Solid-State Exergy Optimized Electric Aircraft Thermal and Fault Management

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Future air vehicles will increasingly incorporate electrical powertrains that require very tight system level integration of power, propulsion, thermal, fault protection, and airframe technologies. This paper provides an overview of a new category of thermal energy conversion technology that can be used to enable a fully solid-state integrated thermal and fault management electric aircraft protection system, while synergistically managing and recycling both the low-grade waste heat from electrical components and the high-grade waste heat from engine components. This is achieved with exergy amplification of the powertrain waste-heat, a new class of fast flight-weight breakers, new class of long variable conductance heat pipe with multiple switchable condensers, new class of turbofan integrated heat exchangers and a gradient-based powertrain system optimizer.

I. Nomenclature

P = acoustic power, W
A = area of tube cross-section, m^2
c = sound speed, m/s
C = compliance, m^3/Pa
L = inertance, kg/m^4
V_r = velocity gas-particle right, m/s
V_l = velocity gas-particle left, m/s
COP = coefficient of performance
f = frequency, Hz
p_0 = pressure mean, Pa
T_h = hot side temperature, K
T_c = cold side temperature, K
Q = heat, J
U = volume flow rate, m^3/s
W = work, J
X = exergy, J
Z = acoustic impedance, Pa s/m^3

II. Introduction

Electric air vehicles range from small unmanned aerial systems (UAS) used for package delivery to urban air taxis for commuters to large single-aisle transport class aircraft for airlines. All these vehicles require tight integration of the power, propulsion, thermal, fault protection, and airframe technologies (PPTFA) to reach their full potential fuel, emission, noise, and mobility benefits. Historically, these technologies were designed separately and optimized at the sub-component level. But after decades of development, each component has nearly reached its full potential and only by integrating these traditional components together with new thermal energy conversion technologies is it possible to achieve a new level of aircraft architecture that synergistically integrates PPTFA. This paper will present a new thermal energy conversion technology, Thermal Recovery Exergy Efficient System (TREES), for recycling and managing all the low-grade waste heat on an air vehicle. The TREES system utilizes acoustic mechanical energy

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distribution to pump waste heat to a higher temperature (increase exergy) and then distributes and reuses the more useful higher temperature heat throughout the aircraft via solid-state switching heat pipes that dynamically change where the heat travels during flight while also potentially improving overall fuel efficiency. This technology can be integrated with distributed fast response solid-state fault management technology to provide a unique electric aircraft powertrain configuration that improves both system reliability and performance. This paper will provide an overview of the technology including both design details and test results from a recent prototype demonstration.

III. Technology Barriers for Air Vehicle Adoption

As shown in Fig. 1, the history of electric aircraft propulsion can be traced back to 1883 in the form of all electric propulsion. And like the history of electric ground vehicles, energy storage was a limiting factor in its utility. But today many of the electric powertrain technologies have improved in the three categories of efficiency, specific power, and energy density to the point where small all electric air vehicles now do have utility and larger electric air vehicles when combined with traditional fueled system (hybrid electric) also offer utility. The next technology frontier for greater market adoption requires making these vehicles safe to operate. This includes having the ability to quickly respond to high voltage/high power electrical faults, and safely managing the significant new heat loads these new technologies produce – often at low temperatures that make it difficult to reject heat and distributed throughout the entire air vehicle. Indeed, as shown in Fig. 1, over time the power level, voltage, stored energy, and low-grade heat loads are expected to increase thereby further challenging both the fault and thermal management systems.

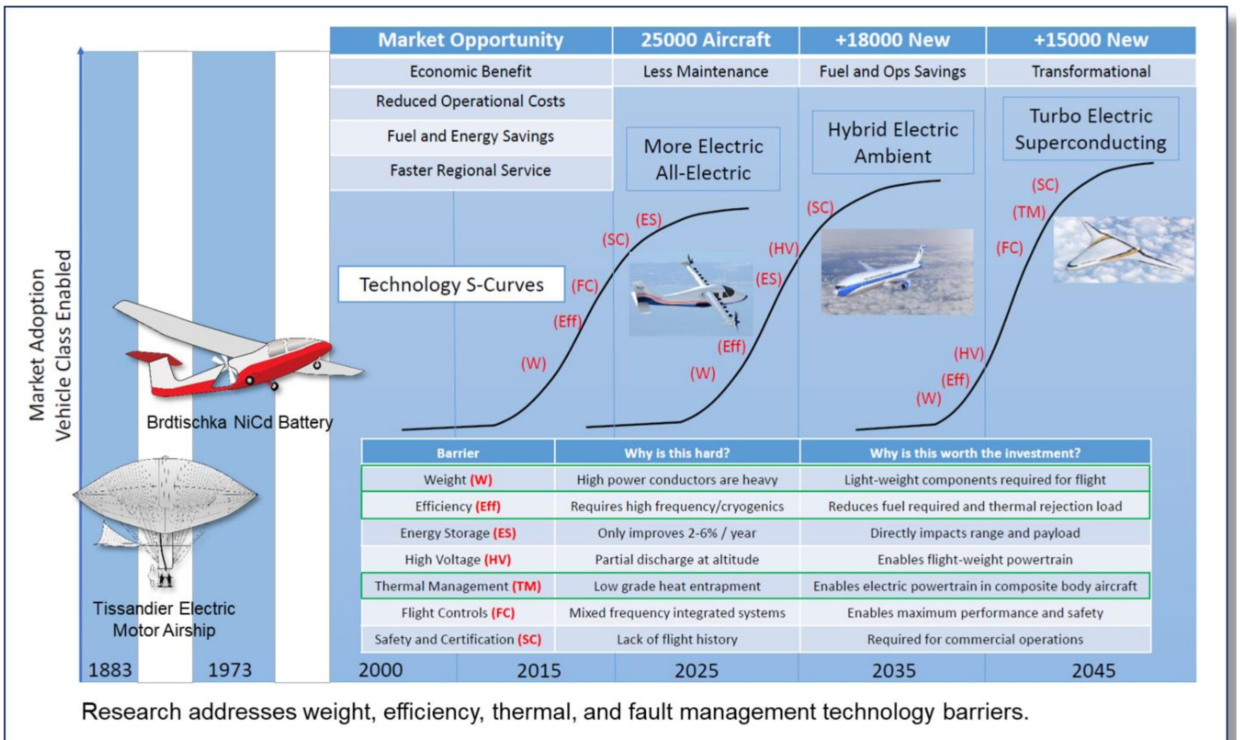


Figure 1. Thermal and fault management technology are barriers for market acceptance

IV. Fault Management Challenge

The high power, voltage, and current required for flight-weight electric aircraft propulsion presents a new challenge for safely managing powertrain electrical faults-especially with the DC power distribution systems currently being employed. While AC fault management is potentially more tractable due to the cyclic zero-crossing of the voltage, most electric air vehicles are using high voltage DC power distribution due to both mass and controllability benefits (fewer distribution cables and machine frequency independence). And due to recent advances in power electronics technology both the efficiency and mass of DC machine drives is now adequate for flight use. However, high voltage DC fault protection technology is still a pacing item for continued progress in this space.

