Electrified Aircraft Propulsion (EAP) Educational Briefing

12/19/2018

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Agenda

- Guidelines/Rules
- Proposal Best Practices
- Overview of NASA's Vision for Electrified Aircraft Propulsion (EAP)
- Overview of the needs in the specific area of battery technology, as it relates to EAP
- Overview of the needs in the specific area of additively-manufactured, multi-functional heat exchanger technology, as it relates to EAP

Guidelines/Rules

Discussion Guidelines/Rules

- This is an educational brief and includes discussions of general programmatic goals
  - NASA will not discuss if/how any of these goals are included in a given ongoing or forthcoming solicitation
  - For any solicitation, please refer to the goals/metrics stated within those requests for proposals (RFPs)/solicitations; proposals must be responsive to the stated requirements of those specific solicitations and not to any other stated or perceived need
  - Forthcoming solicitations may also contain other guidance, technical needs, and or challenge areas; please review solicitations fully

- Because of pending/formulating proposals, NASA will not assess, prioritize, discuss, or answer questions on proposed or ongoing technologies/solutions by those in this forum
  - Also note that this is an open forum with others in attendance

Proposal Best Practices

Small Business Innovation Research (SBIR) & Small Business Technology Transfer (STTR) Programs - Overview

- Because of ongoing/pending/future proposals/solicitations, specifics of the SBIR/STTR solicitation will not be discussed in this forum
- SBIR is a Small Business set-aside program for Federal R&D – including potential for commercialization
- STTR is a sister program for cooperative R&D between small business concerns and **U.S. research institutions** – including potential for commercialization
- For more information on NASA's SBIR/STTR program, please see https://sbir.nasa.gov/
  - The next Phase I solicitation cycle is anticipated to start in ~early to mid January
  - Note that public listings of past awards and companies are searchable at https://sbir.nasa.gov/advanced_search
- See the Small Business Administration website for additional helpful information including links to other agency SBIR sites/solicitations: https://www.sbir.gov/

SBIR/STTR Proposal - Advice

- The proposal process begins right now, not after the solicitation is released.
- Writing a winning a proposal is a long term process that involves:
  - Understanding the needs and interests of NASA
  - Interacting with the technical community
  - Read the solicitation carefully
    - Do not assume it is the same as last year
  - Reread it again, your competition did
- Provide all of the required information, forms, and surveys
- Make sure you properly address all of the listed evaluation criteria from the solicitation
  - Organize it in a way that makes it clear to the reviewers
- Explain (early and concisely) how your effort will benefit NASA interests.

SBIR/STTR Proposal – Writing Responsive Proposals

- Know your Vision
  - Target your work/proposal to the appropriate subtopic – be responsive
- Know the Context
  - Read the solicitation carefully
  - Understand the scientific and technological importance of your idea (who cares, big picture)
  - Understand the programmatic relevance of your idea
  - Use National Academy reports, conference reviews, NASA Strategic Plans, Roadmaps for guidance
- Justify Why You and Not Somebody Else
  - Justify and clearly define your firm and roles of the team
- Define the State of the Art
  - Demonstrate your grasp of the field; offer a short, well-researched overview of relevant science and technology; cite key references
  - Demonstrate an understanding of the state of the art and how you will advance it

SBIR/STTR Proposal – Writing Responsive Proposals

- Describe Your Contribution
  - What will your work contribute to the field? Scientific knowledge, increased capabilities, applications to NASA's missions?
  - Don't over-claim or over-reach; justify the claimed factors of gains
- Defend Your Proposal
  - Can you do the job on schedule/budget?
- Understand and Respect Your Audience
  - Make sure your abstract, charts, etc. are clear/concise; make it so the reviewer can easily identify the information for the evaluation criteria
  - Make sure you address all selection criteria; somebody will be checking
  - Make your key idea clear; repeat
  - Neatness, including spelling and grammar, counts
  - Reviewers are NASA subject matter experts; they understand the field and technical area but may not already know the details of your specific innovation, especially if it differs significantly from the state of the art

SBIR/STTR Proposal – Writing Competitive Proposals

A competitive proposal will clearly and concisely:

- Describe the proposed innovation **relative** to the **state of the art AND** the relevance/significance of the proposed innovation to the **needs of the subtopic**
  - Compare your anticipated/target metrics vs. the state of the art; **state both**
  - State how your metrics address the subtopic metrics/goals; if improving a different subcomponent metric that feeds into improvements on the stated subtopic metric or goal, discuss how these metrics are **derived/involved**
- Address the scientific, technical, and commercial merit and feasibility of the proposed innovation, and its relevance and significance to NASA interests.
  - State what the known **risks/challenges** are and **how** your innovation and/or development plan will **address** them
  - Work Plan: **What** will be done, **where** it will be done, and **how** the R/R&D will be carried out
    - Clear development plan with clear metrics and decision gates where appropriate
  - For all of these, describe also the **'why'**

SBIR/STTR Proposal – Writing Competitive Proposals

A competitive proposal will clearly and concisely (continued):

- Provide a strategy to addresses technical, market, and business factors pertinent to the development, demonstration, and transition into products and services for NASA mission programs, the commercial aerospace industry, and other potential markets and customers.
  - Is there a demonstrated understanding of what is needed to **infuse** this concept
  - End-applications may inform what key developments are needed and justify approach
  - Is your design and development/test plan **informed by end-applications** to justify further investment and **encourage transition** to use?
  - Do **key** milestone **tests** and **prototypes/deliverables** **justify** continued investment/acceptance of the technology?
  - Is your development lifecycle within and beyond this development program **continuous** or does it leave **gaps**?

