NASA Acoustic Stirling IRAD

Energy Conversion in Aircraft

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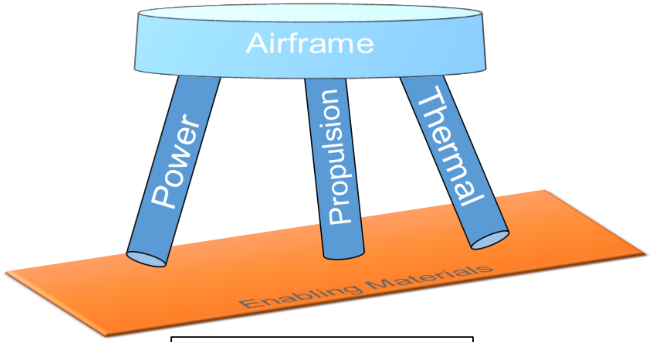
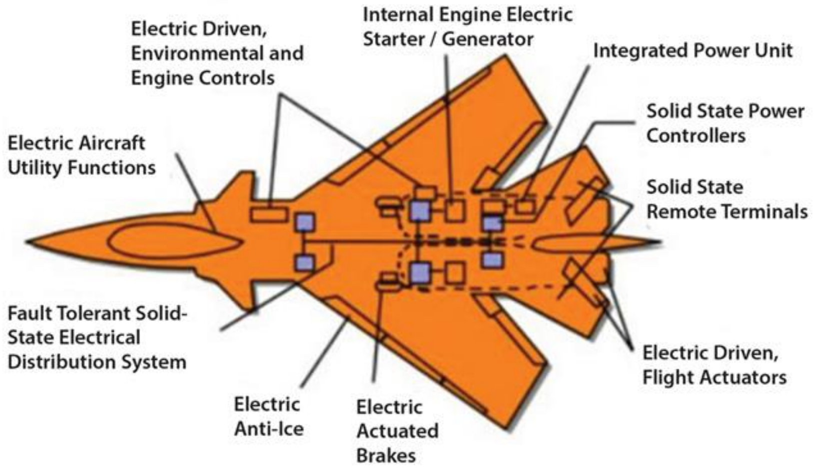
Motivation

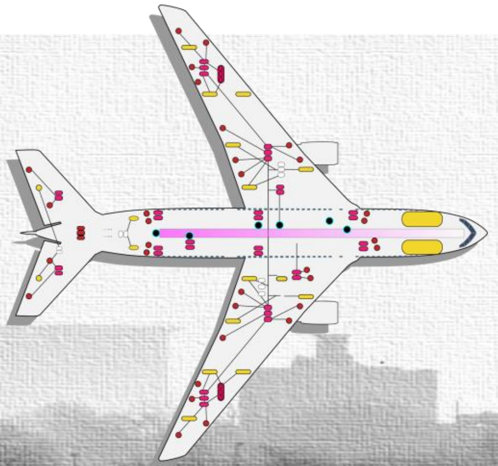
Low Grade Waste Heat Produced Throughout Insulated Aircraft

- Prefer technology that:
  - improves fuel efficiency,
  - reduces emissions,
  - removes heat from:
    - small core engines, more electric composite aircraft, and high power electric propulsion systems
  - reduces vehicle mass
  - reduces thermal signature for military



All components must integrate





Commercially attractive solution would achieve >15% fuel savings

Thermal Challenge

50kW to >800kW of low grade thermal heat trapped within composite aircraft body

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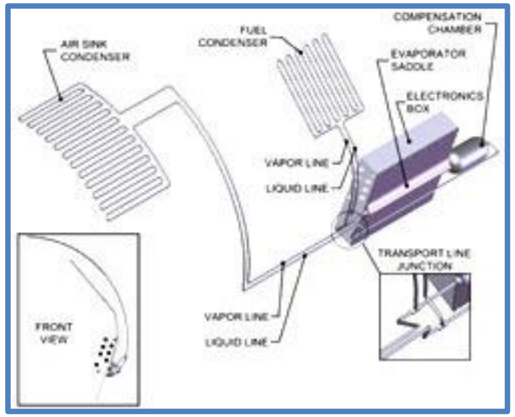
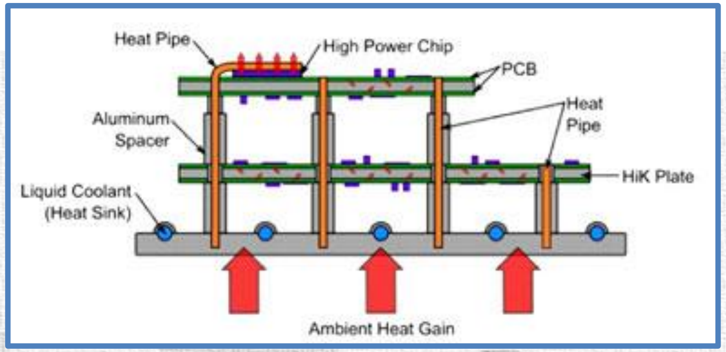
Current proposed solutions include:

- ❑ 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



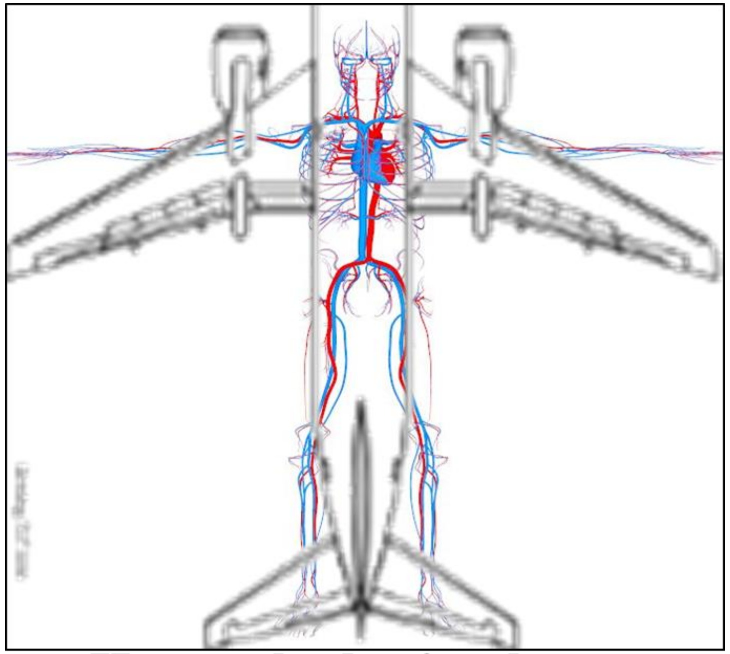


Aero-vascular Energy Management

Human	**Aircraft**
Heart	Turbofan
Artery	Acoustic Pipe
Vein	Heat Pipe
Skin	Skin
Blood	Helium/Gas

Large aircraft ideal for integration- allows each component to be at knee in the curve instead of Achilles Heal of vehicle

- Turbofan-45% eff.
- Powertrain-95% eff.
- Lifting surface
- Large transport highest impact



Human body circulatory system as model for aircraft

Three pillars:
recycle energy,
additive manufacture airframe,
solid-state thermal control

Basic Principles

- Extract waste energy from turbofan core exhaust and convert to ducted acoustic wave
- Deliver no moving part mechanical acoustic energy throughout aircraft in embedded airframe tubes
- Cool and heat pump powertrain and/or more electric components using no moving part thermo-acoustic heat pump
- Recycle waste heat with variable conductance heat pipes

Basic Principles

Today's high bypass ratio turbofan engines are ideal for waste heat extraction from the small core exhaust since most thrust is from the fan

All collected waste heat from powertrain can be recycled

Heat Energy Extraction

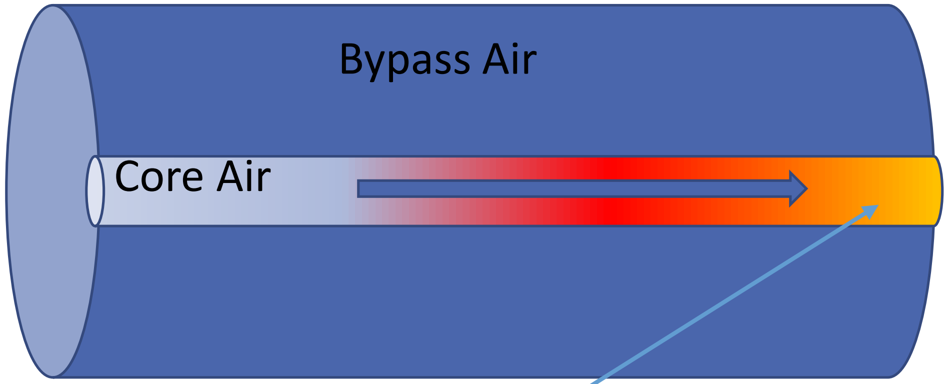
High bypass ratio turbofan (6-12)/turboprop (50-100)

- Small core and distributed propulsion increases ratio, (e.g., PW1000G ideal)
- 787 with RR Trent 1000 - 10:1

Thrust produced mostly by cold bypass air

Extract waste energy from core

- Minimal impact on overall thrust
- Reduce jet noise V^8
- ~30 MW waste heat available



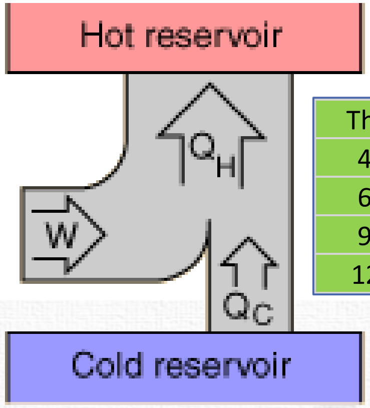
Extract only 10%, 3 MW -> 1MW acoustic energy available

Heat Pumping

Makes more electric parts and powertrain effectively 100% efficient

All airframe waste is now useful

Free Acoustic Mechanical Work Input



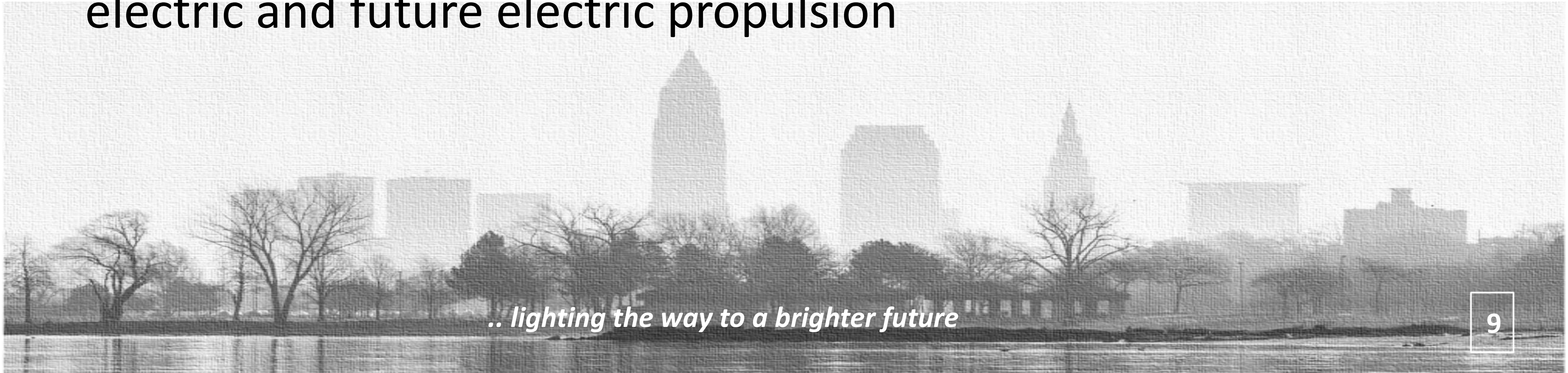
Th (K)	Tc (K)	Th/(Th-Tc)	Qout (W)	WorkIn (W)	Qin (W)
400	300	4	1000	250	750
600	300	2	1000	500	500
900	300	1.5	1000	666.66667	333.3333
1200	300	1.333333	1000	750	250

