Novel Thermal Energy Conversion Technologies for Advanced Electric Air Vehicles

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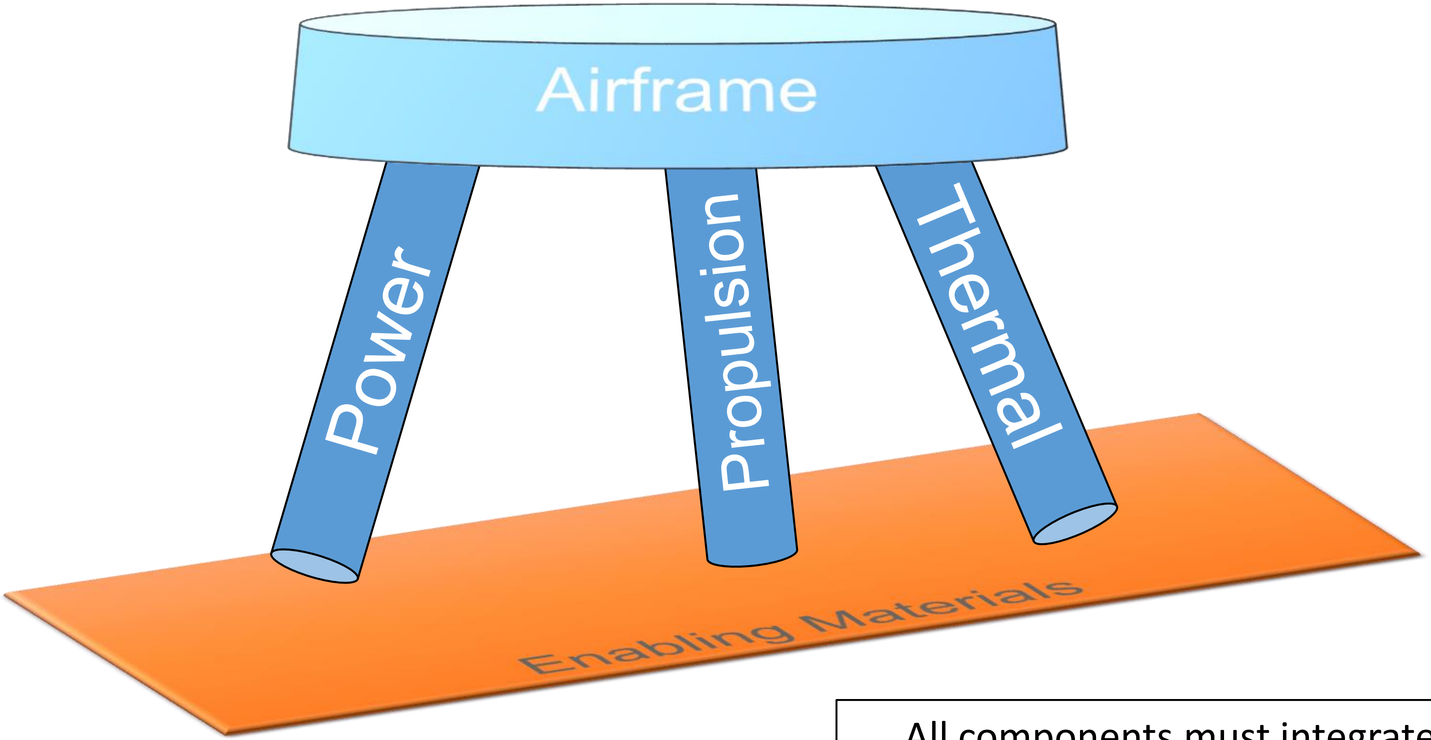
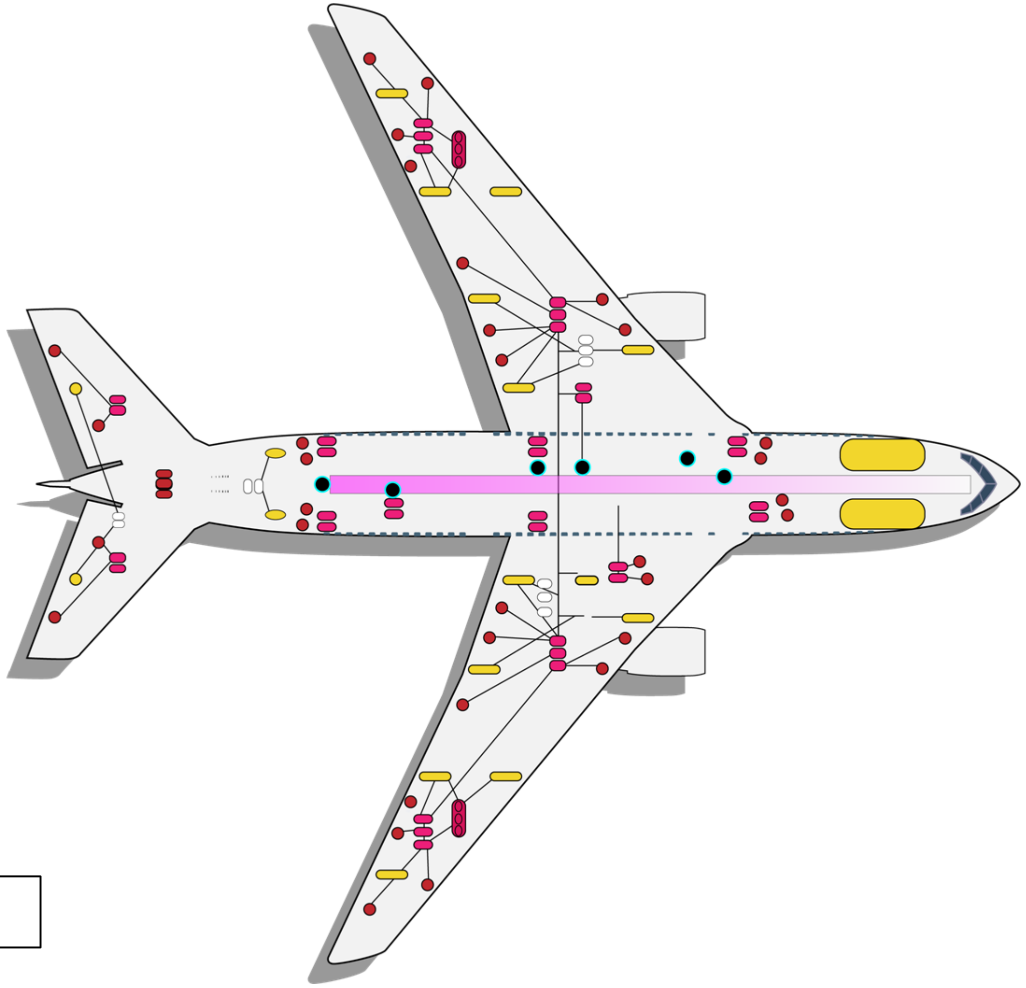
Dr. Rodger Dyson
Hybrid Gas Electric Propulsion Technical Lead
NASA Glenn Research Center

