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NASA Power and Thermal Technology Overview

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TETS2024

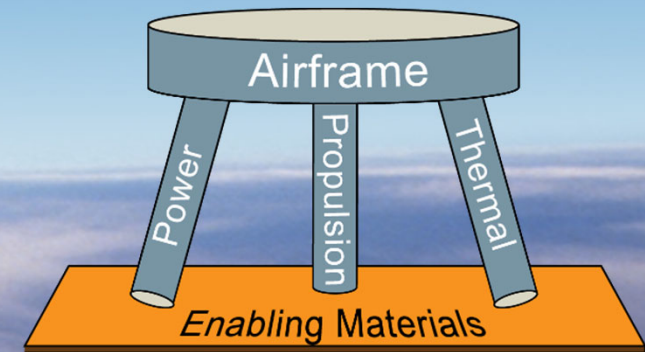
September 10, 2024

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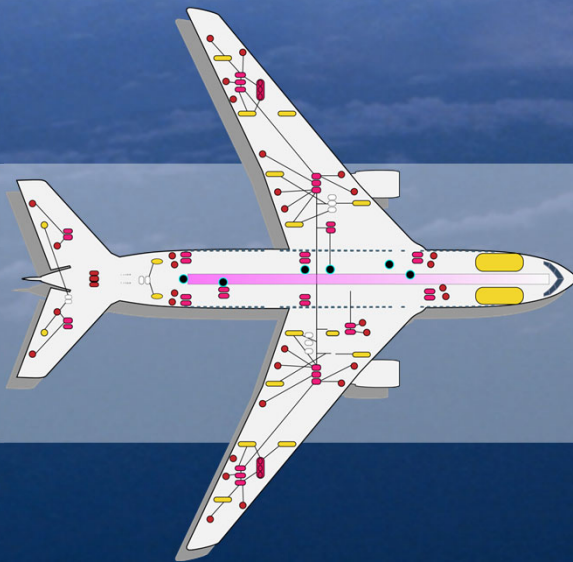
Power, Propulsion, Thermal, and Airframe Integration

- **Challenge is to highly integrate all systems:**

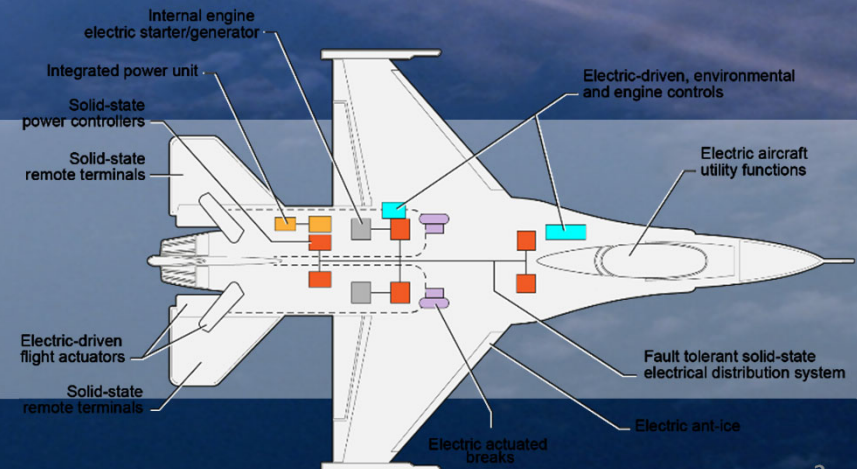
- improves fuel efficiency
- reduces emissions
- reduces low grade waste heat
- reduces vehicle mass



All components must integrate

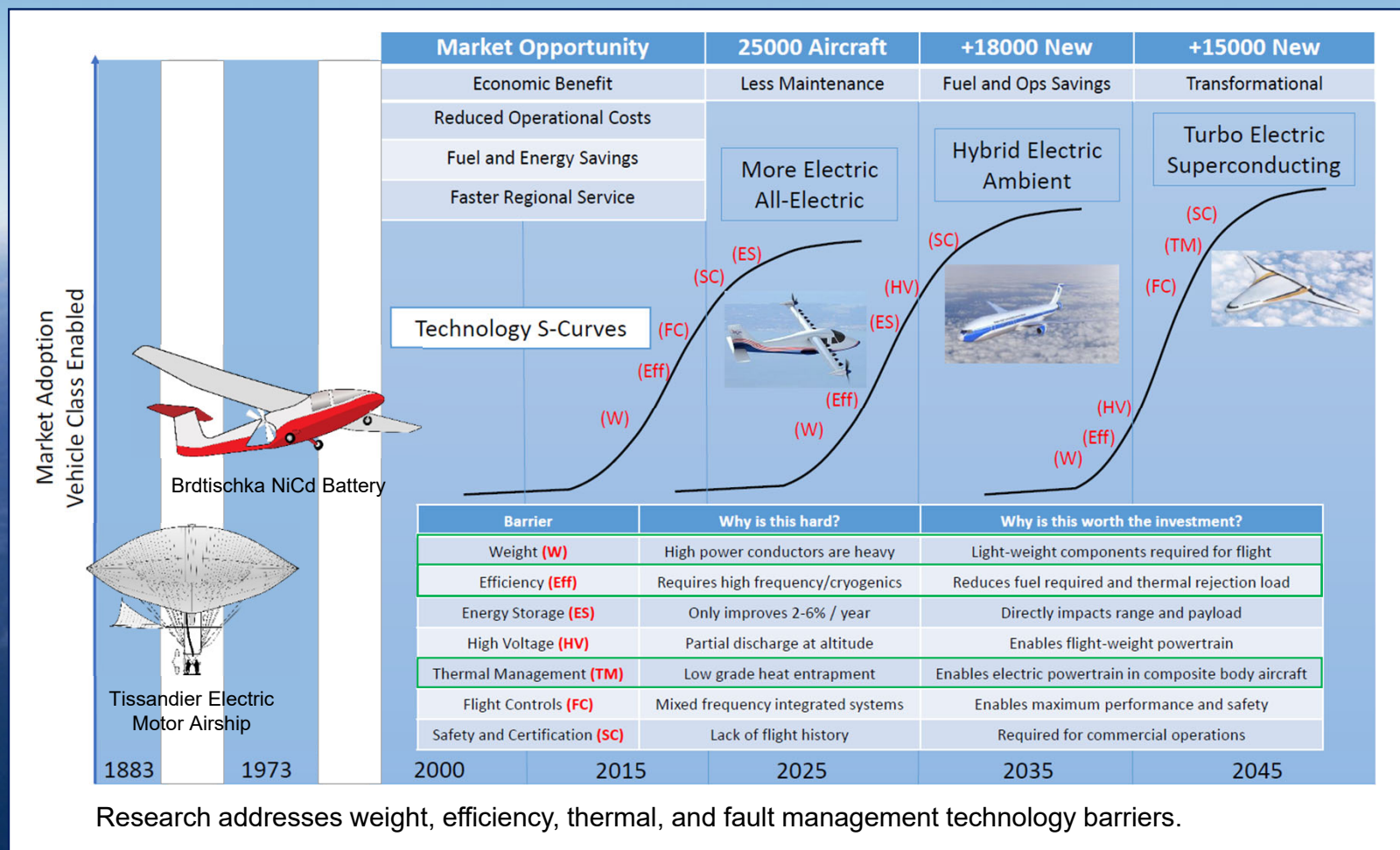


**PM and Induction
Machine is a
Near-term Technology**

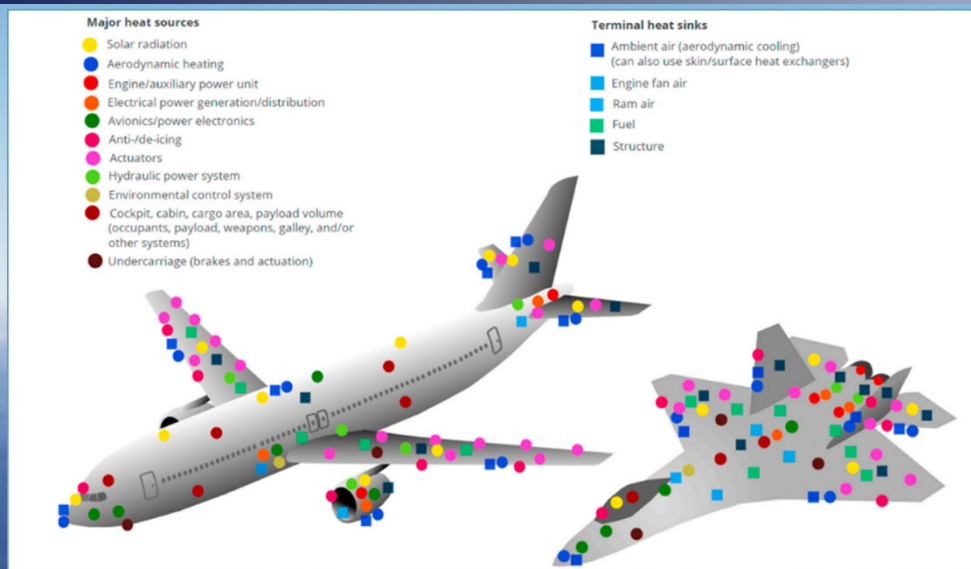


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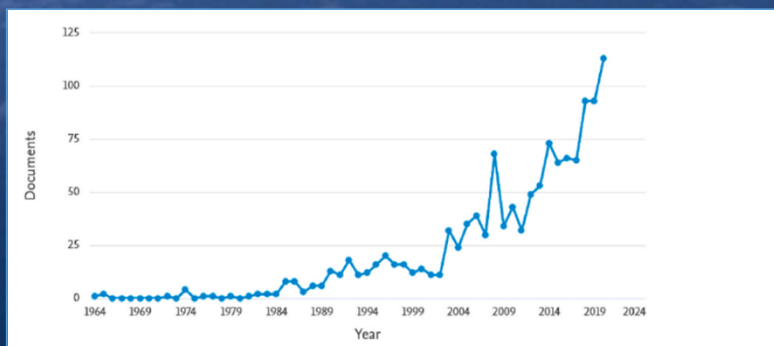
Electric Aircraft Propulsion Technology Adoption



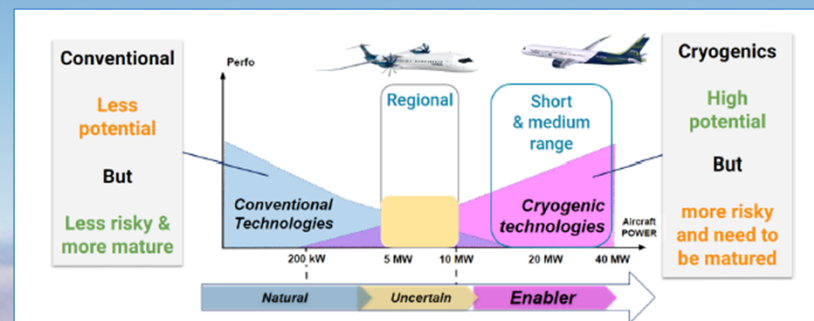
Integrated Electric and Thermal Management Challenge



