



Optimizing Thermal Management Systems in Electric Aircraft

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Cleveland, OH

Tech Briefs Virtual Battery & Electrification Summit

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NASA EAP REPRESENTATIVE ACTIVITIES



NASA has executed a plethora of EAP activities over the last 10 years and is in the process of advancing the future of sustainable flight. Work spans from fundamental research to flight demonstrations.



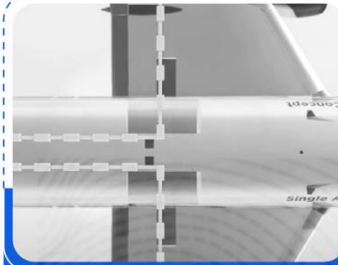
X-57, 100kW class flight demo of all electric distributed propulsion.



Revolutionary Vertical Lift Technology Studies of Electric, Hybrid, Turboelectric Concepts and Technology.

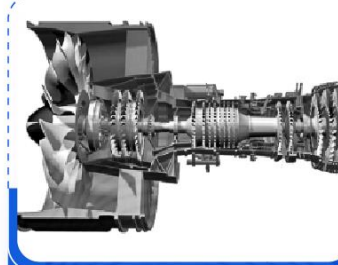


Electrified Powertrain Flight Demo – ground & flight demonstration of integrated MW-class powertrain.



Advanced Air Transport Technology/Propulsion & Power Subproject - powertrain technology

Transformational Tools & Technology – EAP materials & modeling.



Hybrid Thermally Efficient Core (HyTEC)

Advanced turbine engine technologies in a high-power-density core.



SUSAN – A 20 MW hybrid-electric aircraft concept study featuring a single aft engine with distributed wing-mounted propulsors.

Why Electric Aero-Propulsion?



- Why electric?
 - Fewer emissions
 - Quieter flight
 - Fuel savings
 - New mobility options
 - Better utilization of infrastructure



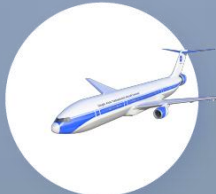
MW-CLASS Vehicle Parameters



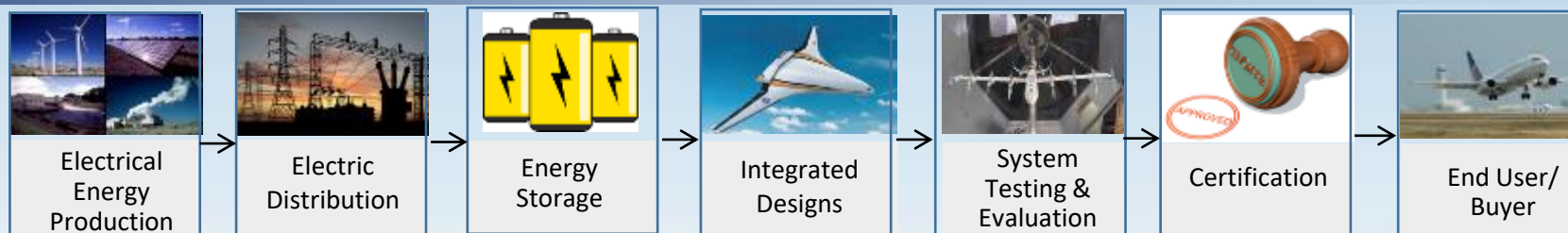
NASA is advancing Electrified Aircraft Propulsion (EAP) technology across a variety of markets, ranges, aircraft sizes, VTOL/CTOL configurations and electrical power levels. Fully electric, hybrid, and turboelectric are potential EAP system configurations. Electrified aircraft propulsion impacts vary on aircraft design, depending on the key requirements of the market the vehicle is intended to serve.



MARKET	AIRCRAFT	PASSENGERS	SPEED	RANGE	POWER	WASTE HEAT
On demand mobility	VTOL	1-19	~50-200 mph	~25-200 miles	~1 MW	~200 kw heat
Regional	General Aviation / Small Turboprop	1-19	~150-200 mph	~100-500 miles	~1 MW	~200 kw heat
Regional	Regional Turboprops & Turbofans	20-150	~300-400 mph	~500-1500 miles	1-5 MW	~200 kw-1MW heat
National/ International	Single Aisle	150+	~500-650 mph	~1500-7000 miles	3-30 MW	~600 kw-6MW heat



EAP Ecosystem

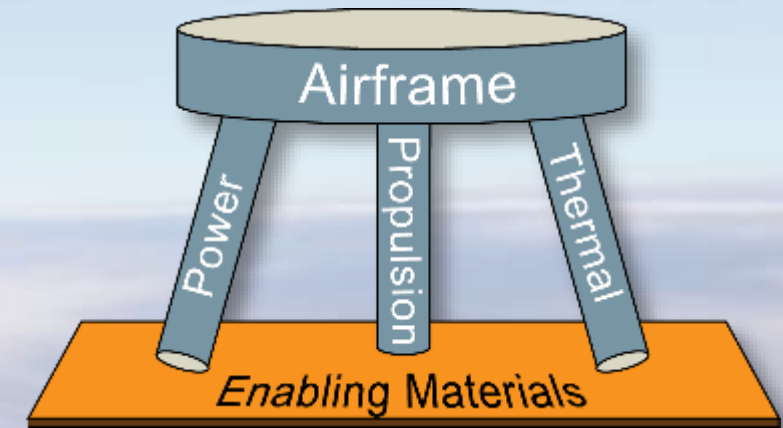


DoD				✓	✓		✓
DOE	✓	✓	✓				
ARPA-E	ASCEND REEACH	CIRCUITS BREAKERS	✓				
FAA						✓	
NASA	Turbogen SOFC	Fault and Thermal	✓ SPACE	✓	✓	Flight Demos	
Engine Companies				✓	✓		
Airframers				✓	✓		
Operators							✓
Energy and Transport Industry	✓	✓	✓				

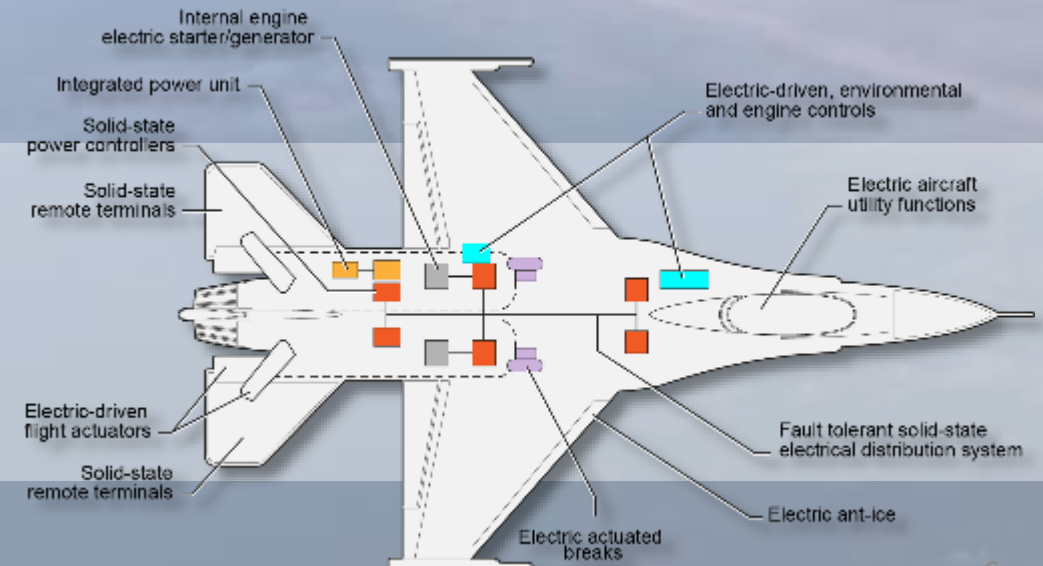
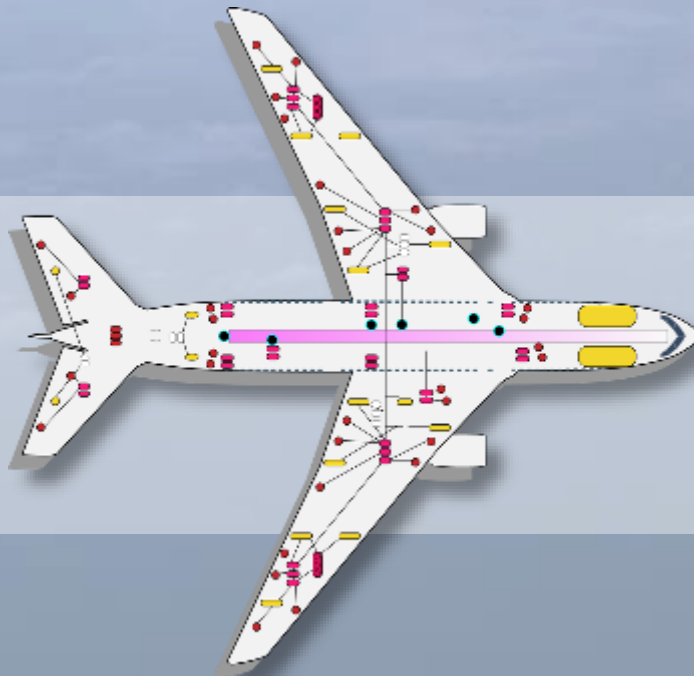
Power, Propulsion, Thermal, and Airframe Integration

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

- improve fuel efficiency
- reduce emissions
- reduce low grade waste heat
- reduce vehicle mass
- manage distributed heat sources