Cryogenic Option 2000Win for 50W@50K

Electric Actuators,
Cabin, Cables, Power Electronics, Protection,
Machines

Effectively 100% Efficient Flight-Weight Powertrain and More Electric Components

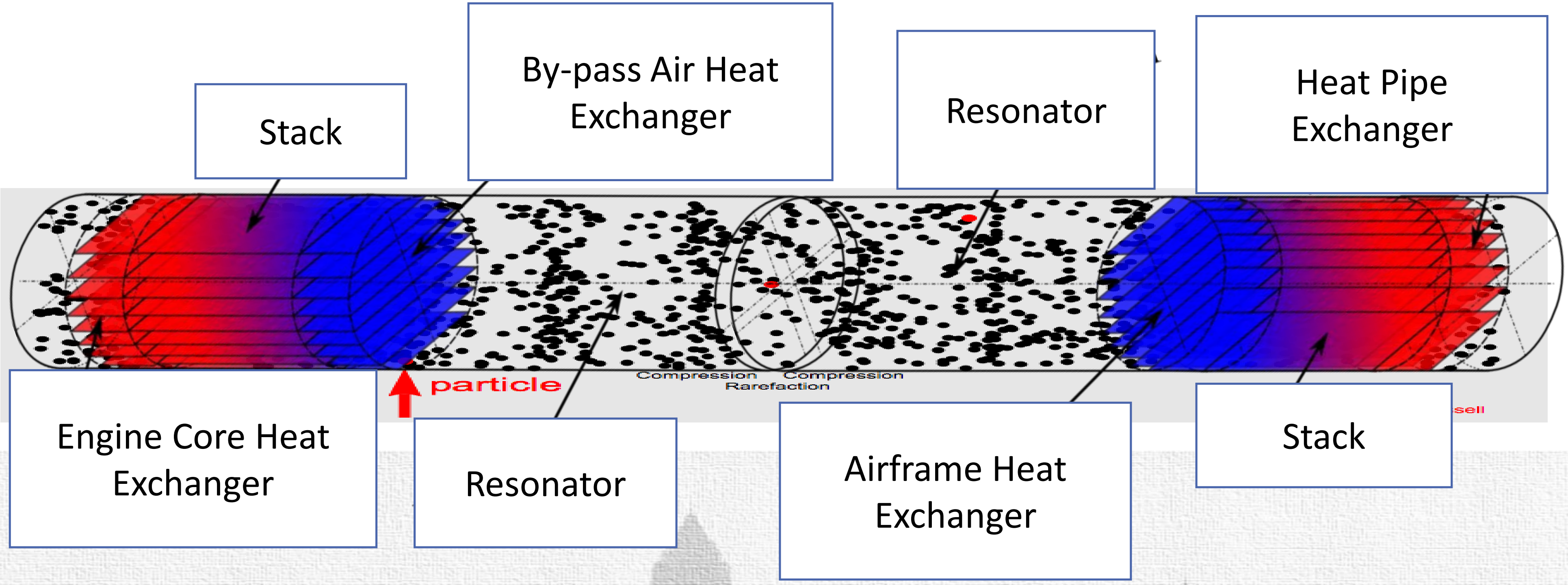
- Cold copper 10X more conductive, keep voltage low, increase specific power, effectively 100% efficient power electronics, cable, motor, protections, actuators, etc.
- Additively manufactured into airframe distinguishes Boeing from competition and enables use of reliable COTS components for more electric and future electric propulsion



COTS Advantage

- 96% efficiency vs. 99% efficiency benefit reduced since waste heat is 100% recycled
  - Recycling waste heat means can use lower efficiency components
- Can keep components cooler for higher specific power
- Can operate at lower voltages since copper conducts more
- Works with any COTS equipment

Traveling Energy Wave Basic Principles – Air Molecules Oscillate



Basic principle is to use aircraft engine waste heat to produce a high intensity acoustic wave with no hot moving parts that can be used for power generation or component cooling. The temperature gradient between hot and cold HX efficiently creates the acoustic waves. All energy is delivered through small hollow acoustic tubes.