STTR: Provide information to convince NASA that the cooperative effort is a sound approach for **converting** technical information resident at the Research Institution (RI) into a **product or service** that meets a need described in a Solicitation research topic.

References:

- For source material for this presentation and additional guidance, please see the SBIR website; one helpful tool is the interactive participation guide and links therein: https://sbir.nasa.gov/guide
- Additionally, some presentation material referenced from “Writing Responsive Proposals”, B. Benvenutti, Z. Burkland, M. Davidson. **Innovation & Opportunity Conference: Advancing Aerospace and Defense**. Nov. 7-8, 2018. Aurora, Colorado

Overview of NASA’s Vision for Electrified Aircraft Propulsion (EAP)

Slides from:

NASA’s Vision for Aircraft Electric Propulsion and Power

Jay Dryer, Director, Advanced Air Vehicles Program
Aeronautics Research Mission Directorate
July 12, 2018

Representative Electric Aircraft Missions and Related Battery Needs

Ralph Jansen, NASA Glenn Aeronautics Project Office
September 25, 2017

Global Growth in Aviation

2017

4 BILLION

PASSENGER TRIPS

2036

7.8 BILLION

PASSENGER TRIPS

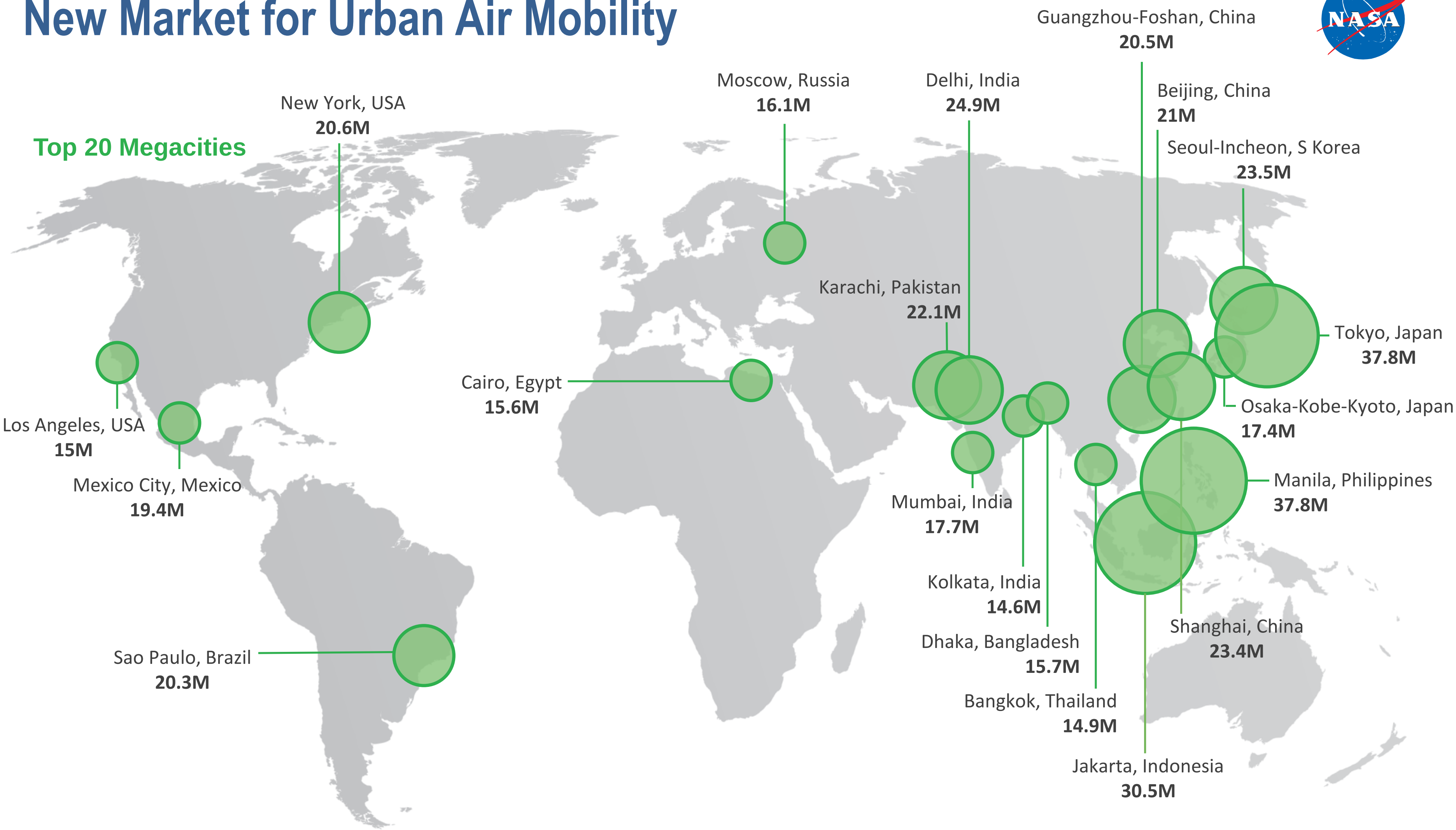
41,030
New Aircraft Deliveries

$6.1 Trillion
Market Value

Asia-Pacific Market is Nearly
40%
of New Aircraft Deliveries

78%
of New Aircraft Deliveries are Single Aisle Class (including Regional Jets)