All components must integrate

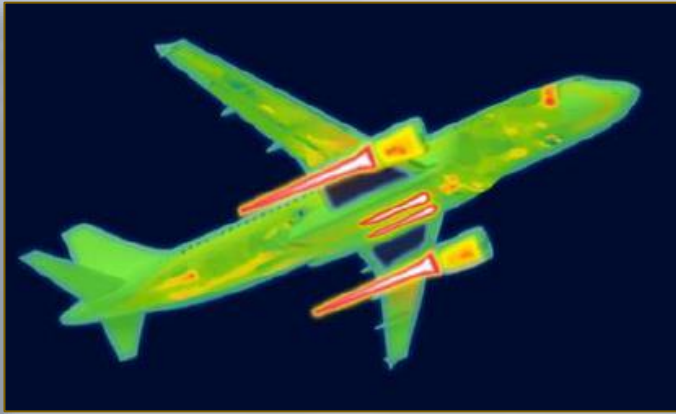
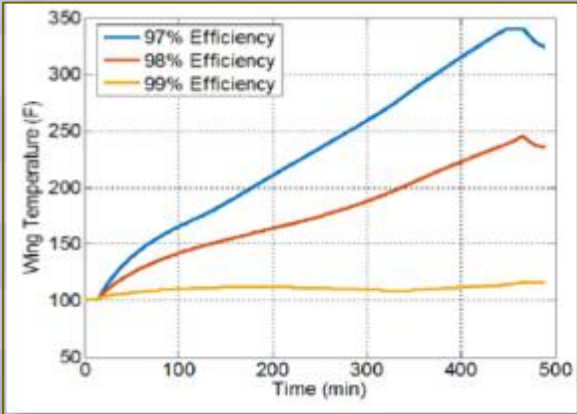


Electric Aircraft Thermal Challenge

Current proposed solutions 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

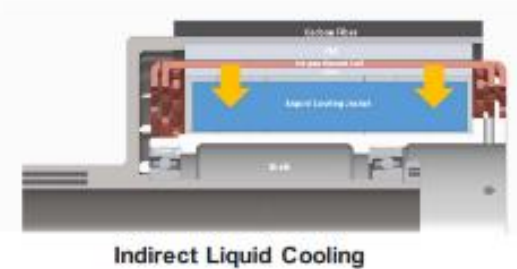
Energy Transfer Medium	Limits	Scale
Electrical	Voltage, Copper Mass and Heat	$I^2 R$
Mechanical	Lubrication, Vibration, Heat, Mass	$0.5 \tau \omega^2$
Fluid	Freezing, Pump, Impurities, Heat, Mass	$\dot{m} C_p T$
Phase Change/Vapor	Gravity, Orientation, Distance, Freezing	<1 m
Acoustic	Design Challenge, Some Heat	$0.5 * p v^2$



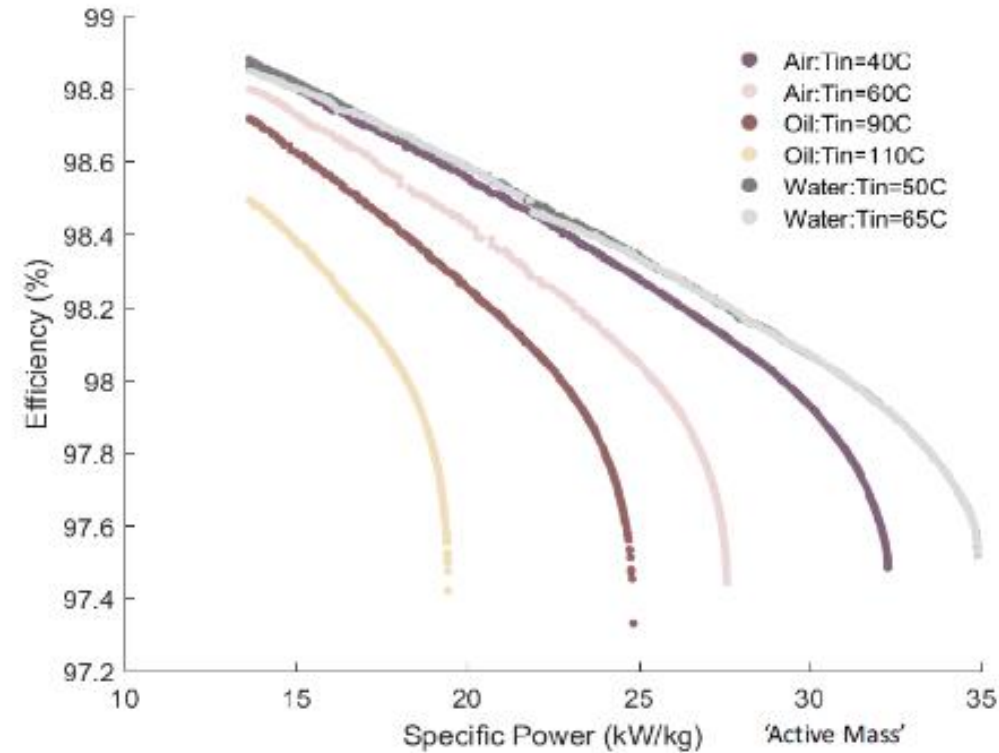
P.C. Krause

50kW to >600kW of low-grade thermal heat trapped within composite aircraft body

Thermal Management System Integration Benefits



Credit: Haran



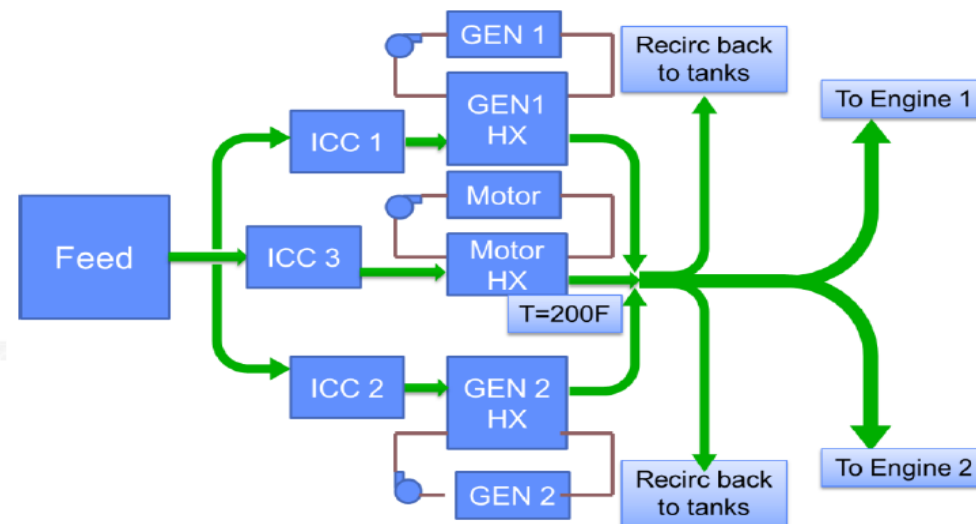
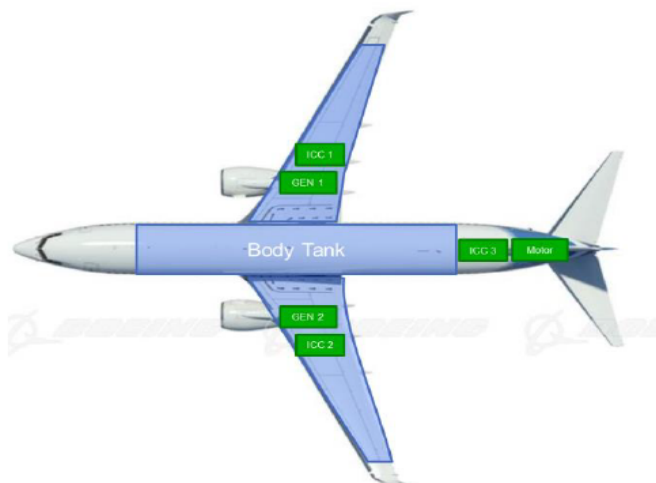
Pareto-Fronts of Motor Efficiency and Specific Power During Takeoff

Can increase specific power of the powertrain components while also increasing system efficiency.

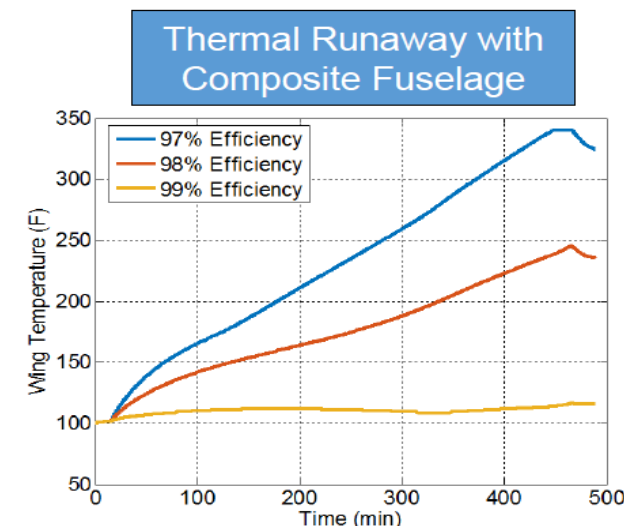
Conventional Aircraft Thermal Rejection Limits

Dumping heat into:

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



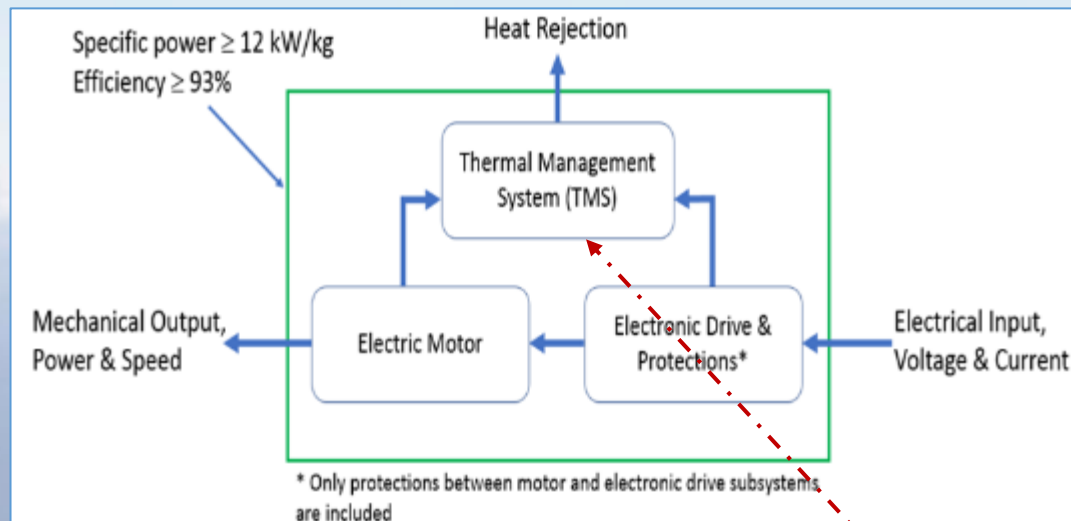
	1% Hot Day		Standard Day	
	Total Penalty (zero exit Velocity)	Total Penalty (non-zero exit velocity)	Total Penalty (zero exit Velocity)	Total Penalty (non-zero exit velocity)
900NM	4.98%	3.31%	2.76%	2.36%
3500NM	5.00%	3.62%	3.01%	2.57%



Powertrain Technology Requirements

- MW-Scale Transport Class Powertrain Requirements:

ARPA-E ASCEND Powertrain



		Absolute and Specific Quantities and Efficiencies					
		TRL 6 by 2020		TRL 6 by 2035		TRL 6 by 2050	
		Property	Efficiency	Property	Efficiency	Property	Efficiency
Kerosene Fuel Specific Energy	kWh/kg	11.9		11.9		11.9	
LNG Fuel Specific Energy	kWh/kg						
LH2 Fuel Specific Energy	kWh/kg	39.4		39.4		39.4	
Thermal Engine Brake/Thrust Specific Fuel Consumption*	(-)	-xx% / -25%		-xx% / -35%		-xx% / -45%	
Turboshaft Gravimetric Specific Power	kW/kg						
Gas-turbine Gravimetric Specific Power	kW/kg						
Battery System-Level Energy Density and Type**	Wh/kg [type]	200 Li-Ion	n/a	430 Li-S/Air/SS	n/a	570 Li-Air/SS	n/a
Battery System-Level Cycle Stability***	cycles	1000		1500		3000	
Battery Cell-Level Energy Density	Wh/kg	280		600		800	
Battery System-Level Specific Power	W/kg	1000		2500		3000	
Battery System-Level Energy Density	Wh/L	200		500		700	
Battery Charger Specific Power	kW/kg	5.0	97.5%	7.0	98.5%	9.0	99.0%
Fuel Cell Percentage of Balance-of-Plant	(-)	40%		35%		30%	
Motors/Generators, Power Electronics and Transmission Technology Notes	(-)	Predominantly Normal Conducting				Emerging High-Temperature Superconducting	
Maximum Electric Motor Shaft Power	MW	1.0		4.0		10.0+	
Motor Specific Power	kW/kg	3.5	90.0%	10.0	93.0%	20.0	95.0%
Motor Specific Torque	N.m/kg						
Generator Specific Power	kW/kg	3.5	90.0%	10.0	93.0%	20.0	95.0%
Gearbox Specific Power and Gearing Ratio	kW/kg [gearing ratio]	7.0	99.0%	9.0	99.0%	10.0	99.0%
Propeller/Rotor Specific Power and Ducted Fan Specific Power	kW/kg						
AC-DC Rectifier Specific Power	kW/kg	7.0	94.0%	9.0	97.0%	12.0	99.0%
DC-AC Inverter Specific Power	kW/kg	3.0	92.0%	7.0	94.0%	10.0	96.0%
DC-DC Converter Specific Power	kW/kg	5.0	97.5%	7.0	98.5%	9.0	99.0%
Controller Specific Power and Type	kW/kg [type]						
Bus Voltage for Propulsion System and Type, Maximum Operating Power	V [AC or DC] kW	800 DC	n/a	1000 DC	n/a	3000 DC	n/a
Transmission	kg/m.kA	2.0	95.0%	1.5	95.0%	0.6	99.0%
Thermal Management Increment	kg/kW(th)	2.0	n/a	1.5	n/a	cryo	n/a

* Year-2000 datum

** Includes provision for packaging, cycle stability with corresponding design life, ageing effects, minimum State-of-Charge (SoC), thermal management, safety features and sensing requirements, amongst others

*** 20% minimum State-of-Charge (SoC) threshold

Goal is to reduce TMS specific mass from 2 kg/kW(th) to <1 kg/kW(th)

Solid-State Dynamic Thermal Management System

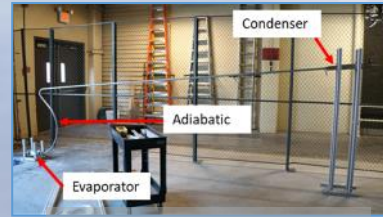
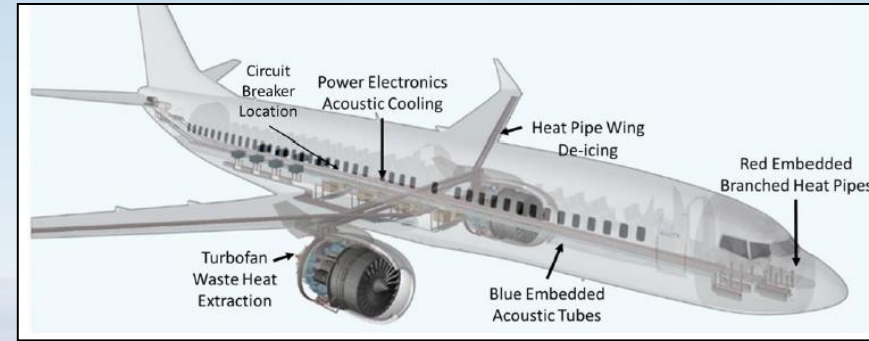


- **Solid-State Exergy Amplification**

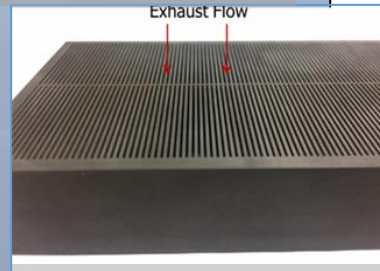
- No moving parts
- No pumped fluids
- No increased drag
- Maximize specific power
- Improve powertrain efficiency

- **Areas of Development**

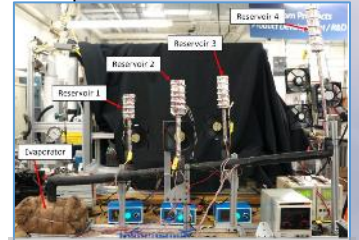
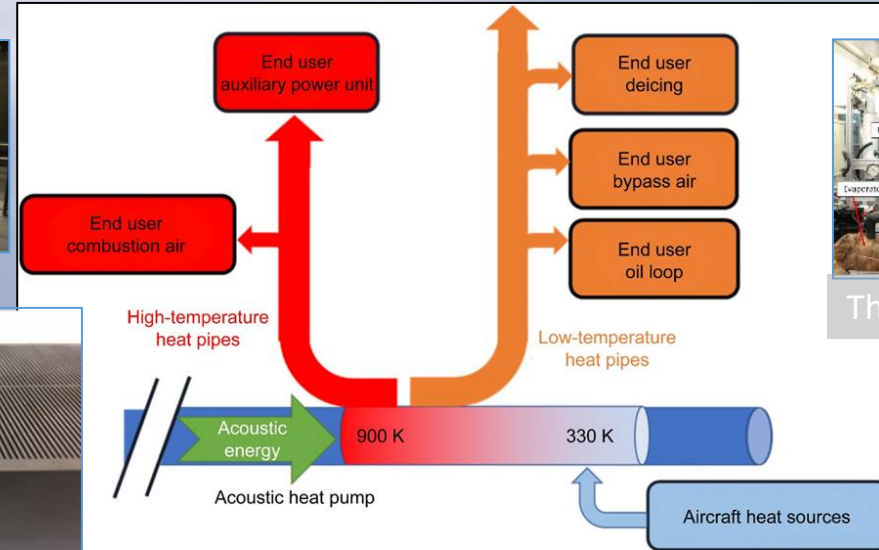
- Turbofan WHR HX
- Acoustic Heat Pump
- OHP Heat Collection
- Thermal Transport
- Thermal Recycling
- Dynamic Thermal Redirection
- Gradient-based System Optimization