Solid-state Heat Transfer Switching

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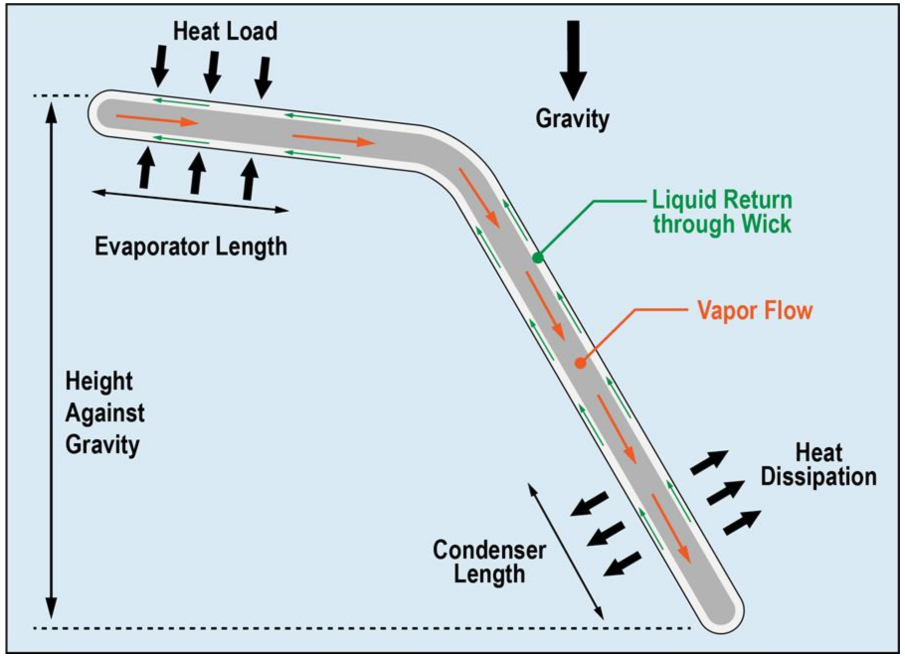
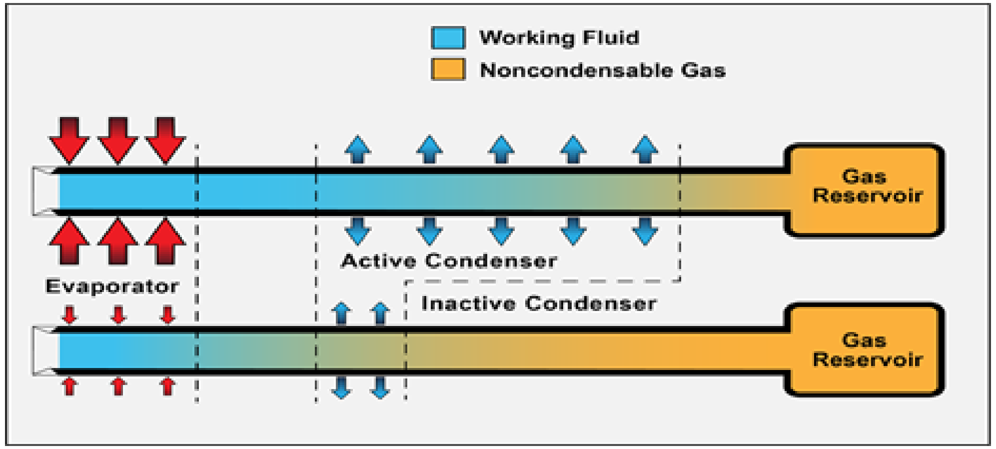