New Market for Urban Air Mobility



Large projected market–McKinsey analysis of demand by 2030 in 15 major U.S. cities:

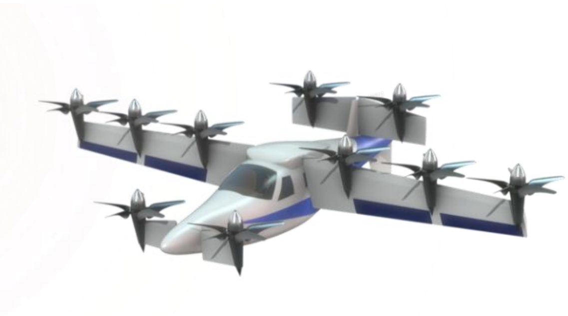
- 500 Million annual UAS package deliveries
- 750 Million annual passenger trips

Extrapolation to the global market would likely increase demand by 5 to 10x

Top 20 Megacities by population
data from allianz.com 03.16.15

Benefits of Electrified Aircraft Propulsion

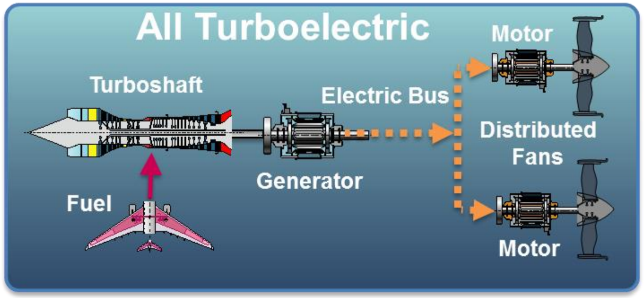
- Improvements to highly optimized aircraft like single-aisle transports
  - Potential fuel burn reduction estimated using turbo electric distribution to Boundary Layer Ingestion thruster in addition to other benefits from improved engine cores or airframe efficiencies.
- Enabling new configurations of VTOL aircraft
  - Enable new VTOL configurations with the potential to transform transportation and services.
- Revitalizing the economic case for small short-range aircraft services
  - The combination of battery-powered aircraft with higher levels of autonomous operations could reduce the operating costs of small aircraft operating out of community airports resulting in economically viable regional connectivity.

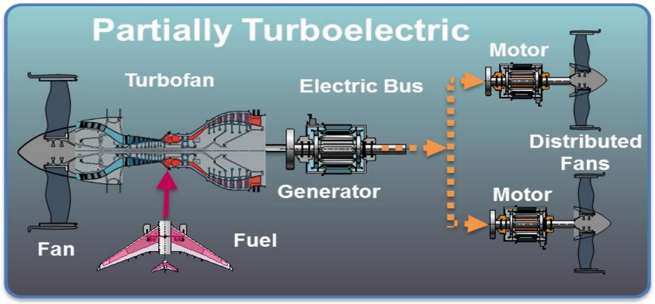


Types of Electrified Aircraft Propulsion

Electrified Aircraft Propulsion (EAP) systems use electrical motors to provide some or all of the thrust for an aircraft

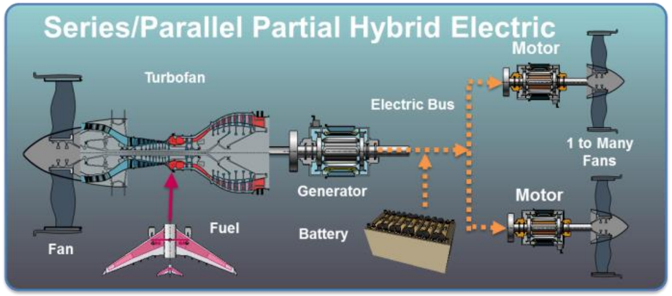
- Turboelectric systems use a turbine driven generator as the power source. Partially turboelectric systems split the thrust between a turbo fan and the motor driven fans.

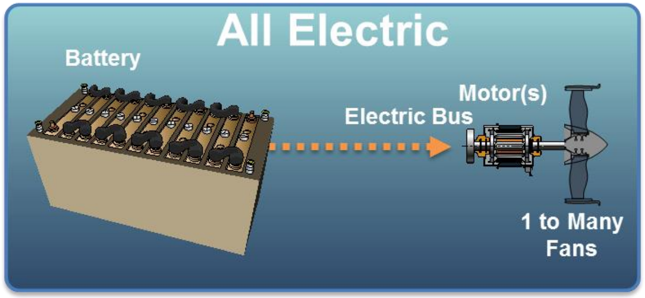




- Hybrid electric systems use a turbine driven generator combined with electrical energy storage as the power source. Many configurations exist with difference ratios of turbine to electrical power and integration approaches.

- All-electric systems use electrical energy storage as the only power source.