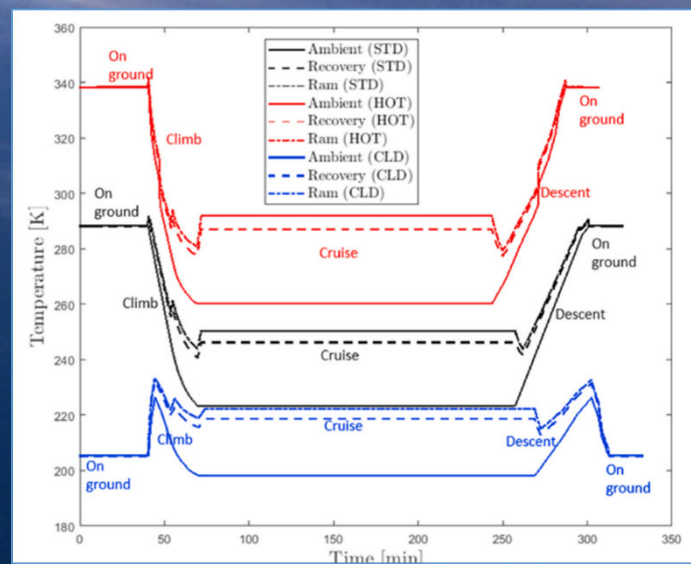
Wide Range of Heat Sources



Growing Interest in Aircraft Thermal Management



Wide Range of Equipment Temperatures



Wide Range of Environmental Temperatures

Current Power Technology Review

- ❑ **Diesel** and **Diesel electric** are the two most used high-power technologies due to their efficiency, reliability, compactness, and low cost, but the emissions are difficult to manage.
- ❑ The only current true zero emission technologies are battery and low temperature PEM fuel cells.
 - The **battery** option is only practical in relatively small systems
 - The **fuel cell** option suffers from lack of tolerance to impurities, shock resistance, size, and limited life
- ❑ The next cleanest technology options include **hydrogen gas turbines**, originally demonstrated in 1937, but they produce NOx even when used with hydrogen fuel.
 - Gas turbine is complimentary to other hydrogen-conversion technologies such as fuel cells:
 - cost-efficient at large scale
 - can utilize lower-purity hydrogen,
 - 43% efficient in open cycle, 63% combined cycle

CRITERION	PEM	DIESEL	GAS TURBINE	STIRLING	CSQG
EFFICIENCY OVER A WIDE RANGE OF LOADS	Flat	Best at >75% load, poor at partial load	Best at >80% load, very poor at partial load	Best at 40%, reasonable at part load	Flat
RESPONSE TO LOAD CHANGES	Fuel/reformer dominated	Good	Fast	Fast	Very Fast
LIFE	10,000 hrs	20+ years	20+ years	30+ years	30+ years
NOISE, VIBRATION	Low	High	Medium	Low	Low
POWER RANGE	20-2500 kW, modular	Up to 68 MW	Up to 50 MW	Up to 25 kW, modular	Up to 10 MW, modular
NO_x, CO, HC EMISSIONS, CO₂	Very low, reduced CO ₂	Medium	Medium, no CO ₂ benefit	Very low or zero	Very low or zero

Closed Strayton Quad Generator (CSQG) provides new long-life efficient option for Zero Climate Impact

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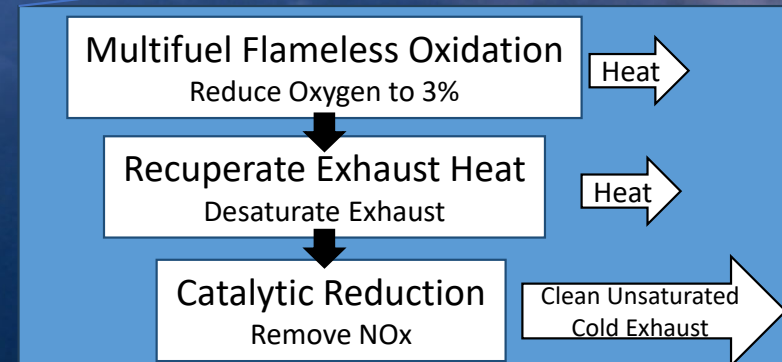
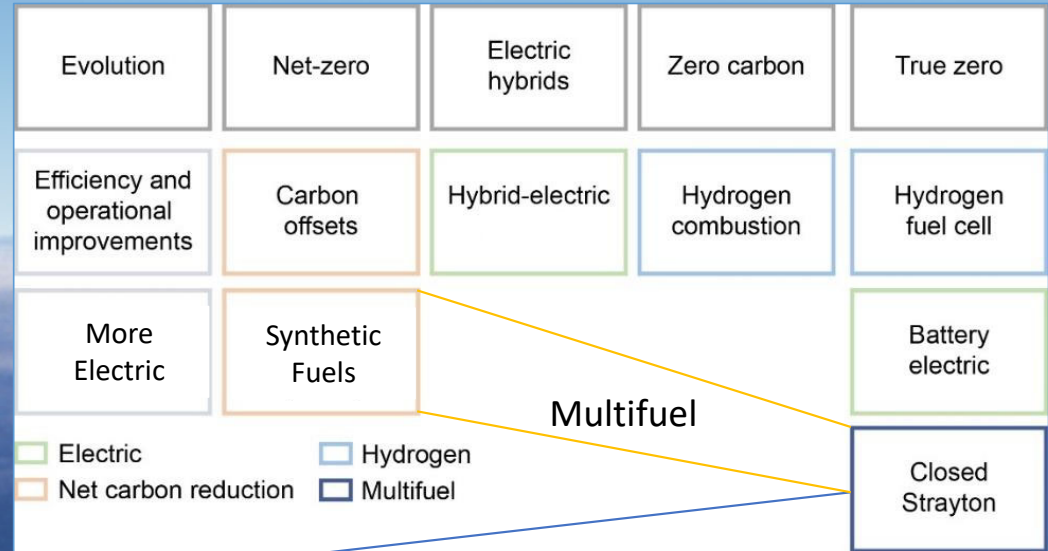
Current Power Technology Review (continued)

❑ H₂ internal combustion (**Otto, Diesel, Turbine**):

- Wet Low Emission to reduce flame temp.
- Dry Low Emission (fuel lean conditions) is difficult with 100% H₂,
 - turbulent (flashback),
 - still fuel-rich early combustion-NOx
- Quenching distance ½, higher steam concentration, higher heat transfer coefficient
- Combustor 1600C or higher, creep rupture, oxidation, and cycle endurance

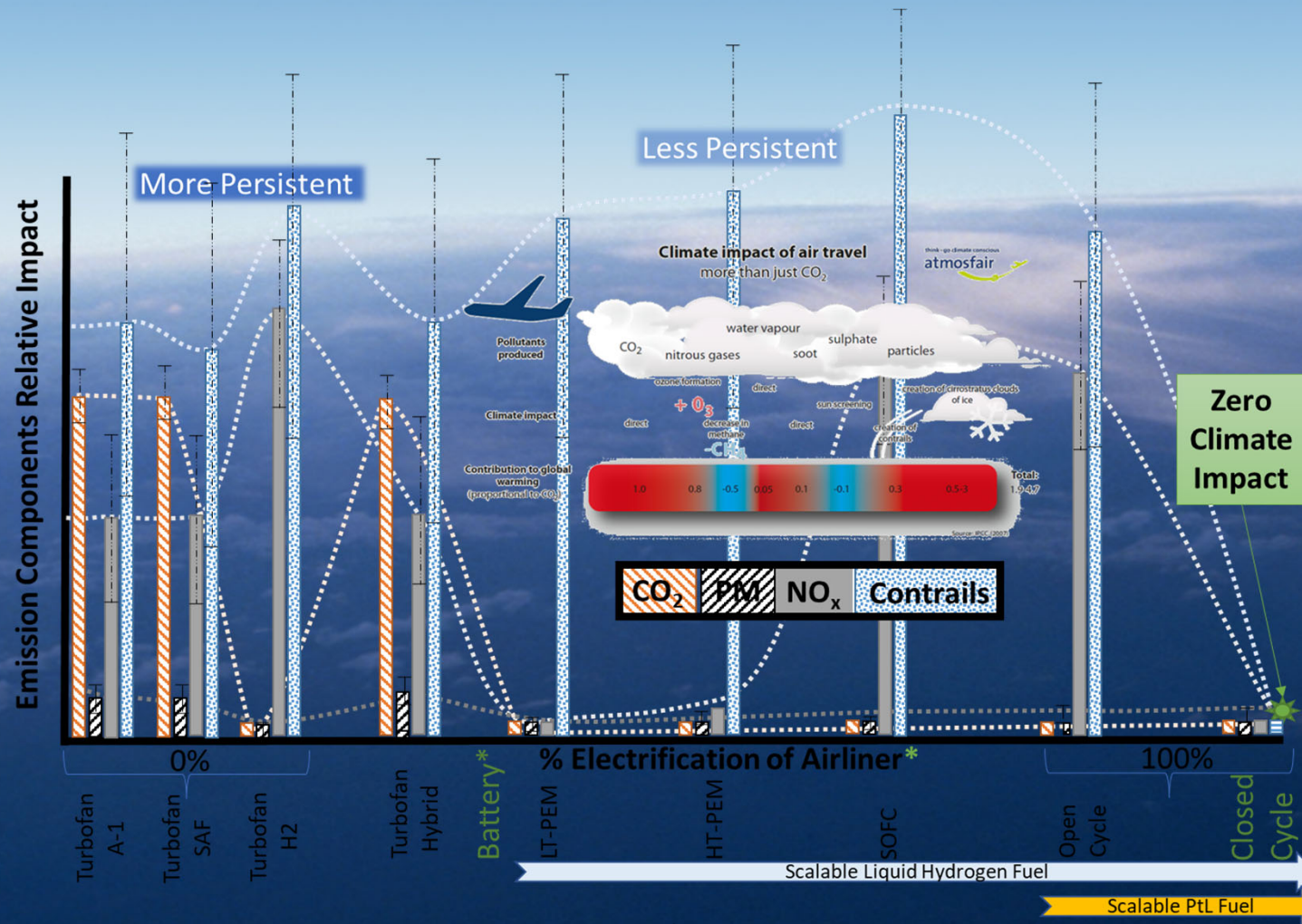
❑ Turbine impacts (**Open Cycle Gas Turbine**):

- High temperature oxidation exposed to H₂+steam
- Larger temperature gradients, smaller flame-wall quenching distance, higher flame temperature, high HTC
- TBC need lower conductivities, fracture toughness from thermal stress, increased steam content impacts barrier coatings
- Dual atmosphere effect (air + H₂)
- Hydrogen embrittlement H-diffusion
- Turbine inlet, 1300-1600C, axial loading, thermal, vibrational, centrifugal stress.
- Hot corrosion from sulphur and alkali metal impurities, higher fuel/air ratio, lower impurity tolerance