Thermal Transport



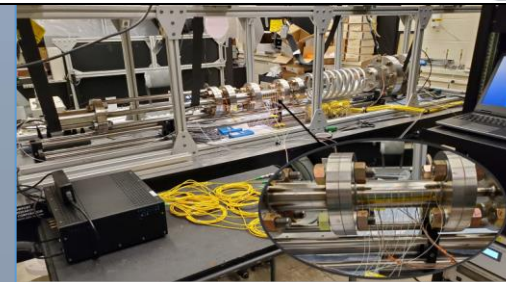
Waste Heat Recovery



Thermal Redirection

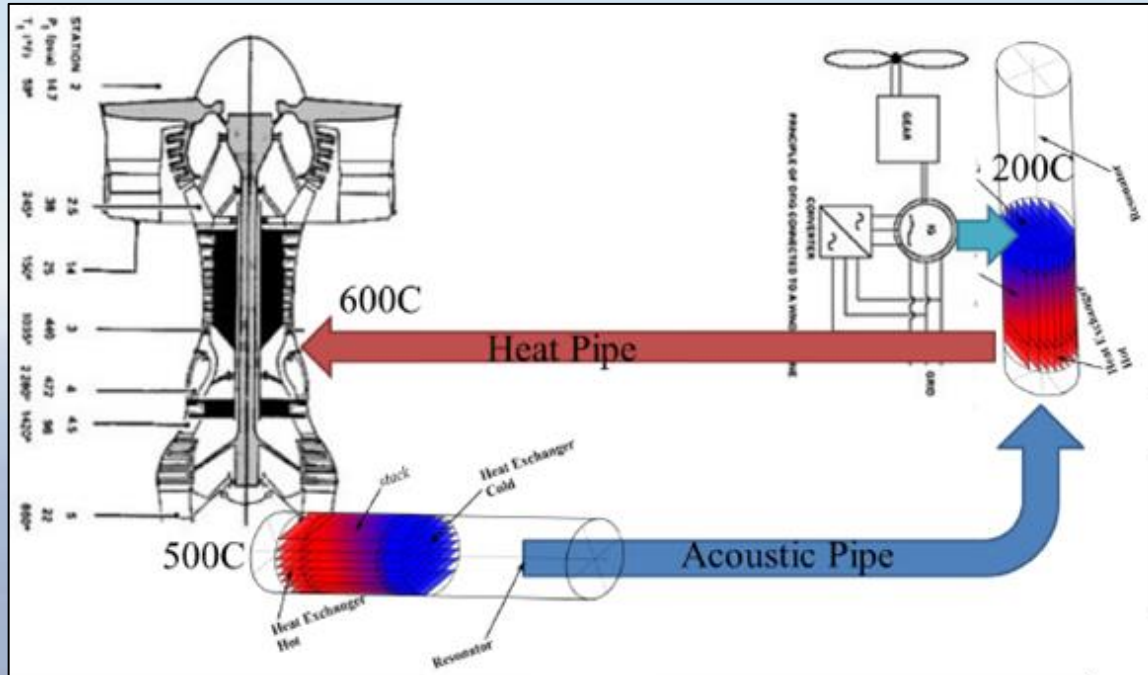


OHP Heat Collection



Acoustic Heat Pump

Thermal Recovery Benefits



Solid-state Energy Recycle Benefits

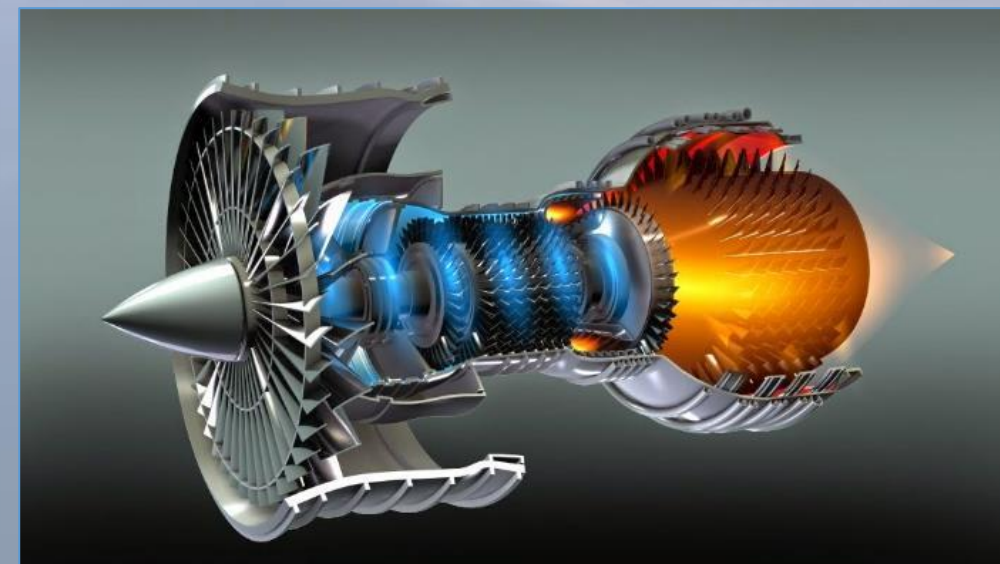
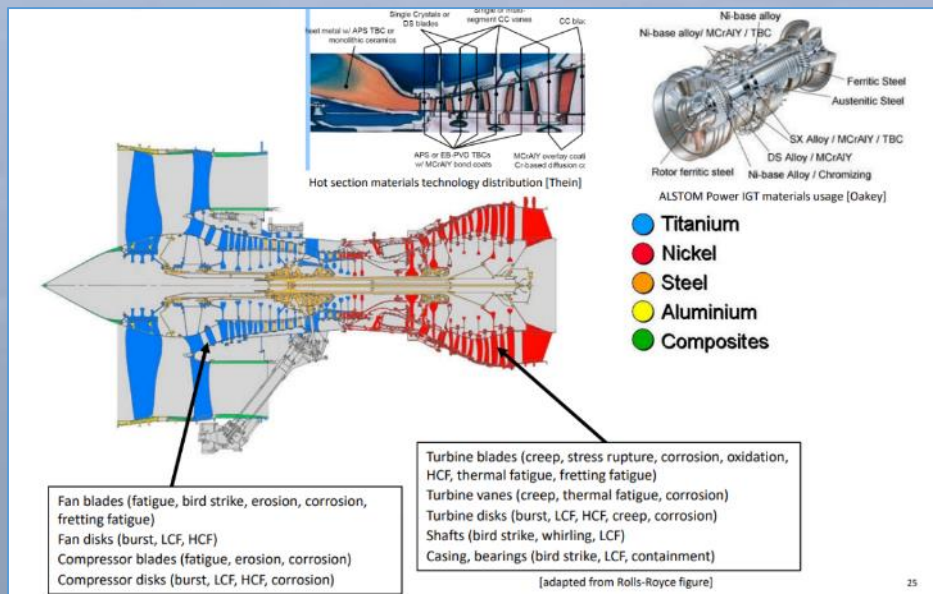
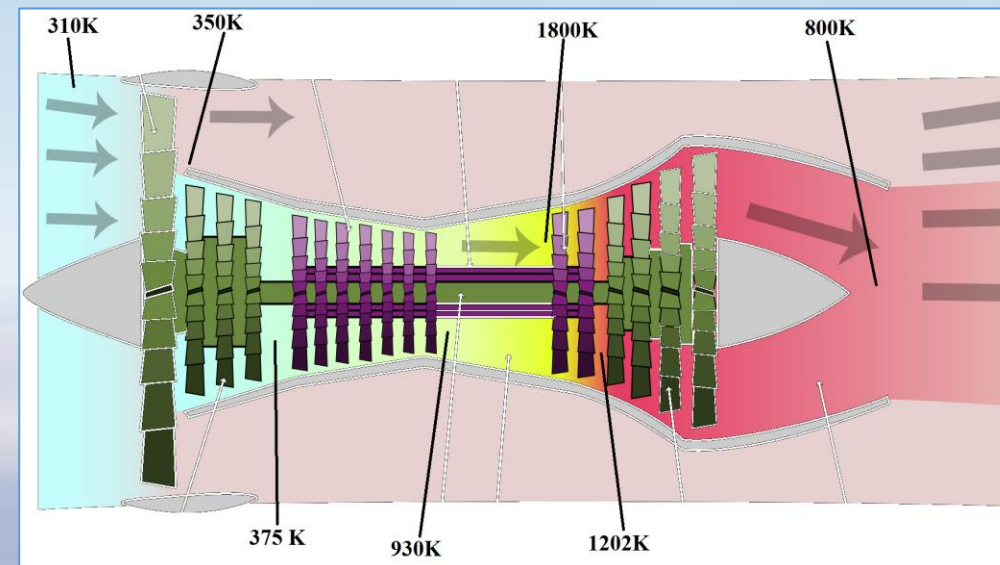
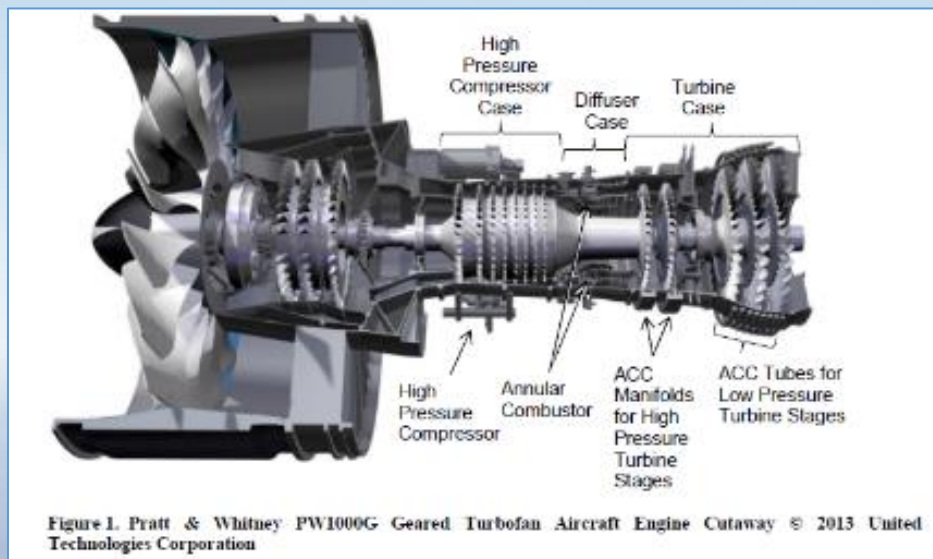
- localized skin heating
 - for active lift/drag management,
- de-icing/anti-icing,
- powertrain cooling,
- cabin thermal management,
- engine recuperation,
- thrust enhancement with by-pass air
- military cloaking

Components	Qty	Power	Max. Allowable Temp.	Locations
Generator	2	50kW each	<100°C	Under wings
Rectifiers	2	15kW each	<100°C	Under wings
Circuit Breakers	4	7kW each	<100°C	Along cables (two behind rectifiers and two in front of inverter)
Inverter	1	25 kW	<100°C	Near tailcone
Motor	1	100 kW	<100°C	Near tailcone
Cabin Cooling	1	10 kW	< 30°C	Bottom
Others	n/a	2 kW	<100°C	Bottom