Example Missions

THIS IS NOT STRICT DEFINITIONS, THEY ARE JUST A FEW REPRESENTATIVE EXAMPLES

Mission	Number of Passengers	Typical Range	Typical Speed	EAP Configurations
Urban Mobility	<=4	<50 miles	<200 miles/hr	• All electric • Hybrid Electric
Thin Haul	<=9	<600 miles	150-250 miles/hr	• Hybrid Electric
Short Haul Aircraft	40-80	<600 miles	350-500 miles/hr	• Hybrid Electric
Single Aisle	150-190	900 mile typical mission, 3500 mile maximum range	≈600 miles/hr	• Hybrid Electric • Turbo Electric

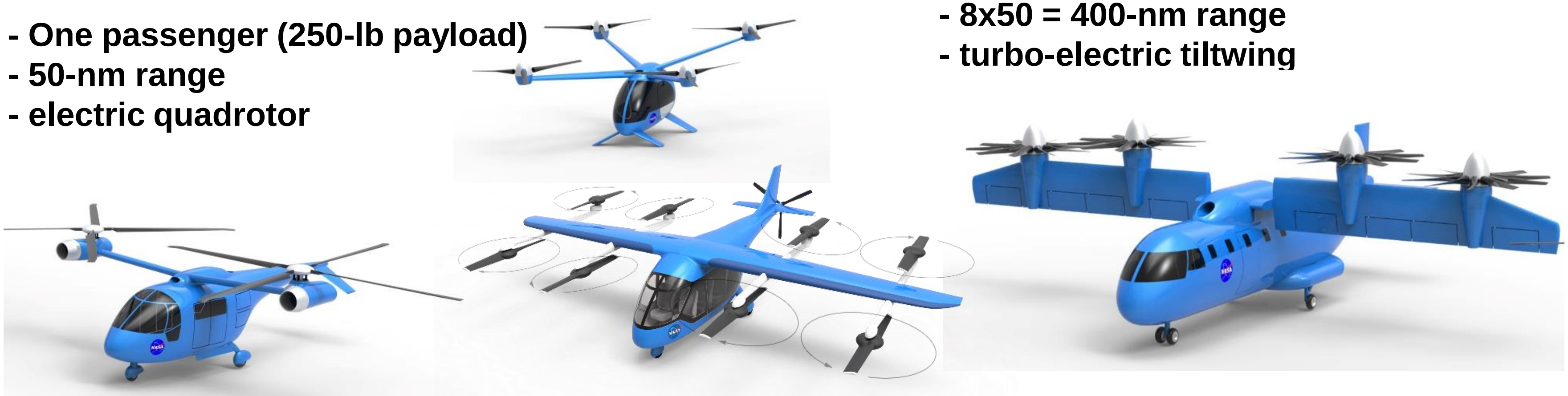
Electrified Aircraft Propulsion Barriers by Vehicle Class

Technology Area	Urban Air Mobility	Thin Haul / Short Haul	Single-Aisle
Power Distribution	• Flight Critical	• Flight Critical	• Flight Critical • High Voltage (>1000)
Energy Storage	• 400 W-hr/kg (at system level)	• 400 W-hr/kg (at system level)	
On Aircraft Power Generation / Turbines	• Light Weight / High Efficiency IC engine, turbine, or fuel cell	• Flight Weight MW turbogenerator	• Combined thrust and MW power extraction
Propulsion / Airframe Integration	• Highly distributed		• Projected PAI benefit
Autonomy	• No pilot operation	• Reduced pilot operation	

Exploring Concepts for Urban Air Mobility

Open, publicly-available reference vehicle configurations

- Cover a wide range of technologies and missions
- Provide focus for trade studies and system analysis
- Assess failure modes and hazards of concept vehicle electrified propulsion architectures



- One passenger (250-lb payload)
- 50-nm range
- electric quadrotor

- Fifteen passengers (3000-lb payload)
- 8x50 = 400-nm range
- turbo-electric tiltwing

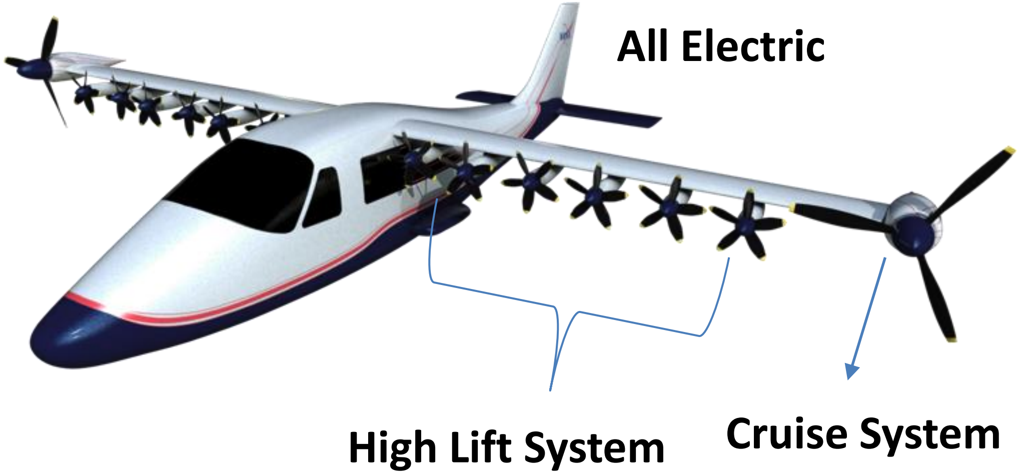
- Six passengers (1200-lb payload)
- 4x50 = 200-nm range
- hybrid side-by-side helicopter

