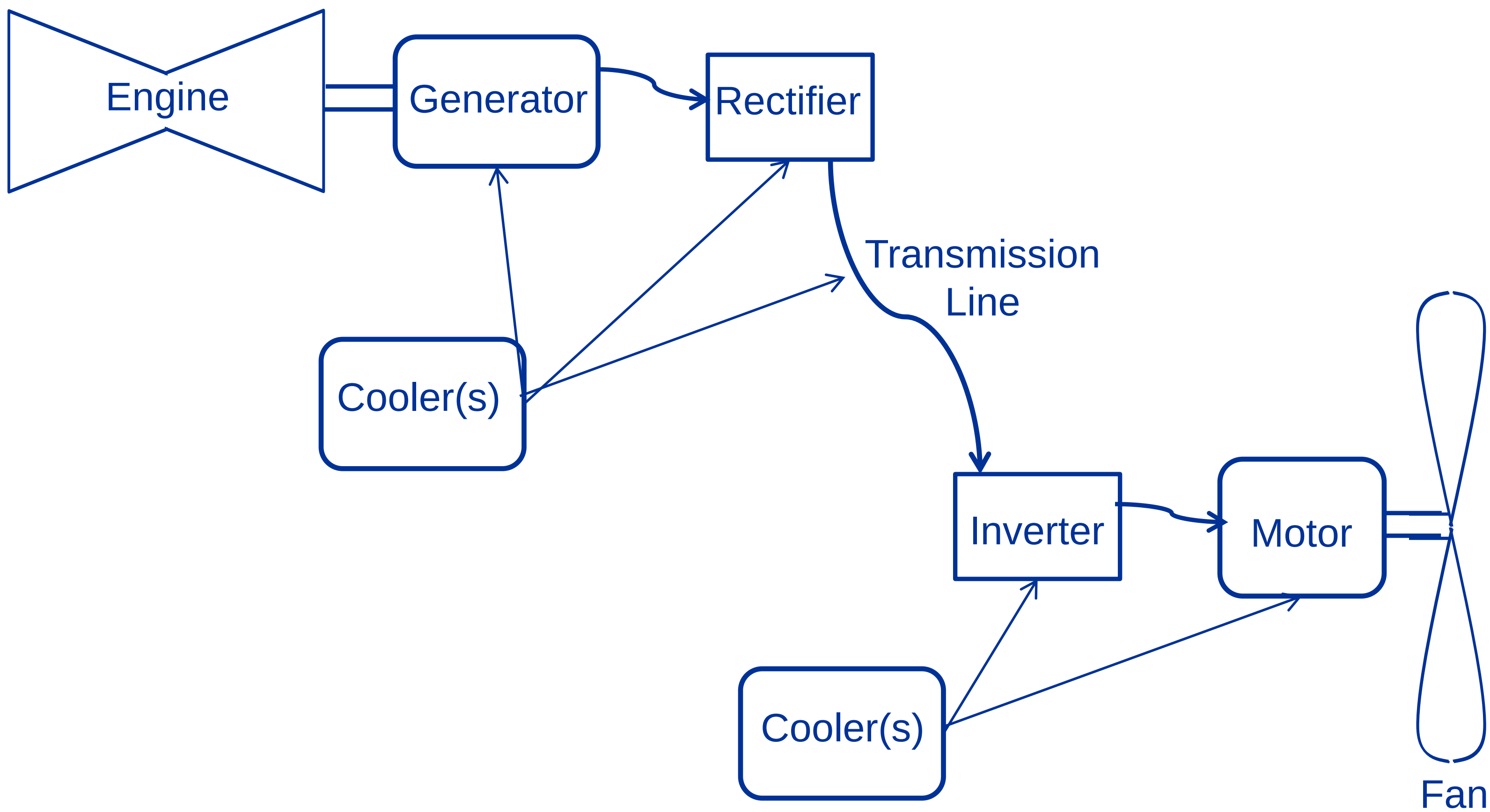
2. Turboelectric Distributed Propulsion (Room Temp.)

Turboelectric Propulsion



Concept is shown without auxiliaries such as inverters and thermal management

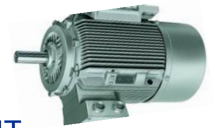
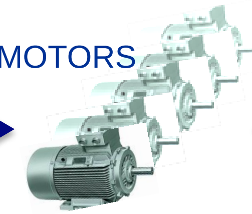
Turboelectric Propulsion



THE MAIN GOALS OF TURBOELECTRIC PROPULSION ARE TO SAVE FUEL AND REDUCE NOISE.