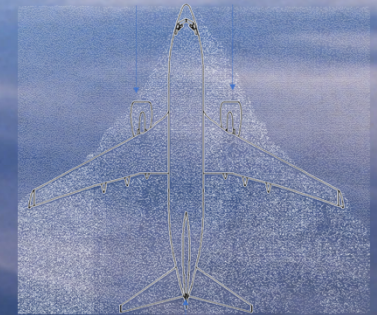


Closed Strayton enables zero climate impact with both hydrogen and synthetic fuels

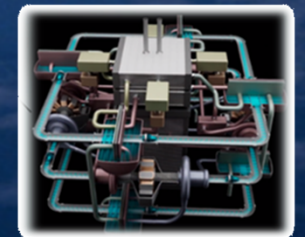
Power Source Relative Climate Impact and Scalability



Superconducting
Electric Propulsors



Closed Strayton
Quad Generator

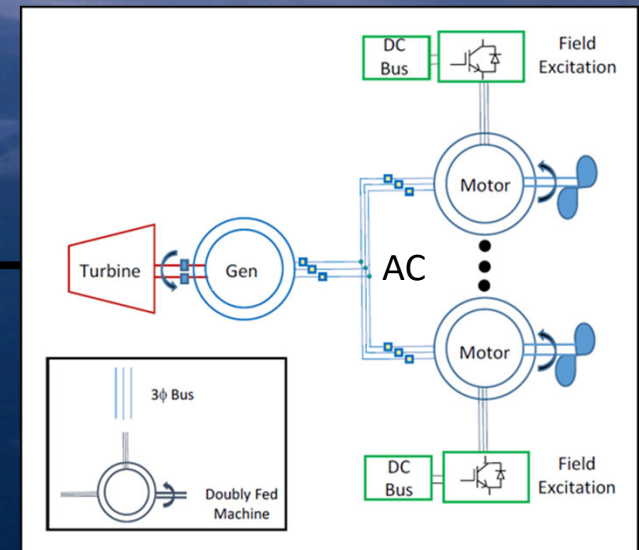
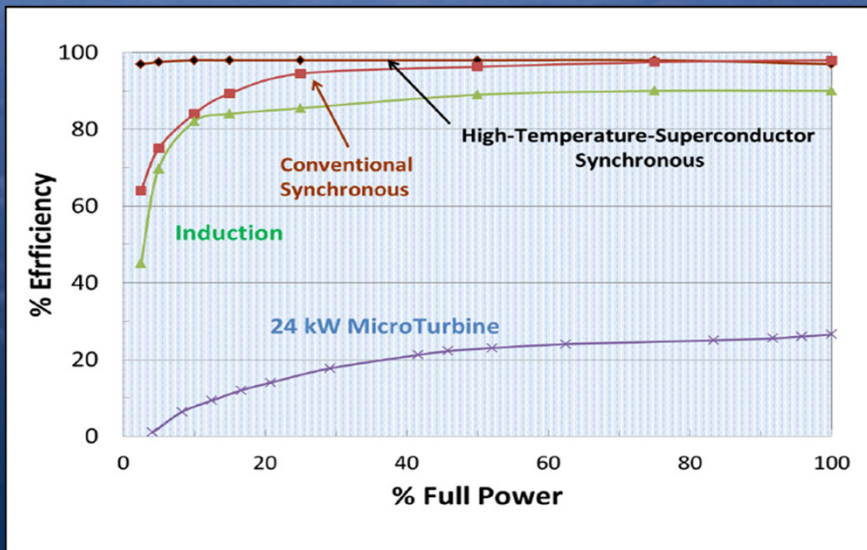
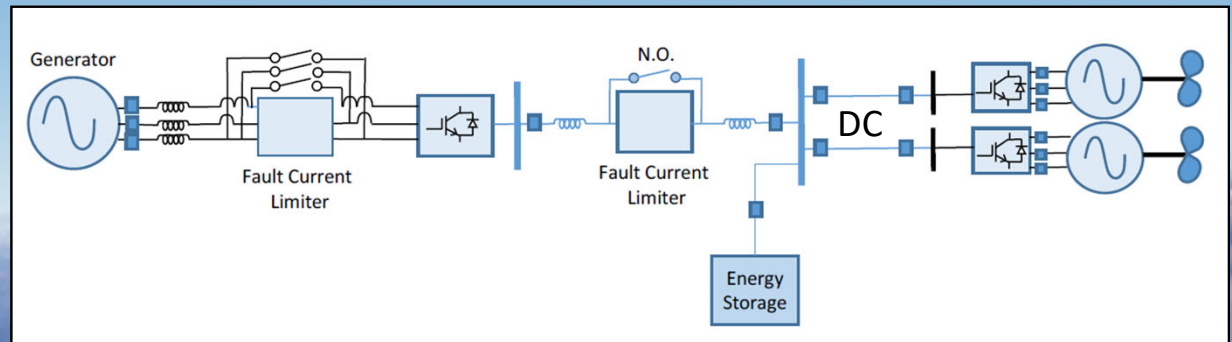


Acoustic Stirling + Brayton =
Strayton

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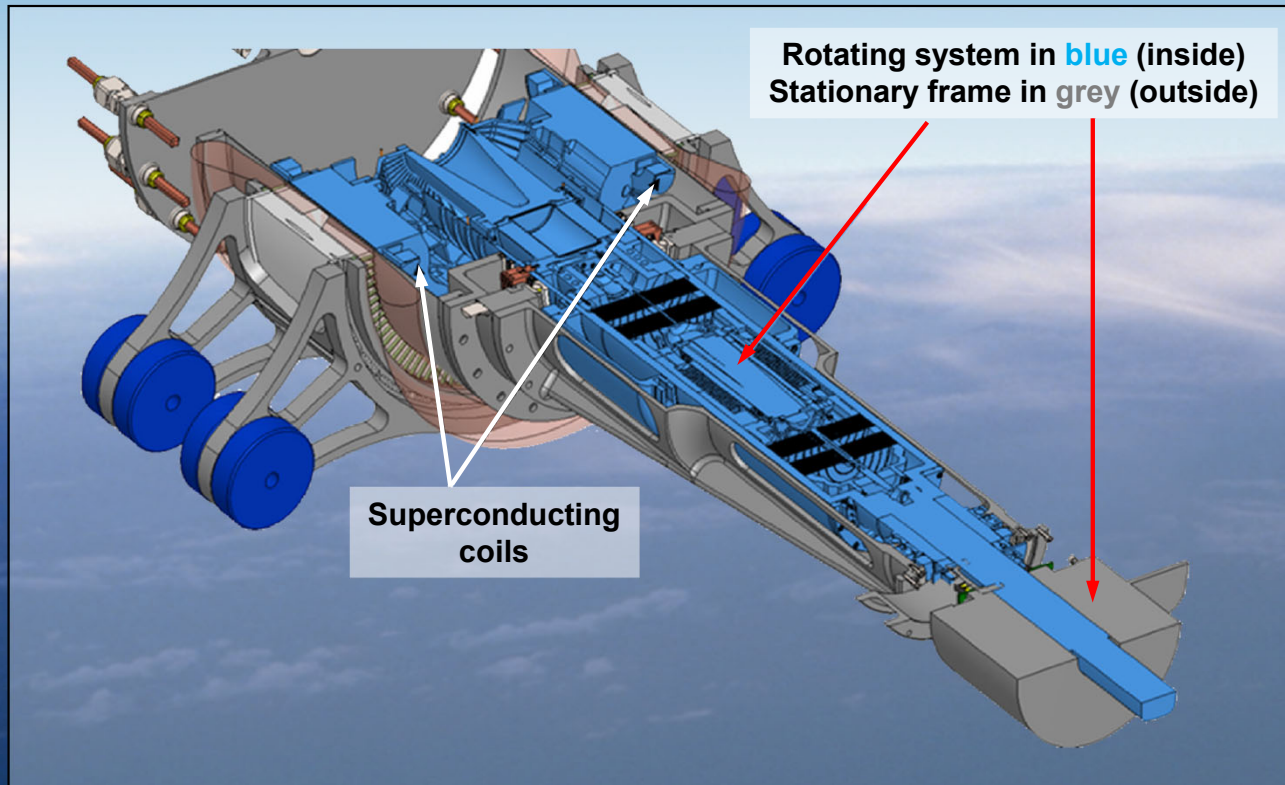
Electric Propulsion Machine Options

- Fully Superconducting (Next)
- Partially Superconducting
- PM Synchronous
- Single-fed Induction
- Double-fed Induction



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HEMM Thermal Loads (Cryogenic and Ambient)

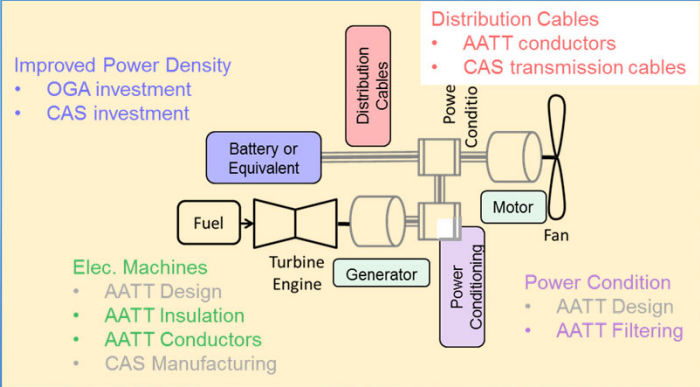


Component	Loss (kW)
Electromagnetic Losses	9.3
Stator Core	3.9
Stator winding (I^2R)	4.6
Stator winding proximity	0.8
Rotor core	0.009
Rotor coils	0
Other Losses	4
Cryocooler Power	2
Bearings	1
Vacuum Seals	1
Total Losses	13.5
Total Losses (+20% margin)	16.2