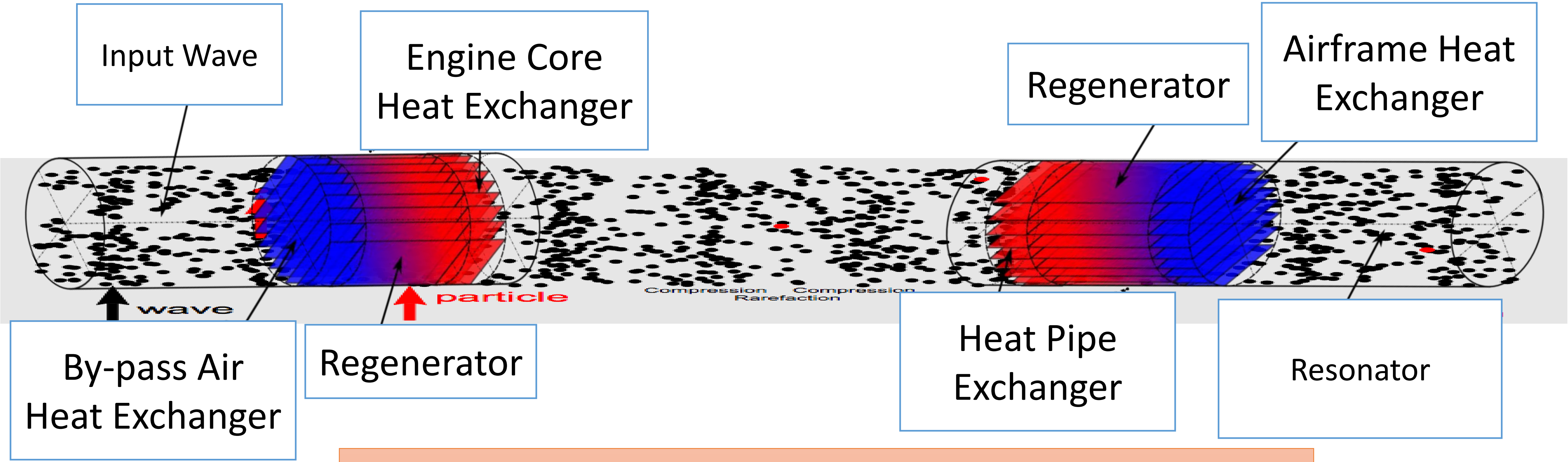
Power, Propulsion, Thermal, Airframe Integration





All components must integrate

Basic Building Block for Electric Aircraft: Thermo-Acoustic Engine and Heat Pumping



KEY PROPERTIES

Can be used for thermal energy conversion:

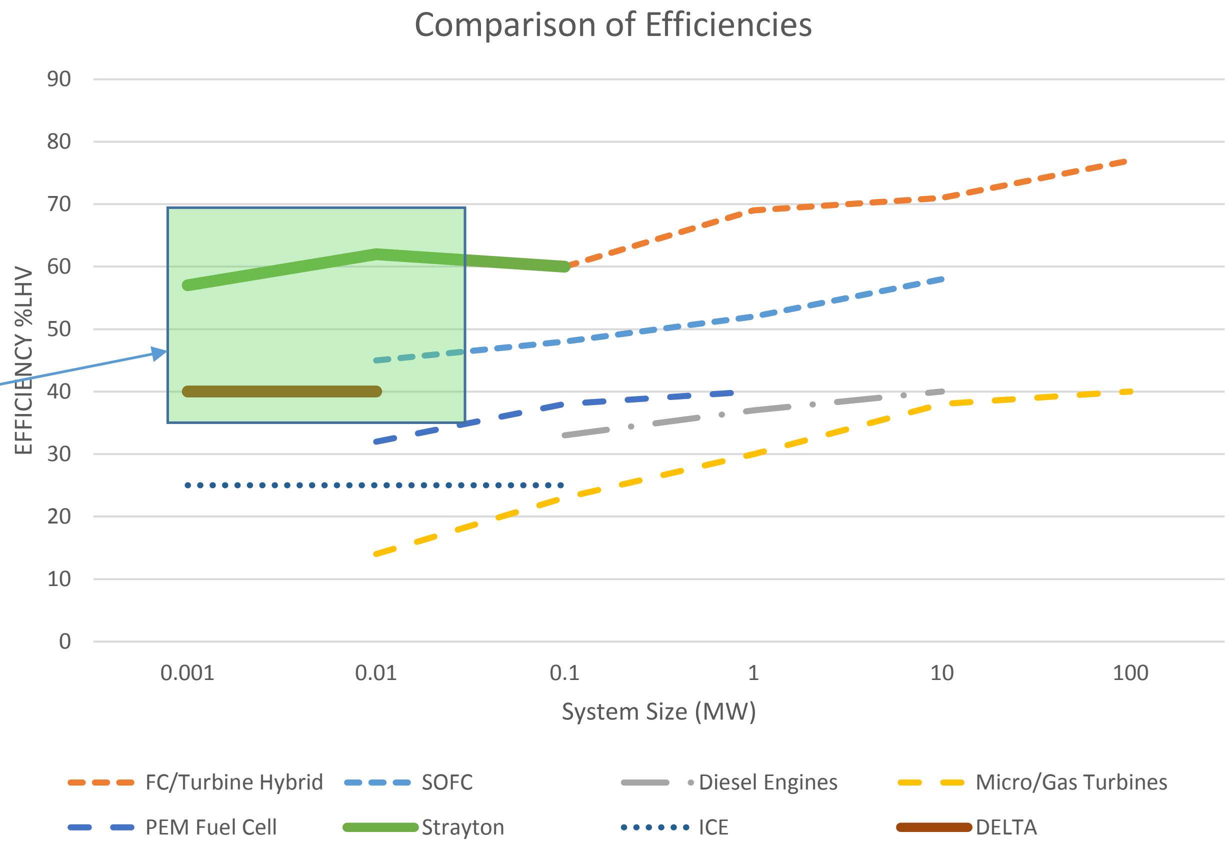
- From heat to mechanical power
- From mechanical power to cooling
- From heat to heat pump when used in double configuration shown

Power Options

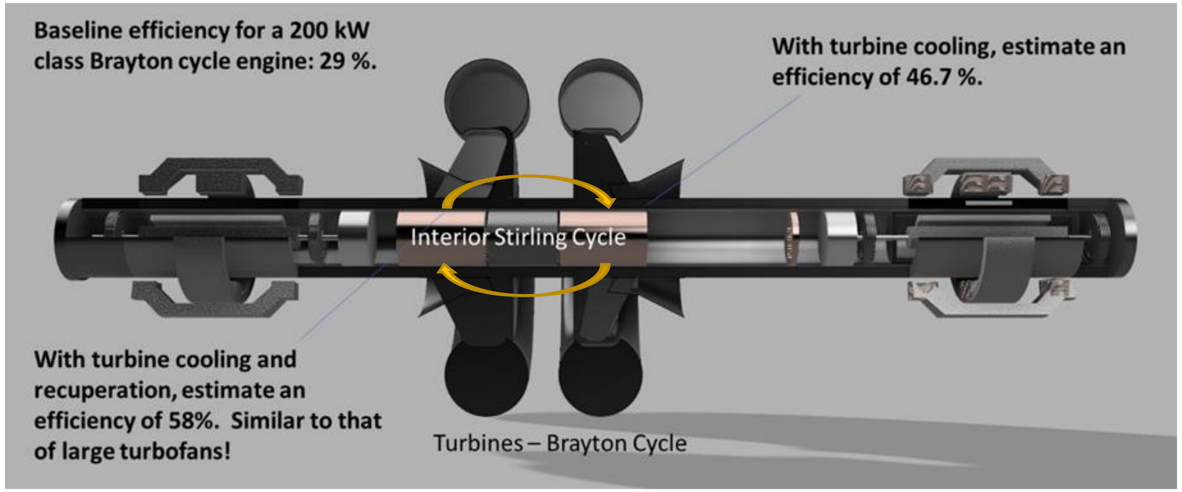
- FC/Turbine Hybrid
- PEM/SOFC
- Micro/Gas turbines
- Diesel
- ICE
- **DELTA**
- **Strayton**

