NASA Acoustic Stirling IRAD

Thermal Recovery Energy Efficient System (TREES)
Energy Conversion and Management in Aircraft

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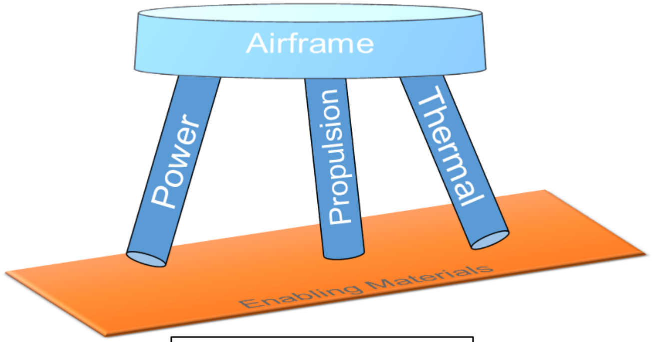
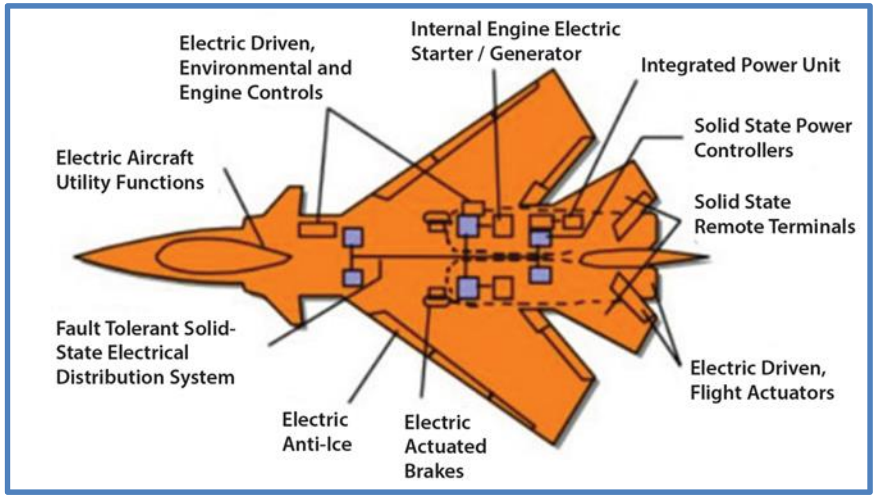
Motivation

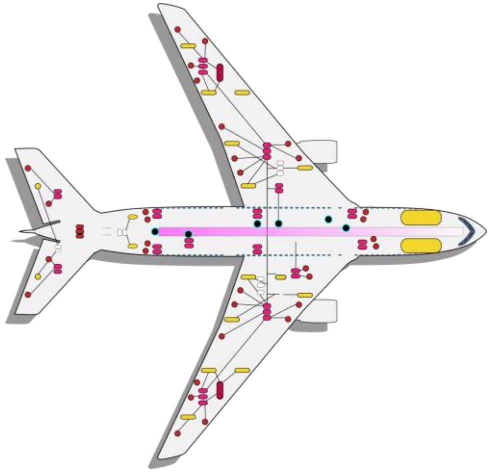
Low Grade Waste Heat Produced Throughout Insulated Aircraft

- 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

Current proposed solutions include:

☐ Ram air HX
  - adds weight and aircraft drag

☐ Convective skin cooling HX
  - adds weight, drag, and inefficient

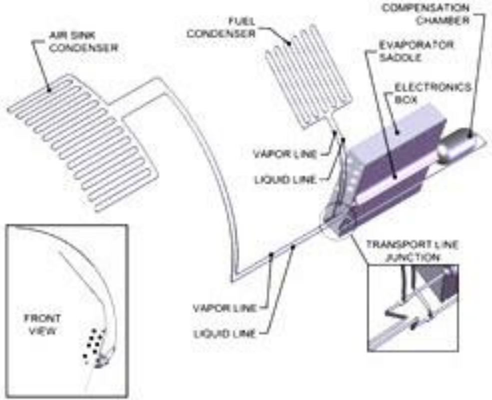
☐ Dumping heat into fuel
  - limited thermal capacity

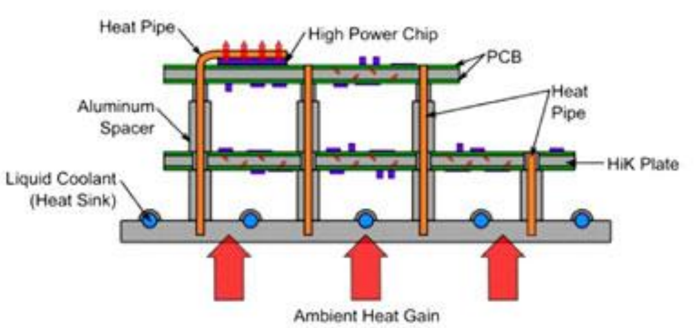
☐ Dumping heat into lubricating oil
  - limited thermal capacity

☐ 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

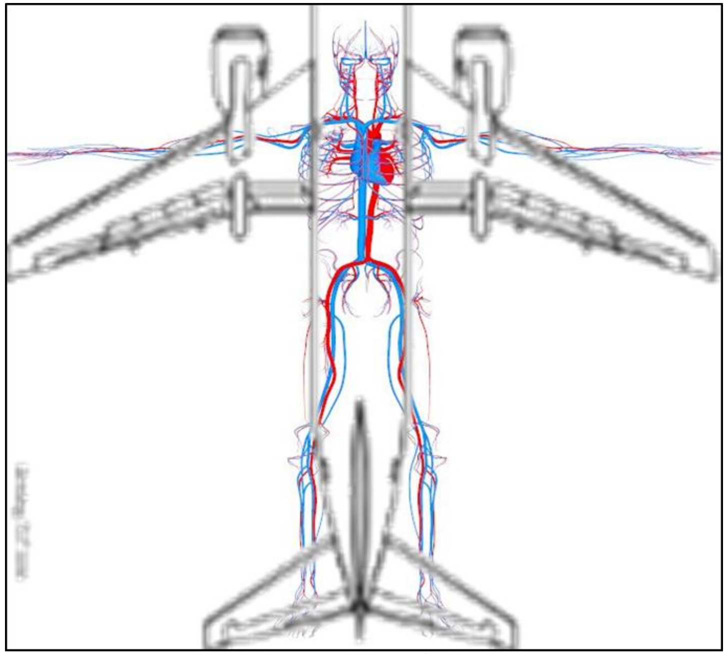




Aero-vascular Energy Management

Thermal management comparison of human and aircraft

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



Human body circulatory system as model for aircraft

Three Key Points:

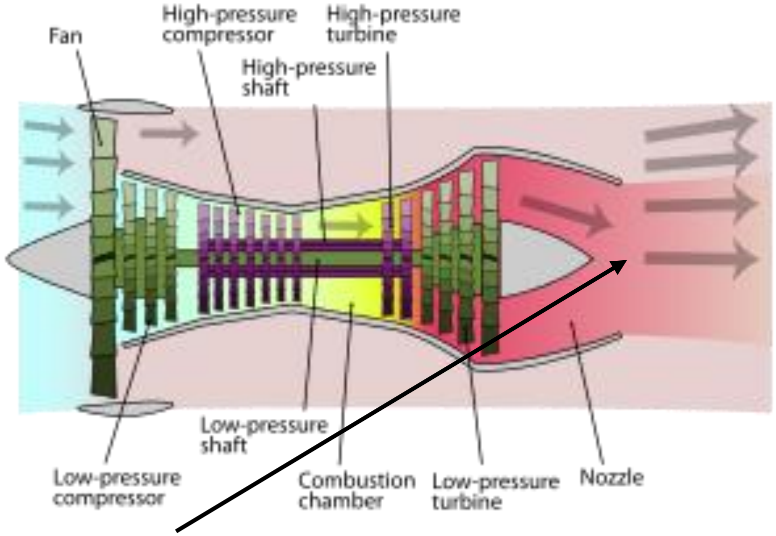
1. Recycle waste energy with heat pumping powered with core waste energy
2. Additive manufactured airframe enables sophisticated heat transport
3. Solid-state thermal control allows transporting energy with no moving parts

Basic Principles

- Extract waste energy from turbofan core exhaust and/or SOFC 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 or additional acoustic tubes.