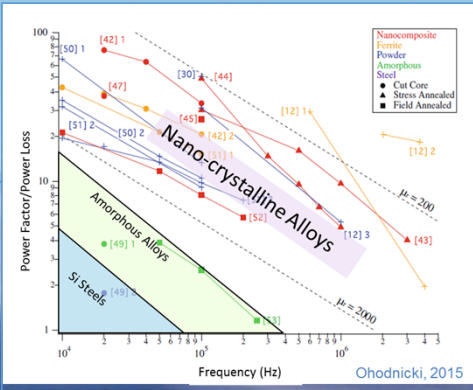
Under 50 W Cryogenic Heat Load Expected

Electric Powertrain Materials Challenge

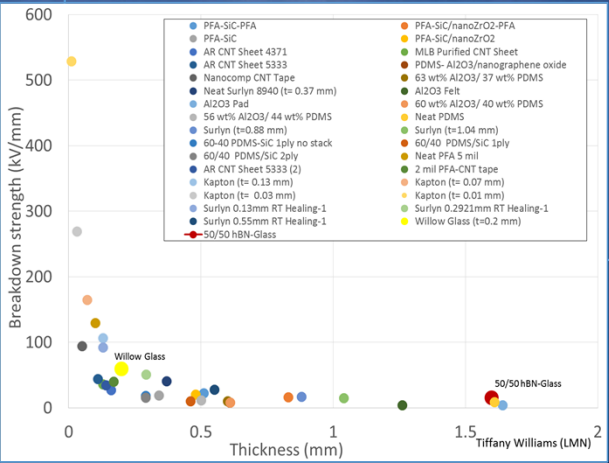
Power System Weight Drivers



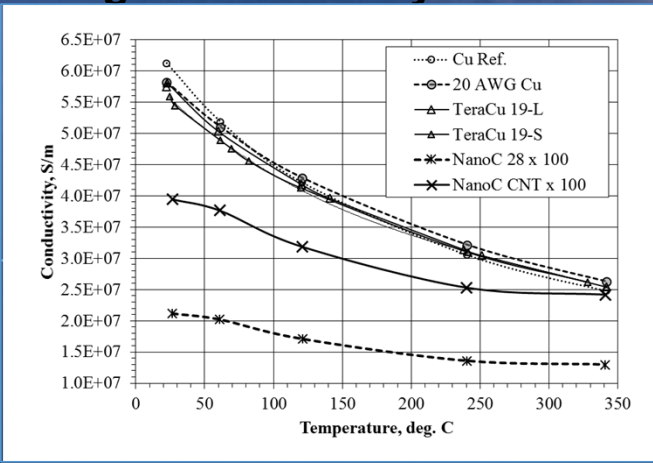
Magnetic Materials



Insulation Materials



High Conductivity Materials



Aircraft Cooling Options

Applied Thermal Engineering 64 (2014) 252-262

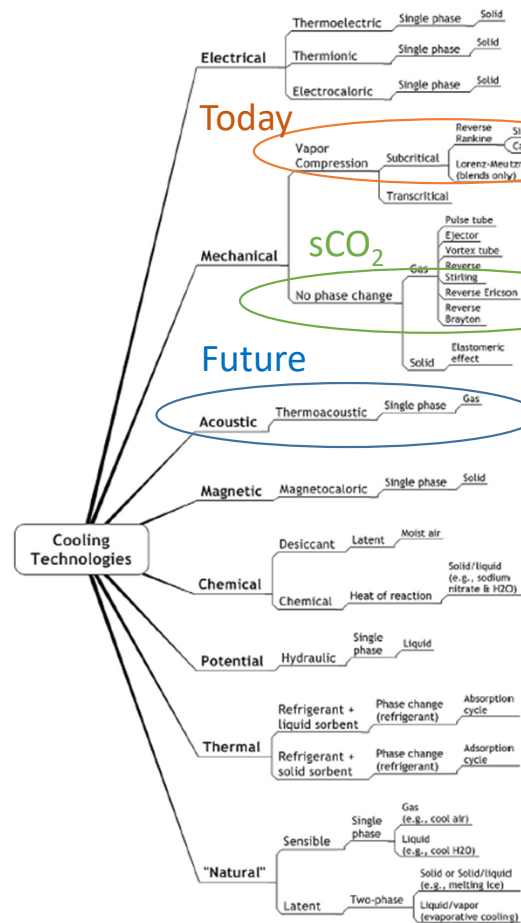


Fig. 3. Taxonomy of cooling technologies.

Table 1
Exergetic efficiencies of cooling technologies.

Cooling/refrigeration technology	Φ Parasitic losses not included	Φ Parasitic losses included	Comments
Vapor compression cycle	0.63 (e)	0.50 (e)	Mature technology; large range of cooling capacities and application temperatures; mainly driven by electric energy
Absorption cycle		0.03–0.09 (e) 0.11–0.16 (e) 0.19–0.23 (e)	Single-effect Double-effect Triple-effect Heat driven cycle; solar applications; uncompetitive in many electricity markets
Adsorption cycle		0.01–0.09 (e)	Heat driven cycle; solar applications; uncompetitive in many electricity markets
Desiccant cooling		0.07 (e)	Coupled with a conventional system; not viable in all operating conditions; high cost
Einstein refrigeration cycle	0.05 (t)		Not feasible for many operating conditions; the cycle is not easy to realize
Ejector refrigeration cycle	0.16–0.28 (t)		Large irreversibilities related to normal shock and fluid mixing
Ericsson cycle		0.03 (e)	
Evaporative cooling	0.19 (e)		Coupled with a conventional system; not viable in all operating conditions; high cost
Hydraulic refrigeration	0.25 (e)		Large size and weight; limited progress since report of Fischer et al. [2]
Magnetic refrigeration/cooling	0.2–0.6 (e)		Strong Φ degradation with increasing temperature lift; limited number of and availability of materials; large internal irreversibilities; high costs; large size; limited reliable experimental results available for comparison purposes
Malone cycle	0.2 (e)		Impractical for most working fluids since it operates near the critical point; limited progress since report of Fischer et al. [2]
Pulse tube refrigeration			Used in cryogenics
Ranque–Hilsh tube (vortex tube)	0.05 (e)		
Stirling cycle	0.2–0.3 (e)		Used in low-temperature applications; low cooling capacities; high costs; large internal irreversibilities; limited progress since report of Fischer et al. [2]
Thermionic cooling	0.2–0.3 (t) <0.1 (e)		Large number of technical barriers need to be overcome; immature technology; small cooling capacities
Thermoacoustic cooling	0.5 (t) 0.03–0.21 (e)		Large size; high costs
Thermoelastic heat pump	0.35 (t)		Limited progress since report of Fischer et al. (1994)
Thermoelectric cooling	0.18–0.37 (t)		Used in niche applications; limited availability of high performance materials; low weight; strong Φ degradation with increasing temperature lift
Thermotunneling cooling	0.5–0.8 (t)		Large number of technical barriers need to be overcome; immature technology; small cooling capacities
Transcritical CO ₂ cycle			Similar Φ to conventional vapor compression cycle at lower ambient temperatures with significant Φ degradation as ambient temperature increases; high refrigerant pressure; high costs

(t) = theoretical; (e) = experimental.

Acoustic cooling very efficient, but earlier designs were too large and costly.

Acoustic Heat Pump Efficiency

Reject at
Higher Temperature

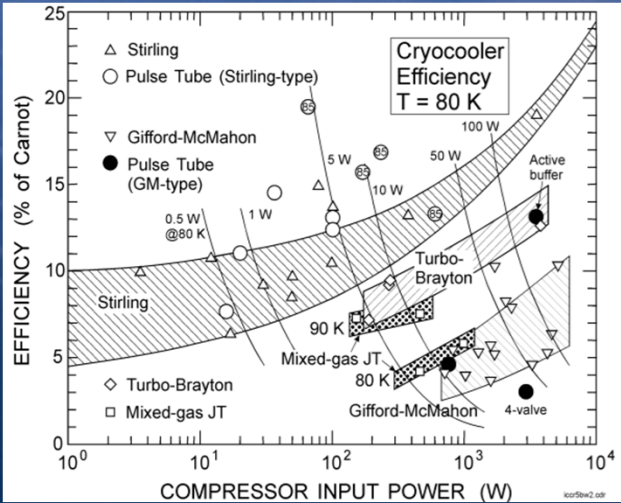
Hot reservoir

Acoustic mechanical
work input from piston

Cold reservoir

Accept at Lower
Temperature

Th (k)	Tc (k)	Ratio (W/Qc)	Qout (W)	WorkIn (W)	Qin (W)
400	300	1:3	1000	250	750
600	300	1:1	1000	500	500
900	300	2:1	1000	666.66667	333.3333
1200	300	3:1	1000	750	250
300	50	40:1	1025	1000	25

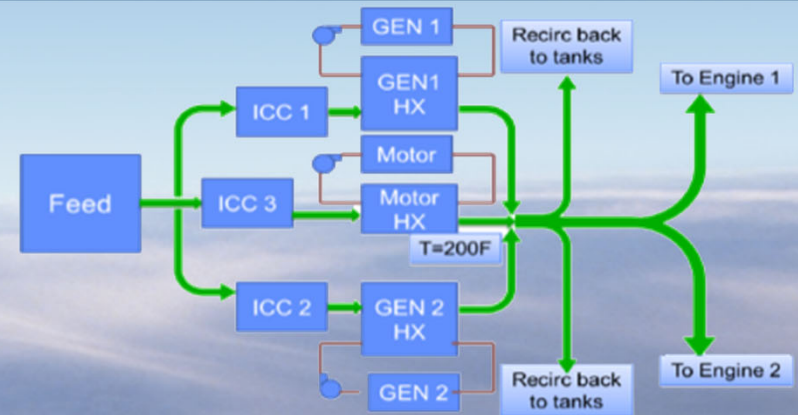


More input acoustic power required as the heat lifted from the cold reservoir increases and/or as temperature gap increases

Thermal Management Limits

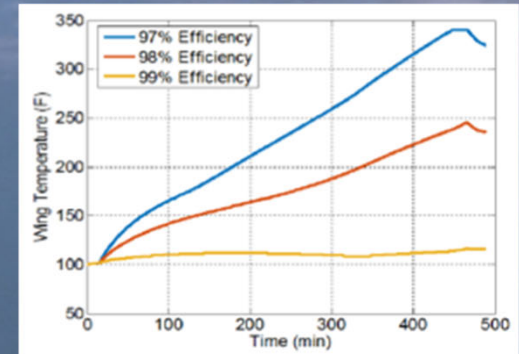
Dumping heat into:

- Fuel (limited 50 kW)
- Outer mold line (limited 300 kW)
- Ram air (see below for losses)
- By-pass air (see below for losses)



	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%

Thermal Runaway with Composite Fuselage



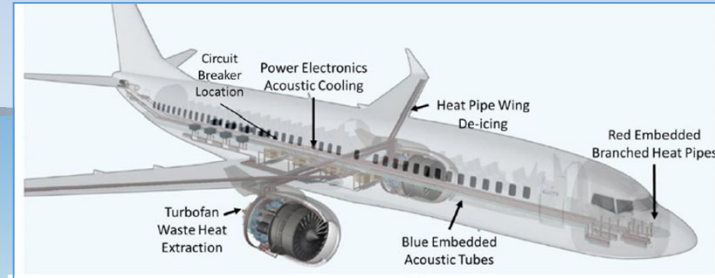
Electric Aircraft Propulsion Thermal management technology impacts performance and safety certification

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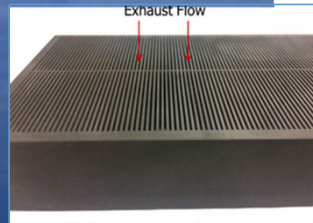
Component Testing Completed