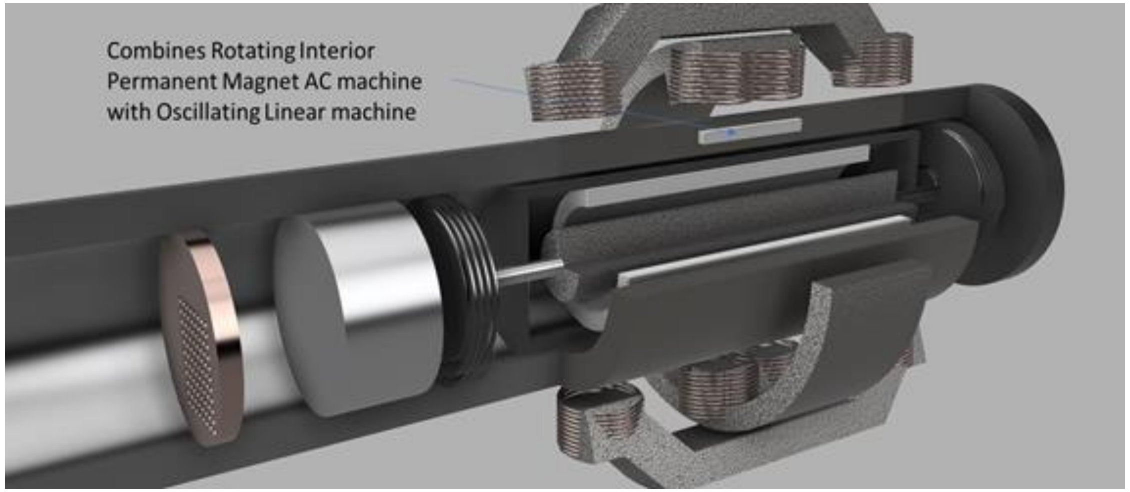
Technology	Net System AC Power (kW)	Net Fuel LHV to AC Electric Power Conversion Efficiency	Full Production Equipment Manufacturing Cost $ per W	System Maintenance Cost $/kwh	System Availability Percent	System Life (yrs)
Ideal	>100	>70	<0.9	0.02	>95	>20
SOFC-GT	>100	>70	<4	<1	>95	>5
Strayton	>100	>50	<0.05	<0.02	>95	>20
Fuel Cell	>100	>50	<5	<1	>95	<5
µ-Turbine	<300	>20	<1	<0.1	>95	<5
ICE OTTO	>100	>25	<0.05	<0.03	>95	<10
Gas Turbine	>1000	>40	<0.5	<0.1	>95	<5

Region of Interest



Stirling and Brayton (Strayton) Engine Genset





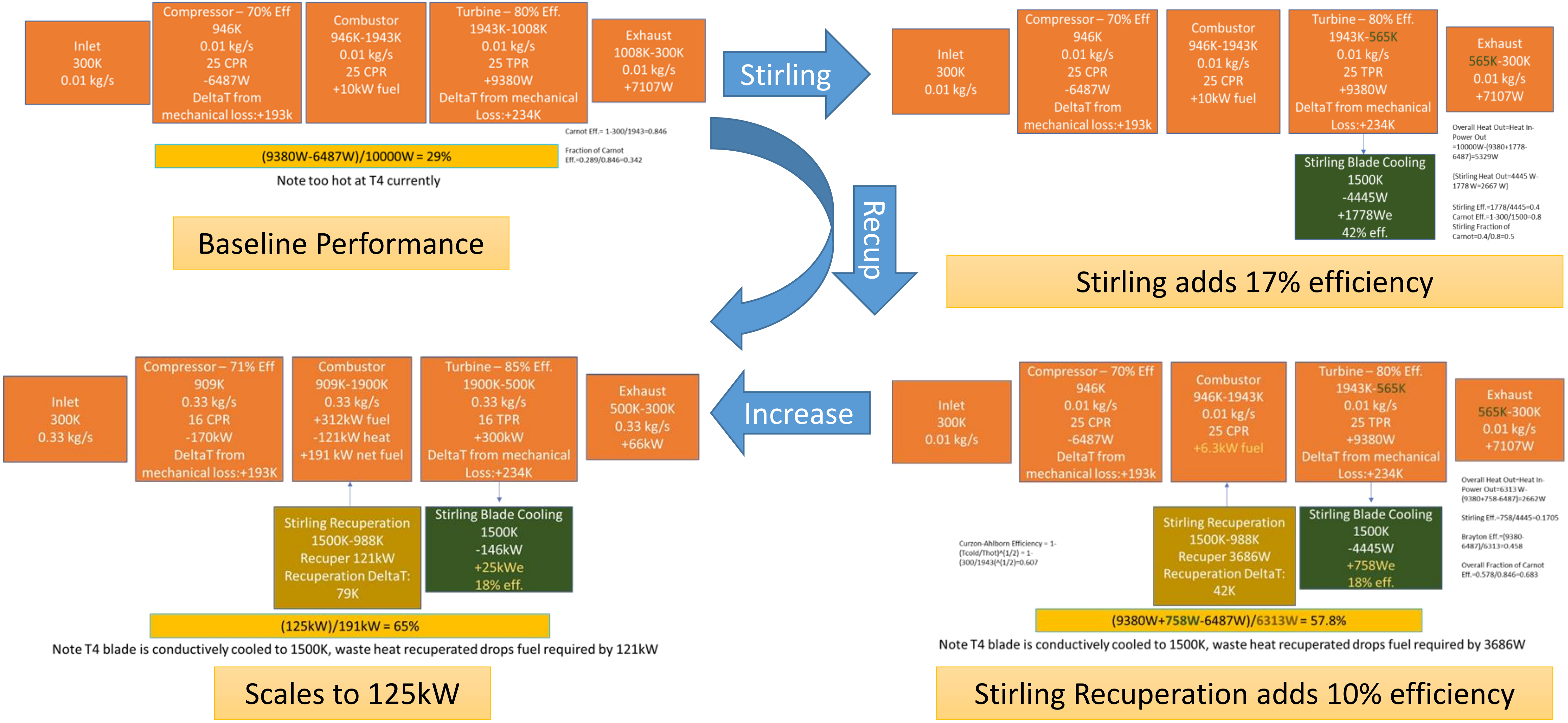
Key Features

- Combines Stirling and Brayton cycles synergistically for <2MW high efficiency and specific power
- Provides both topping and bottoming cycles using a Brayton and Stirling cycle (both are top and bottom!)
- Achieves recuperation without a recuperator
- Naturally cools the turbine blades
- Power is extracted via rotating and oscillation
- Fuel Flexible with high turn-down ratio