The DC breaker technology options include electro-mechanical, solid-state, or a hybrid of the two. A circuit breaker comparison is shown in Fig. 2 (Armstrong, 2015). As listed in Table 1, the benefit of electro-mechanical circuit breaker (EMCB) is high conduction efficiency (>99.97%) through a metal but has a limited opening speed of >10 millisecond. The solid-state circuit breaker (SSCB) is very fast at opening a circuit (<500 microsecond) but produces six times more low-grade heat due to lower efficiency (<99.3%). And a hybrid circuit breaker (HCB) system achieves both high efficiency and reasonable opening speeds of about 1 millisecond which is adequate for most terrestrial applications. Recent work by both ARPA-E and the Navy have continued to develop DC breaker technologies for ground use, but air vehicles have additional requirements including:

- Less than 100 microsecond response to protect sensitive IGBT based equipment, a hybrid breaker at 500 microseconds can protect personnel and aircraft from catastrophic events, but the aircraft powertrain components can still be damaged from over-current conditions lasting this long
- Both the volumetric density and power density must be optimized because mass is such a driver for aircraft (see Fig. 3)
- High voltage altitude related effects need to be managed such as partial discharge, corona discharge, creepage, and clearance at up to 51,000 feet during flight conditions
- Efficiency is not as important as mass because we have many other elements in the powertrain that are less than 99% efficient, and we need to achieve >7 kw/kg powertrain mass overall for a net vehicle benefit (and we propose recycling the waste heat for a net system benefit)
- Cooling can be done with fluids, air, or other approaches on aircraft whereas terrestrial micro-grid applications may only have air convection for example (we propose solid-state acoustic heat pumping for exergy amplification)

As shown in Table 1, the solid-state circuit breaker option is ideal for air vehicles if the electrical losses can be addressed. Specifically, two areas must be addressed before a solid-state circuit breaker could be successfully employed. First, the electrical losses in double-pole bi-directional solid-state circuit breakers can be significant in a megawatt electric aircraft powertrain.

Table 1. Fault Management Technology Options

	Mechanical	**Solid-State**	**Hybrid**
Device to break current	Mechanical Switch	Semiconductor Devices	Semiconductor Devices and Mechanical Switch
Benefits	Low Conduction Loss	Super-fast response time (<10 us) Simple structure	Low conduction loss Fast response time (1-5 ms)
Limitations	Slow Response Time (50 ms)	High conduction loss (~0.5%)	Complexity

Shown in Fig. 2 is schematic of a new class fault management technology being developed by a team from the Naval Postgraduate School that can achieve flight-weight, speed, and altitude requirements if the loss of efficiency can be mitigated with thermal recycling. And previous system studies (Jansen, 2019) (see Fig. 3) clearly show any efficiency losses in the powertrain must be traded with an equivalent amount of mass reduction to continue to show a net vehicle block fuel benefit unless the waste heat can be recycled. Secondly, between 7 kW and 10 kW of low-grade thermal heat is produced for each Megawatt scale breaker in the system. Generally, the combined negative impact of both the significant loss in powertrain efficiency and the new distributed heat loads would constrain breaker technology to the selection of a hybrid circuit breaker despite its relatively slow response time. And electric air vehicles would need to be designed to compensate for this increased risk of powertrain component damage during fault events. But as will be shown, a new integrated approach for managing the low-grade heat on an aircraft can mitigate both the reduction in powertrain efficiency and the release of low-grade heat throughout the aircraft from solid-state circuit breakers. And then the potentially very high-speed fault response can be leveraged to protect not just personnel and airframe, but also all the sensitive power electronics and sensors on the powertrain during both hard and soft fault events.

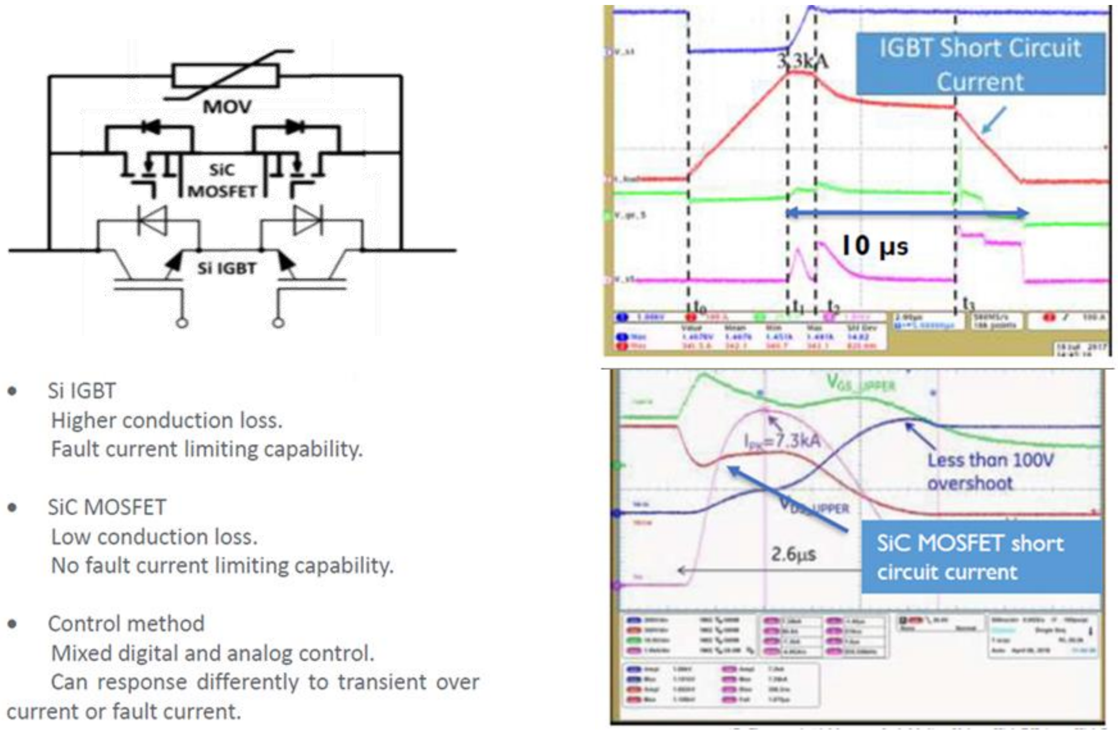


Figure 2. Very Efficient, Light-Weight System Requires Dynamic Thermal Recycling System (Zhang)

Note in Figure 2 that this breaker system naturally provides both current and voltage limiting without requiring inductors and can operate at the time-scales necessary for Megawatt scale aircraft. And despite the higher conduction losses compared to a hybrid breaker, we can still maintain an effective high drive efficiency shown in Figure 3 by recycling the waste heat with a distributed thermal management recycling system to be described.