Room Temperature Turboelectric Propulsion

(Assume 60,000 hp total into 15 fans for N3-X BWB aircraft)

	GENERATOR	RECTIFIER	TRANS. LINE	INVERTERS	MOTORS	
						Cum. Loss 12%
COMPONENT LOSS:	3%	3%	0.1%	3%	3%	
	(3 hp/lb) Wt: 20 klb	(10 hp/lb) Wt: 6 klb	Wt: 1 klb	(10 hp/lb) Wt: 6 klb	(3 hp/lb) Wt: 20 klb	

N3-X aircraft mean weight (300 PAX):	440 klb		
Engine & fan mass w/o electric components:	15 klb		
Electric component total weight:	53 klb	(12% of aircraft wt.)	
Extra fuel burn for electrical losses	12%		(before iterating)
Extra fuel burn for added weight:	12 %		(before iterating)
Fuel burn saving from BLI and higher BPR:	16%		(before iterating)
Net extra fuel burn:	8% increase!		(before iterating)

BATTERY

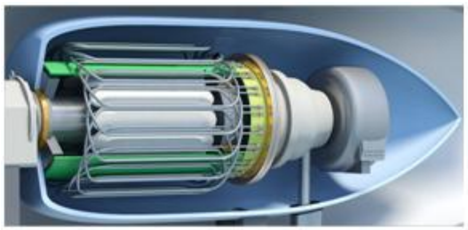
TeDP at room temp. will not likely save fuel, unless conductors superior to copper are developed (CNTs?), but might be used for other reasons such as low noise or as a demonstrator.

3. Turboelectric Distributed Propulsion (Cryogenic and Superconducting Components)

“N3-X” Distributed Turboelectric Propulsion System

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

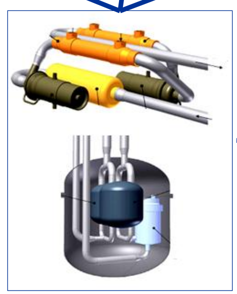
Turboelectric Propulsion System Requires Cryogenic and Superconducting Components for Light Weight & High Efficiency



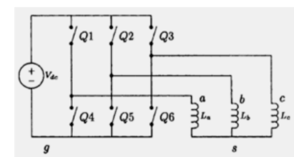
Superconducting generator

Superconducting transmission lines

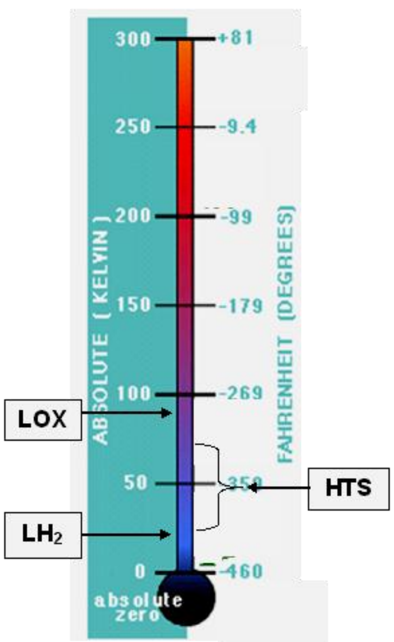
Superconducting motors



Cryocooler(s)