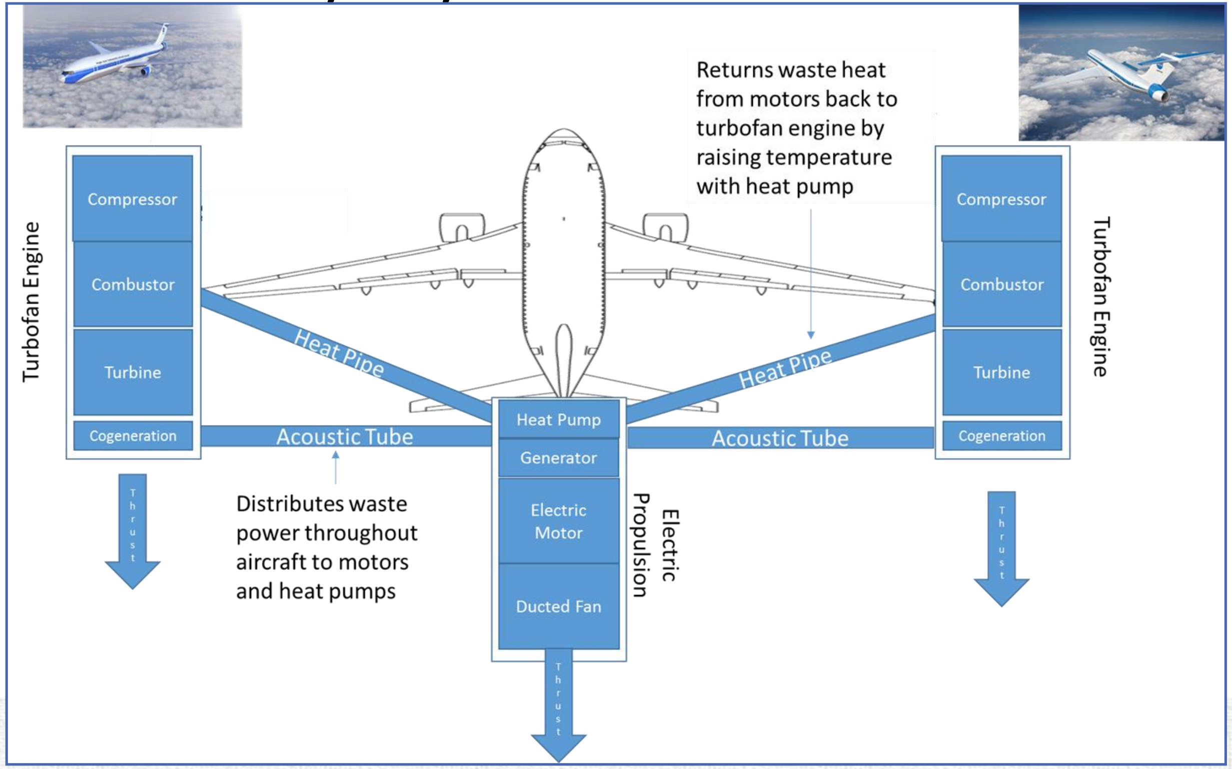


Solid-state Heat Transfer Switching

Can control where the heat goes with solid-state no moving parts

.. lighting the way to a brighter future

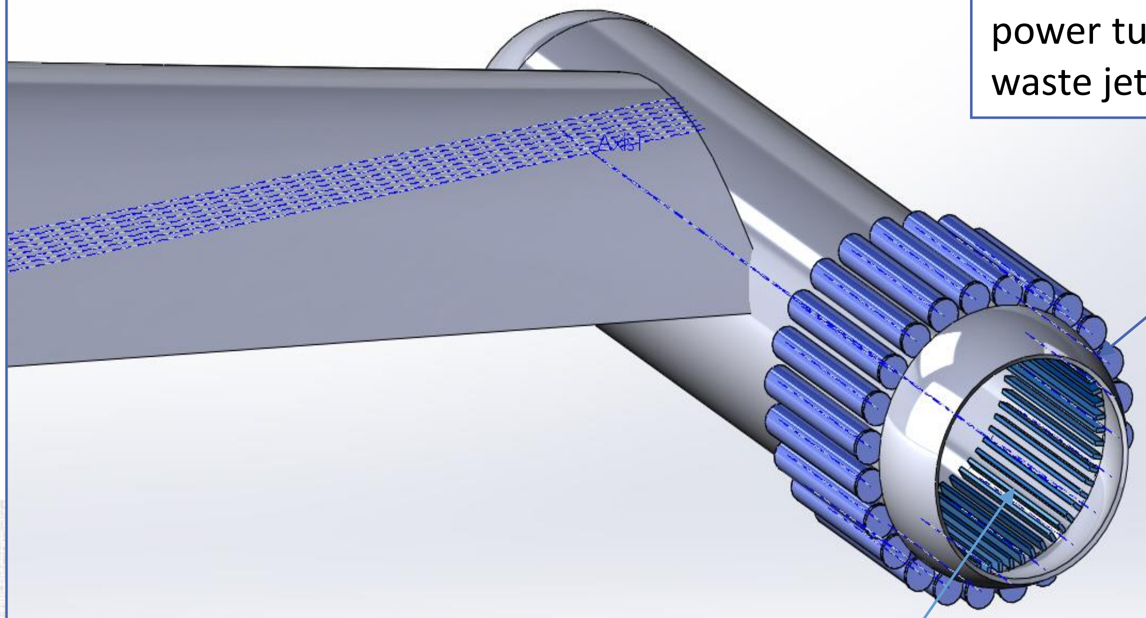
TREES Heat Recovery Cycle – LEW-19353-1



A thermal management system for an aircraft is provided that includes thermo-acoustic engines that remove and capture waste heat from the aircraft engines, heat pumps powered by the acoustic waves generated from the waste heat that remove and capture electrical component waste heat from electrical components in the aircraft, and hollow tubes disposed in the aircraft configured to propagate mechanical energy to locations throughout the aircraft and to transfer the electrical component waste heat back to the aircraft engines to reduce overall aircraft mass and improve propulsive efficiency.

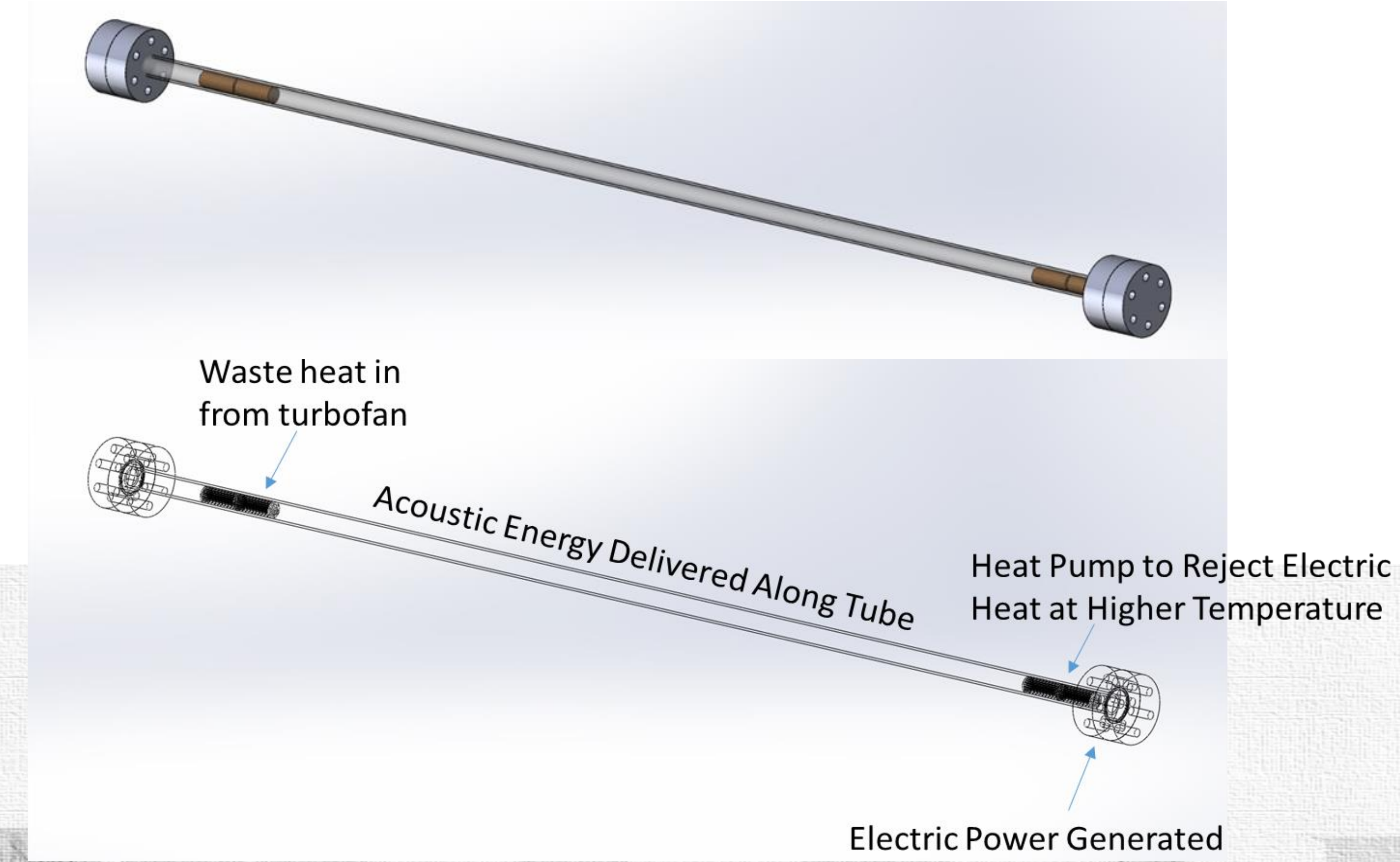
Turbine Exit Waste Heat Extraction Installation