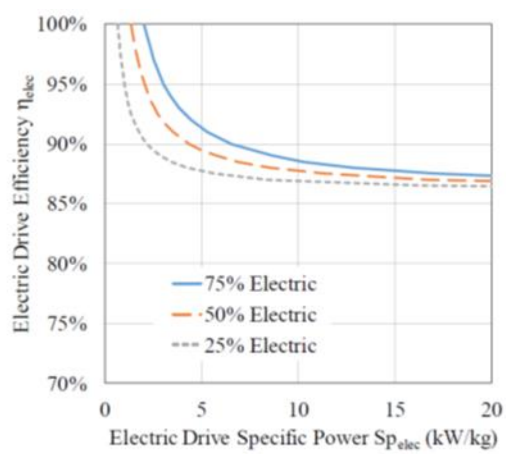


Figure 3. Example Breakeven Curves for Electric Aircraft Propulsion - Efficiency trades with Specific Power (Jansen)

V. Thermal Management Challenge

Electric aircraft have not only the challenge of managing the electrically related risks of high voltage, power, and current, but also just as important is managing the significant new low grade heat loads that are introduced each time an electrical component is added to the aircraft (Dooley, 2016).

The challenges with low grade waste heat in aircraft is five-fold:

- low Exergy heat energy is not useful for work and difficult to reject
- adds system mass from large heat exchangers, plumbing, fluids,
- reduces net propulsive power from increased drag, compressor bleed, and turbine power extraction,
- has a limited thermal capacity due to sink temperature or surface availability
- maintenance increases due to thermal management system complexity or structural integration challenges

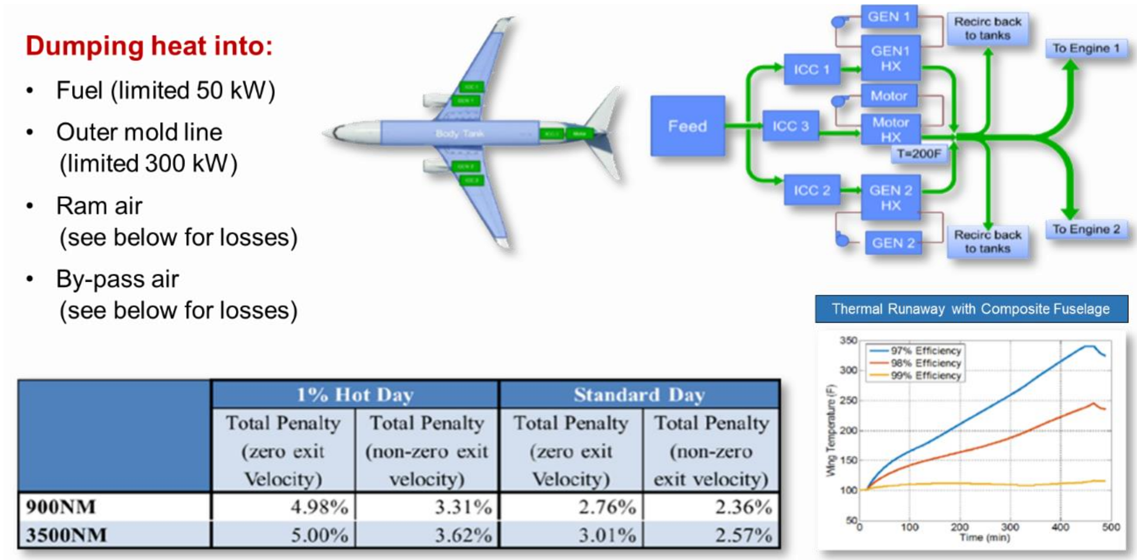
Figure 4. High Exergy (>20MW) and Low Exergy (<1MW) heat sources distributed throughout the aircraft

As shown in Fig. 4, aircraft have a range of thermal conditions distributed throughout the aircraft. High exergy waste heat is emitted from the turbofan core, and low Exergy waste heat is distributed nearly everywhere else on the aircraft. And the current approaches for managing this heat (and its drawbacks) are listed in Table 2 (Dooley, 2016):

Table 2. Thermal Management Technology Options

Thermal Management Technology	Drawback
Ram air HX	Adds weight, aircraft drag, displaces fuel capacity
Convective skin cooling HX	Adds weight, drag, and requires liquid pumping losses
Sinking heat into fuel	Limited thermal capacity due to coking and volume
Sinking heat into lubricating oil	Limited thermal capacity, Low delta T adds HX mass
Active cooling	Reduces propulsive efficiency, Adds weight and maintenance
Phase change cooling	Limited thermal capacity, Adds weight
Heat Pipe, Pumped Multiphase	Does not increase Exergy which impacts mass and efficiency

The heat pipe technology is shown as a drawback in Table 2 when used in isolation because it does not increase the exergy (Fleming A. L., 2016). It is a means for transporting heat energy relatively short distances and at constant temperature. However, when integrated with Exergy increasing components and dynamic heat pipes it no longer has that drawback and its mass impacts are mitigated from reusing the waste heat which serves to increase the effective powertrain efficiency. And as shown in Fig. 3, if the powertrain efficiency can be increased with exergy recycling, then the system can add system mass and still have a net benefit. And as shown in Fig. 5, if exergy recycling is not used, then large transport aircraft cannot be fully electrified due to inherent heat sink limits and system level 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%

Figure 5. Electric Aircraft Propulsion Thermal management technology impacts performance and safety certification (P.C. Krause)

Note that in this P.C. Krause study shown in Fig. 5, that commonly suggested methods for rejecting low-grade waste heat has both intrinsic heat load Q, limits, and/or negative system level drag losses on the scale of 3% total fuel burning. At this loss level, the projected benefits of transport class electrification can be nullified. Moreover, even an ideally 99% efficient component, will often be required to operate outside its peak performance zone and this can result in a thermal runaway scenario unless active thermal control features are available to mitigate this response.

VI. Integrated Fault and Thermal Management

As shown in Fig. 6, future electric aircraft propulsion systems will be based on a variety of configurations. But they all have in common the need to protect against electrical faults with DC breakers as indicated by the yellow dots and to manage the waste heat produced by everything shown.

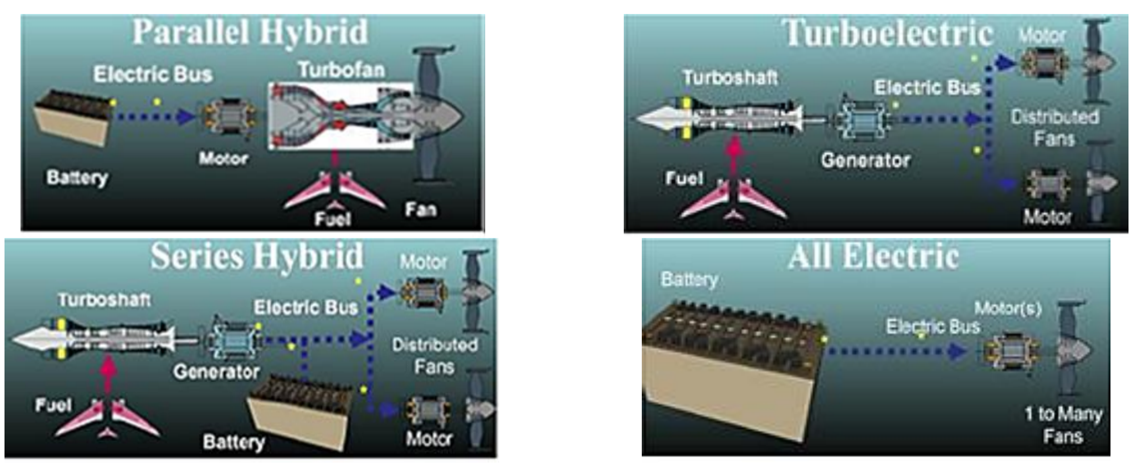


Figure 6. Powertrain configurations require both thermal and fault management protection (yellow dots)