Key Features

- High-speed Brayton cycle and internal Stirling cycle use no-maintenance air and flexure bearings
- Power balancing between cycles via direct control
- No contact rotating bearings and power transfer
- High speed rotation enable short conductive blades
- No hot moving Stirling cycle parts
- Leverages recent HEMM work for flexure stiffness
- Pedigree from previous DOE/Reliance Electric 2008

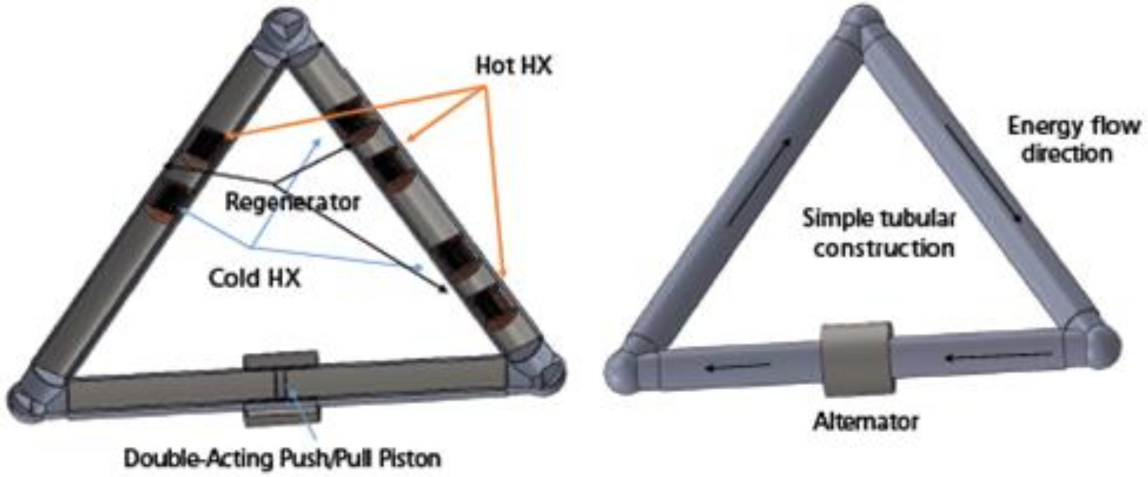
Thermodynamic Efficiency Step-by-Step



Double-Acting Extremely Light-Weight Thermo-Acoustic Generator (DELTA)

Key Features

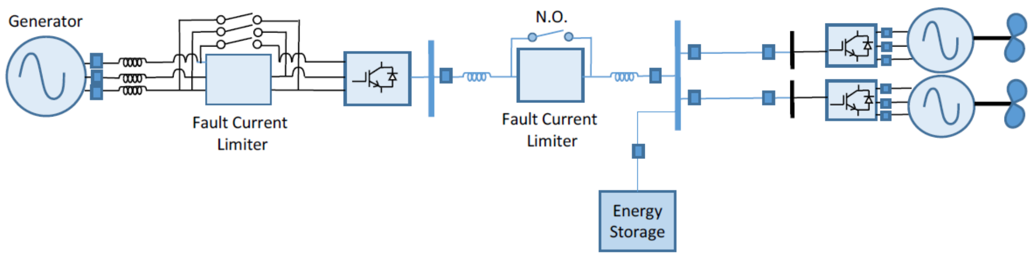
- Utilizes multistage high frequency thermo-acoustics
- Uses a double-acting piston and engine reactive power to minimize required spring
- Fuel flexible including cryogenic
- Shape flexible for embedding in unusual locations
- Silent operation
- Higher efficiency and comparable specific power with ICE

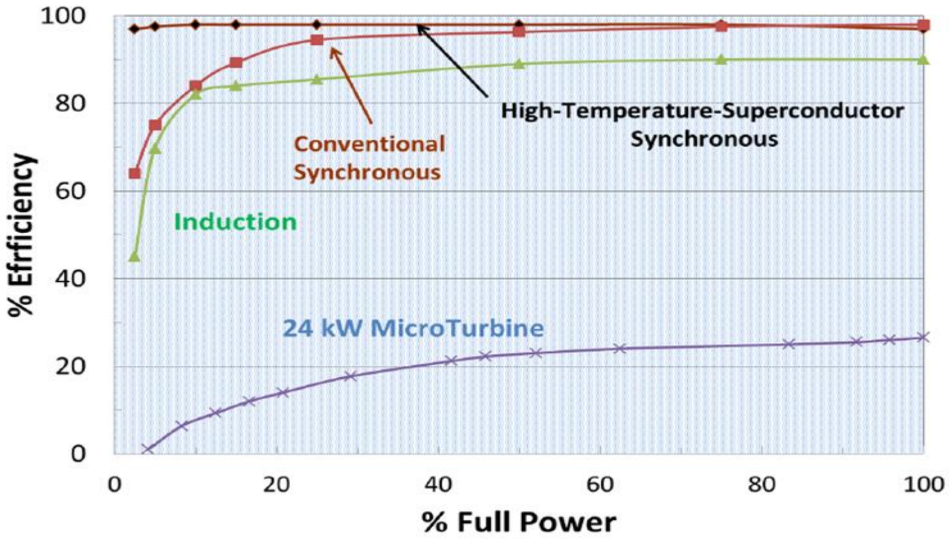


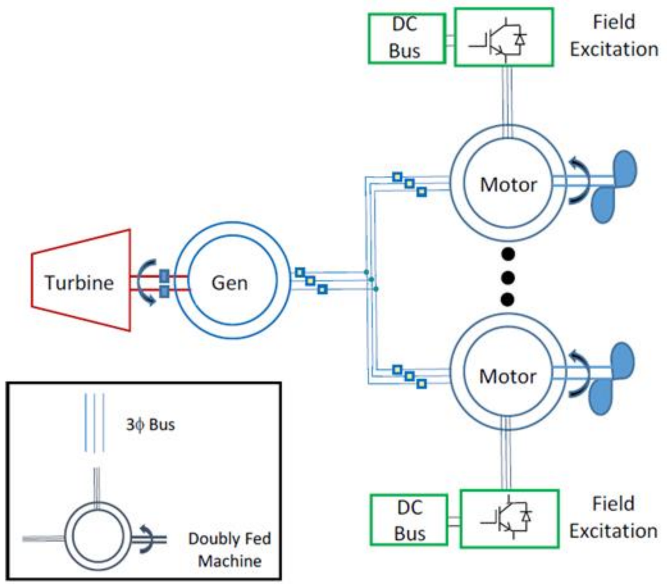
Provides silent power for APU and UAV applications

Propulsion Options

- Fully Superconducting
- Partially Superconducting
- PM Synchronous
- Induction
- Double-fed