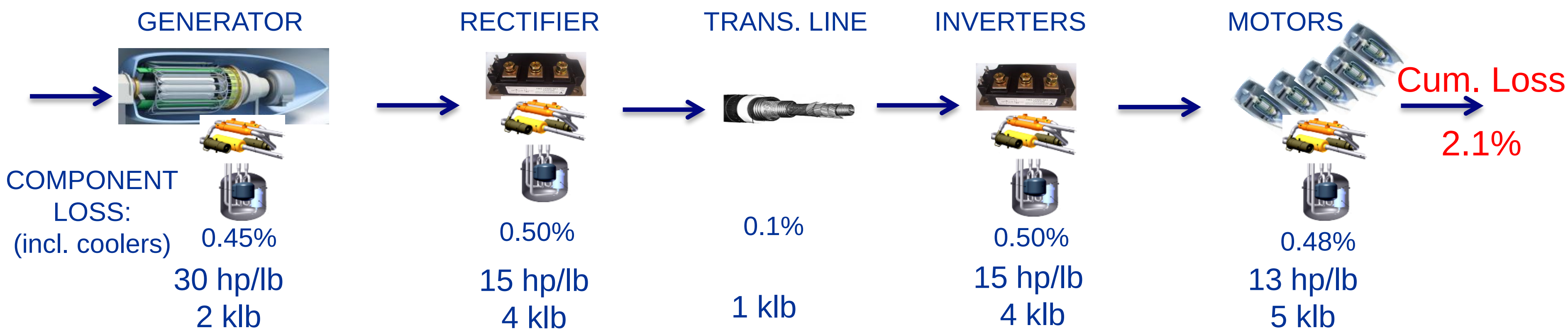


Cryogenic Inverters/ Rectifiers



CRYO & SUPERCONDUCTING TURBOELECTRIC PROPULSION

(Assume 60,000 hp total into 15 fans for N3-X)



N3-X aircraft mean weight:	~440 klb	
Engine & fan mass w/o electric components:	~20 klb	
Electric component total weight:	16 klb (3.6% of aircraft wt.)	
Extra fuel burn for electric losses:	2.1%	(before iterating)
Extra fuel burn for added weight:	3.6%	(before iterating)
Fuel burn saved by BLI and higher BPR:	16%	(before iterating)
Net fuel burn saved:	10% saving	(before iterating)

This is the system for which I'll discuss tech challenges.

Summary of Performance Estimates

- *Room Temperature Hybrid Electric* (94% efficient)
  - Electric losses and added weight require 10% battery over-sizing
  - Almost no emissions (incl. CO_2 or H_2O) on short flights
  - Battery & electric system are a weight penalty on longer flights
- *Room Temperature Turboelectric* (88% efficient)
  - 24% more fuel burn for electric losses and added weight
  - 16% benefits from BPR & BLI on BWB
  - 8% <u>more</u> fuel burn required
- *Cryogenic and Superconducting Turboelectric* (98% efficient)
  - 5.7% more fuel burn for electric losses and added weight
  - 16% benefits from BPR & BLI on BWB
  - 10% net fuel burn <u>saving</u>

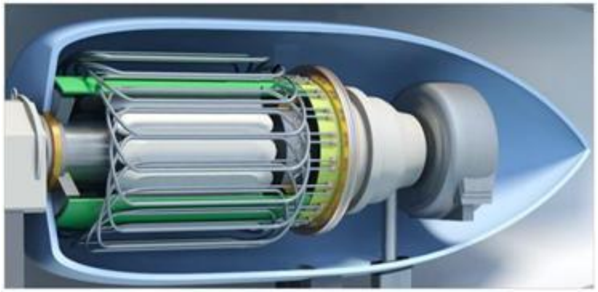
Turboelectric Distributed Propulsion (TeDP) and its Electric Technical Challenges

COMPONENT	TECHNICAL CHALLENGE
Generators & Motors	1/5th SOA weight and low AC losses *NRA (3 yrs @ 300K ea)* *In-house sizing analyses*
Cryocoolers	1/5th SOA weight *Phase 1 SBIR*
Cryo Inverters/Rectifiers	½ SOA weight and ~1/10th SOA loss *Phase 2 SBIR* *In-house cryo-inverter tests*
Total electric system	Distribute ~50 MW in a stable, responsive grid *RTAPS contract* *In-house subscale system model*

A ROADMAP FOR EACH AREA WAS DEVELOPED AT A 2009 WORKSHOP.

EACH GOAL IS DEEMED REACHABLE WITH PLANNED R&D,
BASED UPON SIZING AND OTHER MODELS - - NOT JUST NEED!