Use multiple independent flight-weight no moving part thermo-acoustic power tubes to generate acoustic waves from waste jet exhaust heat



Remove waste heat from turbine exhaust with OGV fins located parallel to exhaust flow for flow straightening and high heat transfer rate.

Example Wave Generation, Acoustic Tube, and Heat Pump as One Unit



Note the power generation, distribution, and heat pump tube can be any length and curved to fit within aircraft. Electric power or cooling can be delivered anywhere in the aircraft without power conductors.

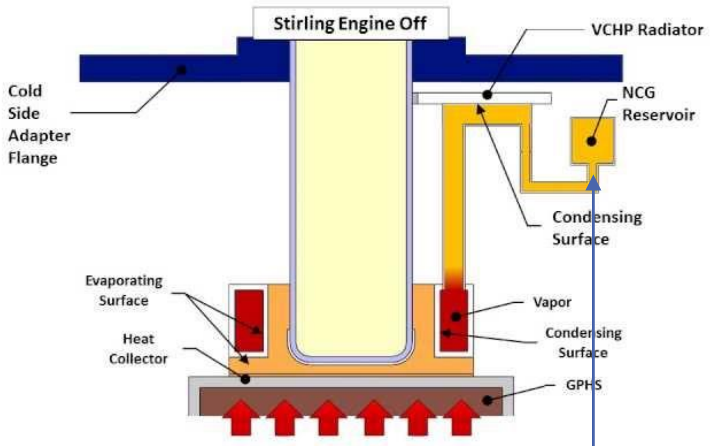
Example Variable Conductance Heat Pipe

Solid-state heat flow control to heat pump and combustor

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

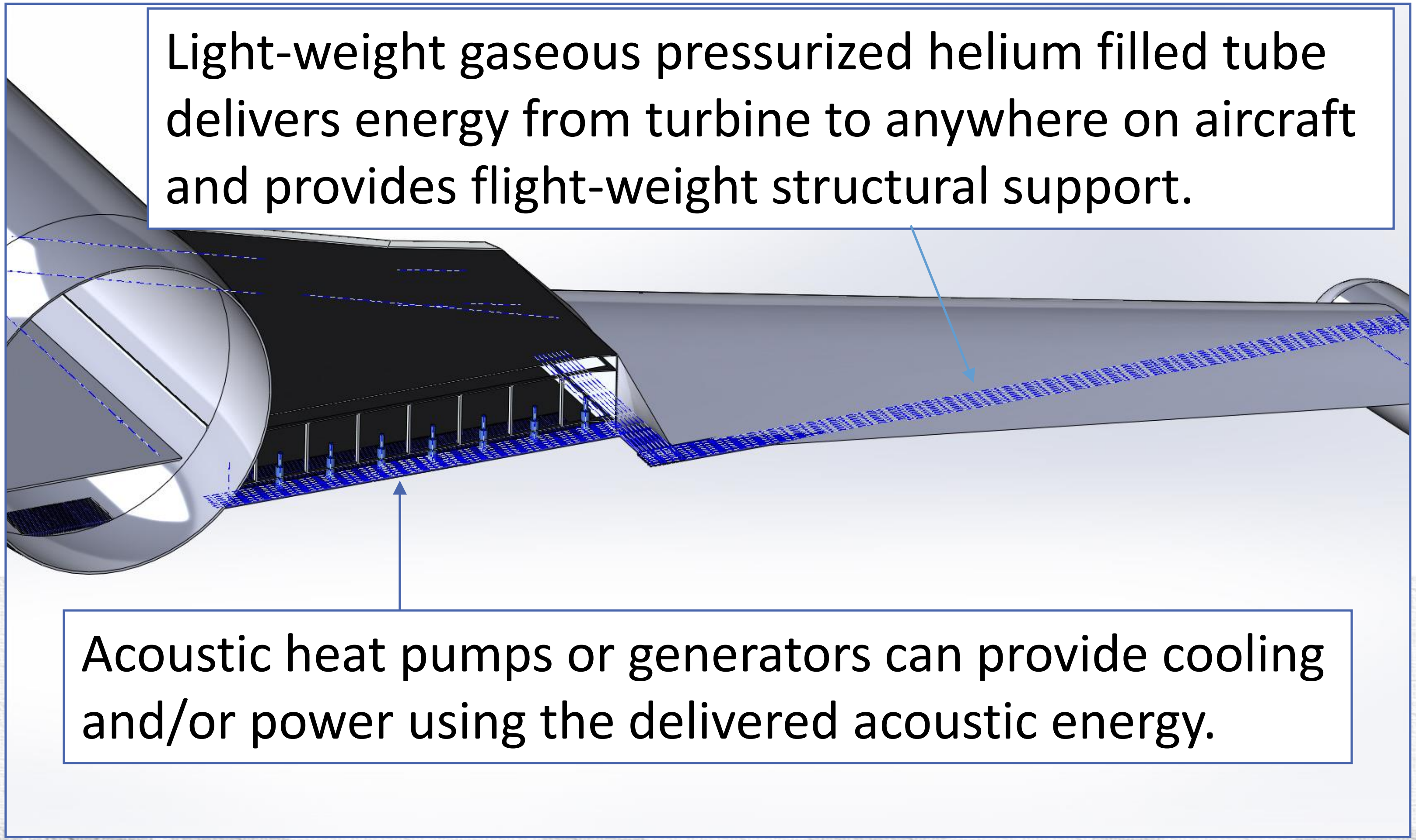
- Localized skin heating for active lift/drag management, de-icing, powertrain cooling, cabin management, and military cloaking