- **Technologies Developed**

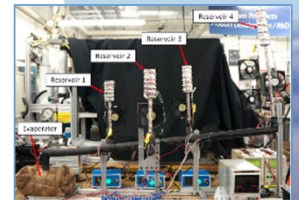
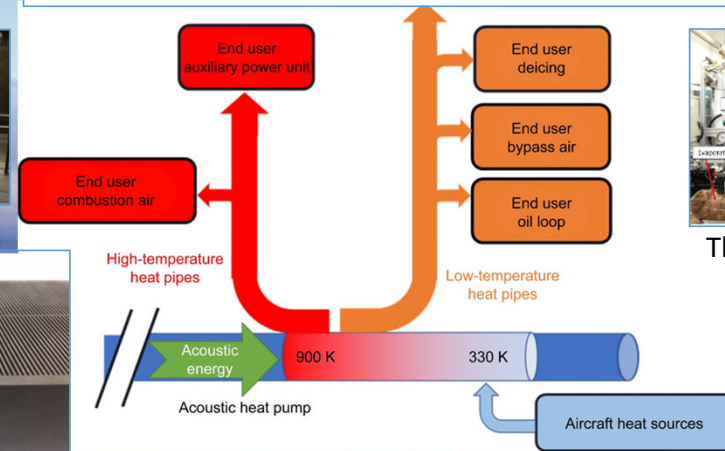
- Turbofan WHR HX
- Acoustic Heat Pump
- OHP Heat Collection
- Thermal Transport
- Thermal Recycling
- Dynamic Thermal Redirection
- Gradient-based System Optimization



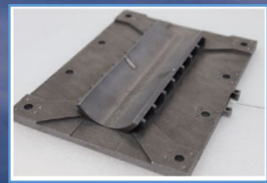
Thermal Transport



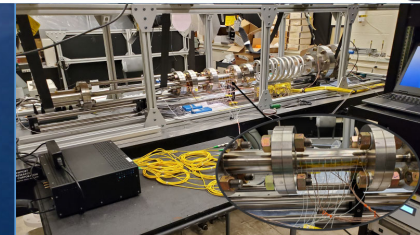
Waste Heat Recovery



Thermal Redirection



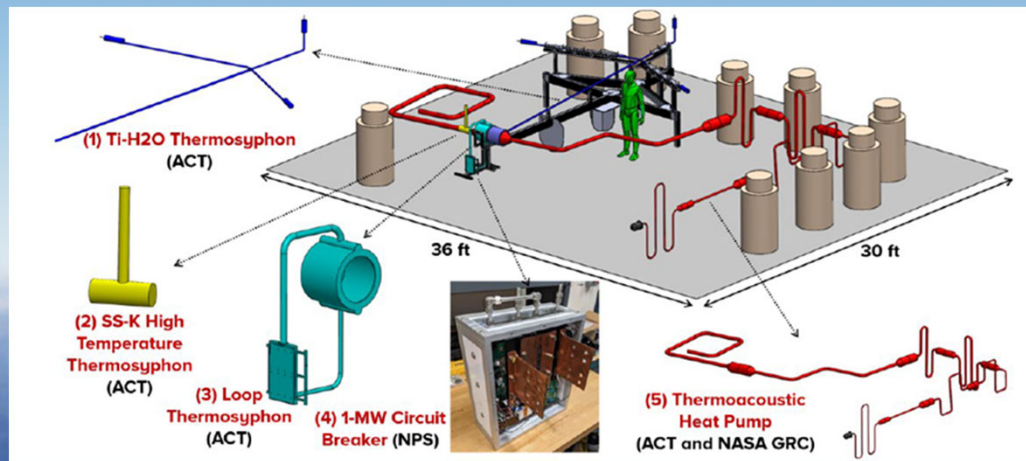
OHP Heat Collection



Acoustic Heat Pump

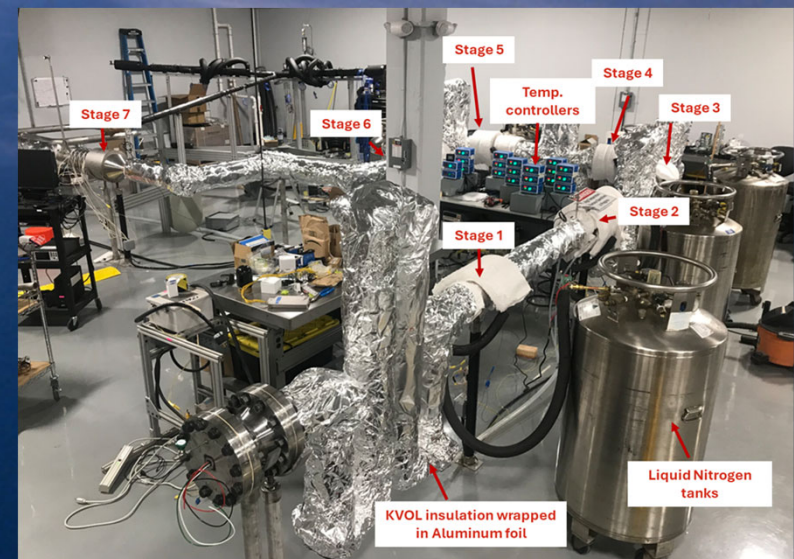
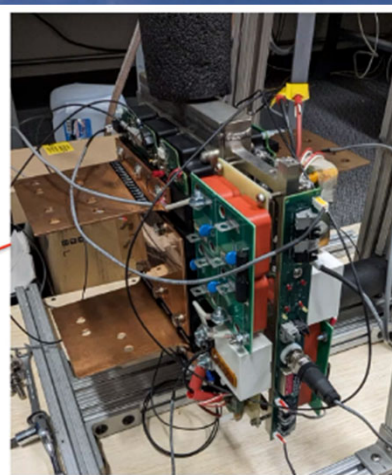
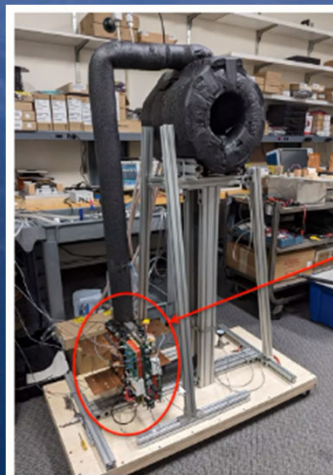
Entire Suite of Electric and Thermal Technologies Invented, Designed, Built, and Successfully Tested as a System

TRL-4 Integrated Capstone Demo



Includes 5 new MW-scale and Aircraft Sized technologies:

1. Aircraft length thermosyphon
2. Aircraft engine compatible high temperature thermosyphon
3. Loop thermosyphon for MW-scale breaker (replaces pumped cold plate with no moving part system)
4. Fastest and Lightest MW-scale Circuit Breaker with no moving parts required for cooling
5. Full-scale Acoustic Heat Pump for changing low-grade waste heat to useful high-grade heat (deicing, combustion, bypass thrust, electric generation)



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Circuit Breaker and TMS Form Integrated Solid-State Safety System

Objectives

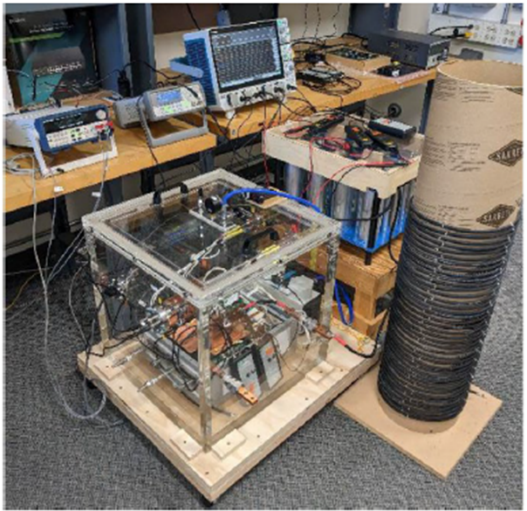
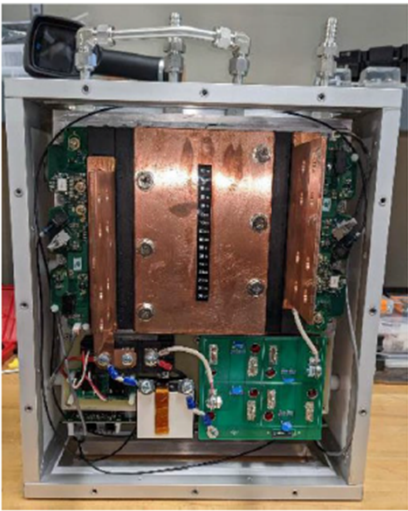
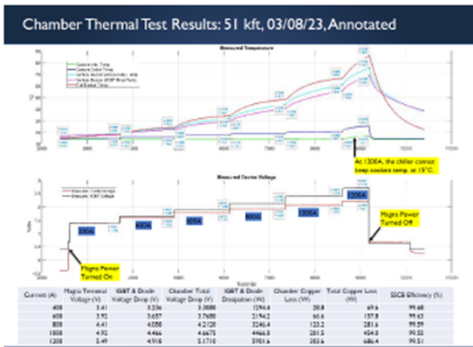
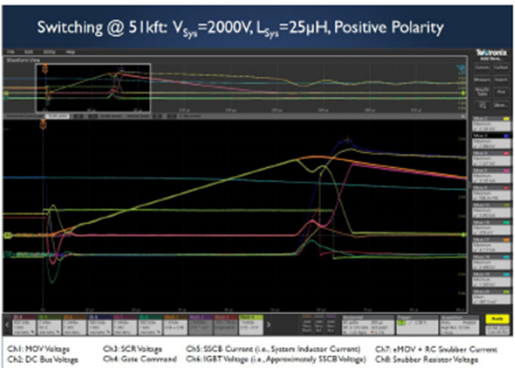
- Develop advanced circuit breaker technology
- Execute TRL 6 demonstrator of 2kV, 1kA, 100 kW/kg, 99.3%-99.8% efficiency, 10-500 uS response time with 0 to 50 uH powertrain inductance at 35 kft
- Design and build a full fault protection system based on the advanced circuit breaker

Accomplishments

- Achieved all objectives on time and within budget
- Established new standard for aircraft solid-state protection that is 10X faster and 10X lighter than state of the art solutions
- Eliminated need for heavy inductor by leveraging inherent current saturation of Si IGBT with reduced gate voltage controls
- Uses completely open source components for broad availability to industry of this technology

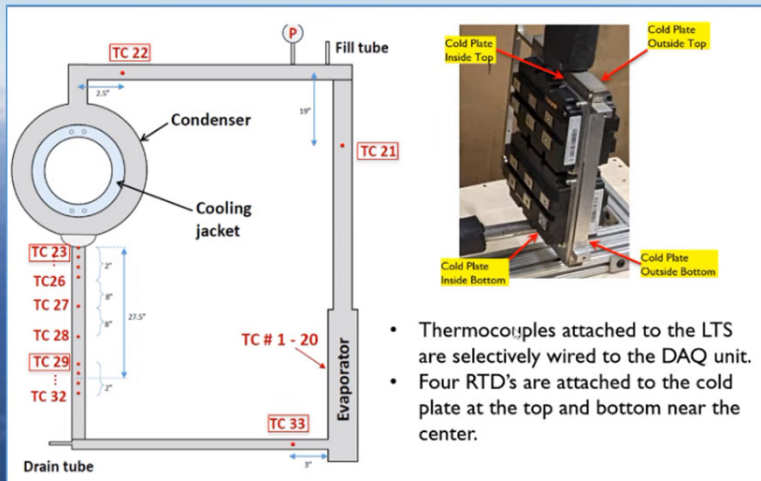
Significance

- Enables extremely fast response transport-class aircraft electrical protection of passengers, aircraft, and powertrain.
- This advanced protection capability is an important next step in the FAA certification of electric aircraft propulsion for transport aircraft.