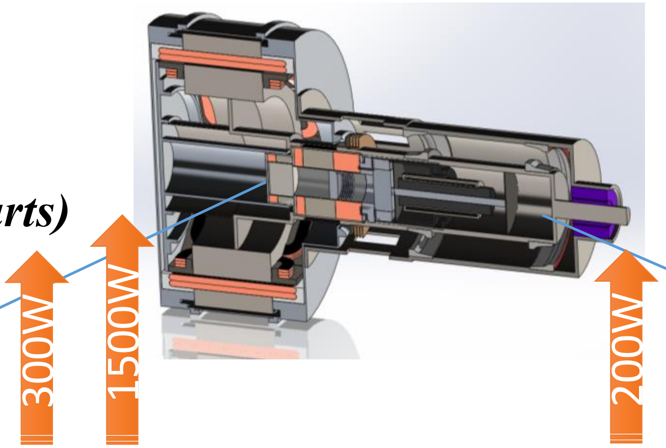




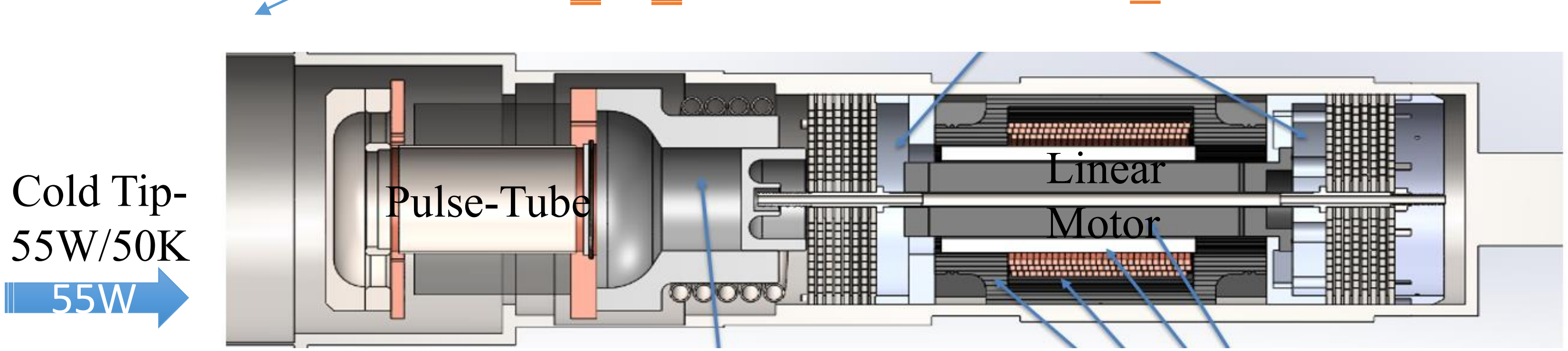


HEMM w/Embedded Cryocooler

HEMM is designed to operate as
- a ***1.4 MW*** motor
- with ***direct drive***
- ***High torque/low speed***
- ***>98% efficient***
- ***>16 kw/kg (active E-M parts)***



Cryocooler Key Features:
- Cool superconducting rotor
- Fit inside rotating motor
- Integrates cooler and linear machine
- Operate rotating or stationary
- No cold moving parts



Ambient HX- 310K

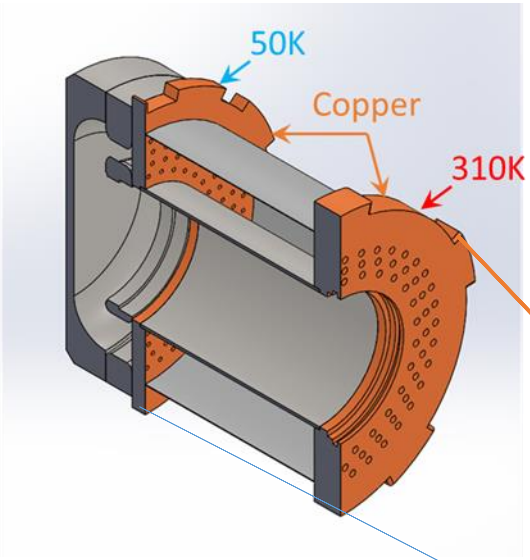
60 Hz, 2000W in

Top Level Parameter	Value
Frequency	60 Hz
Gas	Helium
Pressure	6.2 MPa
Heat Lifted @ 50K	55W
Heat Rejected	2000W
Electrical In	2000W
Mechanical PVin	1661W
Coil Current Density	4 A/mm2
Piston Amplitude	1.3 cm

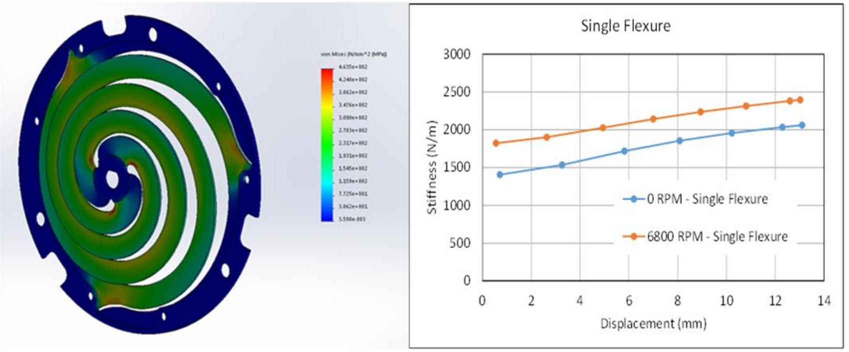
Superconducting inside the motor and provides Strayton risk reduction