VCHP for Stirling



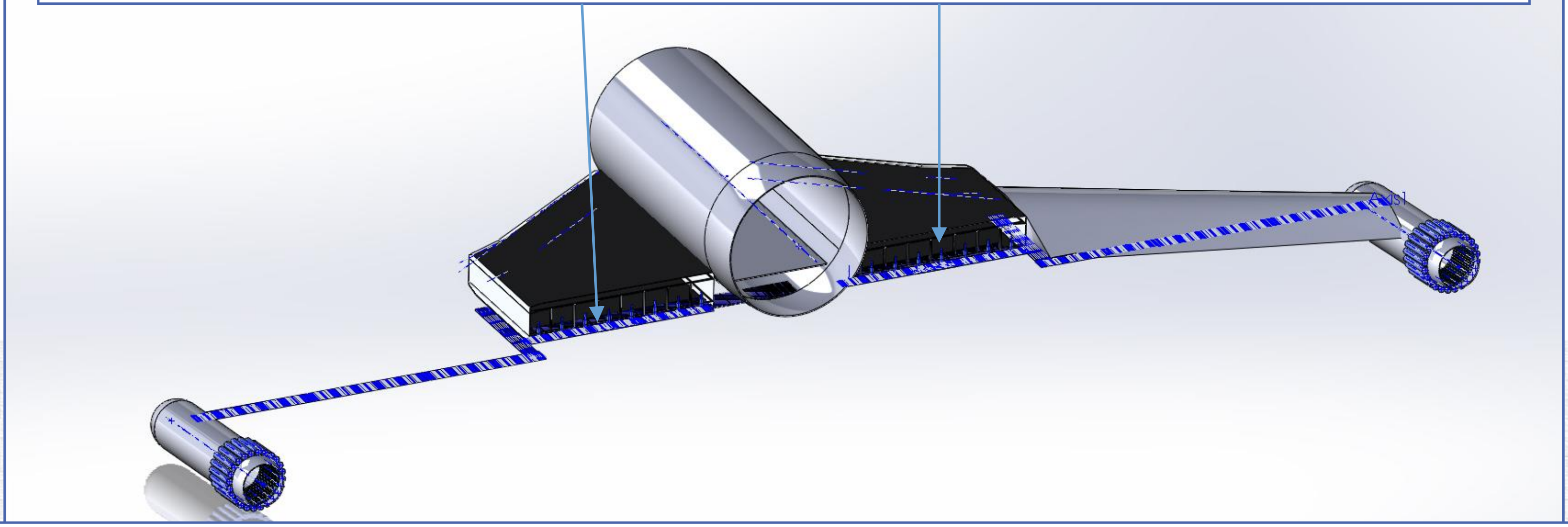
Simple transistor control of heat flow path