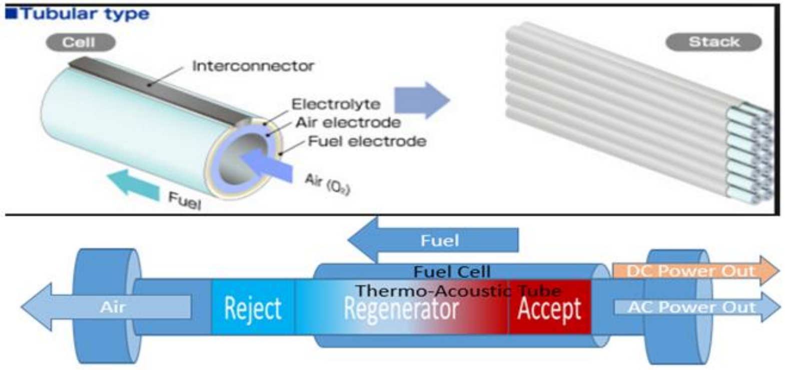
Heat Energy Extraction

- 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

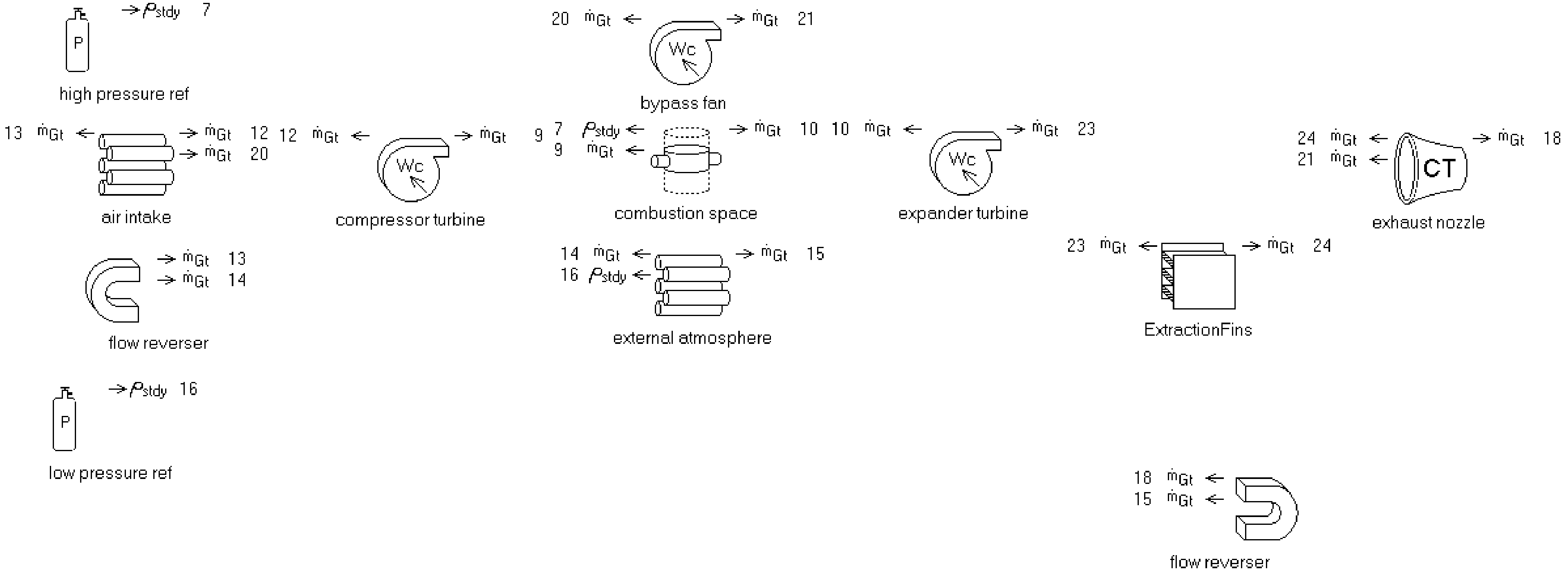


- Also can extra waste energy from inside fuel cell

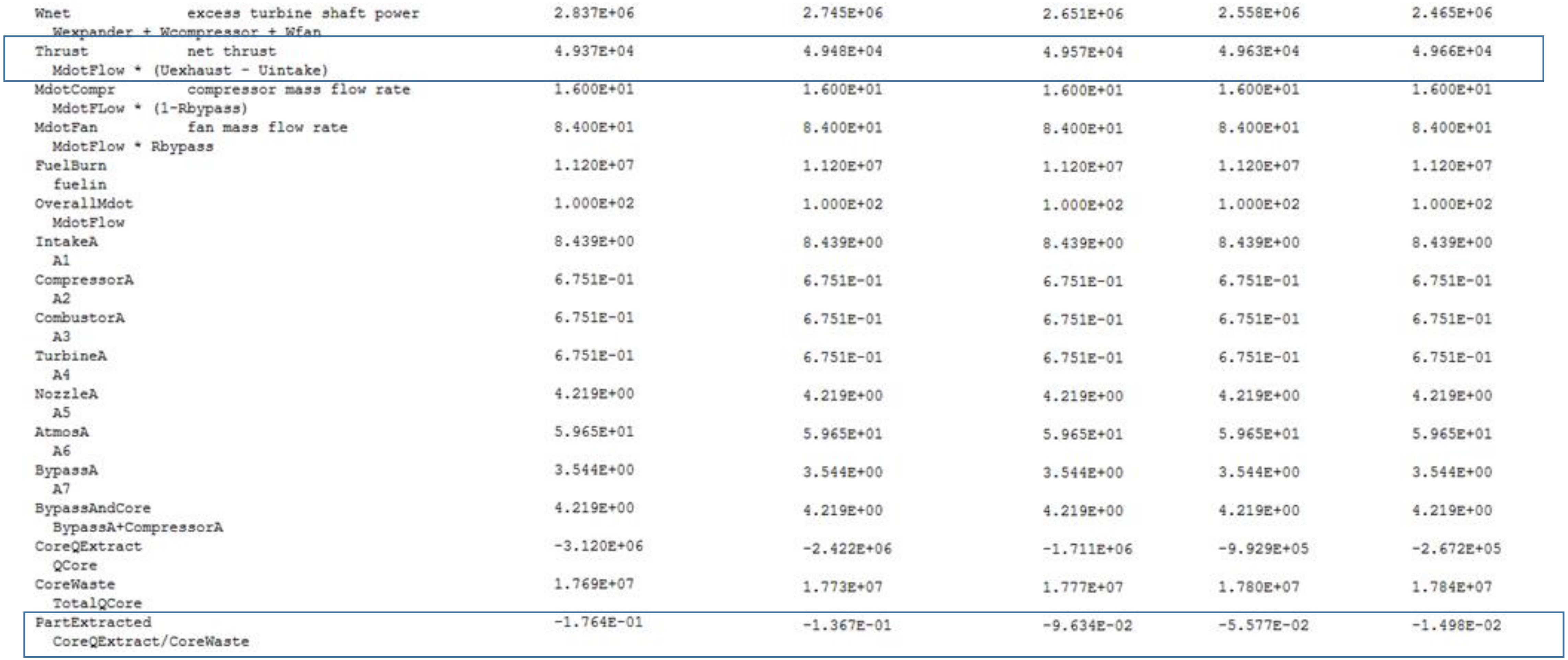
Turbo-Acoustic Fuel Cell



Basic Turbofan Model with Core Extraction



Thrust VS. Core Extraction



```
Wnet             excess turbine shaft power      2.837E+06    2.745E+06    2.651E+06    2.558E+06    2.465E+06
  Wexpander + Wcompressor + Wfan
Thrust           net thrust                      4.937E+04    4.948E+04    4.957E+04    4.963E+04    4.966E+04
  MdotFlow * (Uexhaust - Uintake)
MdotCompr        compressor mass flow rate       1.600E+01    1.600E+01    1.600E+01    1.600E+01    1.600E+01
  MdotFLow * (1-Rbypass)
MdotFan          fan mass flow rate              8.400E+01    8.400E+01    8.400E+01    8.400E+01    8.400E+01
  MdotFlow * Rbypass
FuelBurn                                         1.120E+07    1.120E+07    1.120E+07    1.120E+07    1.120E+07
  fuelin
OverallMdot                                      1.000E+02    1.000E+02    1.000E+02    1.000E+02    1.000E+02
  MdotFlow
IntakeA                                          8.439E+00    8.439E+00    8.439E+00    8.439E+00    8.439E+00
  A1
CompressorA                                      6.751E-01    6.751E-01    6.751E-01    6.751E-01    6.751E-01
  A2
CombustorA                                       6.751E-01    6.751E-01    6.751E-01    6.751E-01    6.751E-01
  A3
TurbineA                                         6.751E-01    6.751E-01    6.751E-01    6.751E-01    6.751E-01
  A4
NozzleA                                          4.219E+00    4.219E+00    4.219E+00    4.219E+00    4.219E+00
  A5
AtmosA                                           5.965E+01    5.965E+01    5.965E+01    5.965E+01    5.965E+01
  A6
BypassA                                          3.544E+00    3.544E+00    3.544E+00    3.544E+00    3.544E+00
  A7
BypassAndCore                                    4.219E+00    4.219E+00    4.219E+00    4.219E+00    4.219E+00
  BypassA+CompressorA
CoreQExtract                                    -3.120E+06   -2.422E+06   -1.711E+06   -9.929E+05   -2.672E+05
  QCore
CoreWaste                                        1.769E+07    1.773E+07    1.777E+07    1.780E+07    1.784E+07
  TotalQCore
PartExtracted                                   -1.764E-01   -1.367E-01   -9.634E-02   -5.577E-02   -1.498E-02
  CoreQExtract/CoreWaste
```

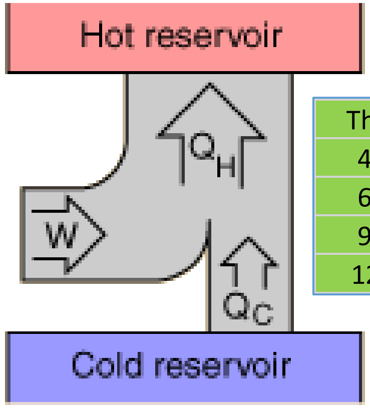
In this example, extracting 17.6% of the core enthalpy (3MW) only reduced thrust 0.5%
And in fully turboelectric or SOFC applications no thrust is impacted.

Heat Pumping

Makes more electric parts and powertrain effectively 100% efficient

All airframe waste is now useful

Free Acoustic Mechanical
Work Input

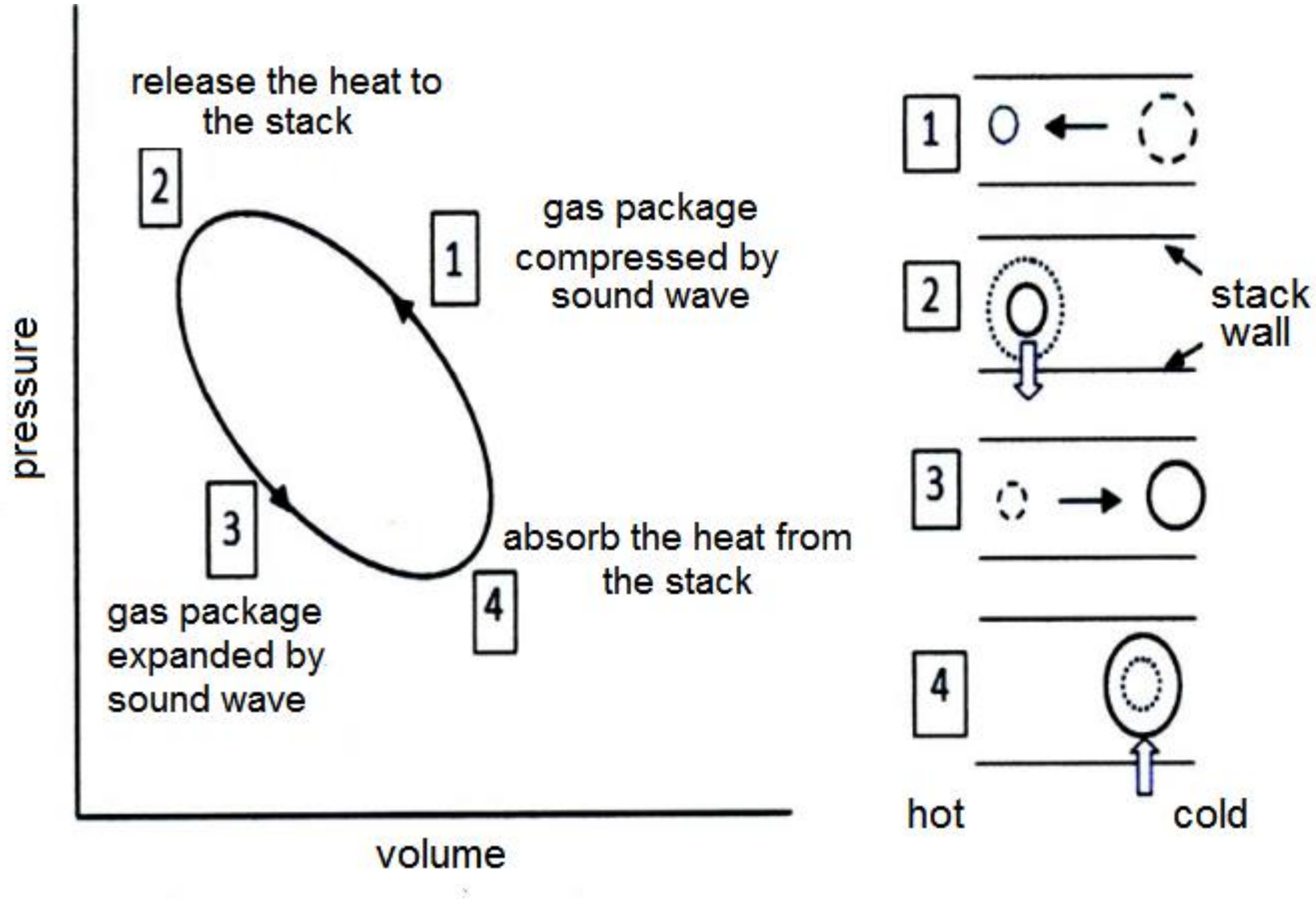


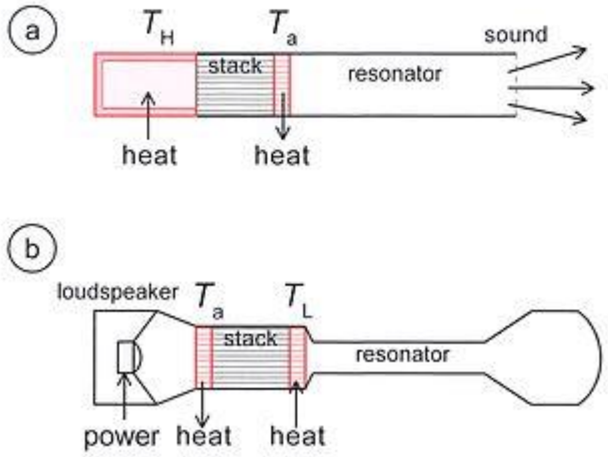
Th (K)	Tc (K)	Th/(Th-Tc)	Qout (W)	WorkIn (W)	Qin (W)
400	300	4	1000	250	750
600	300	2	1000	500	500
900	300	1.5	1000	666.66667	333.3333
1200	300	1.333333	1000	750	250