Fully Superconducting Motor or Generator

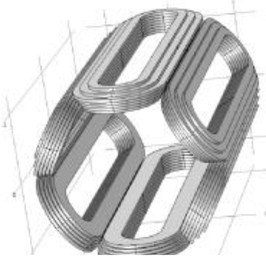


Technical Challenge:

1/5th SOA* weight & low AC losses
Fully superconducting windings for power density
Fine filament superconductor for low loss

Element:

NRA @ Advanced Magnet Lab / U. Houston
(3 yrs @ 300K ea)



SUPERCONDUCTING ROTOR WINDINGS

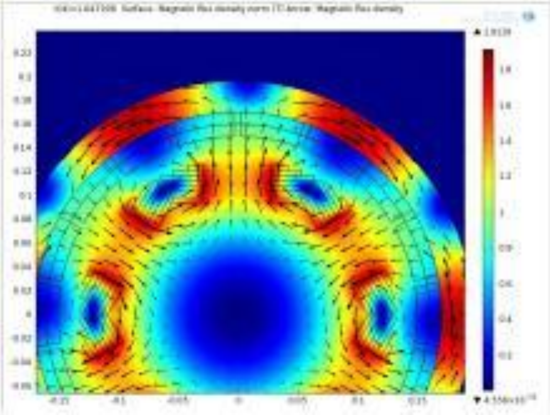
SUPERCONDUCTING STATOR WINDINGS

Tasks:

- Higher fidelity analysis (F.E., Monte Carlo)
- Detailed machine design
- Fabricate stator segment for loss tests
- AC loss validation

Progress @ 9 months:

- Iron magnetization calc. method done
- Coil calc. method in progress
- Mechanical design begun



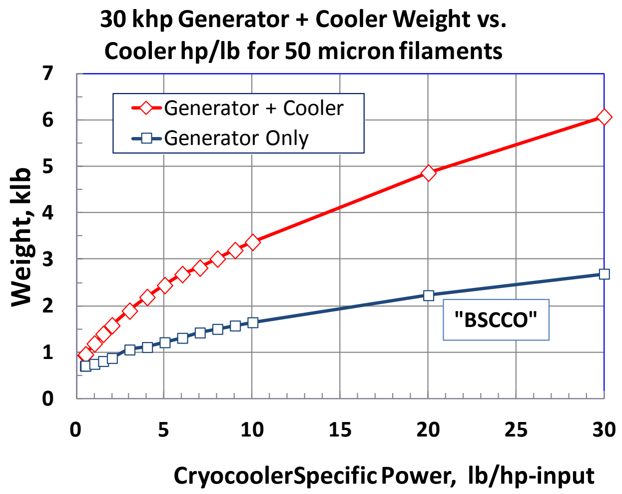
* SOA is 6 hp/lb specific power (Air Force cryogenic exciter).

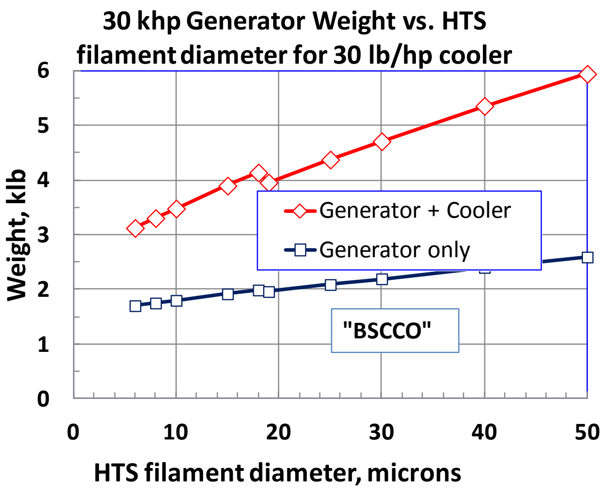
Fully Superconducting Electric Machine Analysis

Technical Challenge:
Machines with 1/5th SOA* weight & low AC losses

Element: In-house analysis

- Sizing model for parametric studies
- Predict weights & efficiencies as functions of superconductor and cryocooler parameters.
- Results: Need light cryocoolers and fine-filament superconductors. See graphs.





Flight Weight Cryocooler

State-of-the-art weight: 30 lb/(hp-input)
30% of Carnot

Elements:

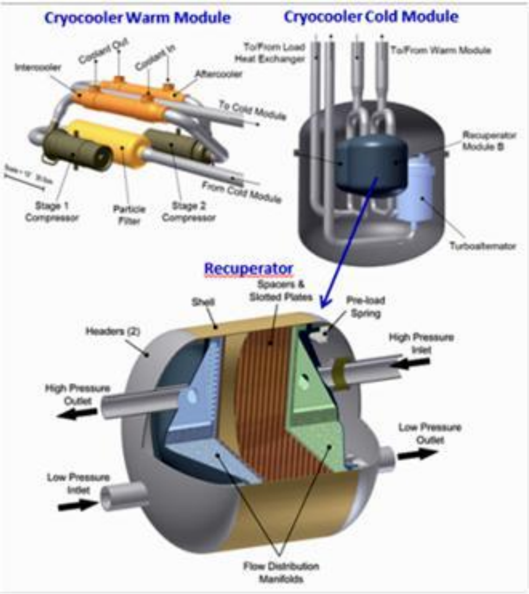
2009 Phase 1 SBIR (Creare): Brayton prelim. design:
5 lb/(hp-input)
30% of Carnot