Components	Temperature	Locations
Preheat Combustion Air	>600°C	Near Turbofans
Preheat Air into Auxiliary Power Unit (APU)	> 400°C	Near Tailcone
Anti-icing System	> 20°C	Wing, engine cowlings and tail flight control surfaces
Warm by-pass Air for Thrust Enhancement	> 50°C	Near Turbofans
Warm the Ram Air	> 30°C	Near Turbofans

Potential Range of up to 16% Fuel Burn Savings with Waste Heat Recovery

Turbomachinery WHR Challenges

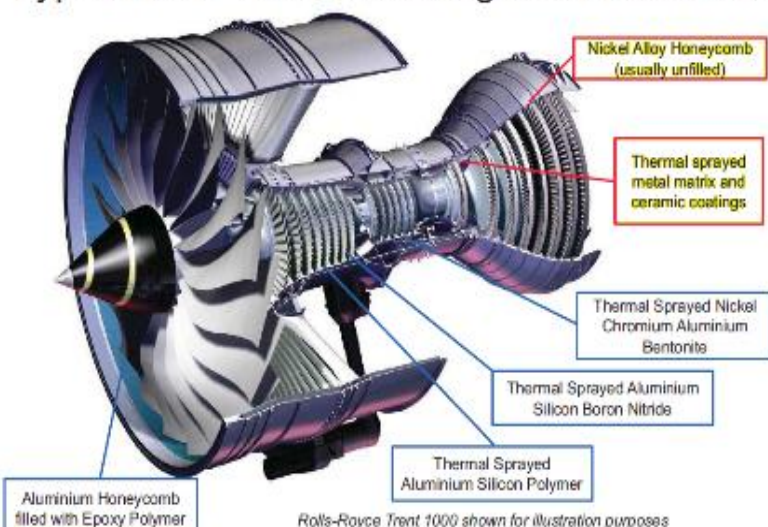


Material, Surface Area, and Engine Cycle Performance Impacts Available Waste Heat Recovery

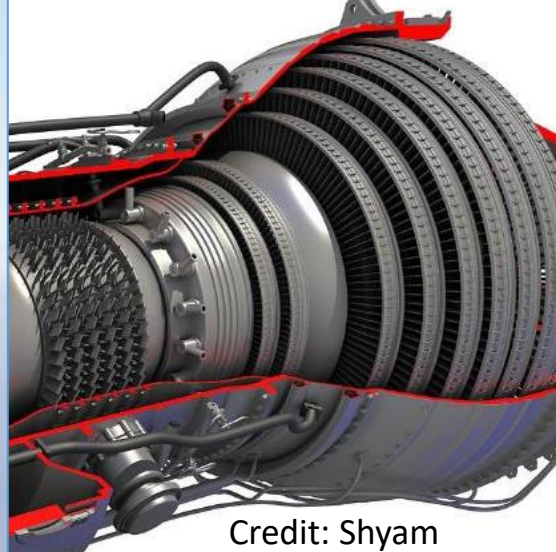
Available Waste Heat Recovery from Turbofan



Typical Gas Turbine Casing Liner Materials

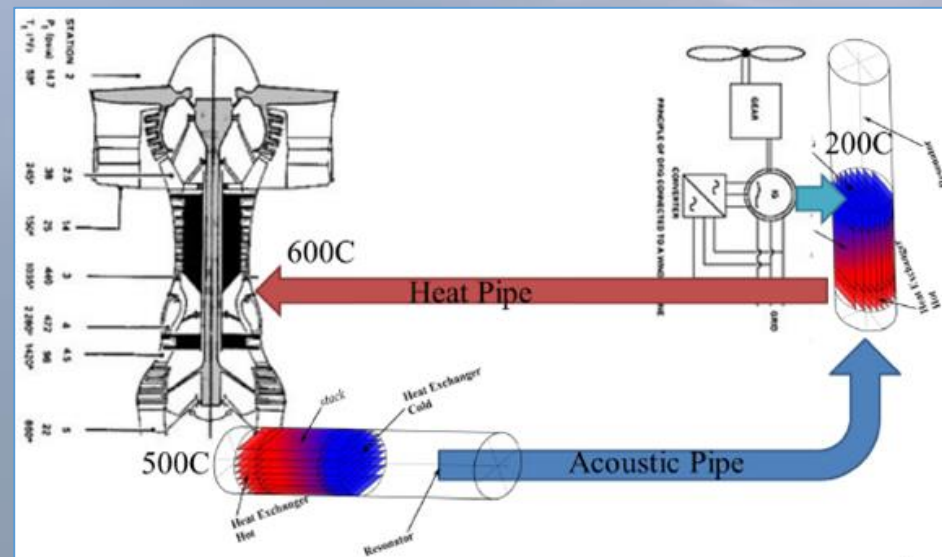
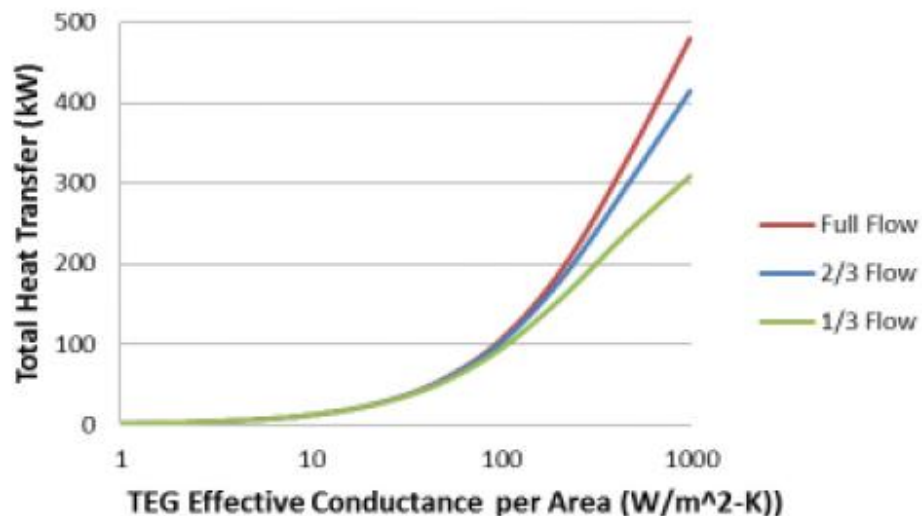
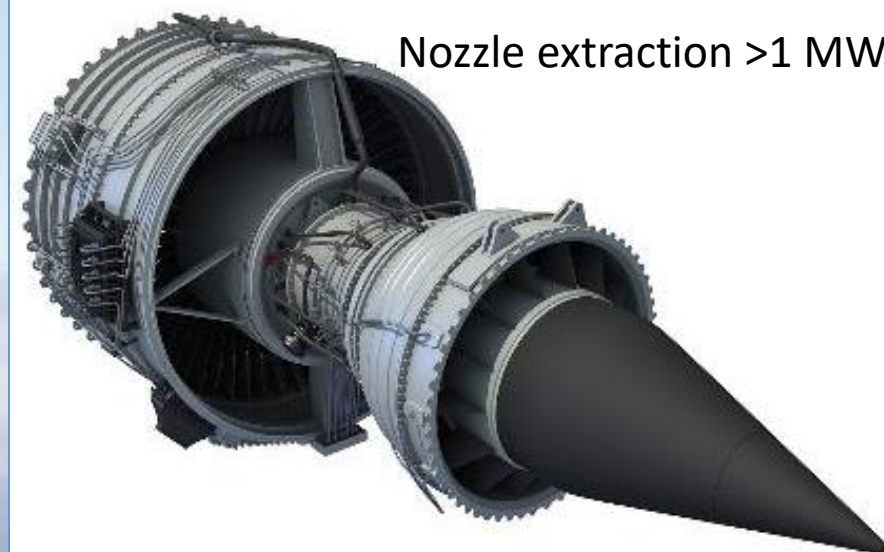