- Six passengers (1200-lb payload)
- 2x37.5 = 75nm range
- turbo-electric Lift+Cruise VTOL

Learning from Development & Flight with the X-57

X-57 “Maxwell”

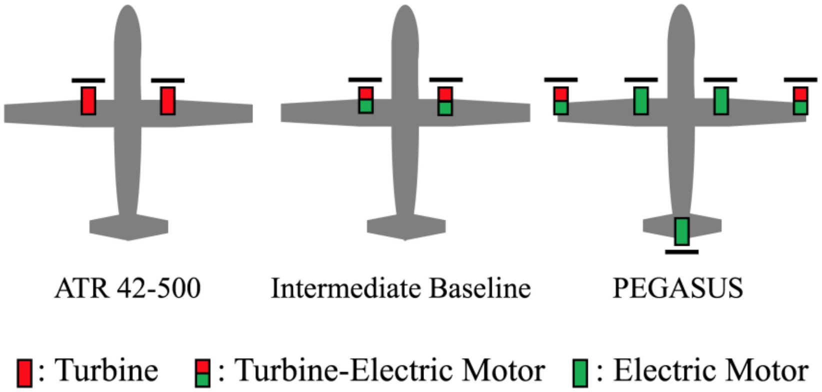
- Cruise-sized wing: enabled by distributed electric propulsion system for takeoff/landing performance
- High-efficiency cruise propellers: electric motors mounted at wingtips
- All-electric propulsion system: 40+ kWh battery, 240 kW across 14 motors
- Fully redundant powertrain
- Documented safety reviews and safe operational procedures



Key learning on more electric systems that can help the community

Example Short Haul

- NASA PEGASUS: Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS) is a novel hybrid electric regional aircraft that strategically locates multiple electric and hybrid electric propulsors to obtain aerodynamic benefits. 48 Passengers, Range 200-600 miles, speed 300 knots (345 miles/hr)



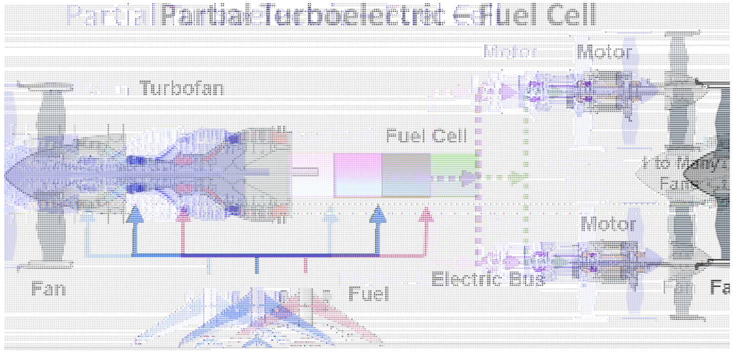
Batteries assumed to be 500W-hr/kg

Example Single Aisle Partial Turboelectric

- NASA STARC-ABL: fuel burn reduction 7-12%, same range, speed, airport infrastructure. Same turbine/airframe technology, advanced 2-3MW power system, BLI, turbogenerator integration

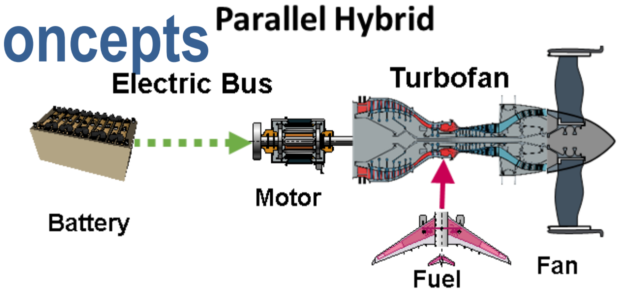
Batteries could be added to these concepts for airport taxi, reduction of peak turbine power, etc.

- Boeing SUGAR Freeze: fuel b n 56% for 900 mile mission, utilizes a truss-braced wing comb boundary-layer ingesting fan in an aft tail cone to maximize a efficiency. The aft fan is powered by a solid oxide fuel cell e and driven by a superconducting motor with a cryogeni agement system



Example Single Aisle Parallel Hybrid Concepts

- Airframe/propulsion remains relatively decoupled

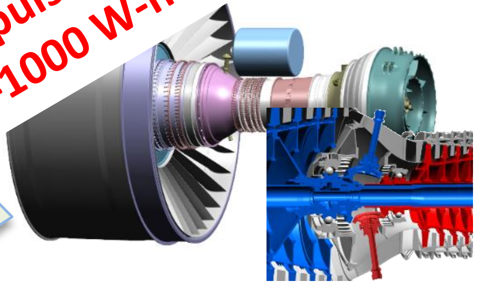


Boeing Sugar Volt

- Parallel hybrid, 150 passenger, 900 nm
- 1.3 and 5.3 MW machines considere
- Fuel off-loaded 750 W-hr/kg ba d from grid
- 60% fuel burn reduction