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

Cryogenic
Option
2000Win for
50W@50K

Acoustic Heat Pump





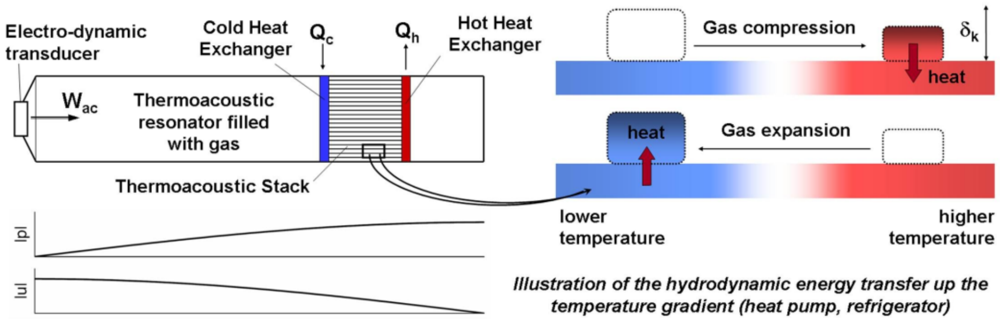
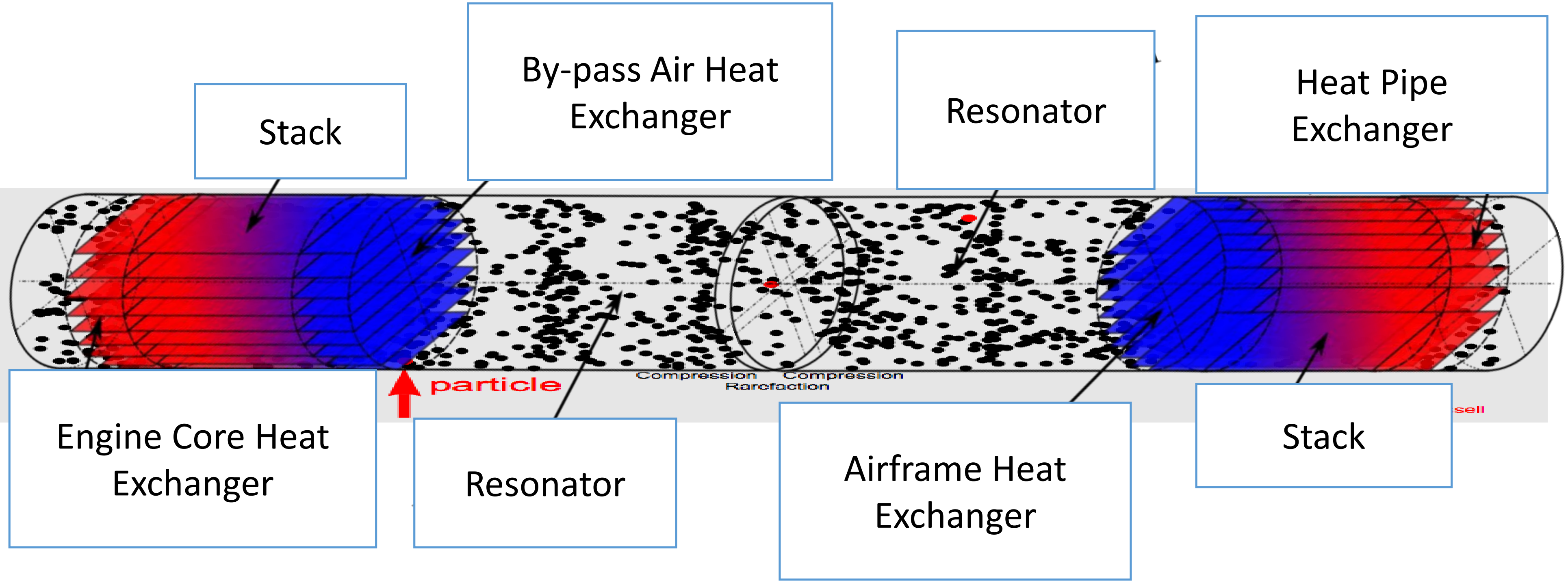


Illustration of the hydrodynamic energy transfer up the temperature gradient (heat pump, refrigerator)

Traveling Energy Wave Basic Principles – Air Molecules Oscillate



Stack

By-pass Air Heat Exchanger

Resonator

Heat Pipe Exchanger

Engine Core Heat Exchanger

Resonator

Airframe Heat Exchanger

Stack

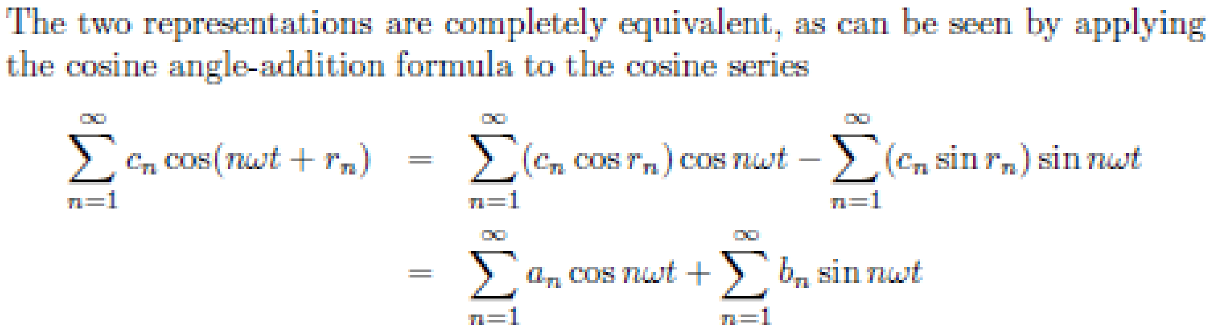
Basic principle is to use aircraft engine waste heat to produce a high intensity acoustic wave with no hot moving parts that can be used for power generation or component cooling. The temperature gradient between hot and cold HX efficiently creates the acoustic waves. All energy is delivered through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

Are there any simple (or complex) equations for estimating the weight and volume requirements relative to the heat conversion to acoustic energy?

- Basic relationship is 30% of the heat input is converted to acoustic energy
- Primary heat transfer limit is surface area but roughly 12kW per 2 inch length of 2” diameter tube with appropriate fin structure
- Interior copper HX is drilled copper with 90% porosity so estimate per 12kW heat input is a copper mass of (400 g per 12 kW heat input (4 copper HX)) and this will provide 4kW acoustic energy to lift 1kW low grade heat (300K) to provide 5kW of high grade heat at (900K).

What are the pressure and duct size relationship to acoustic/thermal energy transfer?

- Pressure = Pm+ Apc * Cos(omega * t) + Aps * Sin (omega * t) [Pa]
- Mass flow rate = Mm+ Amc * Cos(omega * t) + Ams * Sin(omega * t) [kg/s]
- Acoustic Power = 0.5 * (Apc * Amc + Aps * Ams)/Rho
- Rho = Gas density
- Mass flow rate = Rho U A
- Volume Flow Rate = U A



The two representations are completely equivalent, as can be seen by applying the cosine angle-addition formula to the cosine series

$$\begin{aligned}\sum_{n=1}^{\infty} c_n \cos(n\omega t + r_n) &= \sum_{n=1}^{\infty}(c_n \cos r_n)\cos n\omega t - \sum_{n=1}^{\infty}(c_n \sin r_n)\sin n\omega t \\ &= \sum_{n=1}^{\infty} a_n \cos n\omega t + \sum_{n=1}^{\infty} b_n \sin n\omega t\end{aligned}$$

Note pressure and volume flow rate are oscillating – maximizing pressure swing amplitude and frequency increases specific power

Does acoustic energy flow suffer frictional type pressure drop, similar to a fluid pressure drop?

- Very specific example for simple 7 m length tube:
  - 32kW Incoming acoustic wave in a 4.72 cm diameter tube will see a 26% power drop after 7 m of travel. Mean pressure is 3 Mpa and 84 Hz. This is not optimized. Can recover using narrowing tube approach described in page 9 and ref. 4. But gives an idea of potential losses with simple non-tapered very narrow tubes (about 1% per foot).

- And the main point is this acoustic energy is free from the jet core

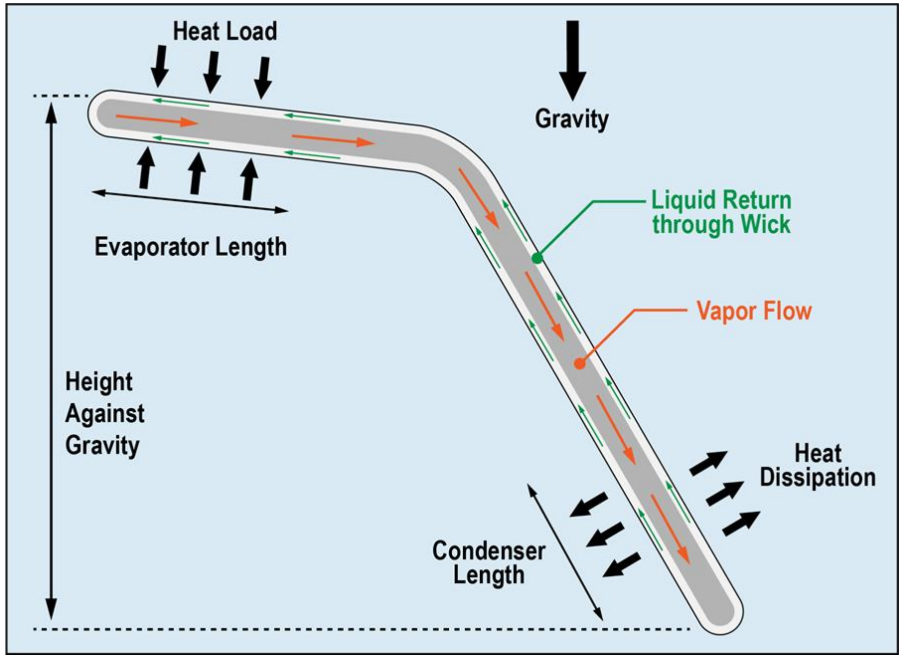
Acoustic Recycling Enables Effectively 100% Efficient Flight-Weight Powertrain Since Waste Energy is Reused

- Cold copper 10X more conductive at 50K,
- Enables lower voltage, increase specific power, effectively 100% efficient power electronics, cable, motor, protections, actuators, etc.
- Additively manufactured into airframe enables use of reliable less efficient, flight-weight components for more electric and future electric propulsion

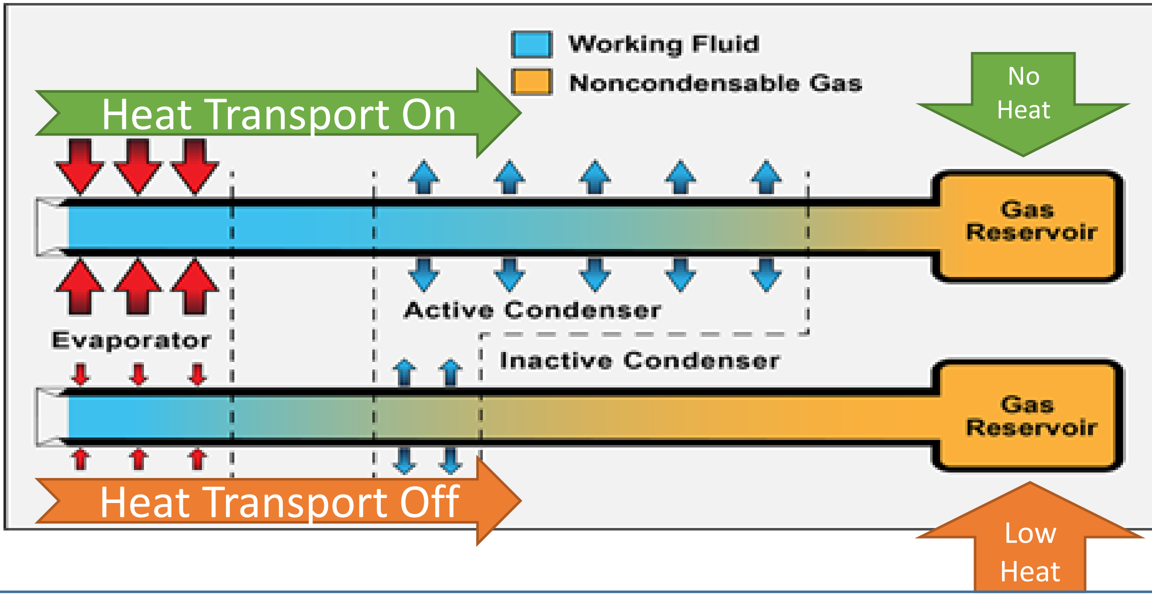
Solid-state Heat Transfer Switching and Distribution

Acoustic Energy Control Method

Heat Energy Control Method



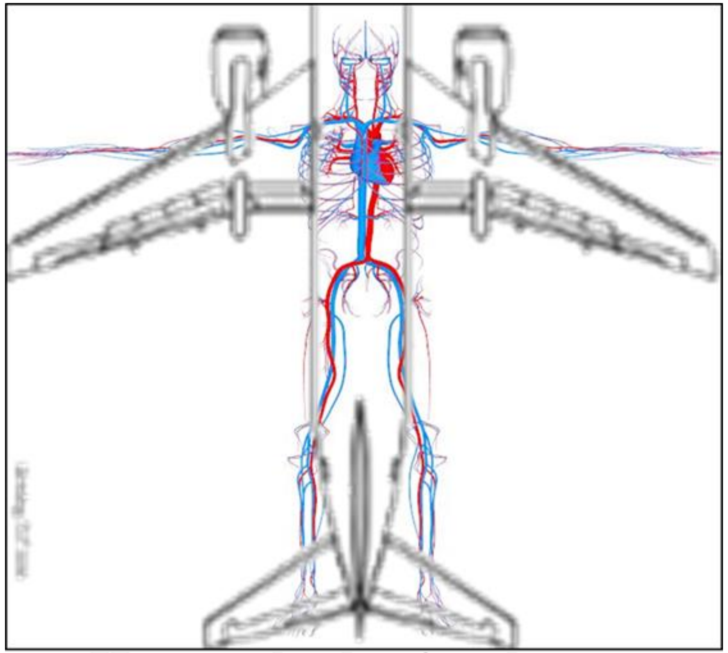
Solid-state Heat Transfer Distribution with Variable Conductance Heat Pipes



Can control where the heat goes with solid-state no moving parts via acoustic waves and/or variable conductance heat pipes