Linear Machine and Pulse-Tube Cooler

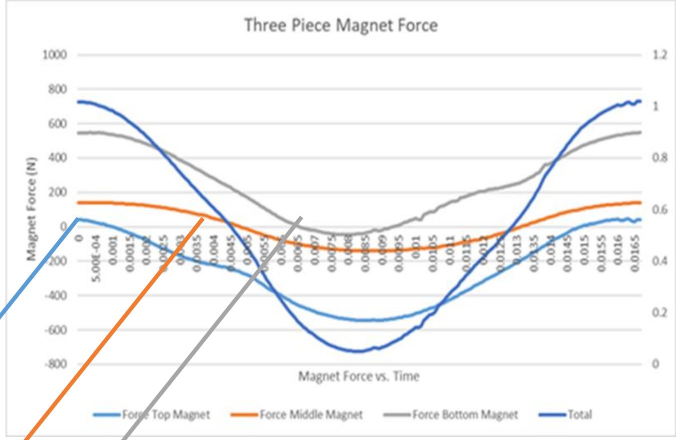
No cold moving parts

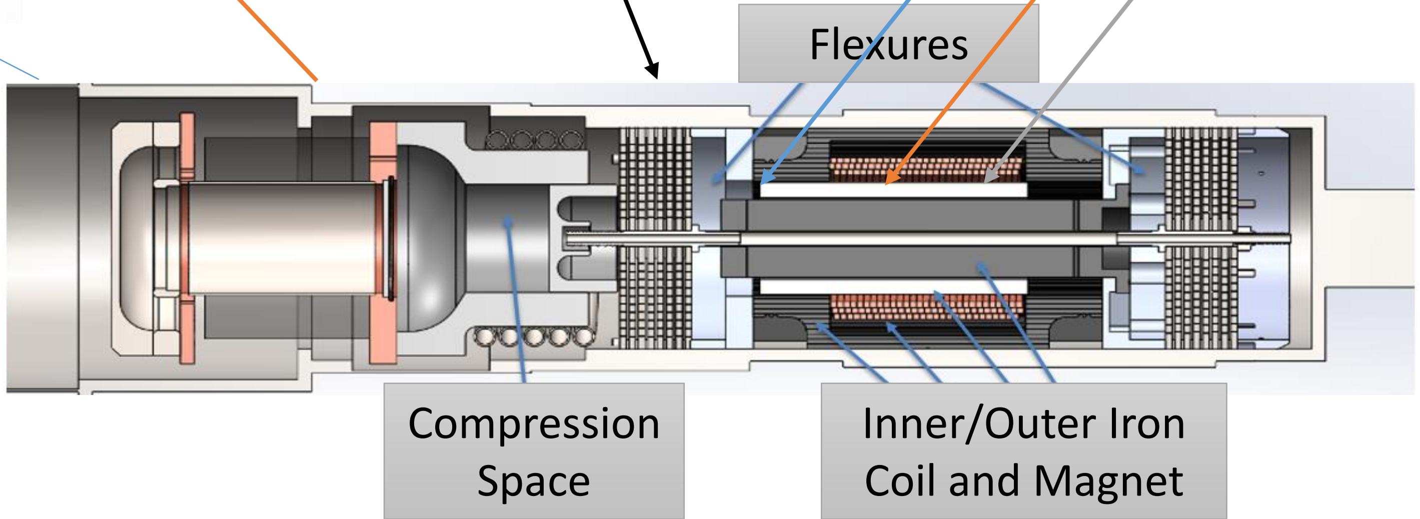


Flexure Stiffness Increases Under Rotation



Long Linear Magnet has Distributed Forces





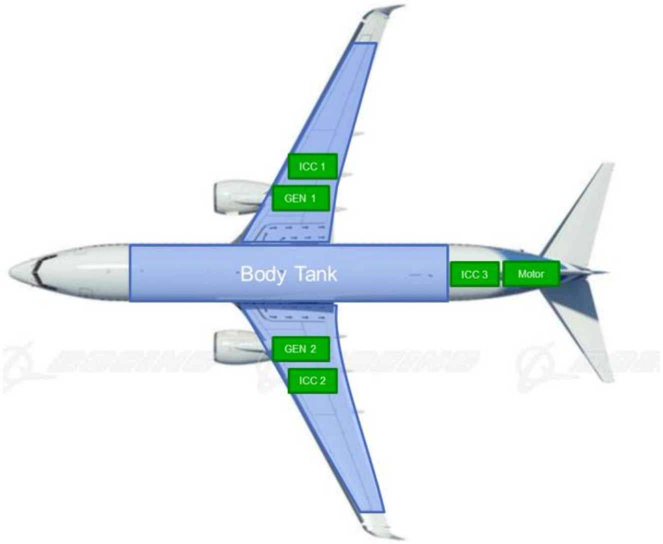
Thermal Options

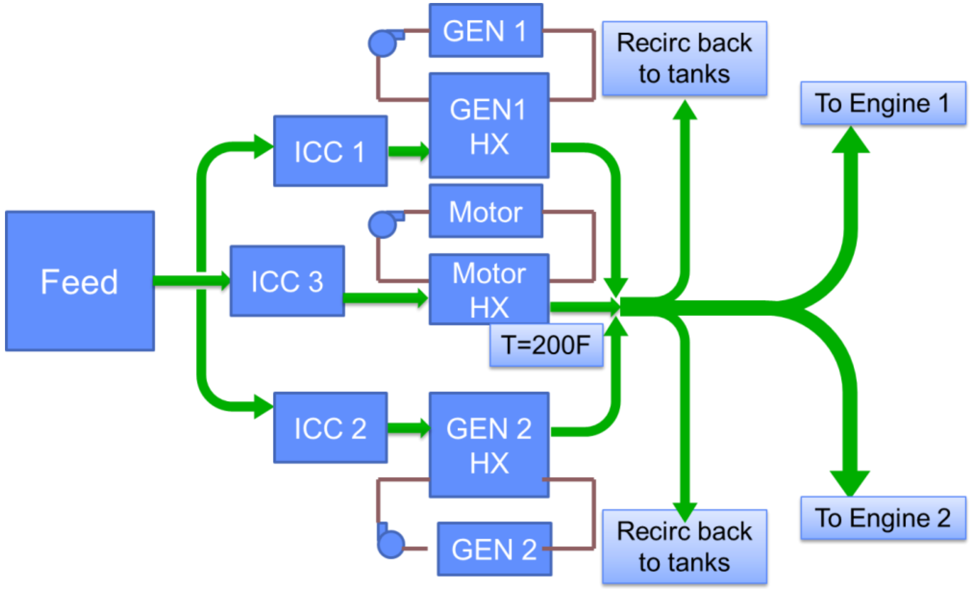
Current proposed solutions (and limits) include:

- ❑ Ram air HX
  - adds weight and aircraft drag
- ❑ Convective skin cooling HX
  - adds weight, drag, and inefficient
- ❑ Dumping heat into fuel
  - limited thermal capacity
- ❑ Dumping heat into lubricating oil
  - limited thermal capacity
- ❑ Active cooling
  - adds weight and consumes engine power
- ❑ Phase change cooling
  - adds weight and limited thermal capacity
- ❑ Heat pipe, pumped multiphase, vapor compression
  - adds weight and consumes engine power