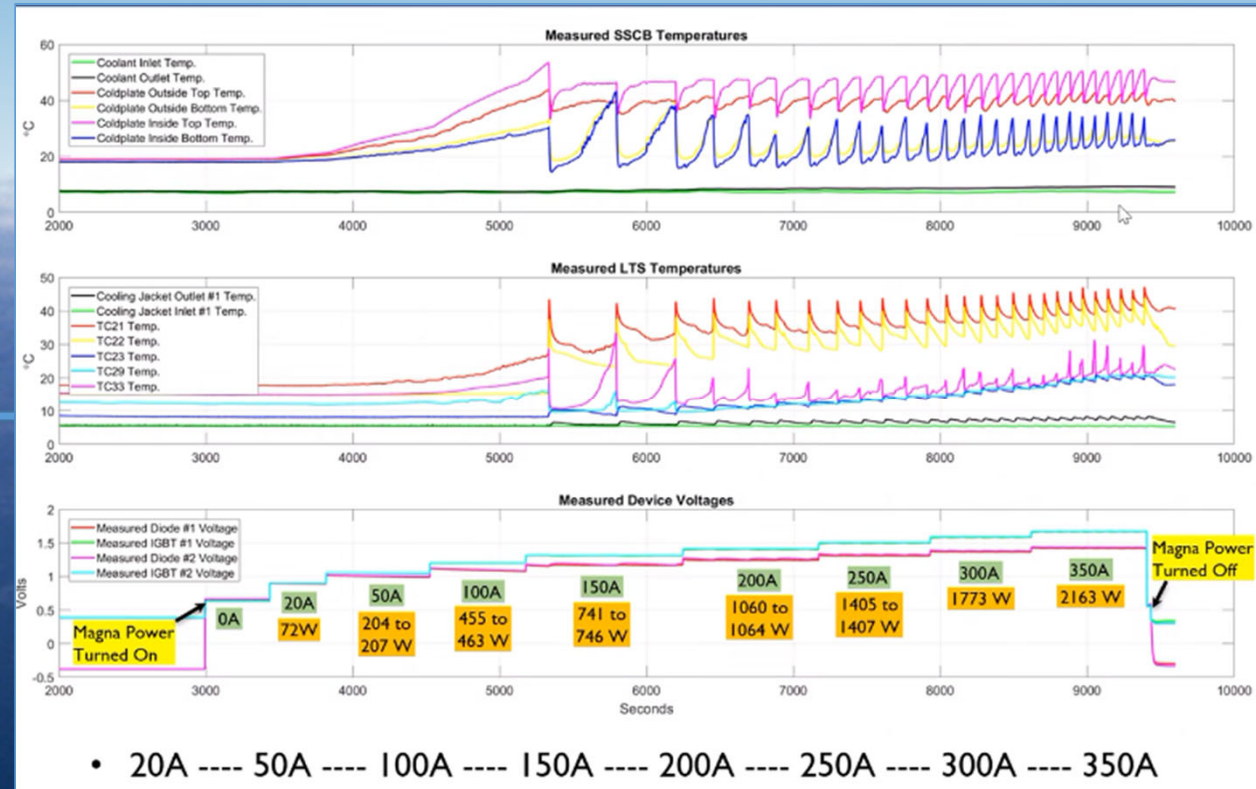


TRL-6 Full voltage and current switching and thermal test at 51 kft completed

Solid-State Fault and Thermal Test Data



- Thermocouples attached to the LTS are selectively wired to the DAQ unit.
- Four RTD's are attached to the cold plate at the top and bottom near the center.



• 20A ---- 50A ---- 100A ---- 150A ---- 200A ---- 250A ---- 300A ---- 350A

Passive Cooling Eliminates Failure Modes and Adequately Cools the Breaker at 2 MW Full Power

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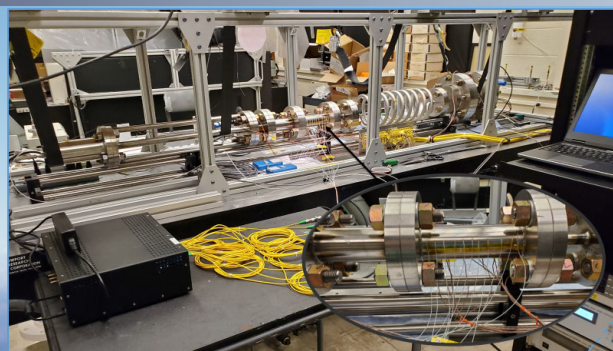
Next Step For Commercial Aircraft Integration

Solid-State Exergy Amplification

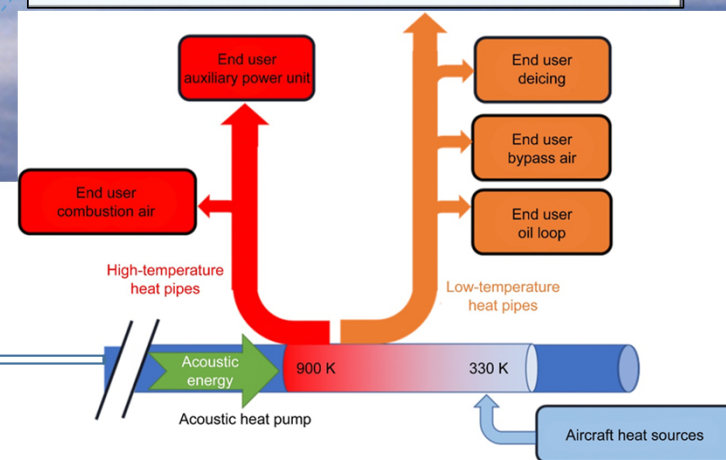
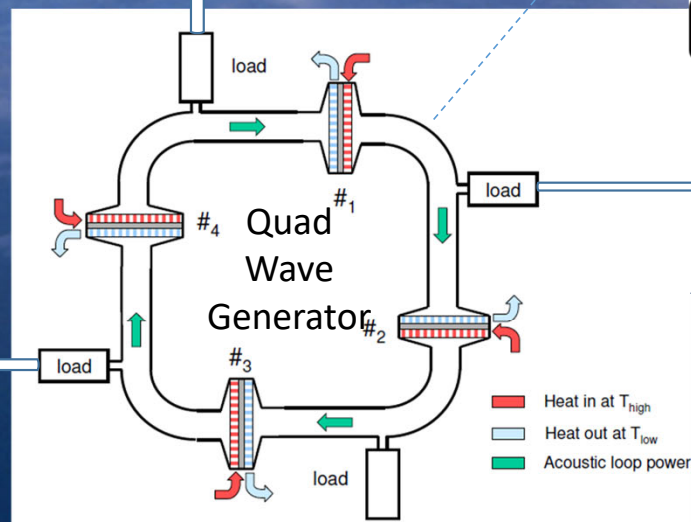
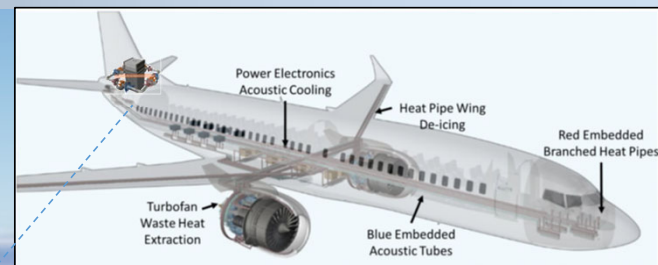
- No moving parts
- No pumped fluids
- No increased drag
- Maximize specific power
- Improve powertrain efficiency
- Recycle waste heat
- Ambient and Superconducting



Solid-state Breaker



Acoustic Heat Pump

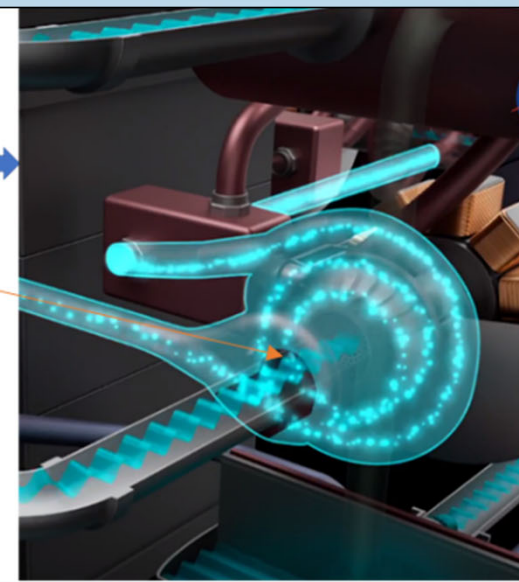
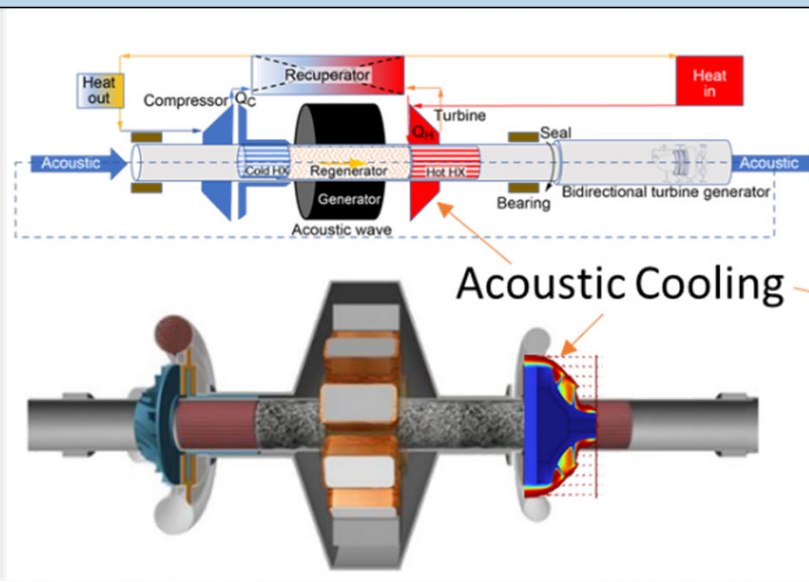
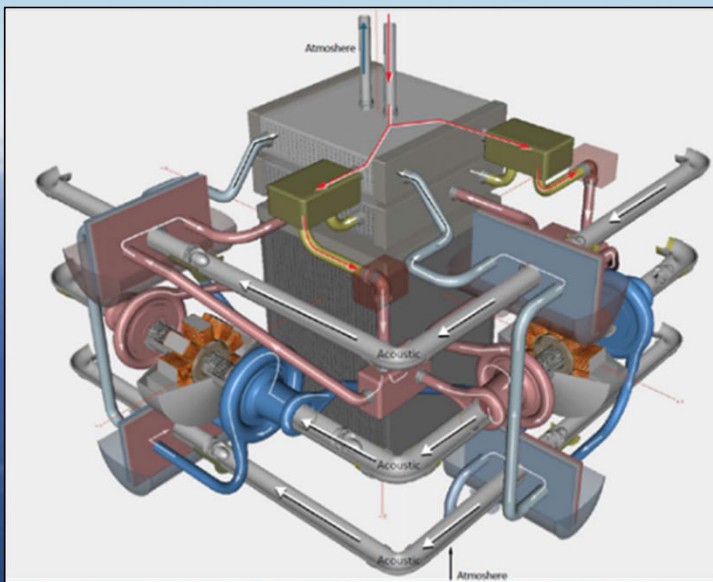