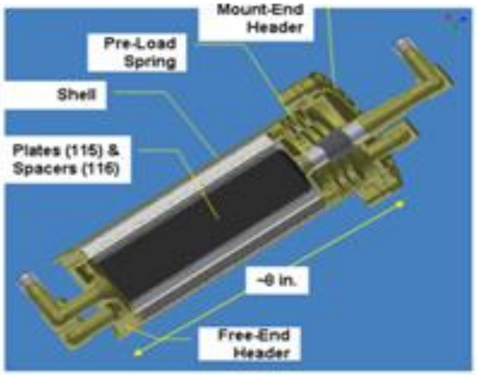
2011 SBIR (Creare) (started Feb 20, 2012):

Phase 1 - Recuperator detailed design
- Risk mitigation tests

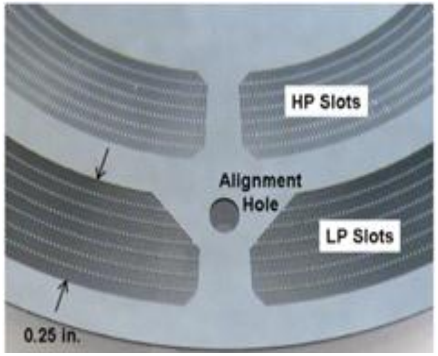
Phase 2 - Fabrication & Test

Navy, Air Force and NASA hope to cooperate on advanced cooler development.





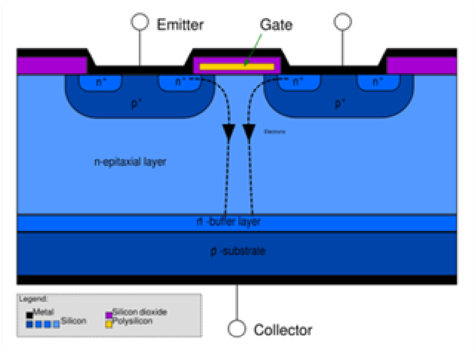
Recuperator stack

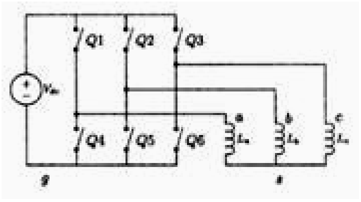


Recuperator plate

Cryogenic Inverter (or rectifier)

- Power transistors change DC power to AC for variable-speed motor drive
- Room temp inverters:
  ~95 to 98% efficiency
  up to 10 hp/lb
- Phase 1 SBIR modeling results (MTECH):
  99.5% efficiency, incl. cooler
  17 hp/lb, including cooler





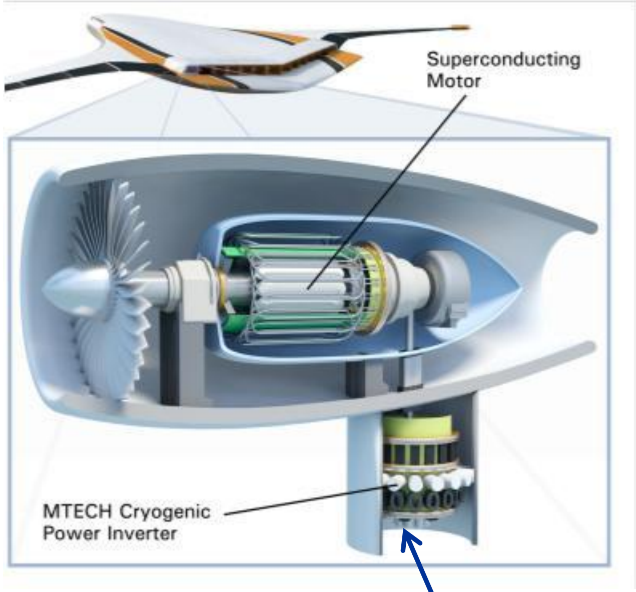
High power density and efficiency at low temp are due to:

Lower forward resistance

Faster switching

Superconducting interconnections

Cryogenic Inverter (and rectifier)



Not in airstream!