And shown in Fig. 7 is an integrated thermal and fault management system applied to a Boeing 737 flight vehicle with parallel hybrid propulsion (United States of America Patent No. 10,507,934, 2019). The basic approach is to extract high Exergy waste heat from the turbofan core using low mass SiC coated graphite heat exchangers to thermo-acoustically generate a ducted acoustic wave that is used to deliver mechanical energy throughout the aircraft. This acoustic energy can then operate a thermo-acoustic heat pump to actively refrigerate the powertrain components while collecting the low Exergy waste heat from the powertrain and convert it to high exergy, useful heat, through which dynamically switchable heat pipes can then deliver throughout the aircraft for beneficial uses shown in Table 3.

Figure 7. Thermal Recovery Exergy Efficient System uses thermo-acoustic and dynamically redirectable heat pipe tubes embedded in the aircraft to recycle both the turbofan and powertrain waste heat

Table 3. Beneficial Uses of Higher Exergy Waste Heat from Powertrain

Sink Location	**Sink Temperature (C)**	**Benefit**
Engine Core	600	Recuperates engine and powertrain heat for efficiency
Engine By-pass	100	Increases thrust with P-51 effect
Outer Mold Line	200	De-icing, Anti-icing, Turbulent Boundary Layer Mgmt
Auxiliary Power Unit	400	Provides electrical power from waste heat
Cabin	40	Provides cabin heating without bleed air from turbine
Battery	20	Maintains batteries above freezing
Oil Coolant Loop	100	Smaller heat exchanger required due to higher temp.
Ram Air	100	Smaller heat exchanger required due to higher temp.

VII. High Exergy Heat Extraction

As shown in Fig. 7, modern turbofan propulsion systems provide thrust using high by-pass ratio architectures in which over 85% of the thrust is NOT from the core. And as distributed electric propulsion systems are employed in the future, the amount of thrust due to the nozzle flow will continue to decrease. And it is anticipated that eventually turbofans will be replaced with turboshaft generators that exclusively deliver electric power to electric motor propulsors (Felder, 2011) – in this case, none of the thrust is produced in the Brayton cycle engine core.

It is also important to note that the by-pass air path and the combustion air path can leverage similar heat exchanger for returning heat energy to those locations to achieve the benefits listed in Table 3.

Moreover, any source of high Exergy waste heat can be used for this system such as solid oxide fuel cells, but the heat exchanger would be a different design in that case since no high-speed air flow is required. Also, since the thermo-acoustic heat engine only requires conducted heat into its system, it is possible to directly conduct heat from the fuel cell directly to the acoustic engine to avoid conjugate heat transfer altogether.

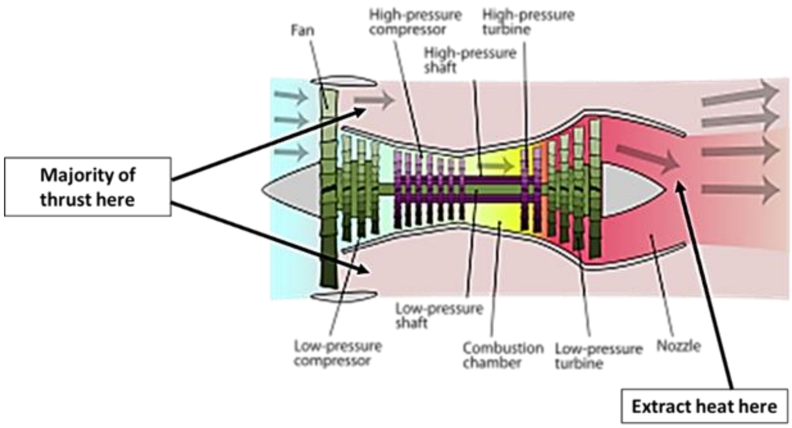


Figure 8. High Exergy Flow Extracted from Turbofan Core

If a low pressure drop heat exchanger is installed in the core, then some of this high Exergy waste heat can be extracted with minimal to zero impact to overall vehicle thrust. Preliminary results in Table 4 below indicate such a heat exchanger is feasible for extracting at least 20% of the energy using 8000 channels (2.5 mm X 5 cm X 10 cm) in the nozzle. A detailed graphite-based heat exchanger development effort (see Fig. 9) is currently underway (Hendricks, 2017) that can collect core heat and reject heat to the by-pass flow or ram air.

Table 4. Minimal Thrust Impact from Extracting Core Heat Energy At Nozzle Exit

Thrust (kN)	**Total Engine Core Enthalpy (W)**	**Extracted Energy (% of core, W)**
49.6	17.7 MW	1% (267 kW)
49.5	17.7 MW	10% (1.7 MW)
49.4	17.7 MW	18% (3.1 MW)

And as mentioned, as the by-pass ratio increases to fully turbo-electric levels then none of the thrust is produced by the core and the turbo-shaft generator exhaust gas ducting can be optimized for maximum Exergy extraction.