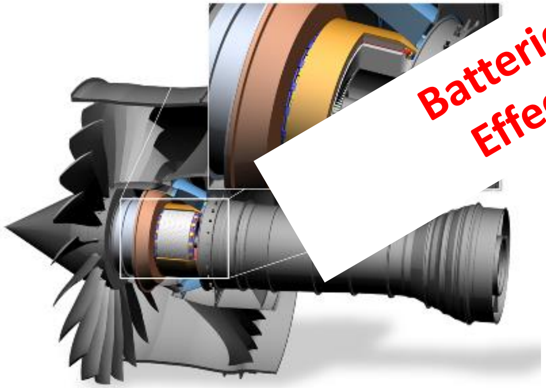
UTRC hGTF – **On-going, optimized geared turbofan engine for crui by adding boost power for take off and climb**

- Parallel hybrid, 150 passenger, 900 nm
- 2.1 MW machines, 1000 W-hr/kg batteri
- 6% reduction in fuel burn and 2.5% energy usage



Batteries used for 500-900 miles of propulsion power

Effective Specific Energy Needs: 750-1000 W-hr/kg



R-R LibertyWorks EVE – **On-going, parametrically optimized engine with hybrid climb & cruise segments**

- Parallel hybrid, 150 passenger, 900 nm
- 28% reduction in fuel burn for a 900-nm mission
- Up to a 10% total energy reduction for a 500-nm
- Optimizing for minimum fuel usage predicts an 18 percent reduction in total fleet fuel usage.

Battery Needs Based on Missions

THESE ARE NOT STRICT REQUIRMENTS, THEY ARE BASED ON A FEW REPRESENTATIVE EXAMPLE STUDIES

Mission	Power Level	Specific Energy	Cycles	Reliability
Urban Air Mobility	200-500kW	250 – 400 Whr/kg	≈25-50/day 12,000/year	Flight Critical
Thin Haul	200-500kW	300 – 600 Whr/kg	≈4-12/day 2600/year	Flight Critical
Short Haul Aircraft	500-1500kW	300 – 600 Whr/kg	≈4-12/day 2600/year	Flight Critical
Single Aisle	1000-5000kW	750 – 1000 Whr/kg minimum	≈4-8/day 2000/year	Important / Flight Critical

Conclusion

- There is potential for aircraft with more electric propulsion systems to have tremendous impact on a number of aviation markets.
- Small prototype electric aircraft are flying (1-2 persons).
- NASA and Industry are making investments in technology to enable larger electric aircraft.
- NASA and Industry are making investments in aircraft demonstrations and certification standards to help enable the transition to certified production aircraft.
- NASA is working to address some of the key enabling technical challenges to realize this new capability.

Overview of Battery Technology

Battery Needs Based on Missions

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High Specific Energy

> 400 Whr/kg battery level

- Higher energy chemistry
- Improved, lightweight packaging
- Multifunctionality
- Improved functional thermal operation window

High Specific Power

Capability to respond to aircraft power needs without sacrificing specific energy density

- Hybrid chemistries
- Electrode configurations
- Cell and / or battery configurations
- Rapid recharge capability

Cycle Life

High Cycle life without sacrificing specific energy density

Cycles per year: 2000 - >10,000

- Improved battery chemistries
- Improved electrode configurations
- Improved cell and / or battery configurations

Safety

Safe battery design without sacrificing performance and/or specific energy density

- Improved battery chemistries
- Nonflammable components
- Thermal runaway propagation prevention
- Improved cell and battery configurations
- Improved sensing and predictive modeling

Reliability

Minimize cell and battery failures

- Improved battery chemistries to improve consistent performance
  - Wide environmental operating envelope
  - Wide performance operating envelope

- Improved cell and battery configurations
  - Connections
  - FOD
  - Matching Impedance

- Minimize moving parts

Thermal

Minimize the impact of the thermal subsystem to the overall battery specific energy density

- Wide environmental (temperature) operating envelope
  - Improved battery chemistries with large range of operational temperature

- Improved cell and battery design
  - Optimize passive thermal rejection
  - Improved thermal materials

Advanced Configurations

Optimal designs to maximize specific energy densities, performance, reliability and safety

- Multifunctionality
  - Structure
  - Thermal
  - Other?
- Improved cell designs
- Advanced packaging concepts
- Advanced fabrication methods to improve
  - Utilization
  - Specific Energy Density
  - Performance metrics

Conclusion

There is a need for significant advancements in energy storage technologies for future aircraft needs

Higher Specific Energy
Higher Specific Power
Higher Cycle Life
Safety
Reliability
Thermal Management