Liner extraction > 500 kW



Credit: Shyam

Nozzle extraction > 1 MW



Turbo-electric Potential Energy Extraction > 10 MW

Nozzle Waste Heat Energy Extraction Example

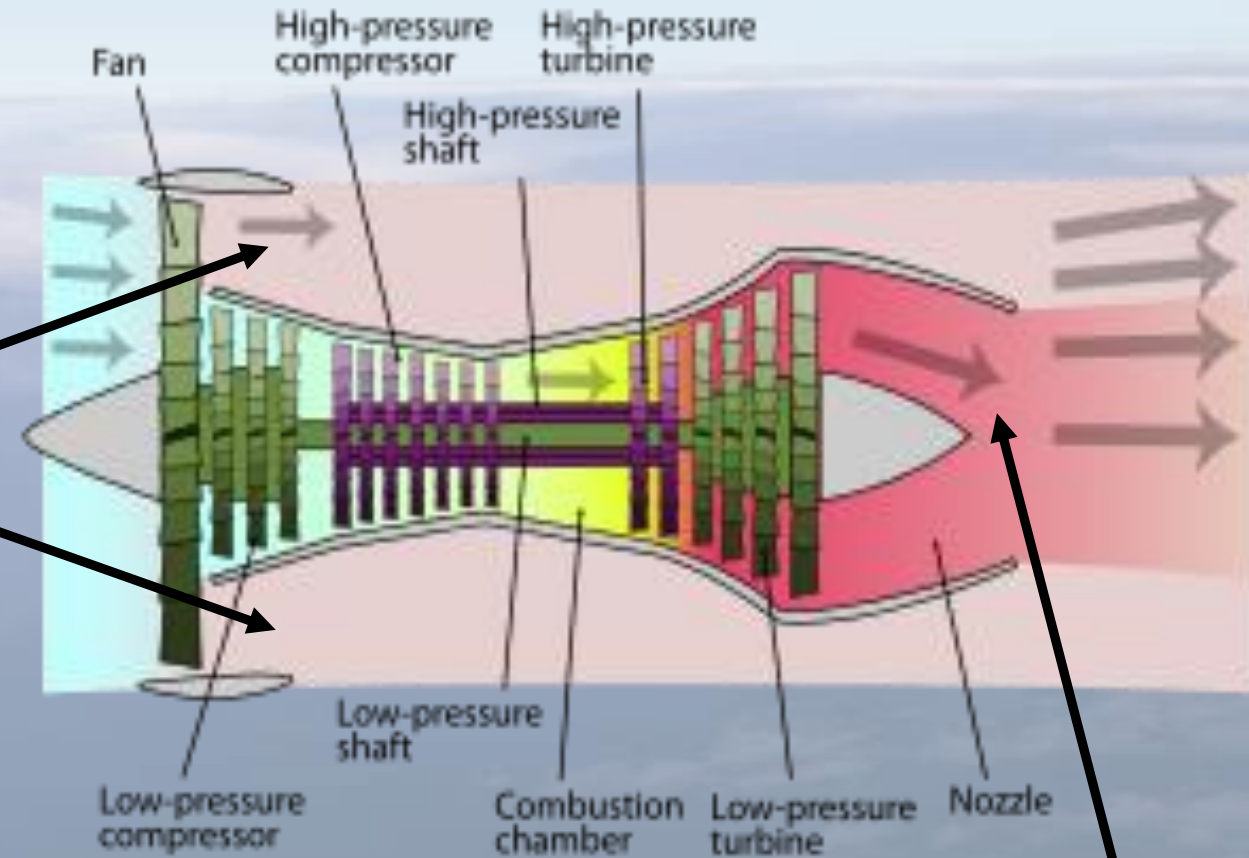


- Key Point: Most thrust (>80%) produced in by-pass air of commercial aircraft
 - Turbofans have bypass ratio from 6 to 12
 - Turboprop have bypass ratio from 50 to 100
 - Hybrid electric distributed propulsion up to 100
 - Small core further increases by-pass ratio

Majority of thrust here

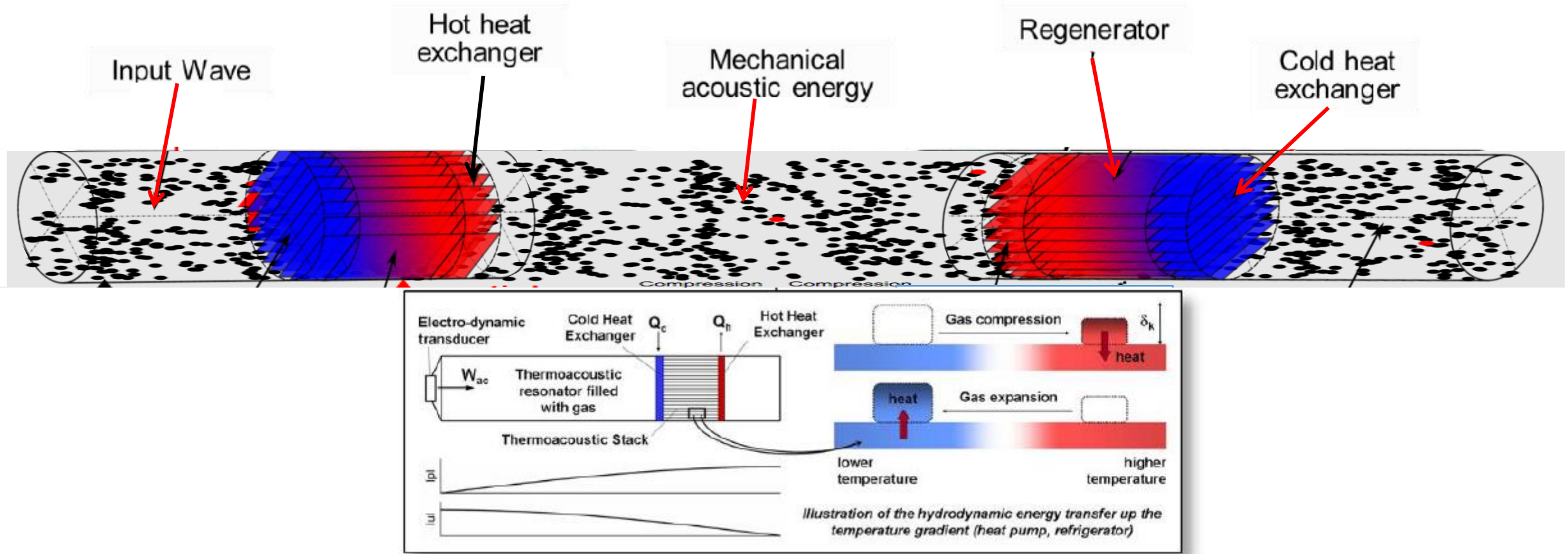
- Idea: Extract waste energy from core
 - Minimal impact on overall thrust
 - Reduce jet noise that scales as V^8
 - ~30 MW waste heat available on B737