Benefits of recycled heat pumping

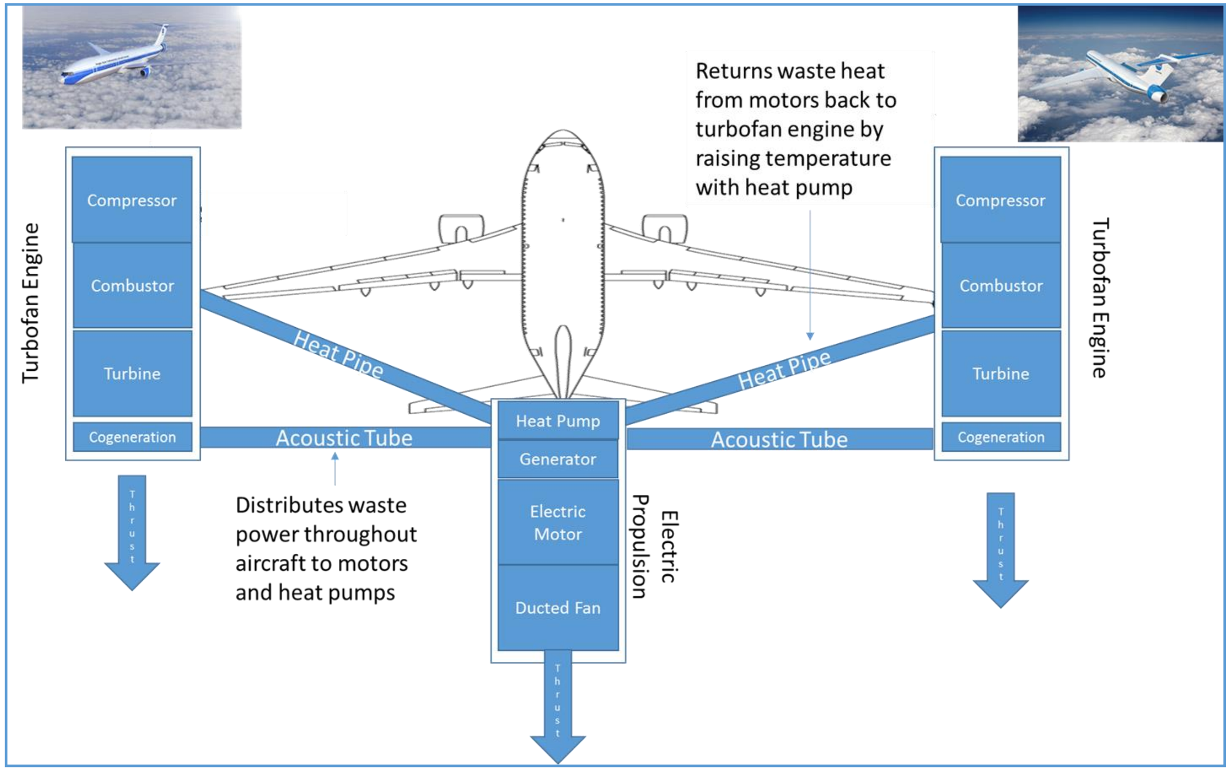
Solid-state (no moving part) energy recycle and distribution
- localized skin heating
  - for active lift/drag management,
- de-icing/anti-icing,
- powertrain cooling,
- cabin thermal management,
- engine recuperation,
- thrust enhancement in by-pass air
- military cloaking with thermal skin temperature shifting



Human body circulatory system as model for aircraft

Simple solid-state control of heat flow distribution

TREES Heat Recovery Cycle – LEW-19353-1

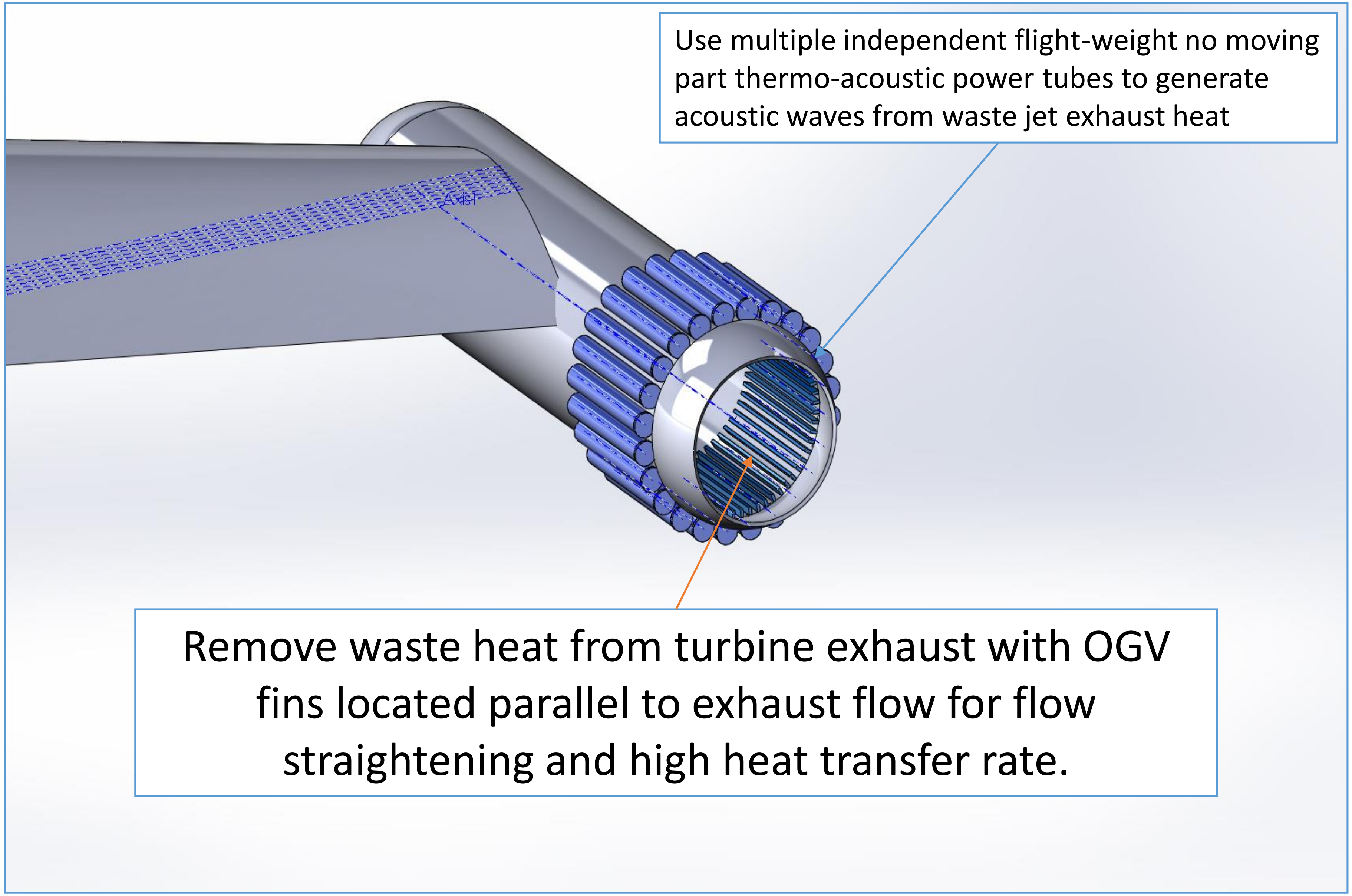


Returns waste heat from motors back to turbofan engine by raising temperature with heat pump

Distributes waste power throughout aircraft to motors and heat pumps

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.

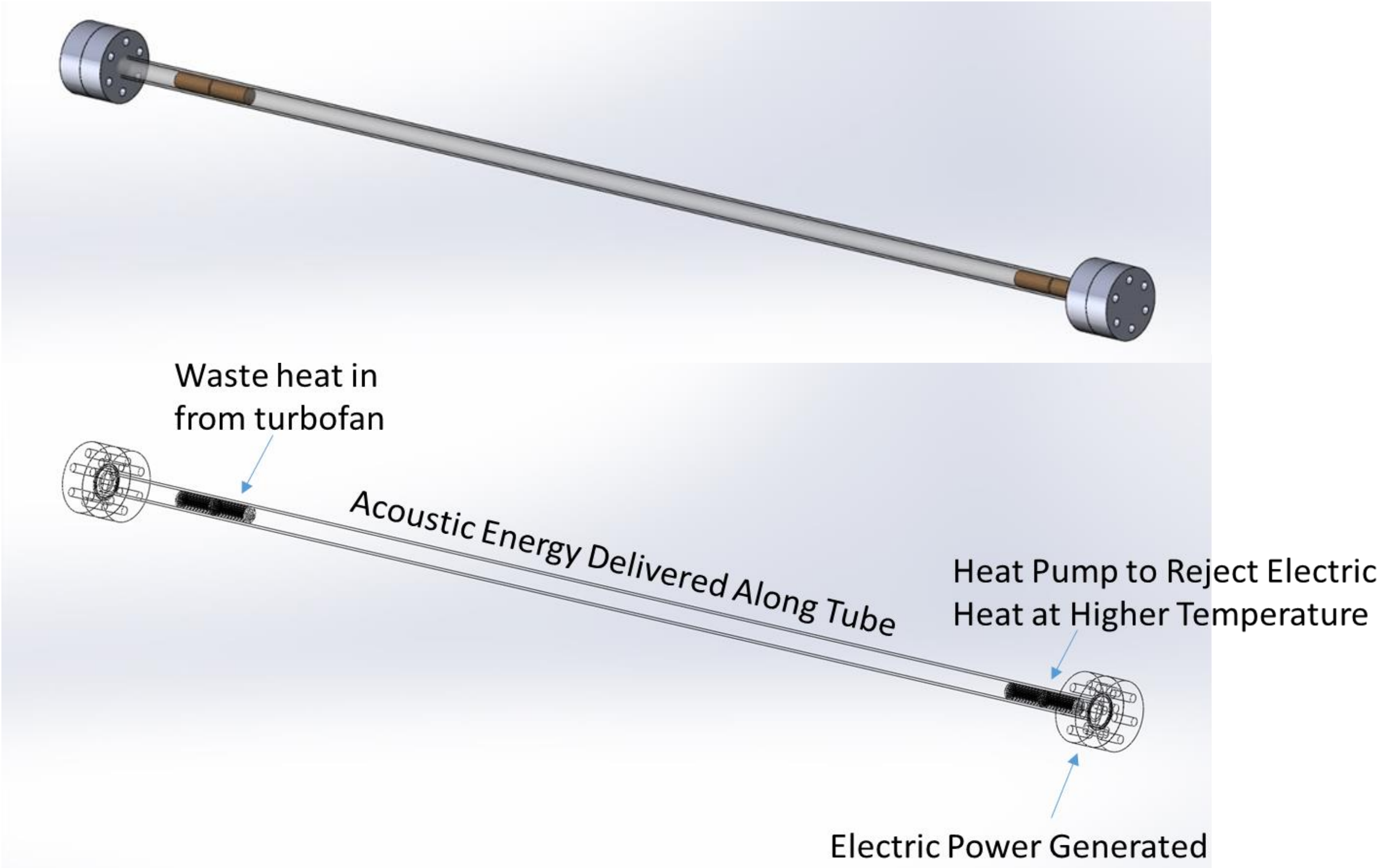
Turbine Exit Waste Heat Extraction Installation