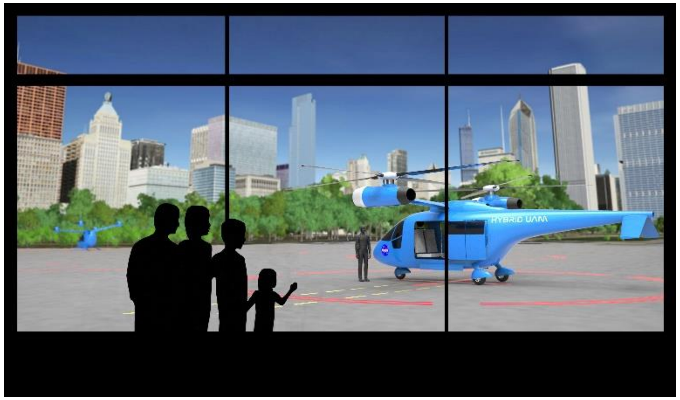
Overview of Heat Exchanger Technology

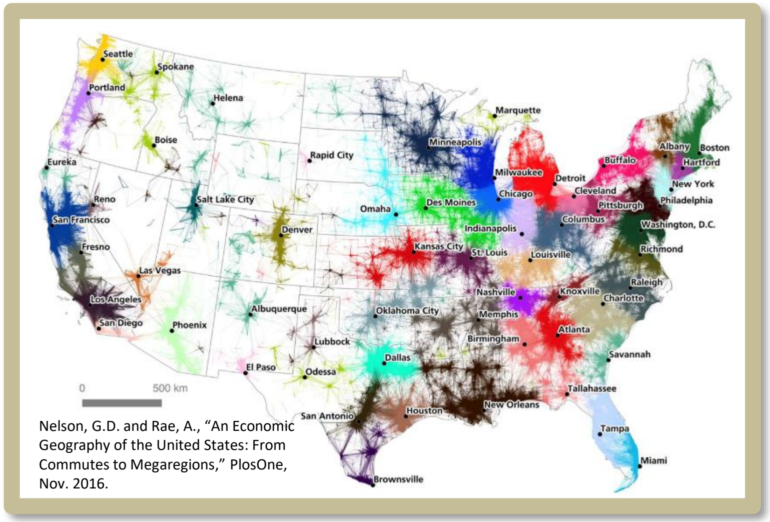
Technical Challenges Overview

- **The problem: Electric aircraft propulsion (EAP)requires electric components that produce low grade heat loss. Managing this heat requires heat exchangers, which in turn add a weight penalty that may cancel out the benefits of EAP.**
- What advanced materials or manufacturing processed can make the most lightweight, multifunctional heat exchangers?
- What other functions could a heat exchanger provide that might offset its weight penalty? (i.e. structural, managing heat from another system, etc.)
- What applications of a multifunctional heat exchanger can produce the most impact?

Possible Application: Small Recuperated Turbine Engine

- On Demand Mobility (ODM) may find benefit in a hybrid solution.
- Fully electric vertical takeoff and landing (VTOL) vehicles are have limited range abilities.
- Hybrid electric may allow the completion of more missions in a day because aircraft will not be on the ground as long or as often charging. This may also lead to a reduction in the number of vehicles required to meet demand, driving down cost.
- Hybrid electric might also allow the service of “megaregions” (bottom right), or people that commute further distances than the range that can be supported by batteries.
- Further, hybrid electric may offer a near term solution as battery technology continues to mature to the energy densities needed for air taxi operations.