Technical Challenge:

½ SOA weight and ~1/10th SOA loss

Element:

Phase 2 SBIR @ MTECH Inc.

Tasks:

- Design cryogenic multi-chip module
- Fab & test multi-chip module and ancillary circuits
- Design, fab & test one phase leg of a half-bridge inverter

Progress @ 9 months:

- Characterized components in liquid nitrogen, etc.
- Preliminary design of a compact module

Study of TeDP Electrical System Issues

Challenge:

Develop stable and responsive high power propulsive electric grid (~50 MW)

Element:

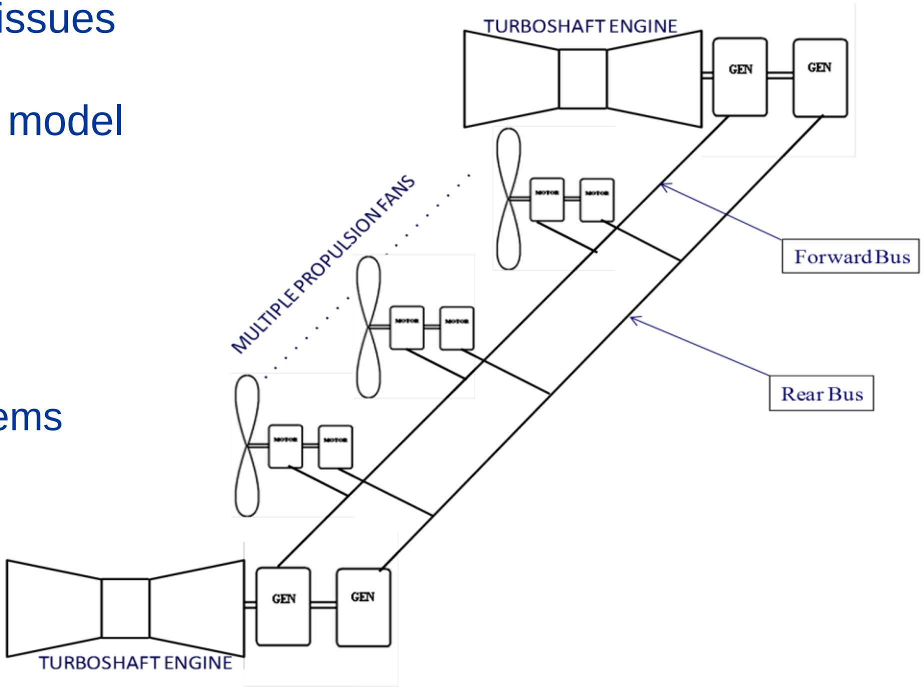
Liberty Works RTAPS contract, 1 year, 250K,
"Stability, Transient Response, Control and Safety of a High-Power Electric Grid for TeDP Aircraft"

Tasks:

Identify & rank TeDP electric system issues
Develop candidate architecture
Develop and deliver dynamic system model

Progress @ 6 months:

Prioritized list of issues developed
Now defining architecture
- Choice of bus voltage
- Level of redundancy for all systems
- Need energy storage?
- Physical layout
- Means for failure response



NOTIONAL ARCHITECTURE OF PROPULSION ELECTRIC GRID

In-House Work

- Analysis of motors and generators (to feed into aircraft system models)
- Cryo-inverter testing

- Subscale electrical system model

- Small HTS machine

- New synthesis method for low-AC-loss MgB_2 under consideration

Concluding Remarks

- Hybrid electric with room temperature components appears viable for reducing emissions aloft, including CO_2 and H_2O. *(NRA)*
- Turboelectric distributed propulsion (TeDP) requires superconducting and cryo components for good efficiency and power density.
- TeDP will save fuel if the identified technologies are developed.
- Fully superconducting generators and motors are feasible. *(NRA)*
- Cryocoolers and cryo-inverters can meet goals with R&D. *(SBIR)*
- Stability and response of electric system are being studied. *(Contract)*

- Some presently set goals may be surpassed and further reduce weight.

- New superconductors or carbon nanotube conductors, etc., may appear in the N+3 time frame and contribute to success.

Conventional Motor & Generator Efficiency vs. Power