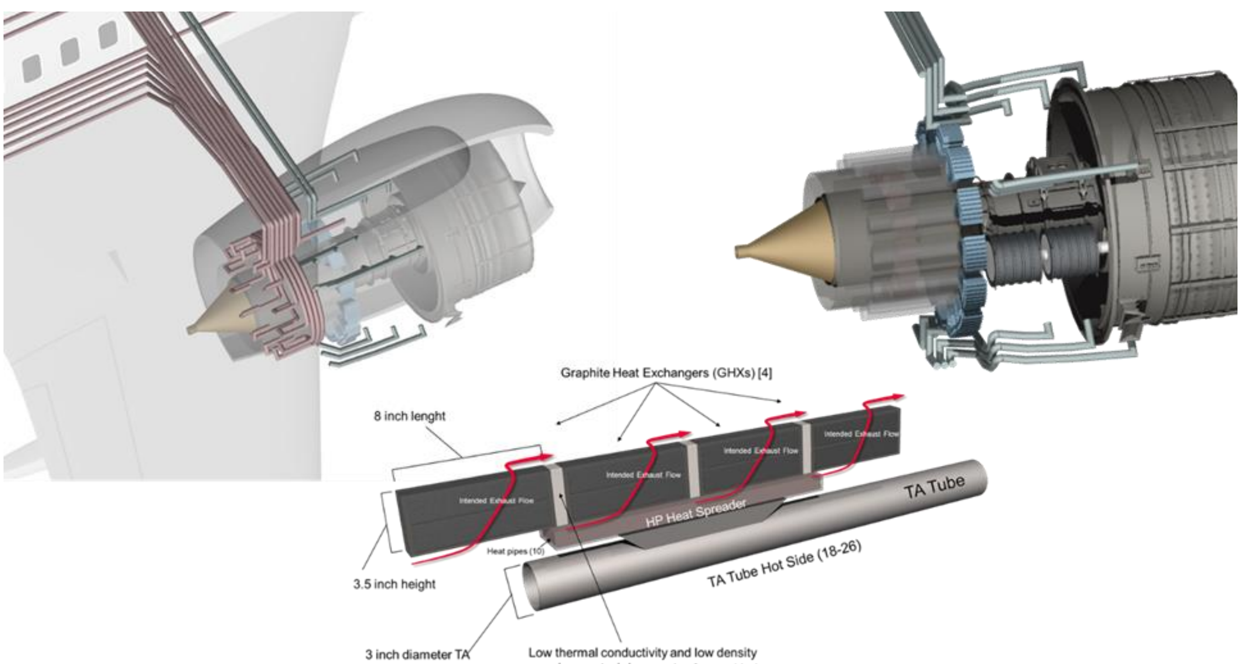


Figure 9. Turbofan Heat Exchanger Integration (Hendricks)

VIII. Acoustic Exergy Pumping Tubes

As shown in Fig. 10, a forward and reverse thermo-acoustic heat engine and heat pump can be combined into a duplex configuration with a long acoustic wave guide tube between them (Swift, 1999). The high Exergy heat from the turbofan core can be used to create an acoustic wave on the left side of the tube that travels the length of this tube and then operates as a heat pump to increase the Exergy of the waste heat from the powertrain. In Fig. 10, it is assumed the incoming heat from the turbofan core is about 800K and a portion of that energy (70%) is rejected into the by-pass stream at 300K. And based on the results in Table 4 the incoming heat would be about 3MW and the produced acoustic energy would be about 1MW.

The amount of mechanical acoustic energy traveling through the long wave-guide duct tubes is given by:

$$P = \frac{\gamma p_0}{2\,c} A(V_r^2 - V_l^2)$$

The amount of sound amplification is a function of the temperature ratio, T_h/T_c. And the efficiency is also a function of both temperature ratio and the proper pressure and volume velocity, V, phasing in the regenerator regions to achieve amplification and heat pumping respectively. In addition, the system must be designed to resonate to achieve high acoustic gas-particle displacement while also matching the proper acoustic impedance, Z, with the boundaries and appropriate compliance, C, and inertance L. The input wave can be created with a standing wave thermo-acoustic tube (no moving parts), piezo-electric actuator, turbine blade tip compressor, linear actuator, voice-coil, or solenoid that has acoustically matched impedance with the acoustic wave working fluid. And similarly, the receiving end (heat pump region), can use an inertance tube with reservoir, or any of the same methods used for the input wave. The combination of the end effectors, tube geometry, heat exchanger/regenerator dimensions, operating frequency, and location of the heat engine and heat pump within the tube must all be accounted for in a proper design of the acoustic exergy pumping tubes.

Note that acoustic waves do not generate heat and do not require insulation along their lengths. And since most of the heat exchangers are very porous, and the tube can be directly embedded into the airframe, then the total mass of the system can be kept to a minimum. Typical COP values from thermo-acoustic refrigerators at these temperatures can approach 40% of Carnot efficiency, and the heat engine can approach 50% of Carnot efficiency.

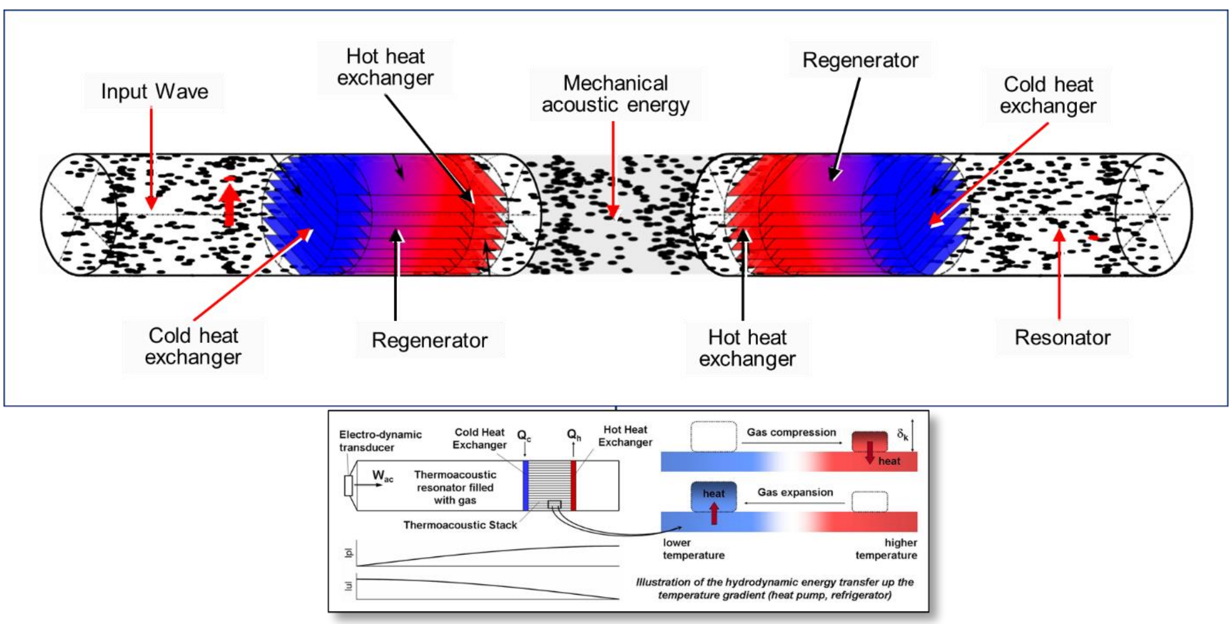


Figure 10. Acoustic Exergy Multiplication Tube

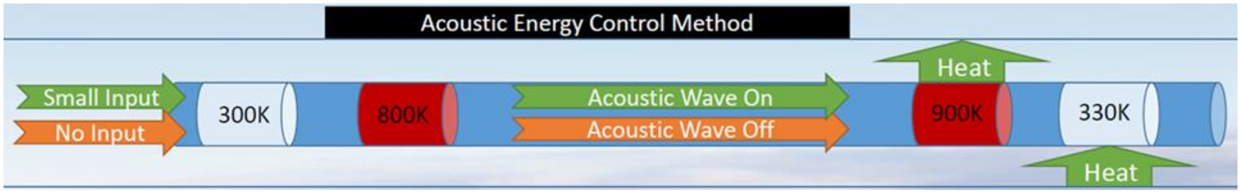
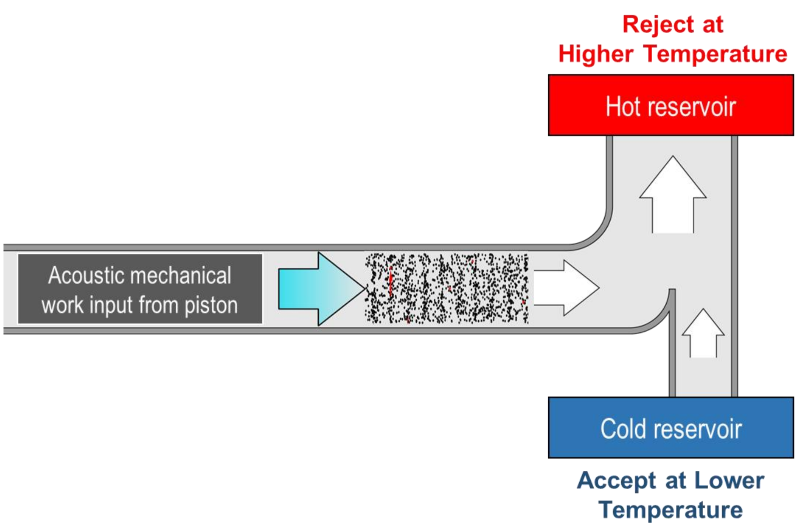