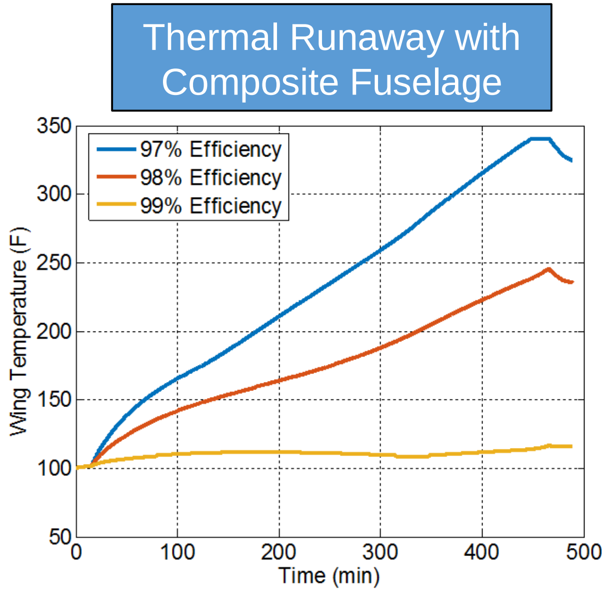
Thermal Limits

Into Fuel
Recirculate Fuel
Ram Air
Into Engine
Vapor-Compression

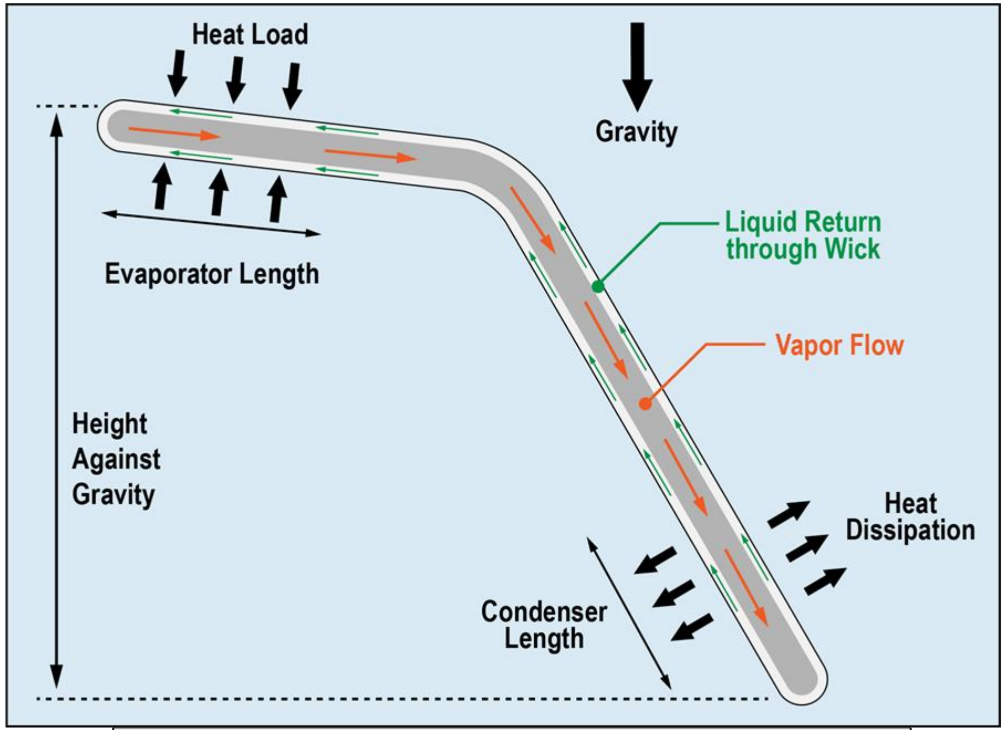


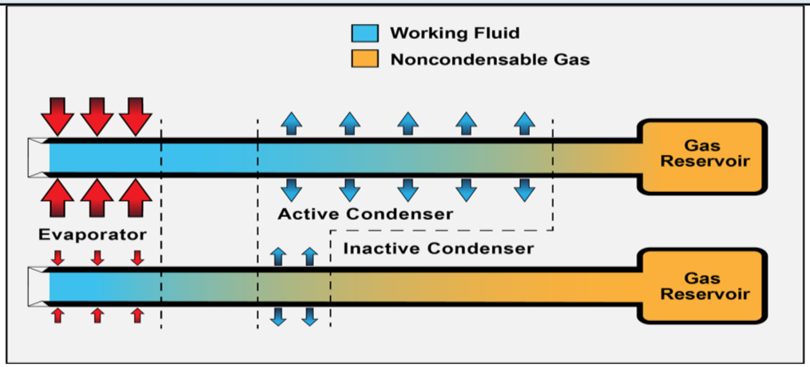


	1% Hot Day		Standard Day	
	Total Penalty (zero exit Velocity)	Total Penalty (non-zero exit velocity)	Total Penalty (zero exit Velocity)	Total Penalty (non-zero exit velocity)
900NM	4.98%	3.31%	2.76%	2.36%
3500NM	5.00%	3.62%	3.01%	2.57%