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



Waste heat in
from turbofan

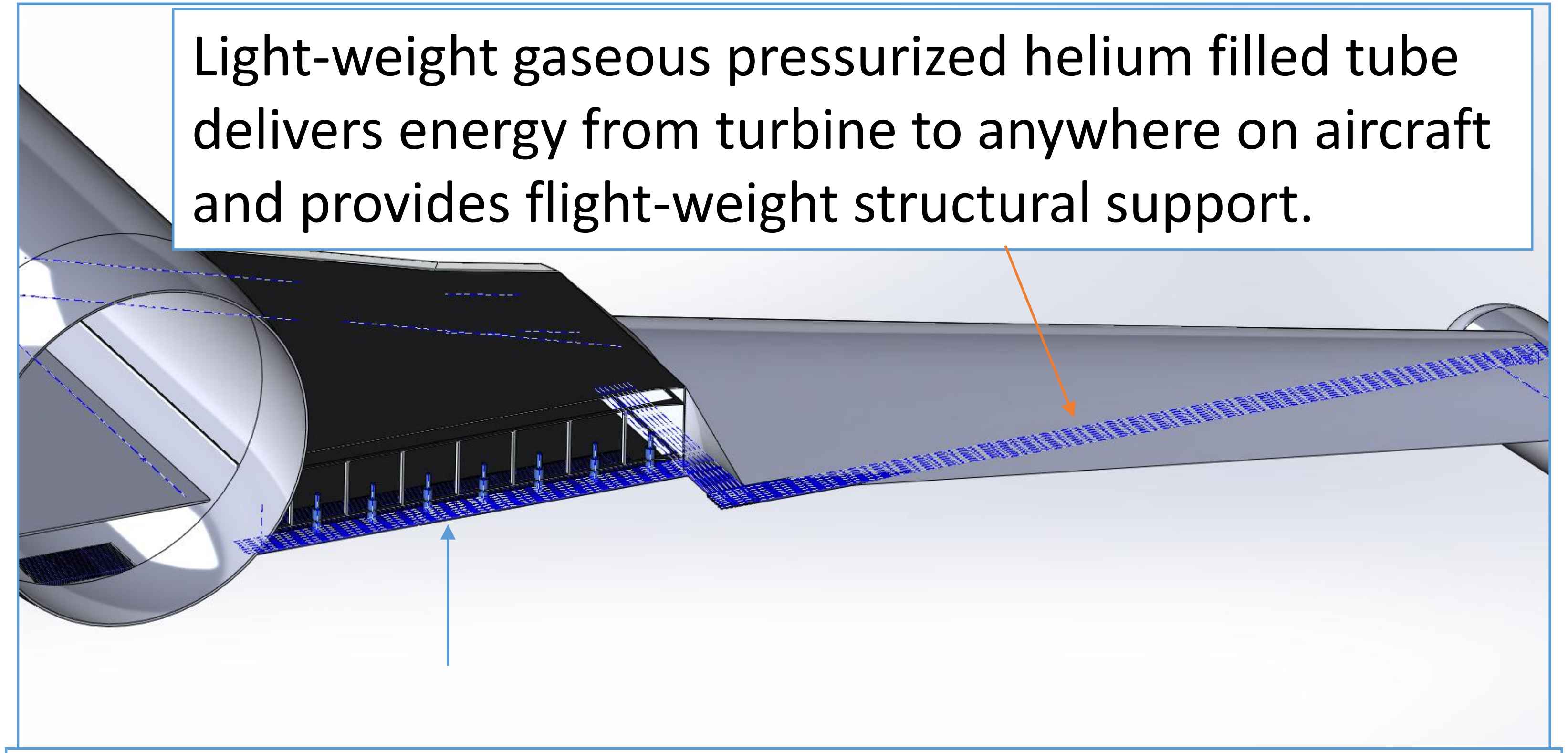
Acoustic Energy Delivered Along Tube

Heat Pump to Reject Electric
Heat at Higher Temperature

Electric Power Generated

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.

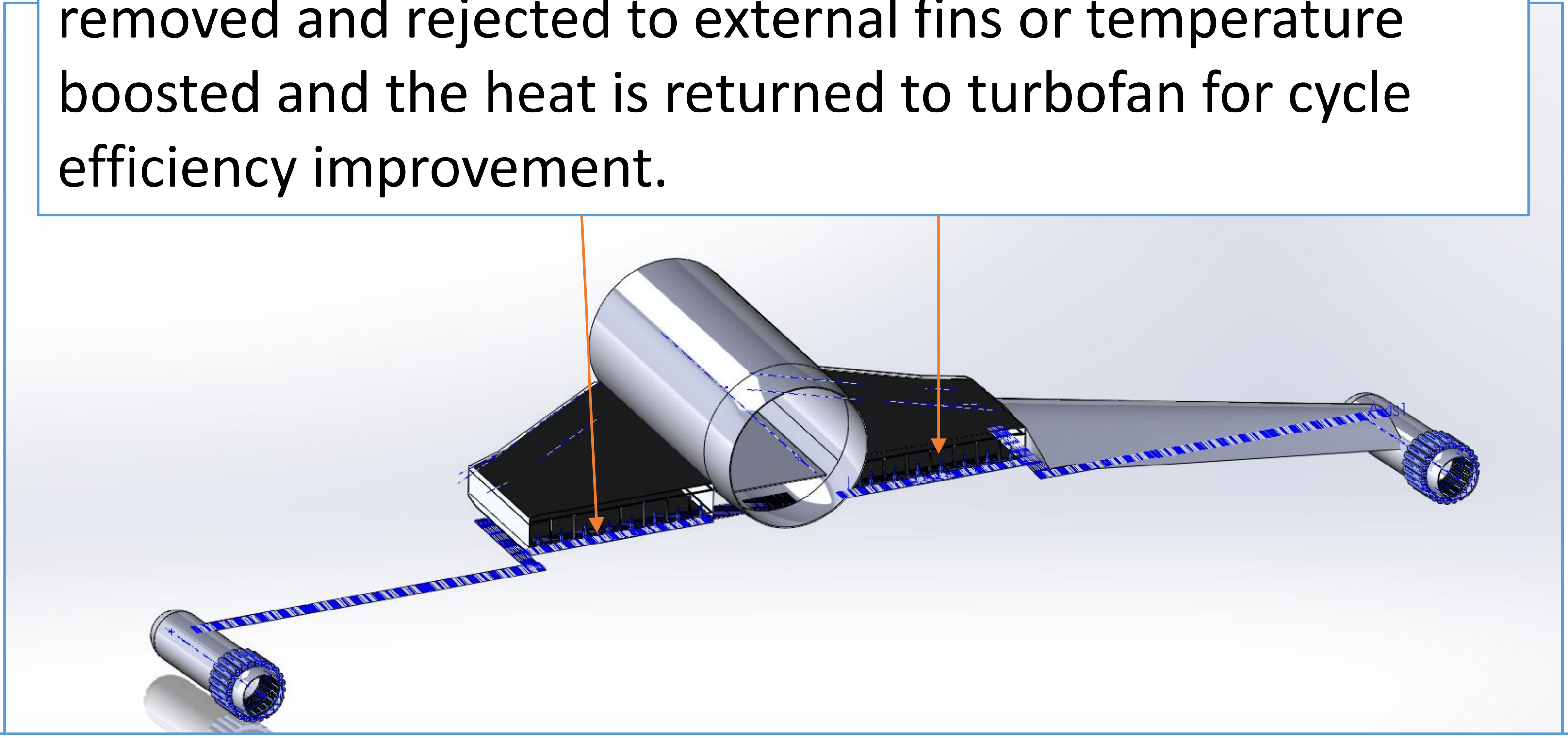
Energy transport with ducted acoustic wave



Light-weight gaseous pressurized helium filled tube delivers energy from turbine to anywhere on aircraft and provides flight-weight structural support.

Acoustic heat pumps or generators can provide cooling and/or power using the delivered acoustic energy.

Component Cooling or Power Generation

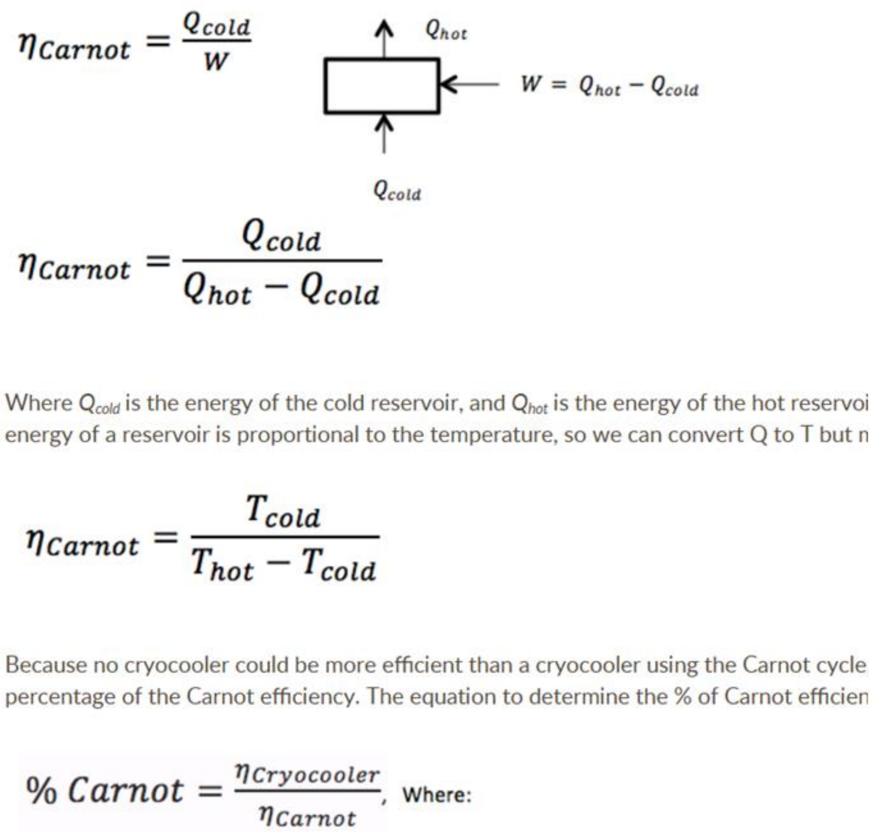


Heat generated from electric motors is conductively removed and rejected to external fins or temperature boosted and the heat is returned to turbofan for cycle efficiency improvement.

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

What percentage of the Carnot cycle efficiency are you seeing in lab testing?

- 52% of Carnot cycle efficiency in converting 850C heat input to mechanical acoustic energy output
- And for converting mechanical acoustic energy to high grade heat flux it depends on heat load:



$$\eta_{Carnot} = \frac{Q_{cold}}{W}$$

Q_{hot}

$W = Q_{hot} - Q_{cold}$

Q_{cold}

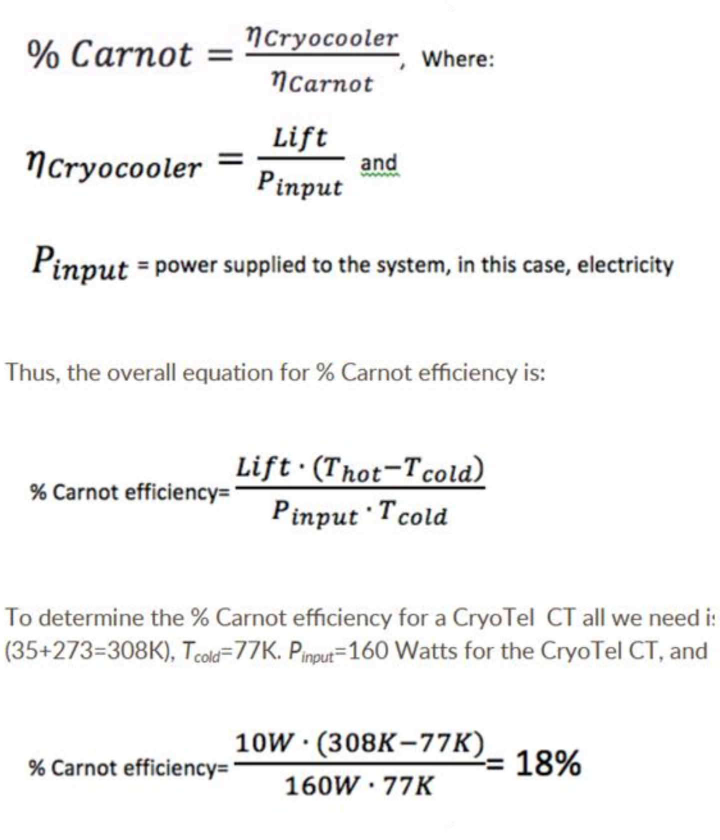
$$\eta_{Carnot} = \frac{Q_{cold}}{Q_{hot} - Q_{cold}}$$

Where Q_{cold} is the energy of the cold reservoir, and Q_{hot} is the energy of the hot reservoi
energy of a reservoir is proportional to the temperature, so we can convert Q to T but n

$$\eta_{Carnot} = \frac{T_{cold}}{T_{hot} - T_{cold}}$$

Because no cryocooler could be more efficient than a cryocooler using the Carnot cycle
percentage of the Carnot efficiency. The equation to determine the % of Carnot efficien

$$\% \; Carnot = \frac{\eta_{Cryocooler}}{\eta_{Carnot}},$$ Where:



$$\% \; Carnot = \frac{\eta_{Cryocooler}}{\eta_{Carnot}},$$ Where:

$$\eta_{Cryocooler} = \frac{Lift}{P_{input}}$$ and

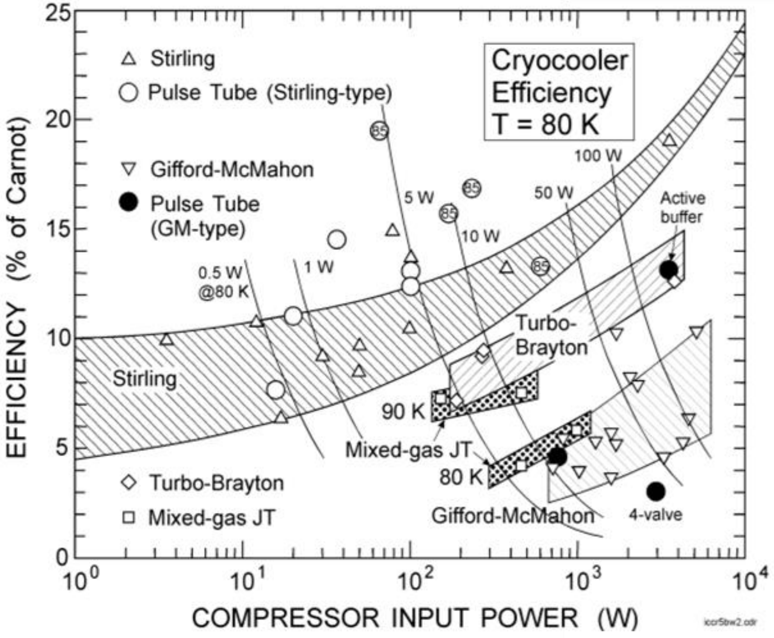
P_{input} = power supplied to the system, in this case, electricity