Figure 11. Acoustic Energy can be switched on/off and delivered anywhere in the aircraft for heat pumping

During a full flight profile, the aircraft heat energy flows will change at both the turbofan and powertrain and the available heat sinks can vary considerably as well depending on altitude, speed, and environmental temperatures, so it is important to be able to actively change the amount of refrigeration and the destination of the waste heat while in flight. As shown in figure 11, the amount of refrigeration can be modulated by adjusting the size of the incoming acoustic wave. If a standing wave generator is used, then the adjustment is accomplished with small thermo-electric heat source changes. If an electric wave generator issued, then the adjustment is accomplished electrically.

And then as shown in Fig. 12, the amount of cooling that can be provided depends on the temperature ratio across the heat pump. As an example, for a temperature ratio of 3 (900K/300K), for every two watts of acoustic energy in, W, one watt of powertrain heat, Q, can be pumped resulting in three watts of high Exergy heat at 900K being rejected to a heat pipe. Therefore, 1MW of acoustic energy can lift 500 kW of low grade 300K electric powertrain heat and then up to 1.5MW of high Exergy heat is available for the beneficial purposes listed in Table 3.



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

Figure 12. Ratio of input acoustic energy required for heat pumping

IX. Thermally Redirectable Heat Pipes

As shown in Fig. 13, solid-state variable conductance heat pipes can be used to deliver the high exergy heat produced by the acoustic heat pump. Moreover, by including a non-condensable gas inside the heat pipe, it is possible to thermally control the conductance of the heat pipe- in essence to control (switch on and off) the heat pipe with no moving parts (Fleming A. , 2004). A detailed development effort is underway to build and test a series of low and high temperature variable conductance heat pipes that can operate over long distances in a changing g-force and slope environment by Advanced Cooling Technologies, Inc. As shown in Fig. 14, by adding multiple non-condensable gas condenser tubes, it is possible to dynamically control where the heat goes with no moving parts and very fast response times. A successful test of this concept was recently completed and will be presented in more detail soon.

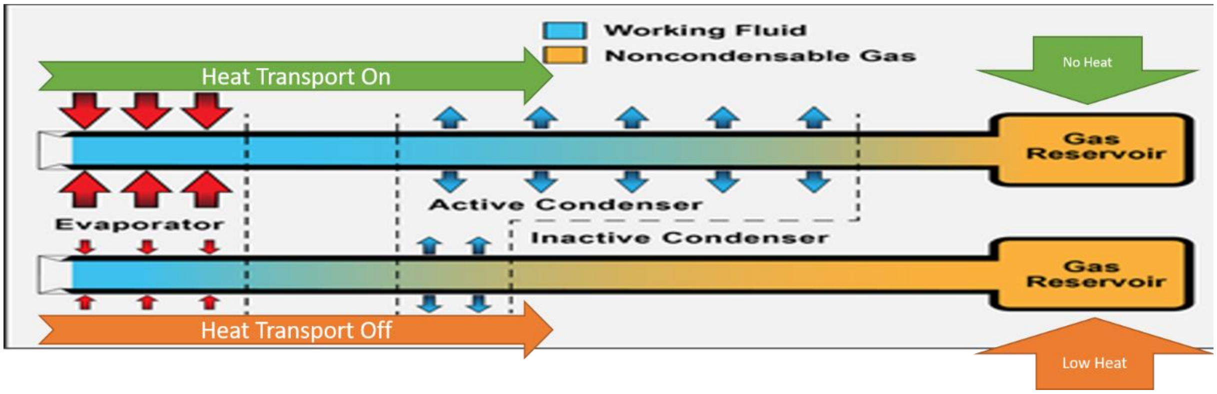


Figure 13. Solid-state switchable heat pipe technology can redistribute the high temperature thermal energy (Tarau)

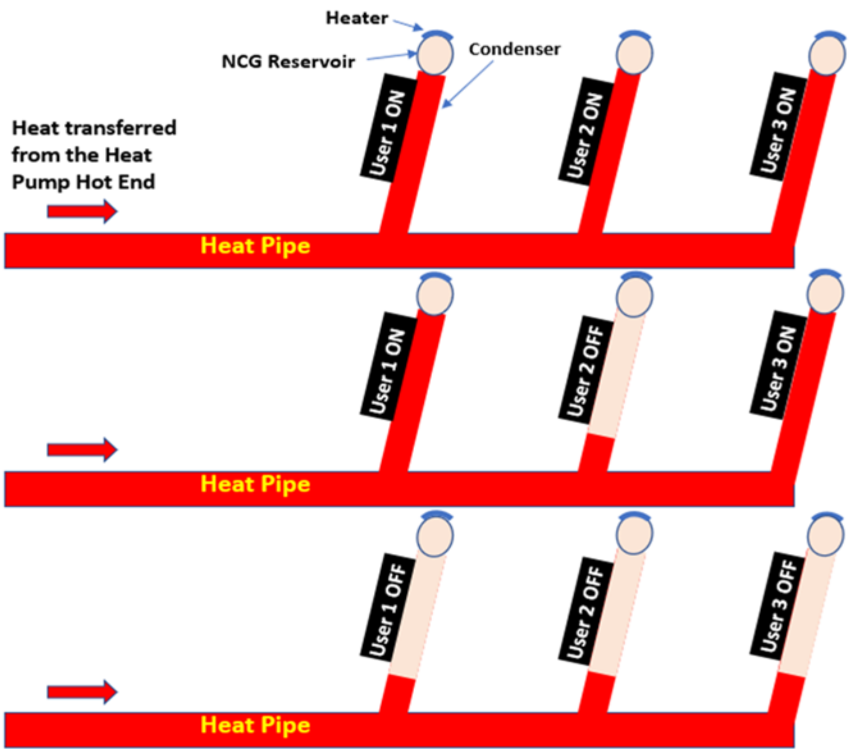


Figure 14. Solid-State Thermal Switching (Tarau)

And as shown in Fig. 15, this new capability enables an entirely new approach to delivering different temperature heat to different locations and at a user adjusted rate while the aircraft is in flight. In this sense, it is a completely generally solution that can support recuperation, de-icing, thrust augmentation, environmental control, or auxiliary power units.