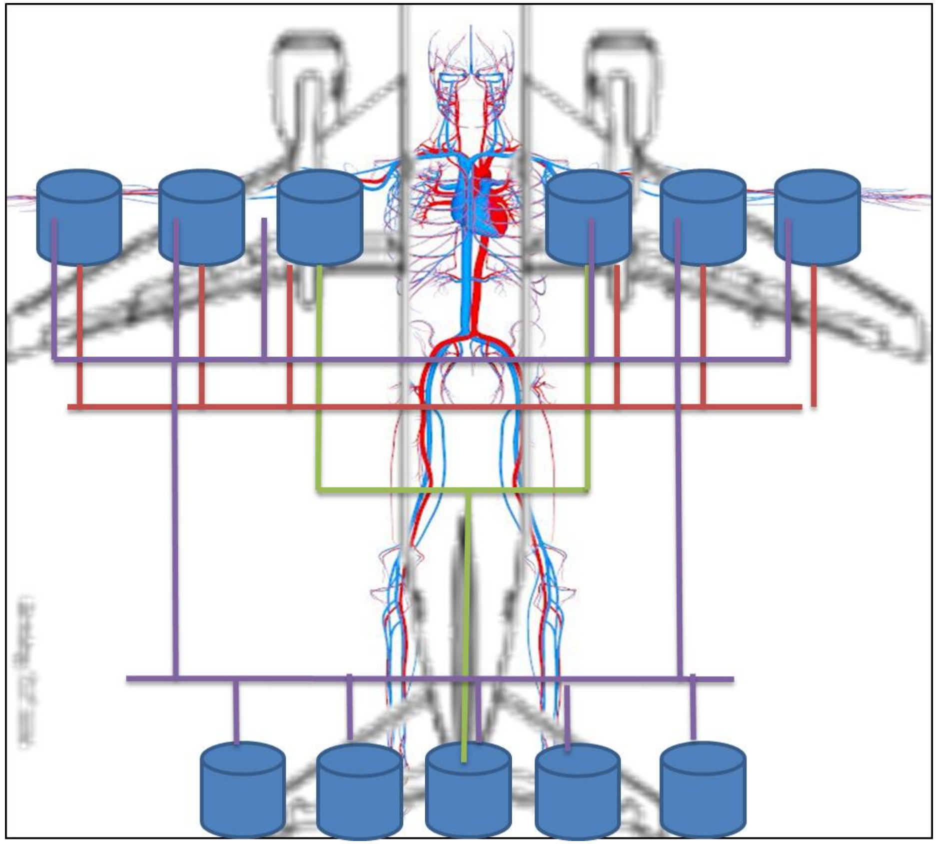


Variable Conductance Heat Pipe





Solid-state Heat Transfer Switching

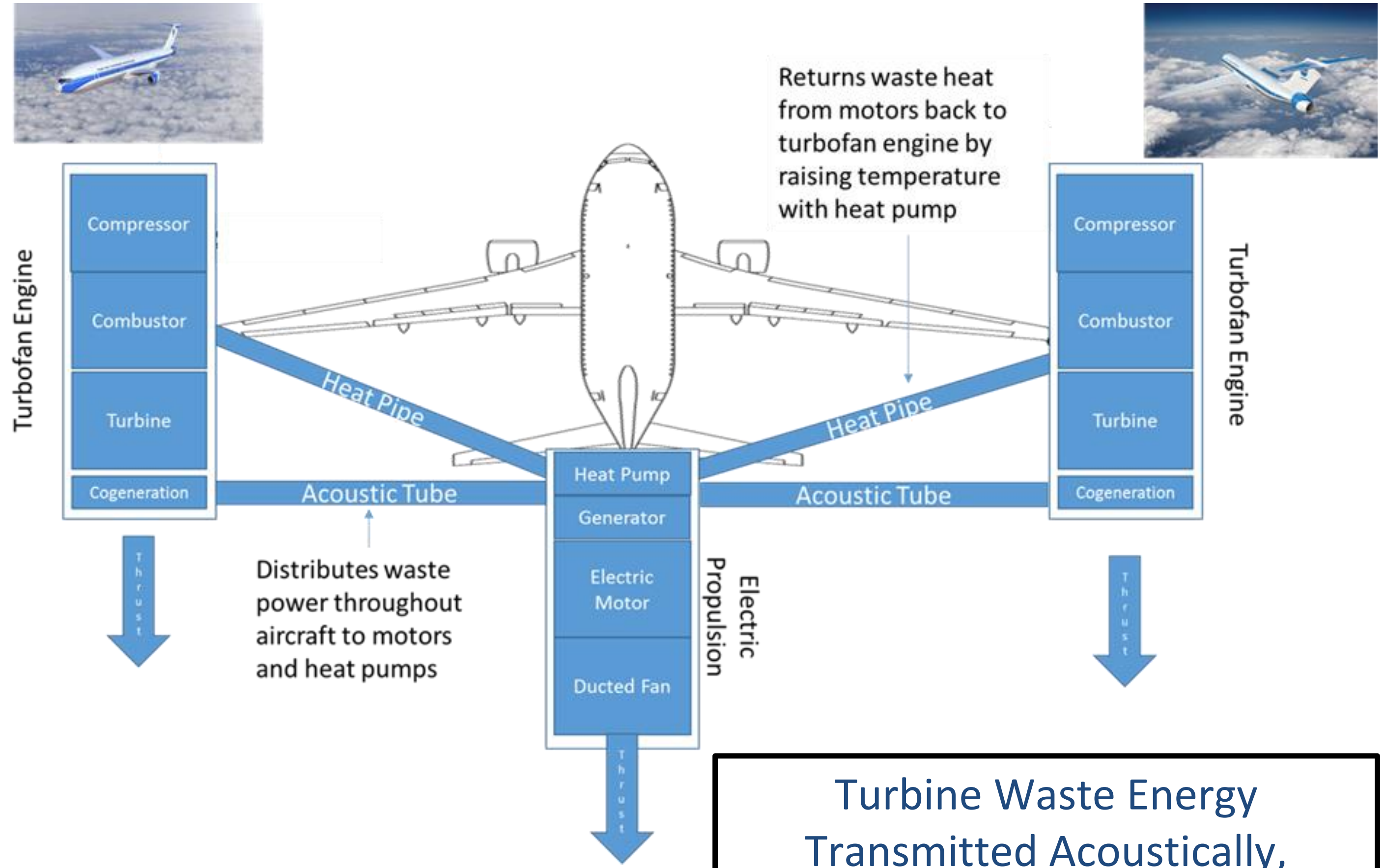


Acoustic and Heat Pipe Tubes
Embedded in Airframe

TREES – Thermal Recovery Energy Efficient System Complete Cycle

Solid-state (no moving part) energy recycle and control

- Localized skin heating for active lift/drag management, de-icing, powertrain cooling, cabin management, and military cloaking

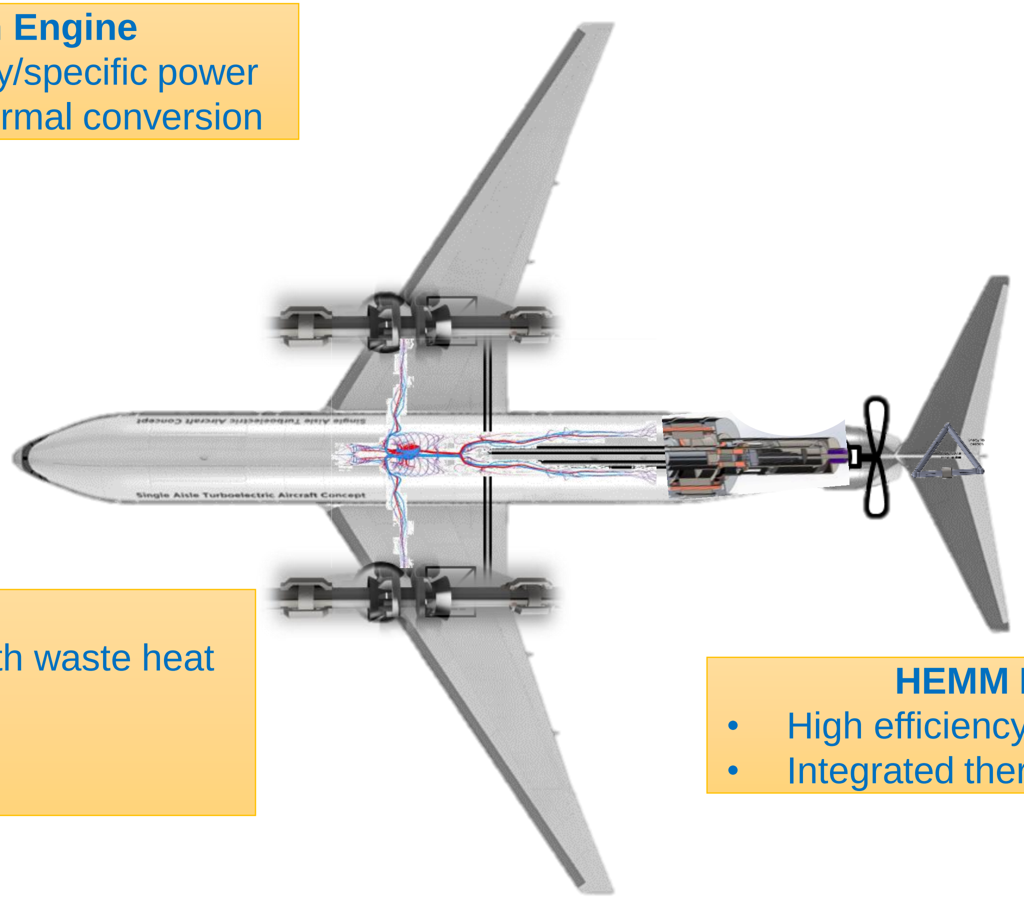


Turbine Waste Energy Transmitted Acoustically, Powertrain Waste Energy Heat Pipe Delivered to Combustor

Integrated Benefit

Strayton Engine
- High efficiency/specific power
- Integrated thermal conversion

DELTA
- High efficiency/specific power
- Quiet



TREES
- Distributes waste heat with waste heat
- Saves fuel
- Improves aerodynamics
- Naturally de-ices

HEMM Motor
- High efficiency/specific power
- Integrated thermal conversion

Advanced Integration is Required at Component and System Level

Conclusion

- Maximum benefit with electric aircraft is achieved by integrating at both the component level and system level.
- Thermal Energy Conversion technologies provide the fundamental building block for this integration.
- **HEMM** motor provides flight-weight high efficiency at high power
- **Strayton** engine provides flight-weight high efficiency at medium power
- **DELTA** engine provides flight-weight high efficiency at low power
- **TREES** enables the tight integration of all these technologies at the vehicle level.

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