Recycle Waste Heat

High Power Wave Generator for MW-scale Cooling

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Combining Power and Thermal Together

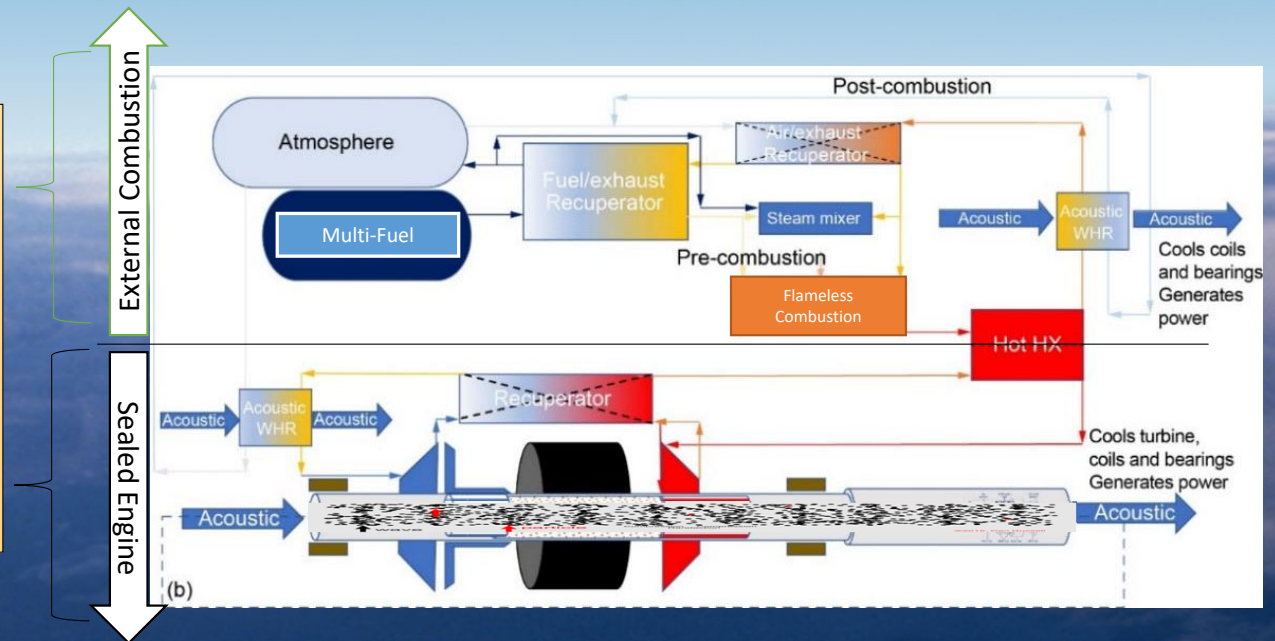


[Multi-Fuel Closed Brayton Quad Generator Video](#)

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Closed Strayton Basic Concept

- Multifuel Flameless External Combustion
- Low or Zero GHG Emissions
- Quiet
- No Maintenance Long-Life
- Very High Efficiency
- Very Compact
- Modular and Scalable
- Sealed from harsh environment
- Synergy with other markets



Combine Compact Closed Brayton with acoustic Stirling Turbine Cooling and External Multifuel Flameless Oxidation

Acoustic Turbine Cooling Enables Multi-fuel Zero-Impact Propulsion

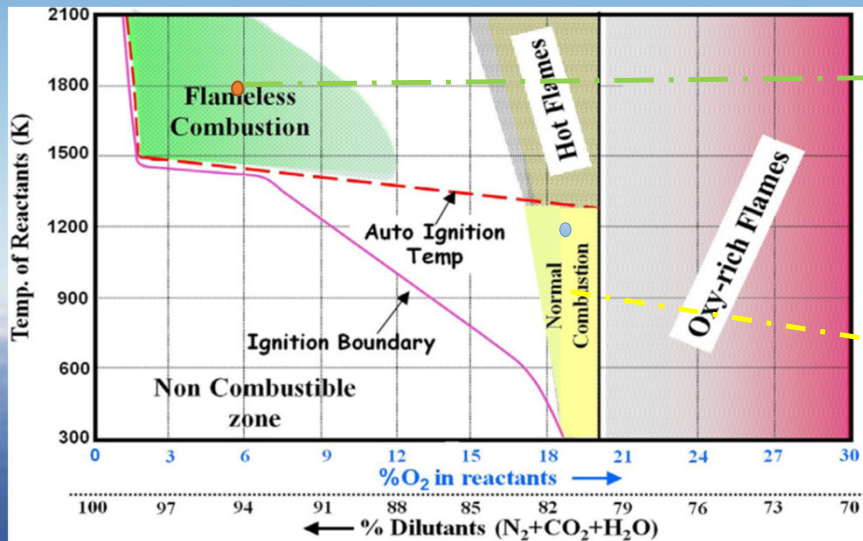


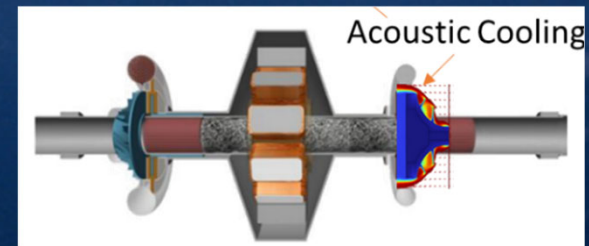
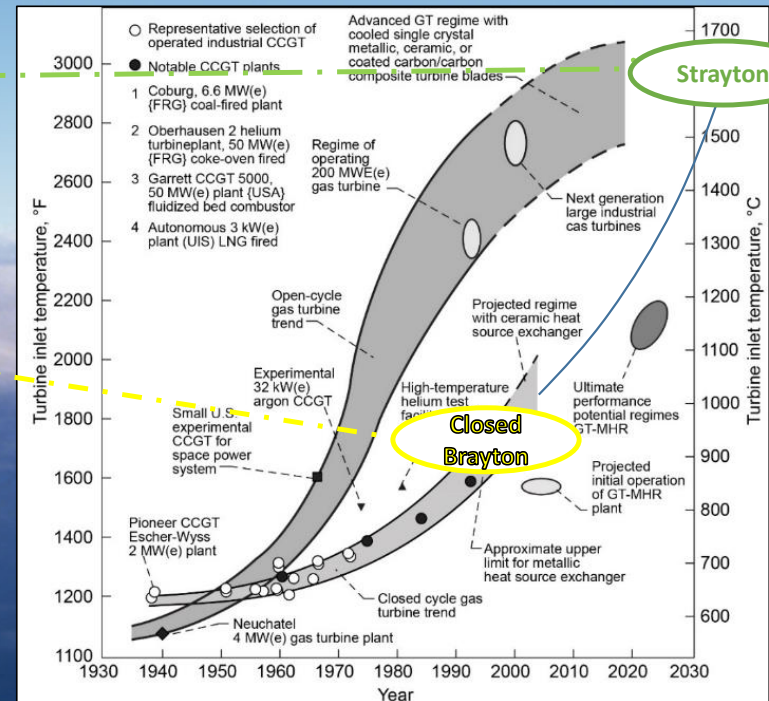
Table 1
Qualitative comparison of different combustor types.

	Combustor type			
	Lean premixed	Lean direct injection	RQL	Flameless-based
Combustion efficiency	High	High	High	High
Combustion instability	High	Low	Low	Low
Fuel flexibility	Moderate	High	High	Moderate
Integration into engine	Moderate	Moderate	Easy	Difficult
Mechanical complexity	Moderate	High	Moderate	Moderate
NOx emission	Low	Low	Moderate	Ultra-low
Operating range	Moderate	High	High	Low
Soot emission	Very Low	Low	Moderate	Low
Volume requirement	Moderate	Low	Low	High