Extract only 10%, 3 MW -> 1MW acoustic energy available



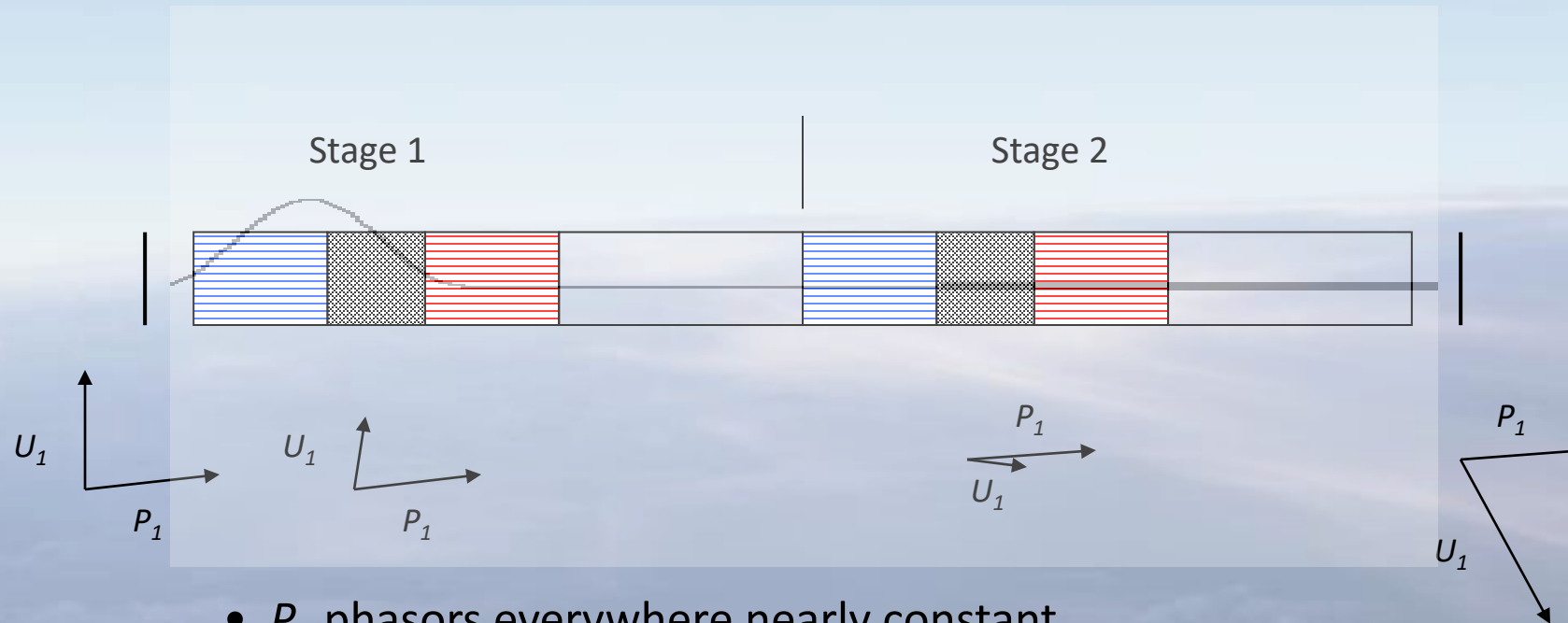
Extract heat here

Acoustic Heat Pump



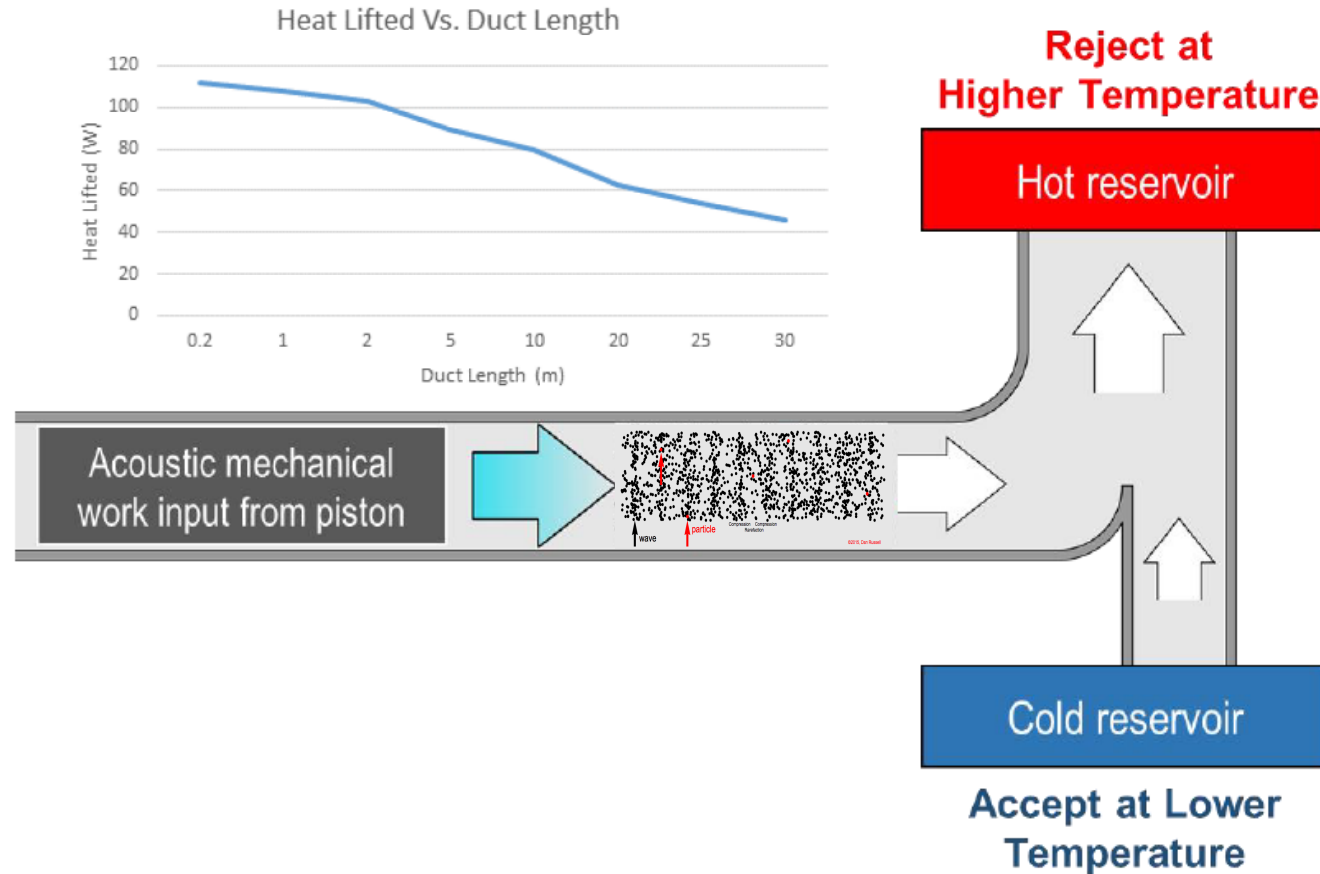
Acoustic Energy Amplification and Refrigeration with Same Traveling Wave

Acoustic Pressure and Velocity Phase Matching



- P_1 phasors everywhere nearly constant
- U_1 phasors progressively lag due to volume (compliance)
- Ideally, P_1 and U_1 in phase in regenerators
- Gas inertia (inertance) can be used to counter U_1 lag
- E.g. Swift inter-stage inertance tube
- Modeling tools like Sage automatically account for distributed compliance and inertance

Acoustic Heat Pump COP



Th (k)	Tc (k)	Ratio (W/Qc)
400	300	1:3
600	300	1:1
900	300	2:1
1200	300	3:1
300	50	40:1