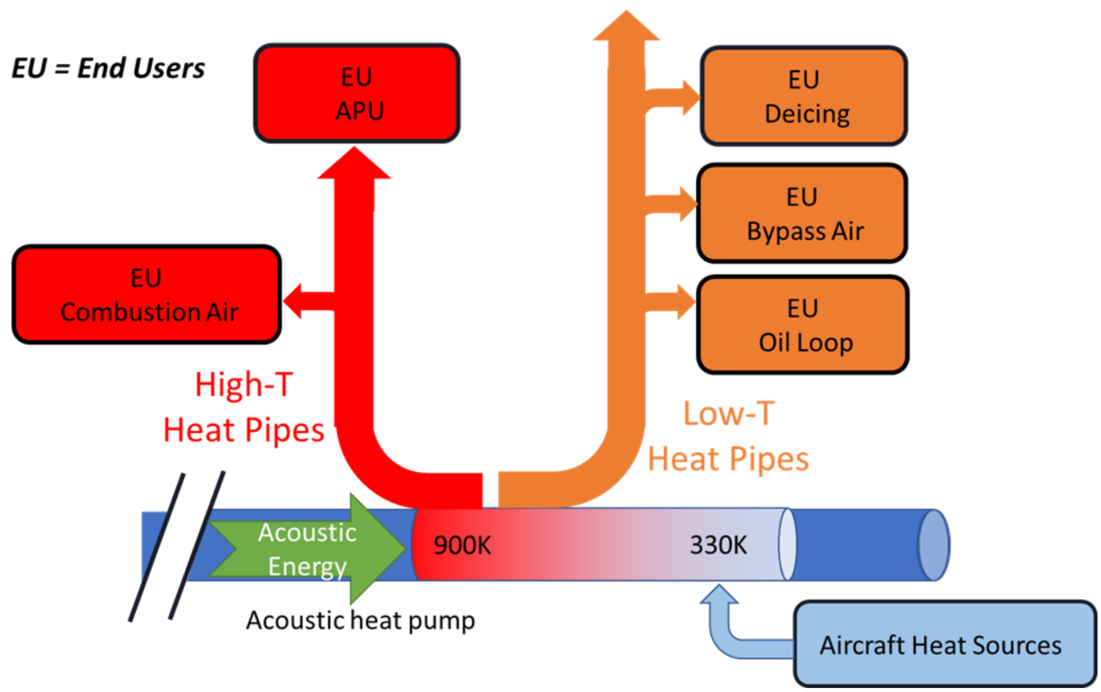


Figure 15. Prototype Layout – Standing Wave Ends – Linear Acoustic Tube (Tarau)

X. Integrated TREES System Operation and Test Results Summary

Ideally, future aircraft thermal management systems can lift 500kW or more of low-grade waste heat ranging in temperature from 50K-300K to a higher temperature greater than 400K without adding excessive mass or system losses or being limited in total heat capacity. As mentioned, the key to making this technology light-weight and efficient is the generation of a ducted acoustic wave to deliver refrigeration energy to distal locations throughout the aircraft that would otherwise be expensive to cool such as fault management and sensor technologies. This eliminates the need to transport energy with electrical, mechanical, or fluids- each of which adds system mass and complexity. For example:

- Electrical power distribution produces EMI, distributed heating, and requires heavy cables.
- Mechanical power distribution such as distributed torque shafts adds weight and requires lubrication.
- And pumping a coolant requires a large volume of fluid, pumping mechanisms, extensive insulation, and heavy heat exchangers to transfer heat energy.
- Passive solutions need to be over-designed to support a full flight profile and don't protect against unforeseen failure modes and have more limited thermal capacity

Instead, once the pressure wave is formed it is a simple matter to channel the wave in small tubes to anywhere in the aircraft. In comparison to reverse Brayton or Rankine systems, the thermo-acoustic engine pressure wave generator requires no lubrication and has no moving parts. Moreover, this technology is useful for aircraft because it does not require extra fuel to operate it, is light-weight, and essentially maintenance-free. It could be used to provide cabin cooling, ambient/cryogenic cooling of converter, cables, and motors, and in addition it can be used to deliver power to remote locations on the aircraft without using wires.

A related thermo-acoustic cooling technology was recently demonstrated in the Netherlands to lift 25kW of heat for residential uses (Bloc, 2019), and is shown in Fig. 16. This success clearly suggests thermo-acoustic cooling is an important new area to include in our suite of thermal management technologies for aircraft.

Figure 16. Example thermo-acoustic cooling technology

Note that it uses a rotational configuration to maintain a traveling wave but would be challenging to install in an aircraft. As shown in Fig. 17, rather than using a circular configuration, we use standing wave end-caps that enable a linear configuration for the acoustic exergy tubes. The initial acoustic tube prototype is being built and tested to confirm modeling predictions are accurate and to confirm the ability to deliver acoustic energy the entire length of an aircraft.

The first phase of development is a simple pulse-tube-like configuration with inertance tube and reservoir end-cap. This is followed by stretching the acoustic tube to aircraft-scale lengths and confirming the acoustic tube losses match the predictions show in Fig. 18. And this is followed by removing the pulse-tube-like end tubes with an active impedance matching to provide better control options and to shorten the length of the end caps.

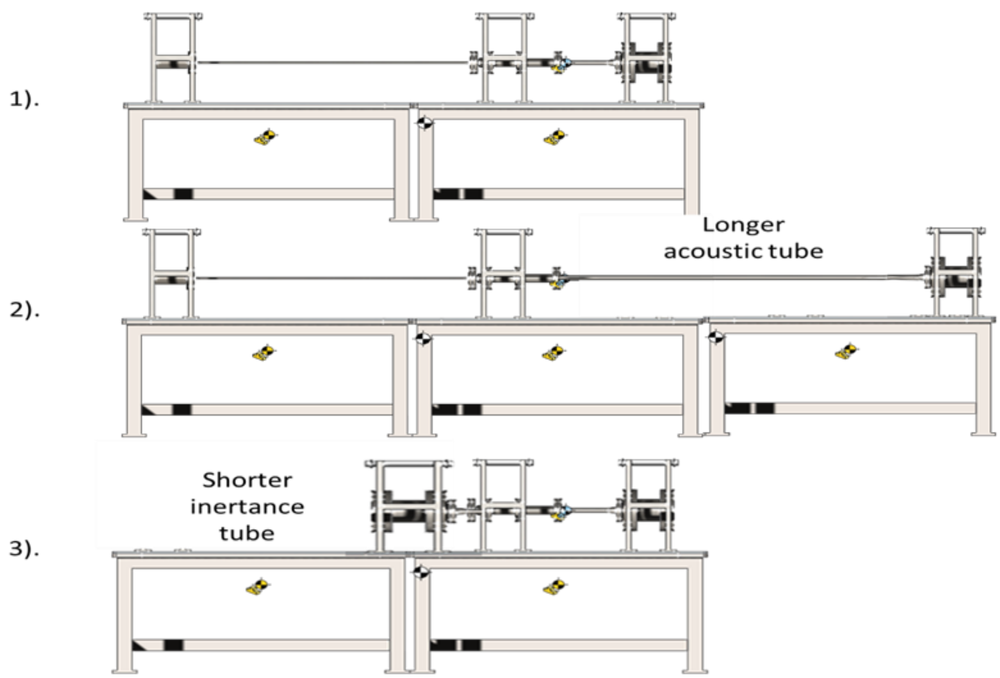


Figure 17. Prototype testbed development steps

Subsequent steps include combining the acoustic exergy amplification tubes with the dynamic heat pipes into a system that actively manages the temperatures throughout an entire powertrain while dynamically optimizing the performance of the air vehicle during flight.