A.A.V. Perpignanetal./ProgressinEnergyandCombustionScience69(2018)28-62

Multi-Fuel

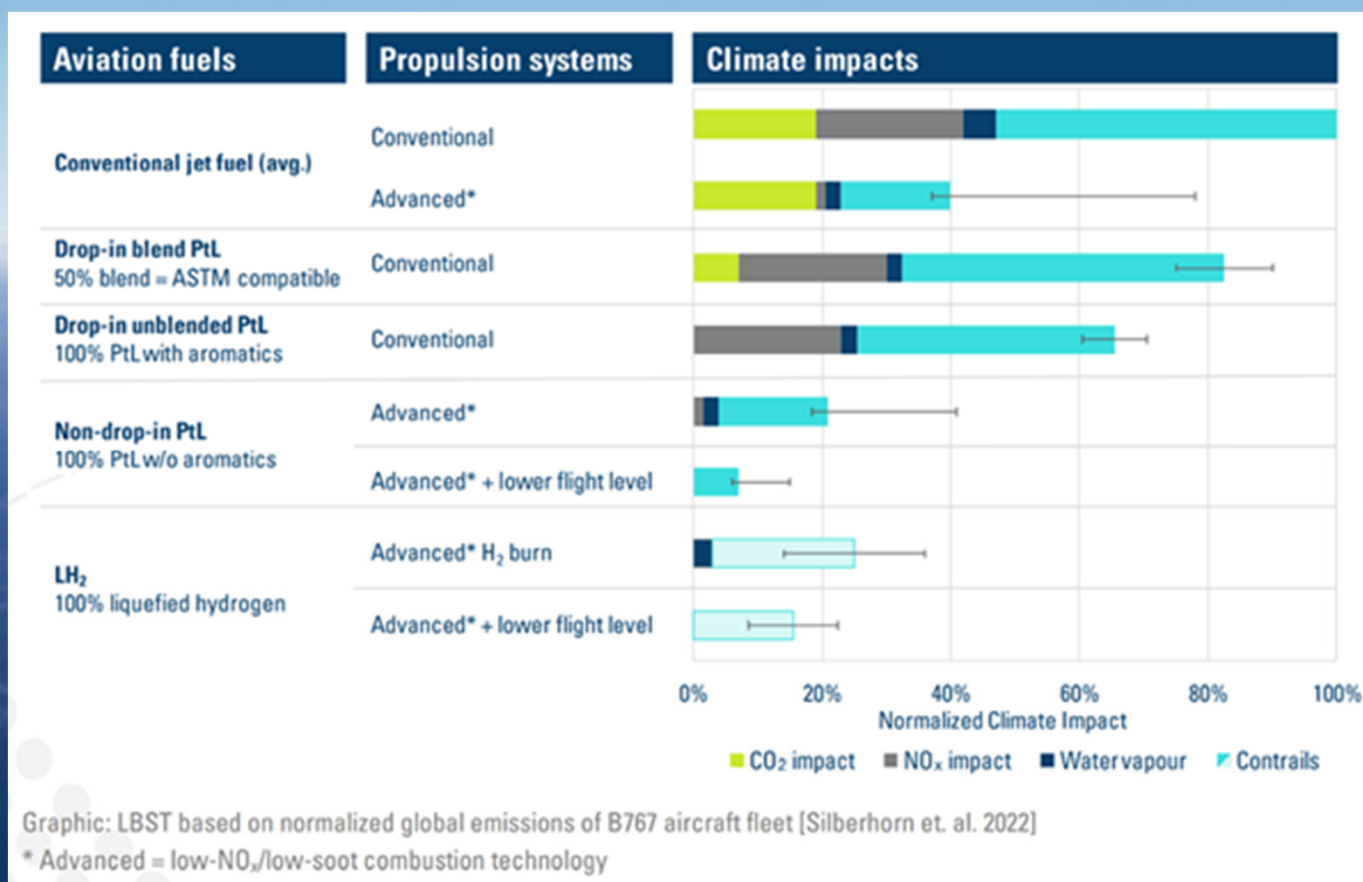
Single-Fuel



Combustor Efficiency and Emissions Improves Significantly

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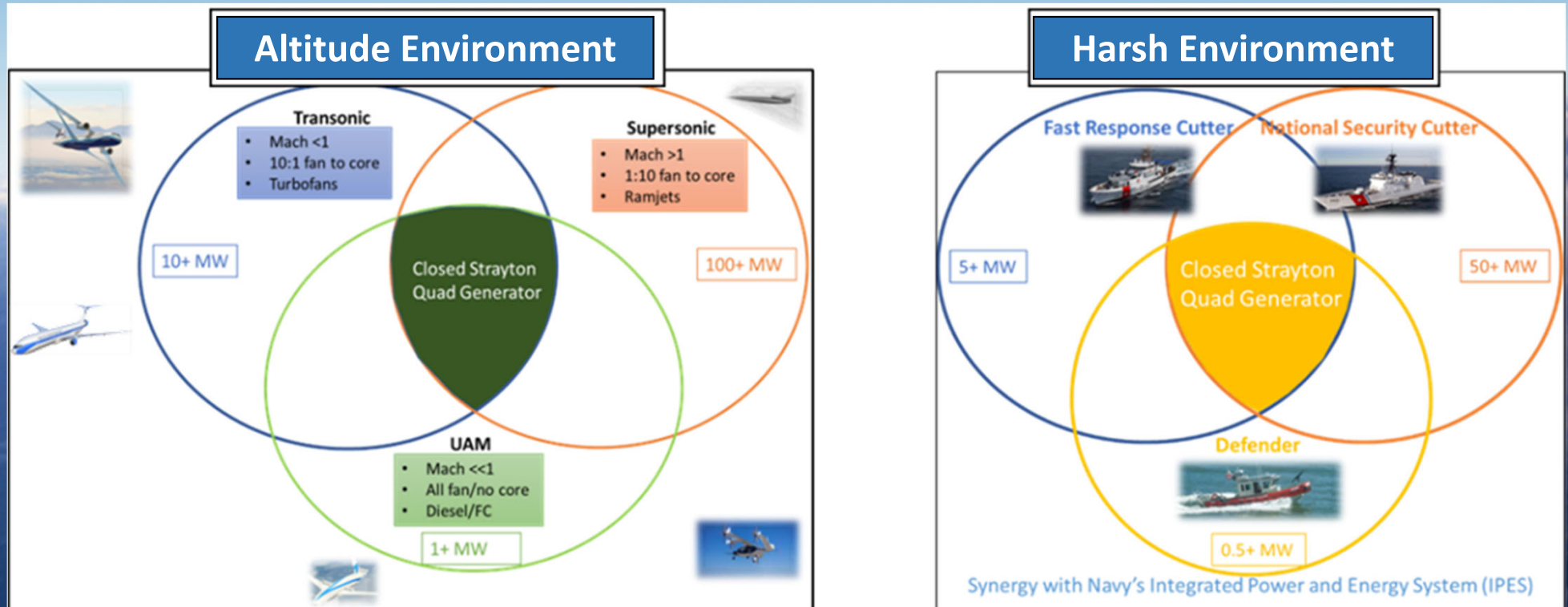
Fuel Flexibility is Key for Infrastructure Compatibility



Recent studies indicate synthetic fuels may be cleaner than hydrogen fuels

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Scalable, Modular, Extensible



Sealed System Supports A Wide Variety of Environments and Applications

Zero-Climate-Impact, Multi-Fuel, Efficient, Quiet, Integrated Power and Thermal System

• Multifuel Flameless Combustion (MFC)

- MFC enables the use of any fuel which is key to transitioning from fossil fuel to new fuel sources

• Emissions

- External combustion and MFC significantly reduces emissions even with fossil fuels and enables zero GHG emission with hydrogen

• Quiet

- MFC and Closed cycle reduce noise significantly

• Efficiency

- MFC is high temperature leading to 70% efficient systems with closed cycles that have acoustic turbine cooling

• Compact

- Sealed high-speed gas bearing systems provide MW-scale with 6" diameter turbines

• Low cost

- Does not require rare earth or exotic materials

• Low maintenance

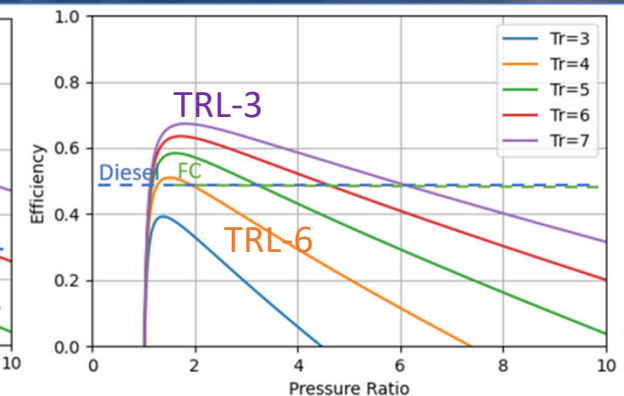
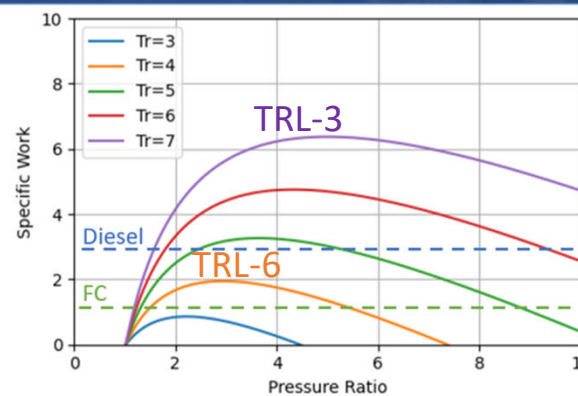
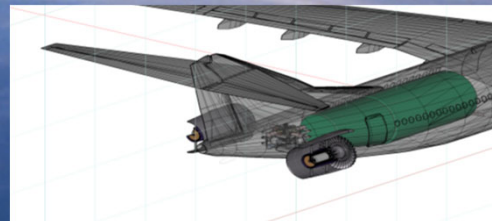
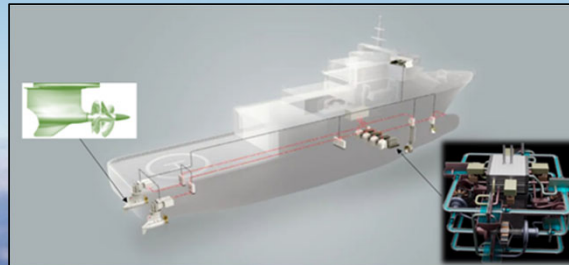
- Sealed system uses gas bearings instead of oil lubrication

• Lifetime

- Never have combustion gases inside the engine and it doesn't degrade like a chemically reacting fuel cell or battery

• Scalable <1 MW to >50 MW

- Modular compact solution 4' X 4' X 4' cube supports 10 MW and can be stacked



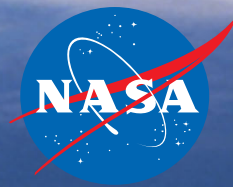
CSQG Key Takeaways

CSQG enables the unusual benefit of zero climate impact with superior vehicle performance as outline below:

- ✓ **Scalable and Modular** with benefits that apply to any vehicle and power level.
 - Stackable and compact closed cycle generators
 - Avoids an abrupt S-curve change in technology and budgets.
- ✓ **Compatible** with existing infrastructure and vehicles to avoid disrupting services and economics.
 - Maintains stakeholder support through different political climates.
 - Industry can focus on a single fuel type (fossil and future synthetic version)
 - Recognizes industry inertia and life of current fleet.
- ✓ **Competitive** by maintaining today's performance and cost expectations with a clear path to ZCI.
 - Path to achieve Net Zero CO₂ with existing fleet with superior performance.
 - Path to achieve Zero Climate Impact with next generation fleet with superior performance.

Conclusions

- **Maximum benefit** with electric aircraft is achieved by integrating at both the component level and the system level.
- **Superconducting** enables flight-weight, high efficiency at MW-scale
- **Solid-state Fault Protection** is required to protect sensitive IGBTs in the powertrain, but it requires constant reliable cooling.
 - Traditional pumped fluid cooling systems fail, and this would result in not only the destruction of the fault protection system but ALL power on the electric aircraft would be impacted.
- Passive **Solid-State Cooling** has been demonstrated with a 2 MW breaker in a representative full-scale single-aisle configuration
- **Closed Brayton Quad Generator** naturally combines both Power Generation and Thermal Cooling while achieving zero climate impact with flameless combustion.
- **Near Term Challenges** include:
 - Flying MW-scale demonstrators to validate ground tests
 - Demonstrating 5-10 MW partial superconducting motor followed by fully superconducting
 - Confirming turbine acoustic cooling, compact heat exchangers, and flameless combustion integrate well



Thank you! Questions?