Thus, the overall equation for % Carnot efficiency is:

$$\text{\% Carnot efficiency} = \frac{Lift \cdot (T_{hot} - T_{cold})}{P_{input} \cdot T_{cold}}$$

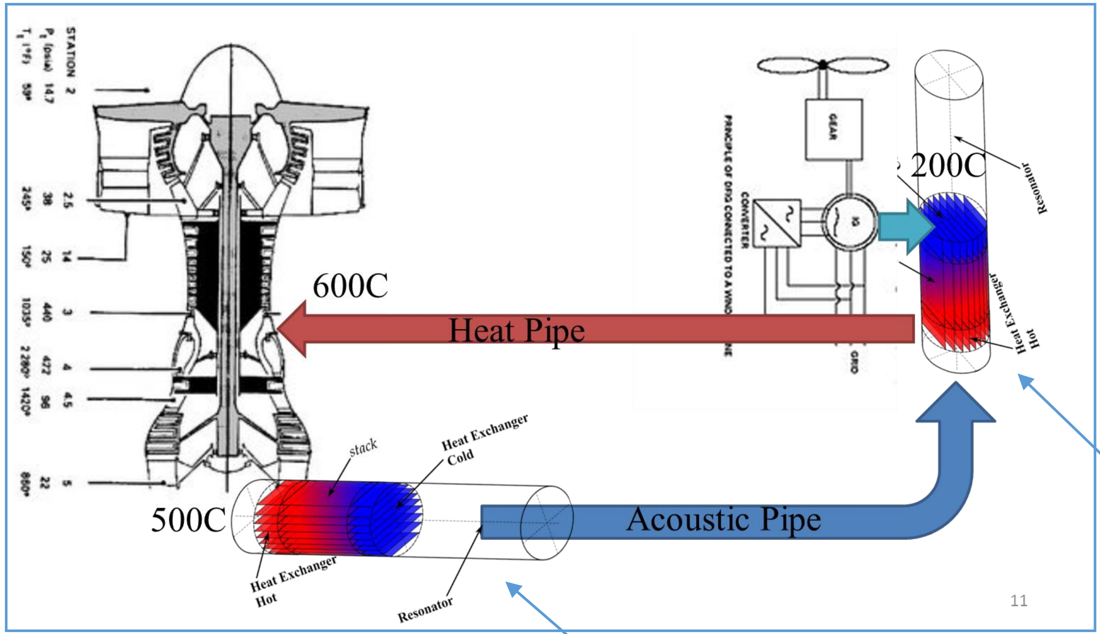
To determine the % Carnot efficiency for a CryoTel CT all we need i
(35+273=308K), T_{cold}=77K. P_{input}=160 Watts for the CryoTel CT, and

$$\text{\% Carnot efficiency} = \frac{10W \cdot (308K - 77K)}{160W \cdot 77K} = 18\%$$



% Carnot Efficiency varies from 15% for small units to 44% for large units

Heat Recycling and Nozzle Rejection



All waste heat recycled and rejected out nozzle.

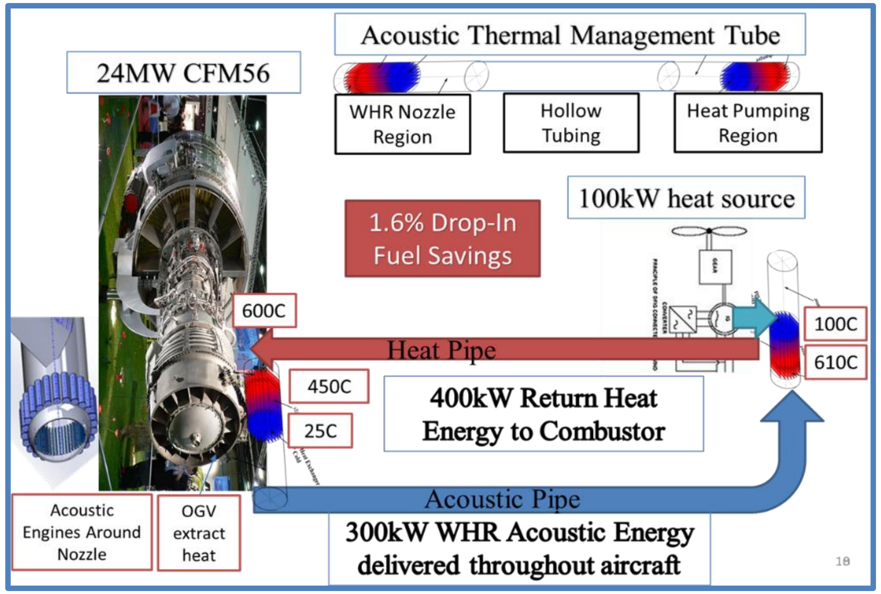
Similar technology for spacecraft because of the reliability, specific power, efficiency, and no maintenance. Only technology option that has no hot moving parts, 52% Carnot WHR power efficiency and 44% Carnot heat pump efficiency, and is bi-directional in that it can both generate its own power and 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%)

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.**

Lip anti-icing

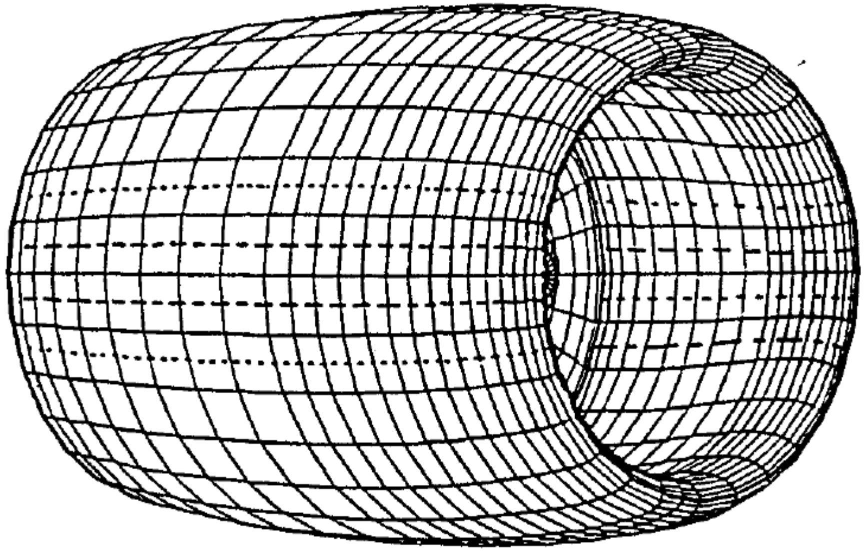


Fig. 1 Panel modeling of the nacelle surface geometry.

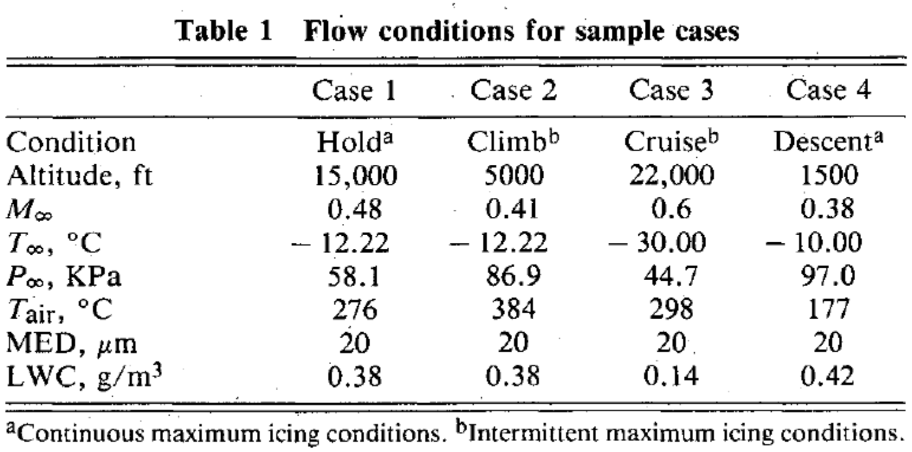


Table 1 Flow conditions for sample cases

	Case 1	Case 2	Case 3	Case 4
Condition	Hold[a]	Climb[b]	Cruise[b]	Descent[a]
Altitude, ft	15,000	5000	22,000	1500
M_∞	0.48	0.41	0.6	0.38
T_∞, °C	− 12.22	− 12.22	− 30.00	− 10.00
P_∞, KPa	58.1	86.9	44.7	97.0
T_{air}, °C	276	384	298	177
MED, μm	20	20	20	20
LWC, g/m^3	0.38	0.38	0.14	0.42

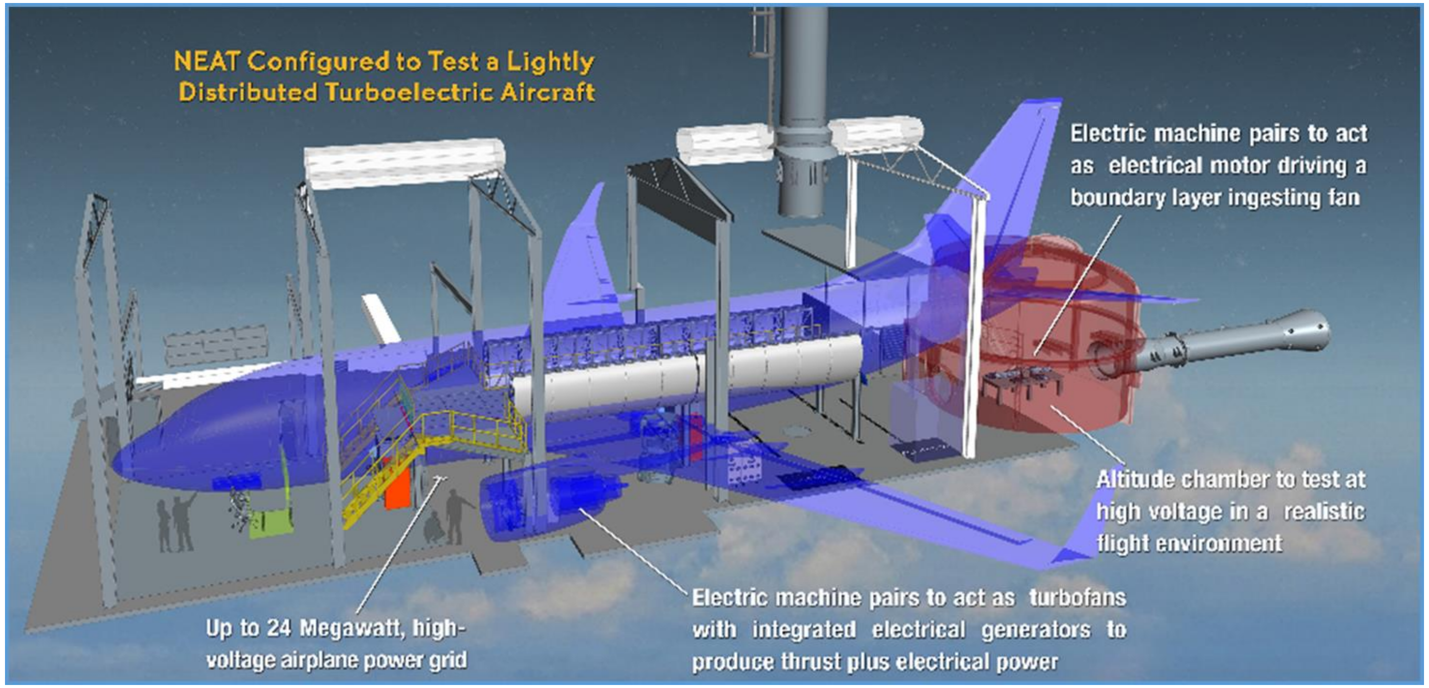
[a] Continuous maximum icing conditions. [b] Intermittent maximum icing conditions.

1MW acoustic energy could be delivered to lip area to pump up free-stream air from -30C to 300C. Effectively can provide continuous 2MW of hot air at 300C.

This is sufficient for anti-ice of entire aircraft without using bleed air or electric power.

Technology Status

- Simple hardware demonstrations completed
- Detailed design tools matured
- Aircraft sized version designed
- Detailed design for your application available upon request
- NASA Electric Aircraft Testbed operational and ready for integrated thermal testing with your powertrain.