Ratio of input acoustic energy required for heat pumping

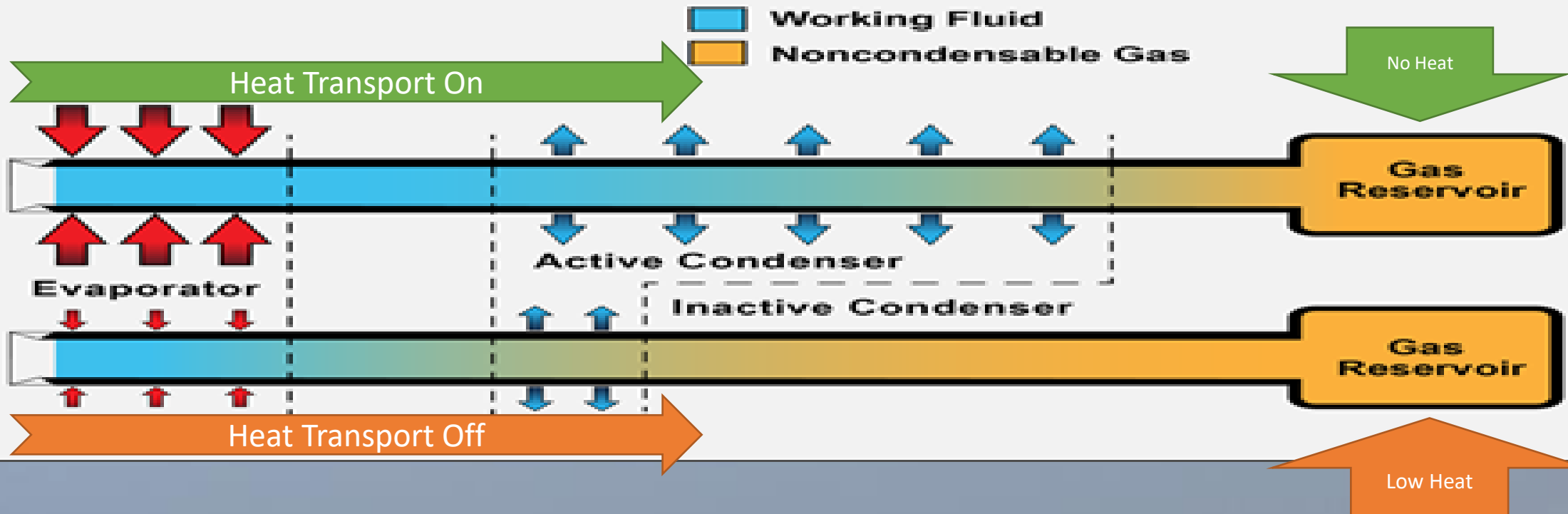
Solid-State Energy Delivery and Control



Acoustic Energy Control Method

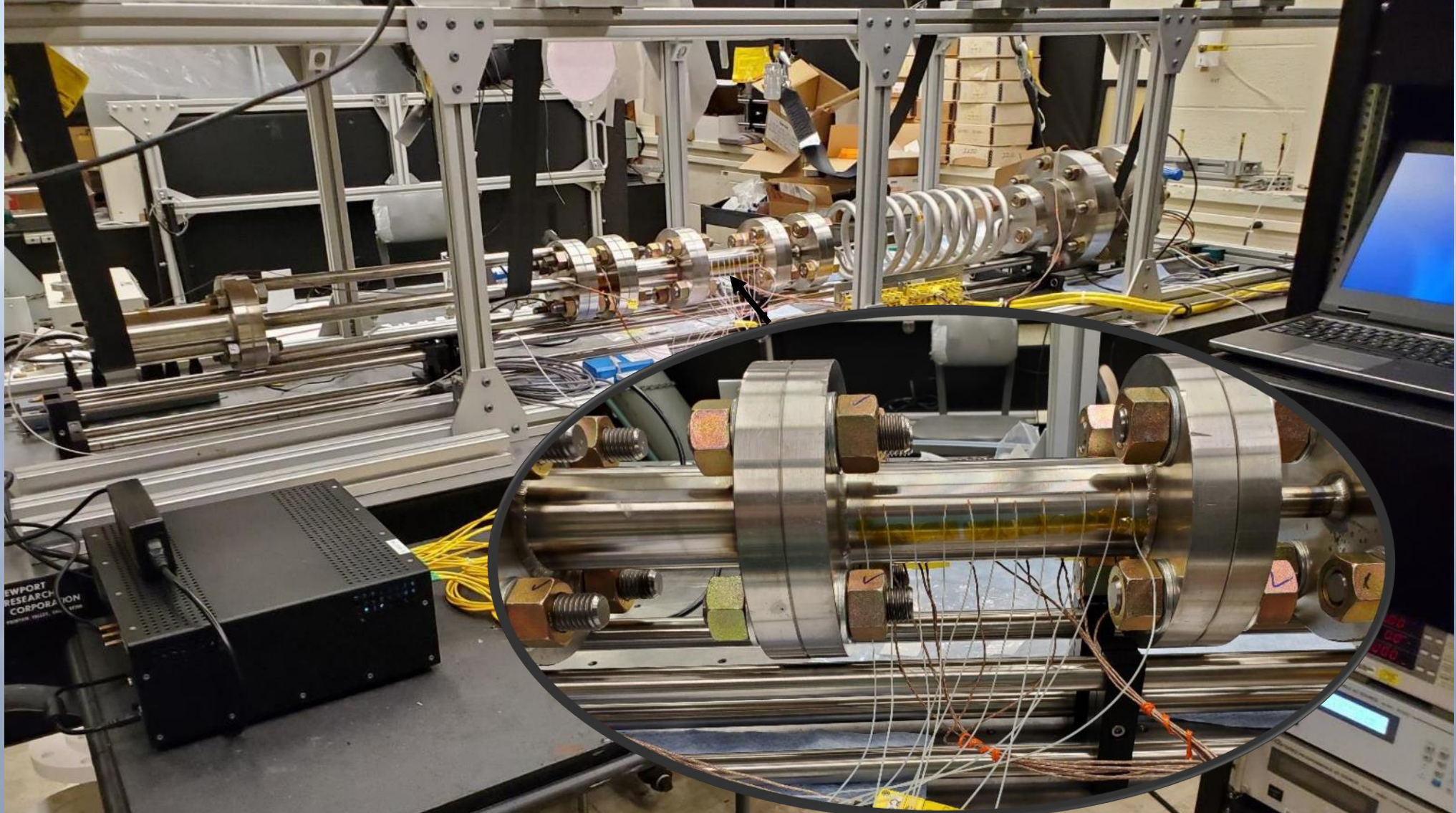


Vapor Energy Control Method



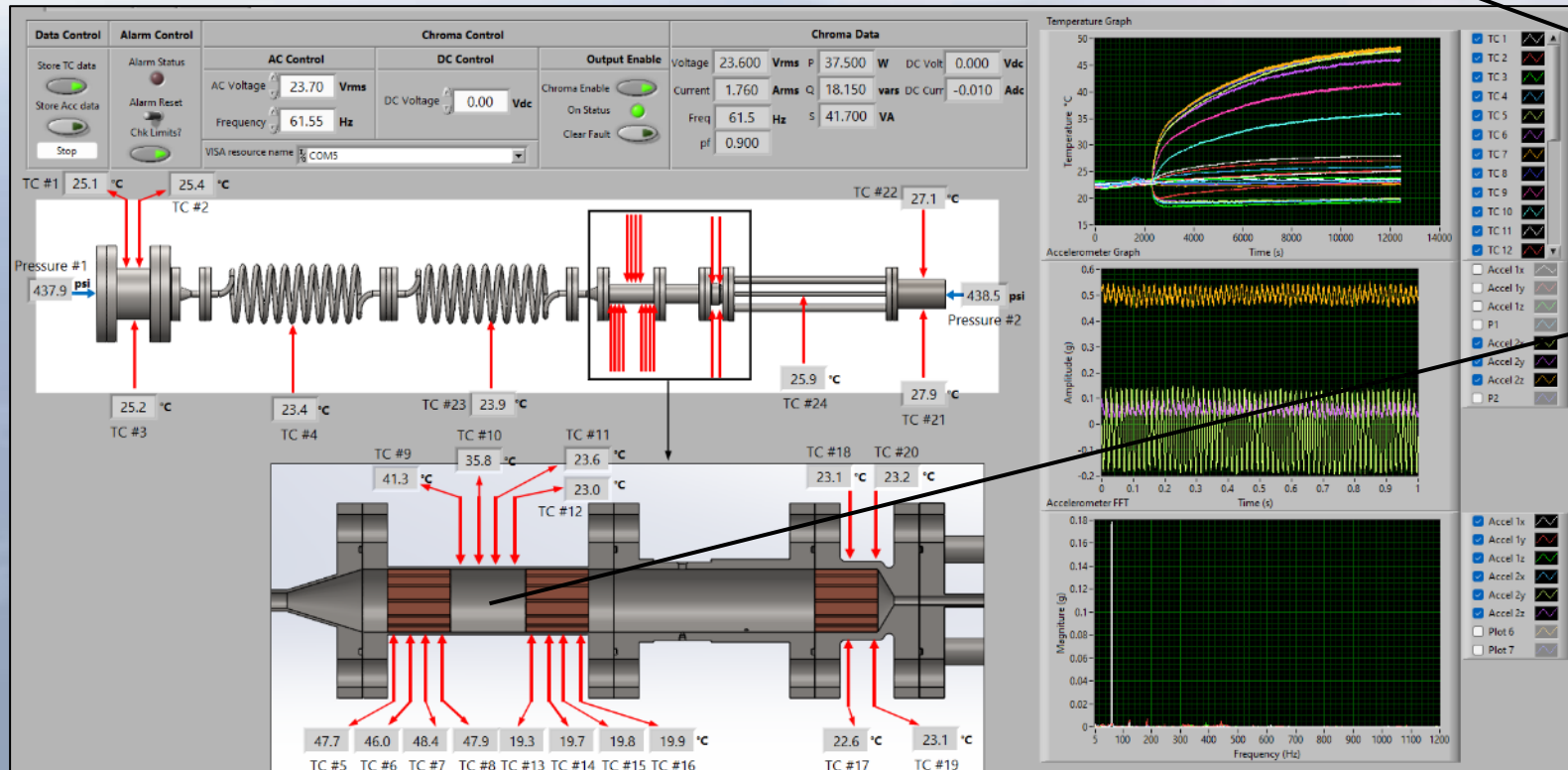
Dynamic Refrigeration and Thermal Transport with No Pumps or Moving Parts

Successful 10-meter Acoustic Heat Pump Test



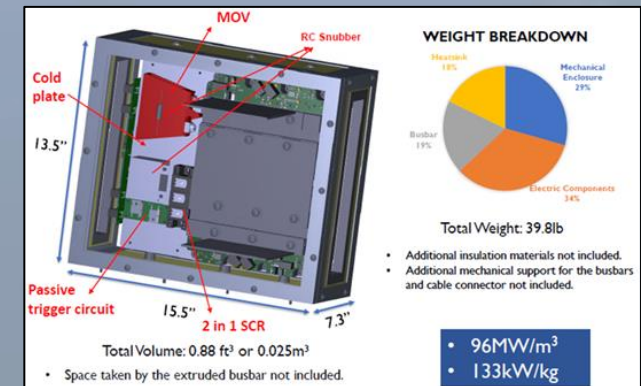
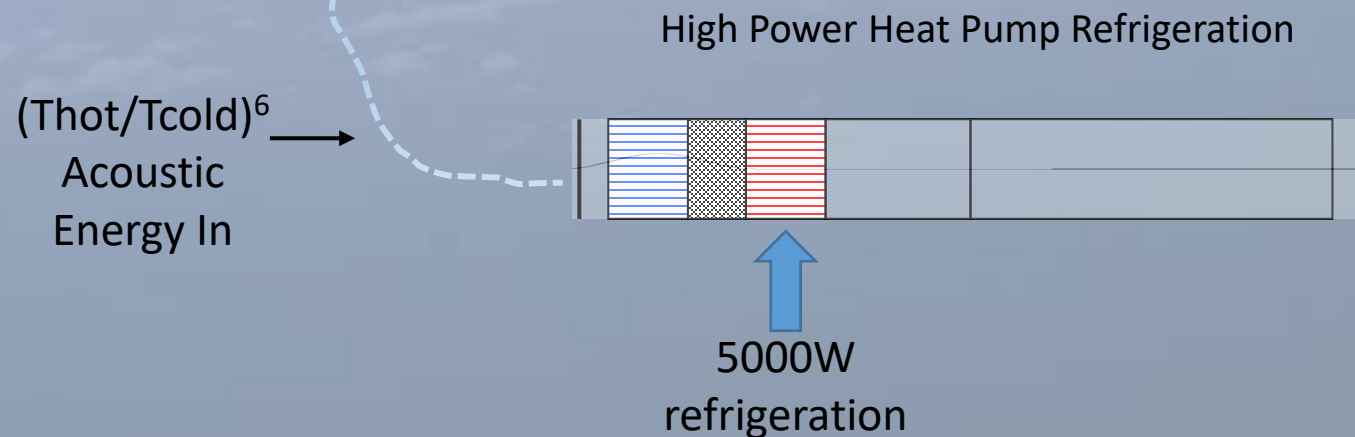
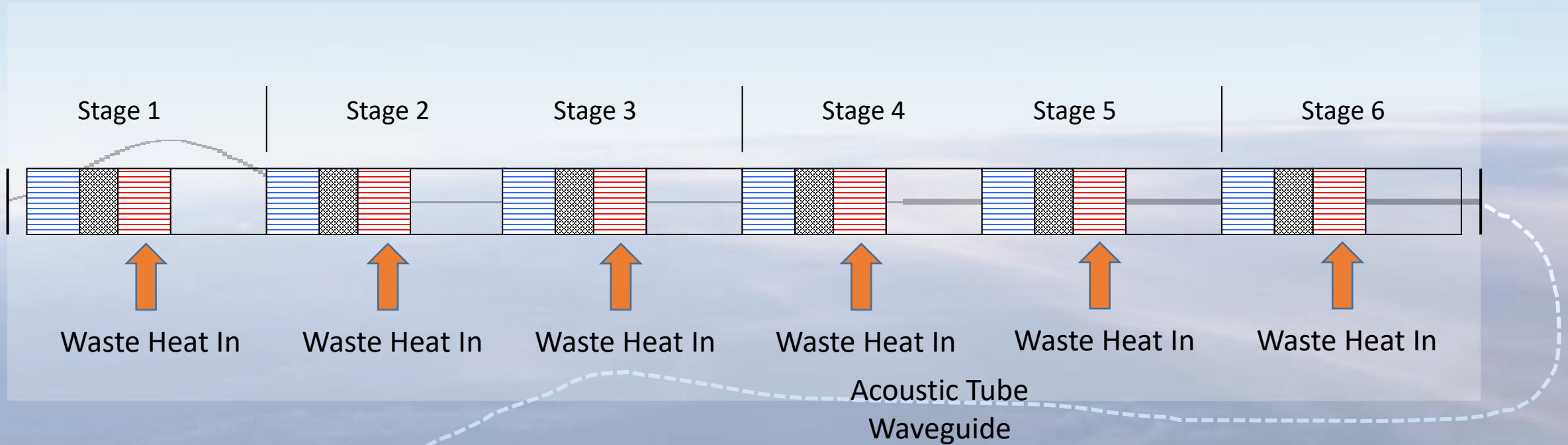
Refrigerated Section Highlighted with Optical Sensors

10-meter Acoustic Heat Pump Prototype Test Results



Thermal energy heat pump at single location along 10-meter tube with no detected acoustic waveguide tube heating

Next Step – 6 Stage Amplification!



MW DC Breaker Refrigerated

Conclusion

NASA IS INVESTING IN ELECTRIFIED
AIRCRAFT PROPULSION (EAP) TO
ENABLE A NEW TECHNOLOGY S-CURVE
OF INNOVATION IN AVIATION

NASA is broadly investing in Electrified Aircraft Propulsion (EAP)

NASA investments are guided by a combination of potential market impacts and technical key performance parameters.

The impact of EAP varies by market and NASA is considering three markets: on-demand mobility, regional and national/international air transportation.

Technical advances in key areas have been made that indicate EAP is a viable technology.

Flight research is underway to demonstrate integrated solutions and inform standards and certification processes.

Additional work is needed to transition the technology to a commercial product and further improve the technology to realize the benefits across the world.

Feasible Vehicle Class Driven by Powertrain Specific Power and Efficiency and Integrated Vehicle Design Optimization
Power, Propulsion, Thermal, and Airframe Integration Key