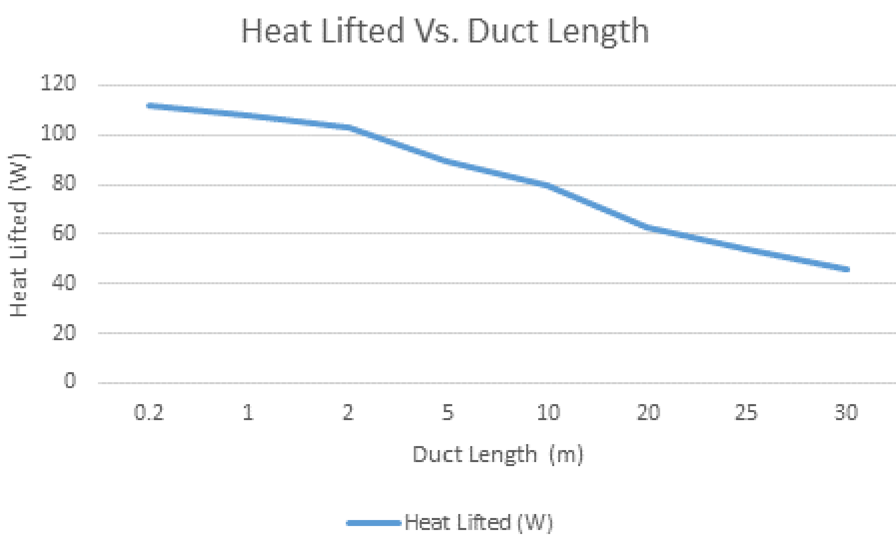


Figure 18. Traveling Acoustic Wave Losses as Duct Length Increases

It's also important to recognize that fully integrating the power, propulsion, thermal, fault protection, and airframe technologies requires the ability to optimize a very complex system to minimize mass, maximize efficiency, and maximize safety. In support of this objective, a new gradient-based powertrain optimizer specifically designed to select the based suite of thermal management technologies, as shown in Fig. 19, is also under development as a new open source optimization design tool called OpenConcept (Brelje, 2019).

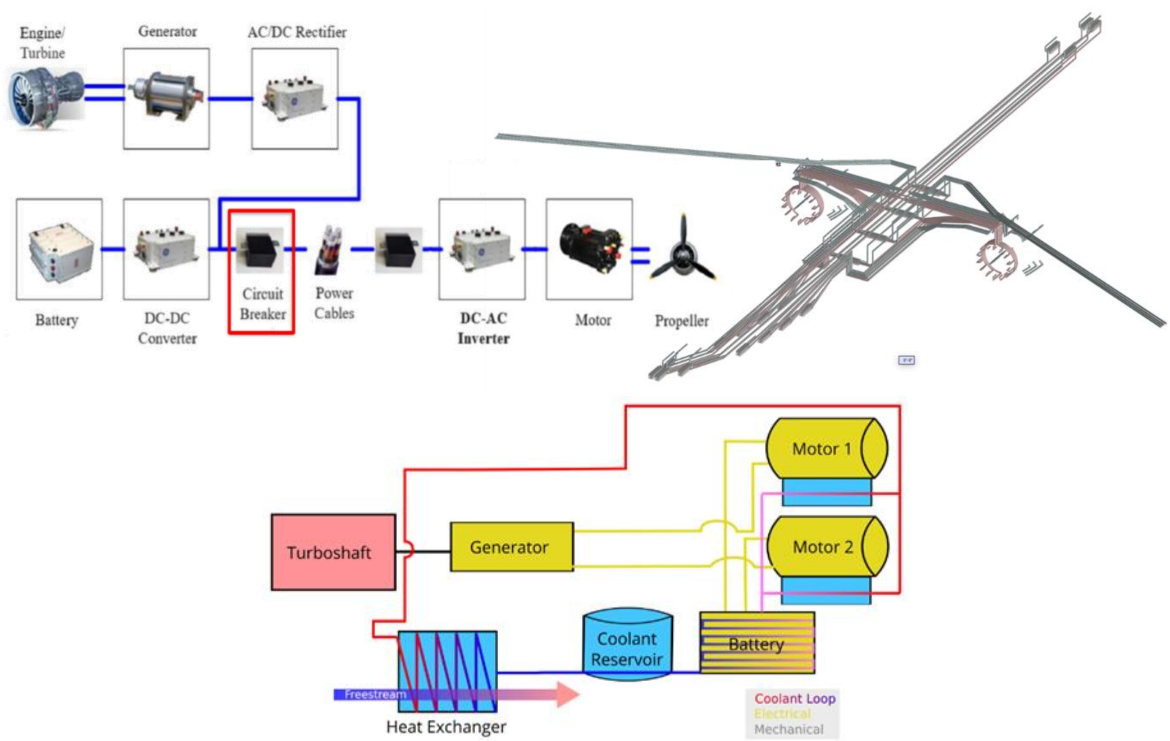


Figure 19. Optimized Powertrain with Integrated Fault and Thermal Management System (Zhang and Brelje)

XI. Conclusion

As summarized in Table 5, through a combination of advanced turbofan core/by-pass heat exchanger, advanced dynamically redirectable heat pipes, advanced hybrid electric powertrain optimization tool, and acoustic exergy amplification tubes, it is possible to provide solid-state cooling and fault management for an entire transport class electric aircraft. More-over, this solid-state system (no moving parts) can increase the propulsive efficiency of the vehicle while enabling ultra-fast response fault management. This increases the safety of the vehicle and protects personnel, aircraft, and sensitive power electronics/sensors.

Table 5. Technical Elements and Status

Subtask	Organization	Status	Deliverable
OpenConcept Thermal System Optimization	University of Michigan	In Development	Open source powertrain optimization tool
Turbofan HX	JPL	Preliminary Design	Core Heat Exchanger Demo
Acoustic Tube	NASA	Prototype Ordered	Full aircraft Exergy Efficient Recycling System
Switchable Long Heat Pipes	Advanced Cooling Technologies, Inc.	First prototype built and tested	Full aircraft heat transport solution
Fast Switchgear	Naval Postgraduate School	System Requirements Completed	TRL 6 Fault Management System compatible with TMS

Overall, when fully integrated into the airframe of the aircraft these technologies can potentially provide fully integrated power, propulsion, thermal, fault protection, and airframe systems that enable significant fuel, emission, noise, safety, and mobility benefits. These developments are critical for achieving new transport class certification standards over the next decade.

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