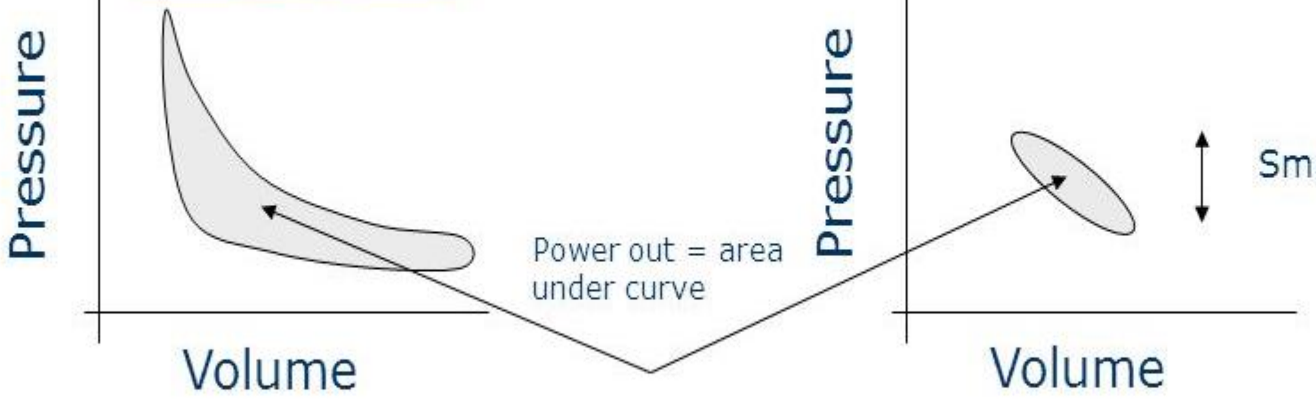


Basic Theory

PV Power and Waves

4 stroke petrol

Stirling Cycle

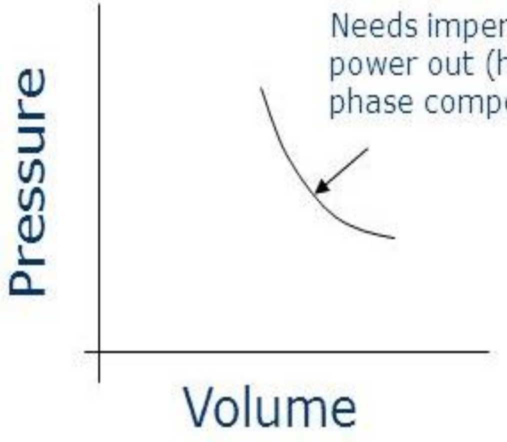


Power out = area under curve

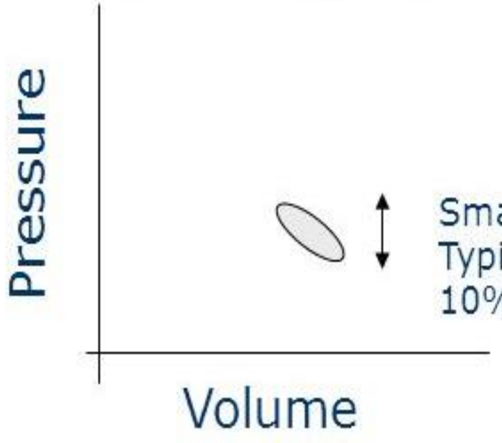
Smaller than 4 stroke

Standing wave TAE

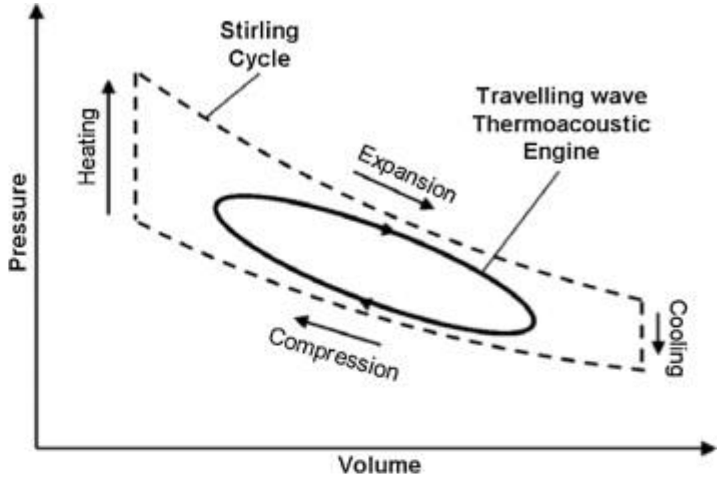
Travelling wave TAE (pressure in phase with velocity)



Needs imperfect stack to get power out (heat lag gives in-phase component)



Smaller than Stirling. Typically less than 10% mean pressure



- Thermo-acoustic engines (TAE)
  - Heat in results in sound in pipes
- Thermo-acoustic coolers (TAC)
  - Sound in results in temperature difference
- Travelling wave (Both)
  - Pressure and velocity in phase
- Standing wave (Both)
  - Pressure and velocity nearly 90 degrees out of phase
- Only travelling waves carry power but
  - Standing wave engines do work well, they always have a small in phase component, i.e. always less than 90 degrees

STANDING WAVES

- Are stationary (as opposed to travelling waves)

STANDING WAVE

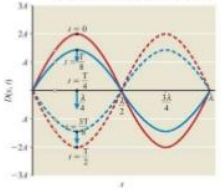


Figure 14-55 Displacement versus position for a standing wave on a string during the first half of a cycle. The position x is expressed in multiples of the wavelength λ.

Vs

TRAVELLING WAVE

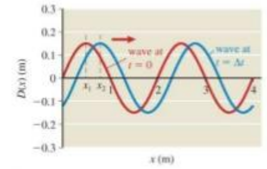
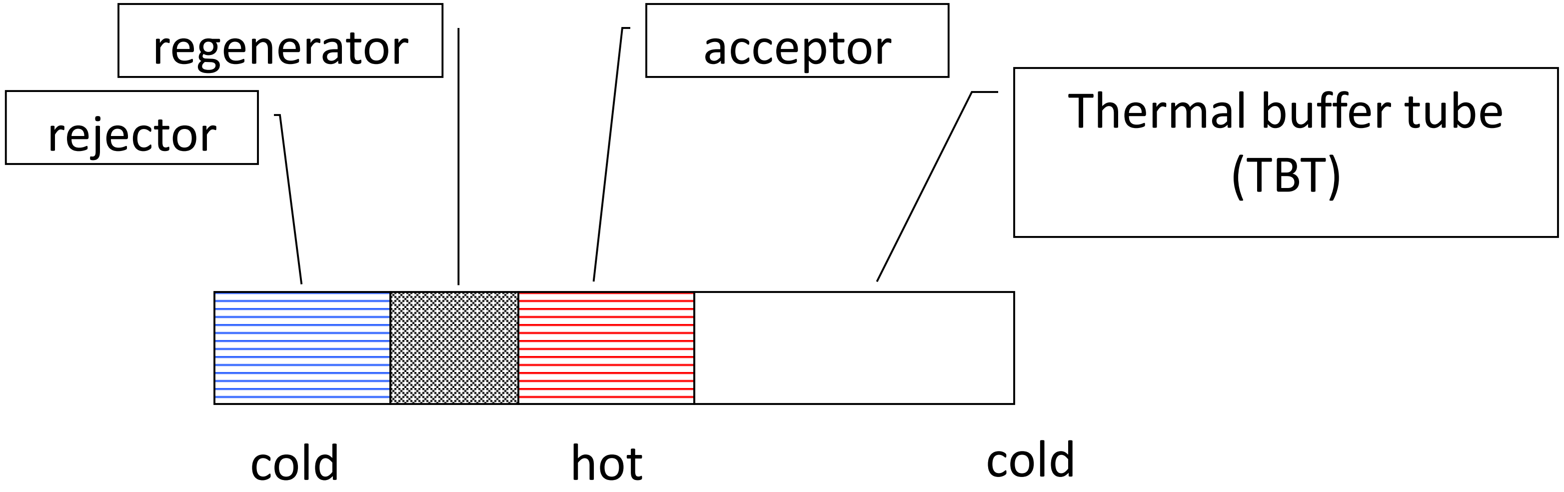


Figure 14-30 The graphs of displacement versus position at time $t = 0$ and $t = \Delta t$ for a sinusoidal wave travelling from left to right

Alpha Stage Physics



regenerator

rejector

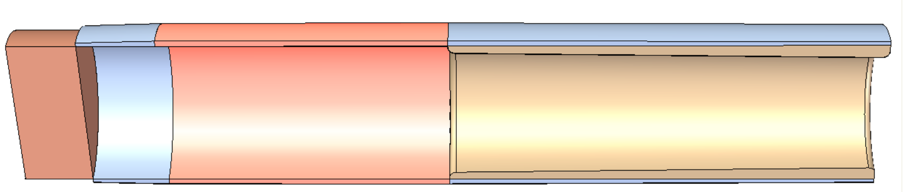
acceptor

Thermal buffer tube
(TBT)