Energy transport with ducted acoustic wave



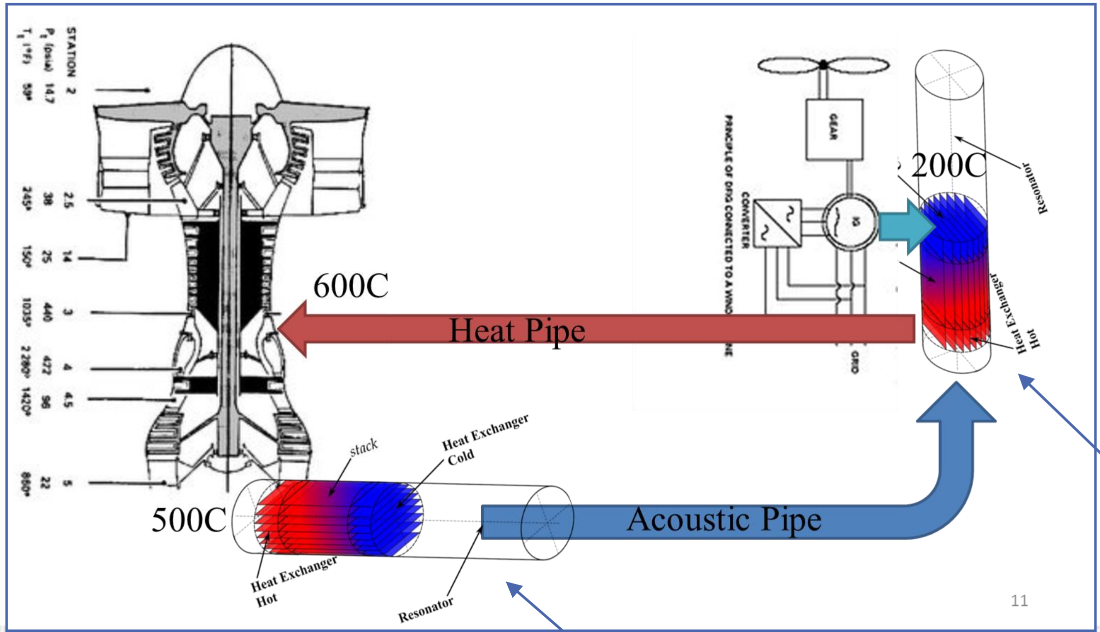
Component Cooling or Power Generation

Heat generated from electric motors is conductively removed and rejected to external fins or temperature boosted and the heat is returned to turbofan for cycle efficiency improvement.



Overall system is flight-weight, efficient, structural, flexible, maintenance-free, and has no hot moving parts while enabling full vehicle heat rejection through nozzle.

Heat Recycling and Nozzle Rejection



All waste heat recycled and rejected out nozzle.

Similar technology for spacecraft because of the reliability, specific power, efficiency, and no maintenance. Only technology option that has no hot moving parts, 52% Carnot WHR power efficiency and 44% Carnot heat pump efficiency, and is bi-directional in that it can both generate its own power and act as a heat pump all in a single contiguous hollow tube that can easily be distributed throughout the aircraft with minimal mass. The key is to optimize the system as a traveling wave device and the tools for doing that have only recently become available.

Net System Cycle Benefit (1.6% - 16%)

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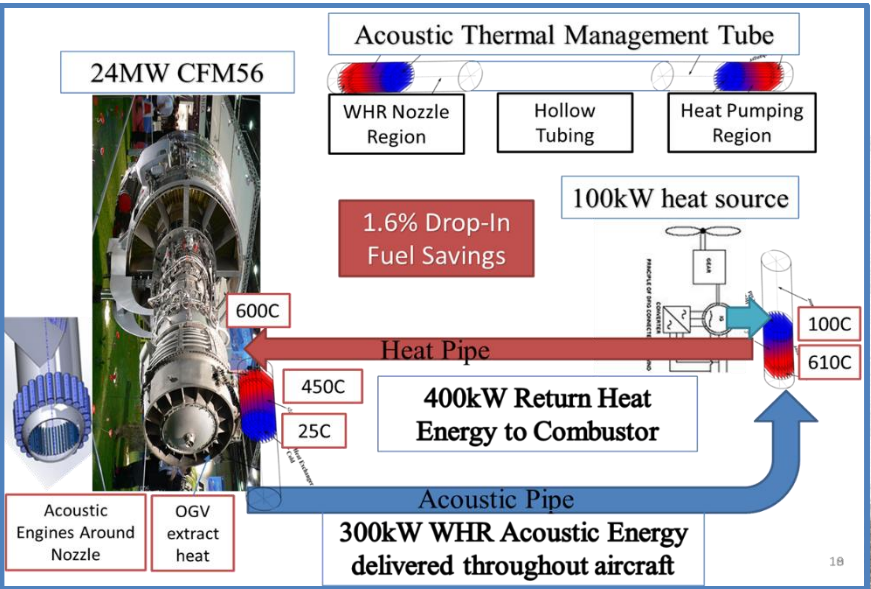
Example idealized net benefit calculation (16% fuel savings):

- 24MW thrust for Boeing 737 using a pair of CFM56 engines operating at 50% efficiency produce ~12MW of waste heat at 450C out the nozzle with 25C by-pass fan air surrounding it
  - 52% of Carnot Efficiency for WHR, approximately 4MW of mechanical acoustic energy available
- 1MW of low-grade 100C distributed heat sources throughout the insulated composite aircraft requires ~3MW of mechanical input to raise to 600C
  - 44% of Carnot Efficiency for heat pump, heat pipes return the 600C 4MW of energy to combustor

Best case idealized scenario achieves fuel savings of 16% while providing a flight-weight method for managing the aircraft's heat sources without adding aircraft drag and weight. All heat is used in the most optimal way and ultimately rejected out the nozzle instead of through the aircraft body.



Drop-in Solution with Conservative Assumptions (1.6% fuel savings):
Note that the outlet guide vanes as currently installed in the CFM56 could act as WHR fins extracting about 10% of the nozzle waste heat so that 100kW of low-grade distributed 100C aircraft heat sources could be returned to the combustor as 400kW, 600C useful heat resulting in a potential fuel savings of 1.6%. **This changes aircraft thermal management from being a burden on aircraft performance to an asset.**

Conclusion

TREES changes aircraft thermal management from being a necessary burden on aircraft performance to a desirable asset. It improves the engine performance by recycling waste heat and ultimately rejecting all collected aircraft heat out through the engine nozzle.

- **Key Features Include:**
  - Turbofan waste heat is used to generate ducted acoustic waves that then drive distributed acoustic heat pumps and/or generate power.
  - Low grade powertrain waste heat is converted into high grade recycled heat and returned to the engine combustor via heat pipes
  - Pressurized acoustic and heat pipe tubes can be directly integrated into the airframe to provide structure support with mass reduction.
  - Fuel savings of 16% are estimated with a purpose-built system
  - All aircraft heat is rejected through engine nozzle
  - Non-provisional Patent Filed With Priority Date November 6, 2015.