cold

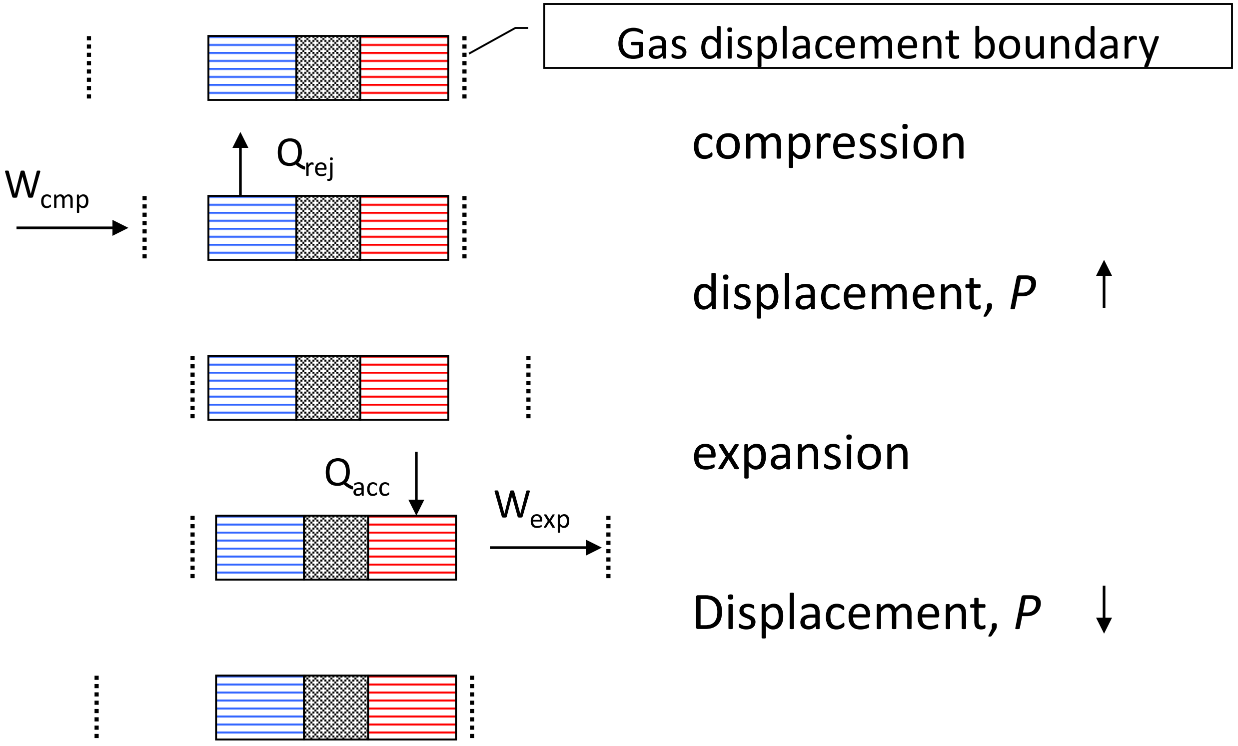
hot

cold



Simplified physical appearance

Thermodynamic Cycle



compression

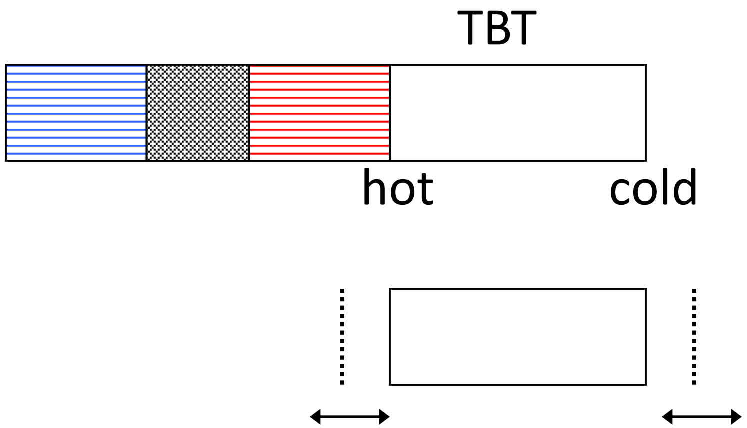
displacement, *P* ↑

expansion

Displacement, *P* ↓

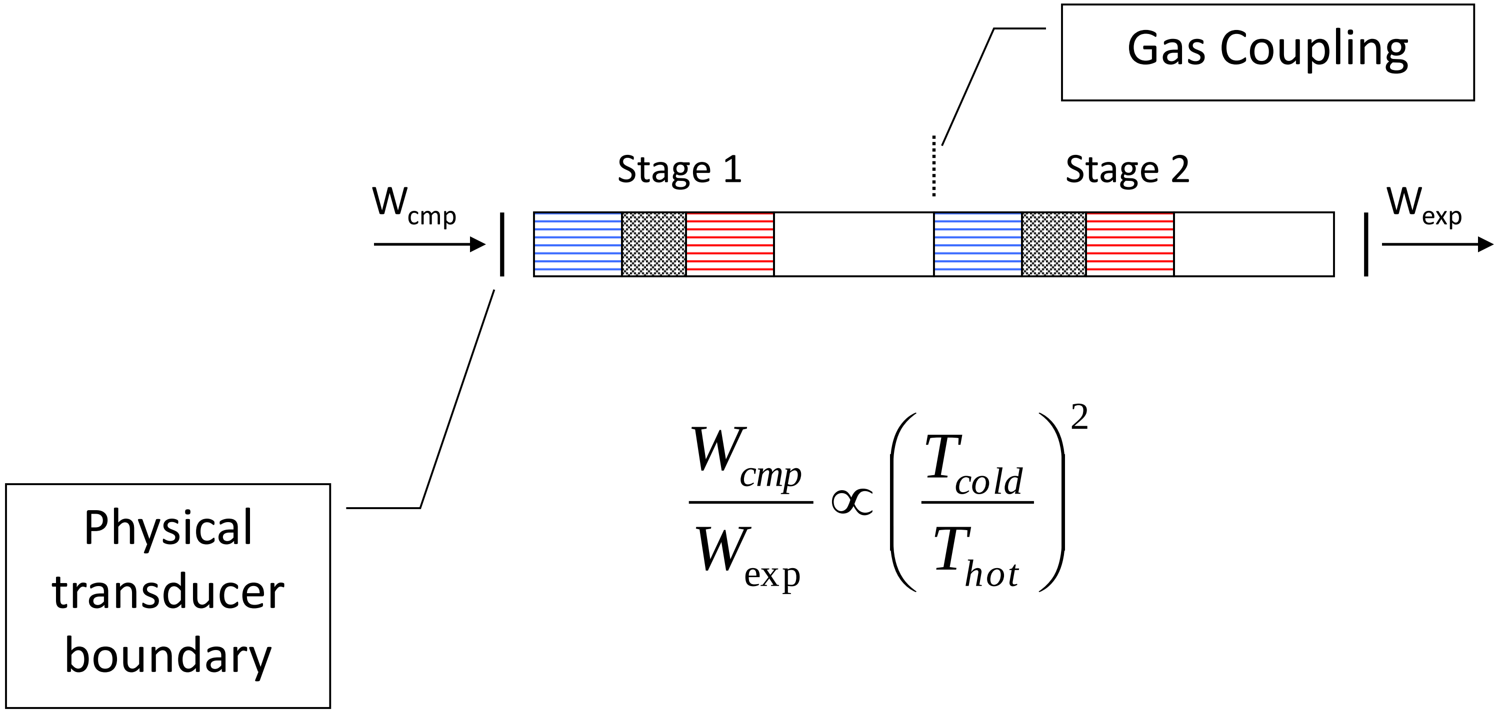
$$W_{cmp} < W_{\exp}$$

Thermal Buffer Tube/Pulse Tube



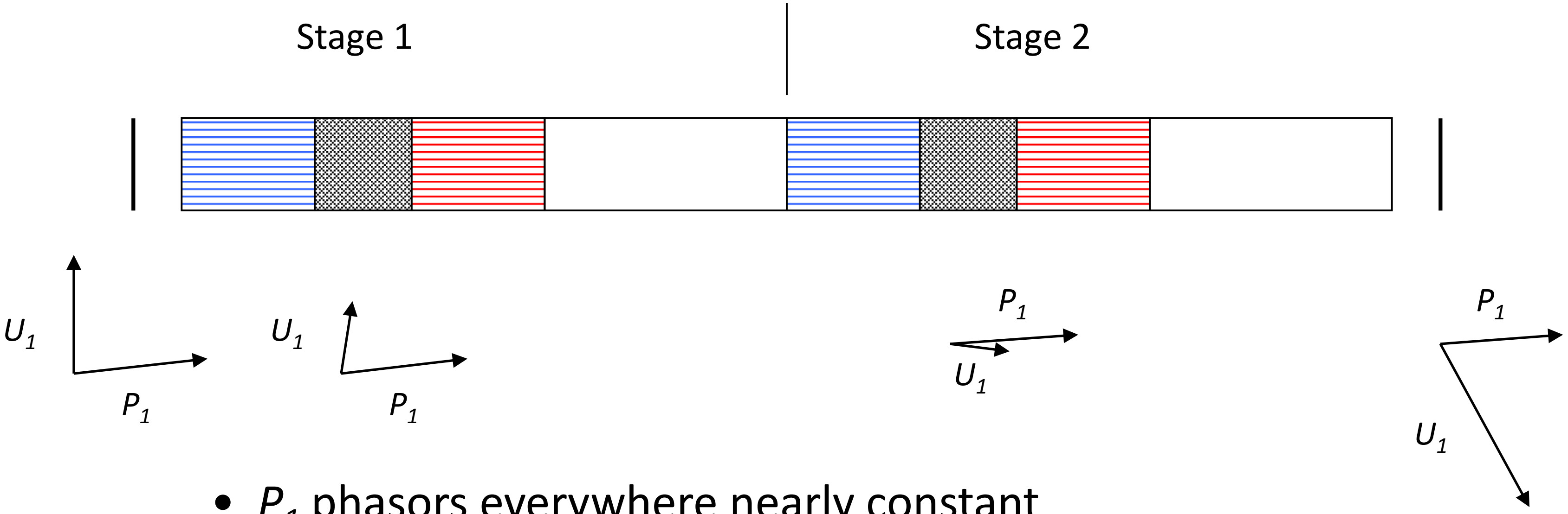
- Isolates hot from cold parts
- Transmits PV power, like a compliant displacer
- Adiabatic (ideally)
- Except for jets, streaming, turbulence, etc.

Two stage cascade



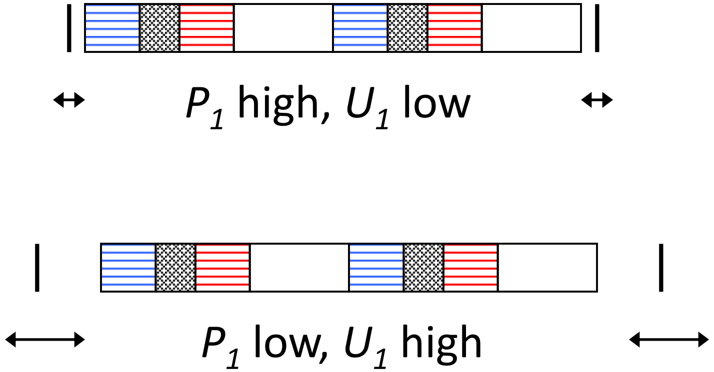
$$\frac{W_{cmp}}{W_{\exp}} \propto \left(\frac{T_{cold}}{T_{hot}}\right)^2$$

PV Phasing



- 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 (see reference 4)

End Transducer Options



P_1 high, U_1 low

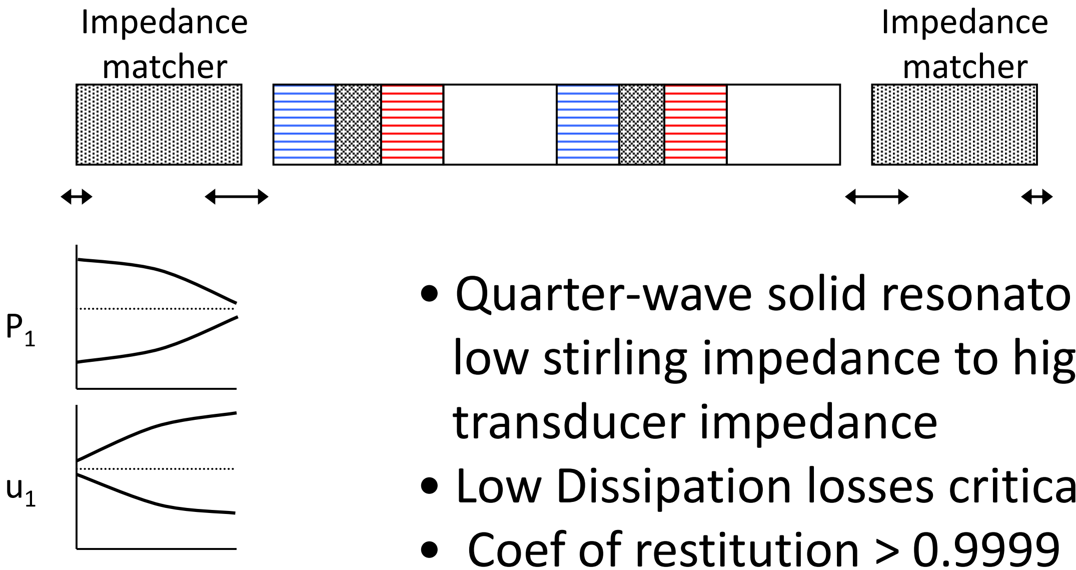
High Impedance
(Piezo or magnetorestrictive)

P_1 low, U_1 high

Low Impedance
(Moving Magnet actuator)

Impedance is P_1 / U_1

High Impedance Matching



- Quarter-wave solid resonator converts low stirling impedance to high transducer impedance
- Low Dissipation losses critical
- Coef of restitution > 0.9999
- Three-dimensional effects?
- Piezo transducers prefer higher frequency than stirling thermodynamics allows

Electro-acoustic transducer (size & weight versus capacity)?

- Not required since can use standing wave driver (see Swift ref. 1)

Key Point is the type and size of driver can be very small because of thermo-acoustic amplification from multiple stages in series. Next series of slides explains this.

And note that TREES uses a traveling wave without the loop shown in F1. b) by using an RC Helmholtz terminator.

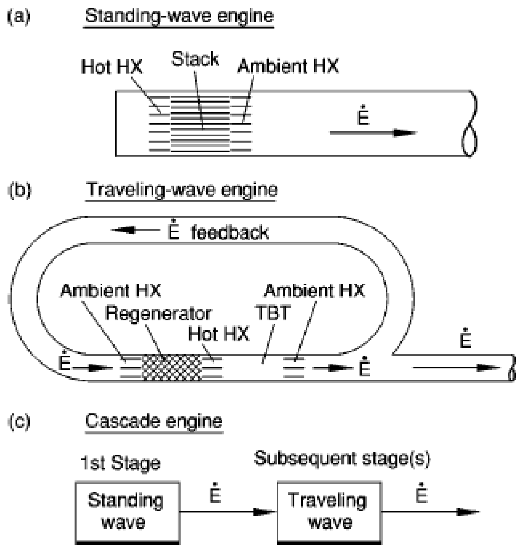


FIG. 1. Some thermoacoustic engine topologies. HX=heat exchanger, TBT=thermal buffer tube, $\dot{E}$=acoustic power. (a) In a standing-wave engine, the temperature difference between the hot heat exchanger and the ambient heat exchanger falls across the stack, whose pore dimensions are of the order of a few thermal penetration depths. Here, the standing-wave engine is in a simple cylindrical resonator, closed at its hot end and delivering acoustic power through its ambient end. (b) In a traveling-wave engine, the temperature difference between the hot heat exchanger and the ambient heat exchanger falls across the regenerator, whose pore dimensions are much smaller than a thermal penetration depth. Acoustic power can only be produced if some is fed into the ambient end of the regenerator, such as through the acoustic feedback path shown here. (c) The cascade engine combines one standing-wave engine with one or more traveling-wave engines. The standing-wave engine supplies the acoustic power needed at the ambient end of the adjacent traveling-wave engine.

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 and/or fuel cell waste heat is used to generate ducted acoustic waves that then drive distributed acoustic heat pumps and/or generate power throughout the aircraft.**
  - **Low grade powertrain waste heat is converted into high grade recycled heat and returned to the engine combustor via heat pipes or additional acoustic tubes**
  - **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, by-pass stream, outer mold line de-ice**
  - **Non-provisional Patent Filed With Priority Date November 6, 2015.**

References

1. Swift. JASA, 114(4), 2003 – Fig. 1c
2. Kim, IECEC 2006-4199
3. Timmer, JASA, 143, 841, 2018
4. Swift, LA-UR 11, 2011
5. Al-Khalil, J. Propulsion, 89-0759
6. Gelder, NACA TN 2866, 1953