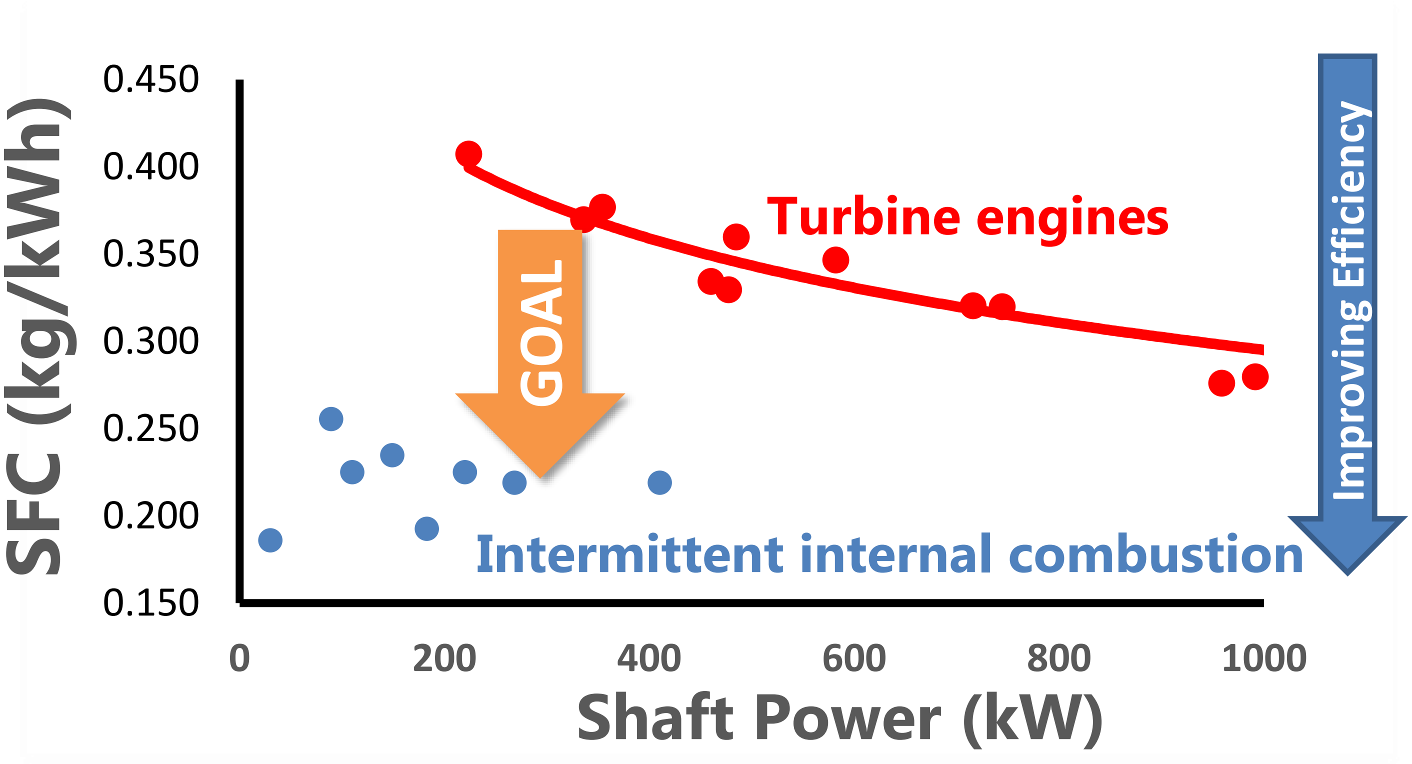




Nelson, G.D. and Rae, A., “An Economic Geography of the United States: From Commutes to Megaregions,” PlosOne, Nov. 2016.

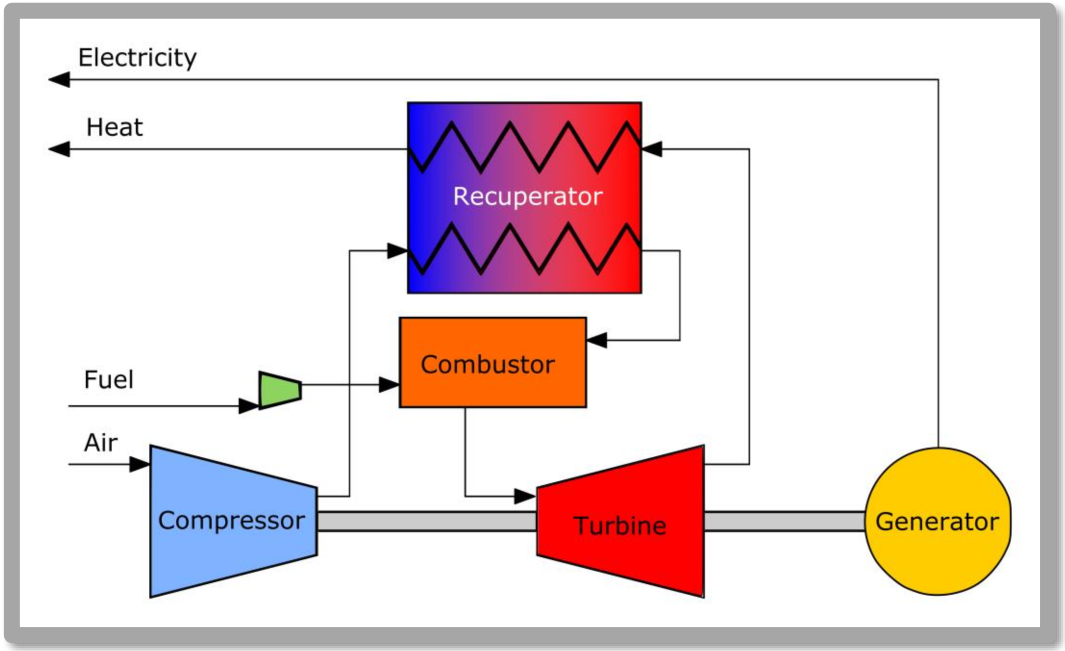
The Problem: Gas Turbines lose some efficiency benefit at small power scales

- Turbine engines have roughly 2x the specific power of Internal Combustion engines at small power scales
- However, at small power scales they are not as efficient (right)
- Can we improve the efficiency of turbine engines while preserving the specific power benefit?



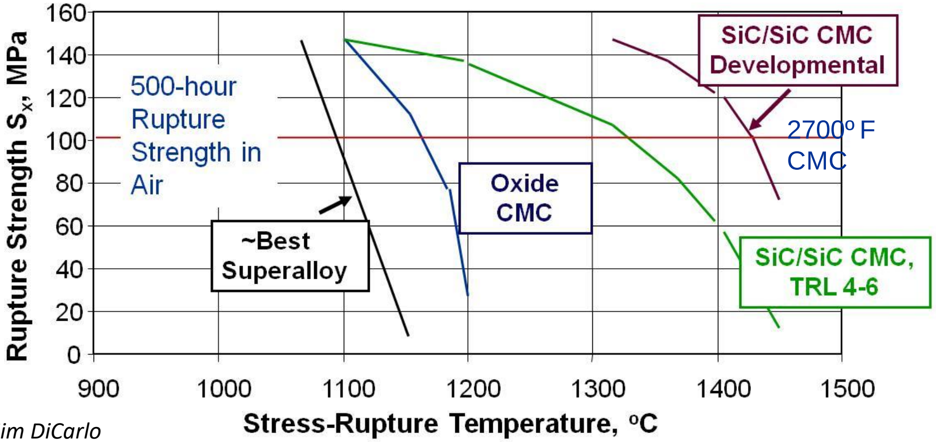
Why recuperation?

- Recuperation uses waste heat from the turbine to heat up air going into the combustor for an efficiency benefit
- Recuperators add significant weight to the system.
- **Can we design a recuperated turbine engine system without a weight penalty by leveraging:**
  - **Advanced materials?**
  - **Additive manufacturing?**
  - **Multifunctionality?**



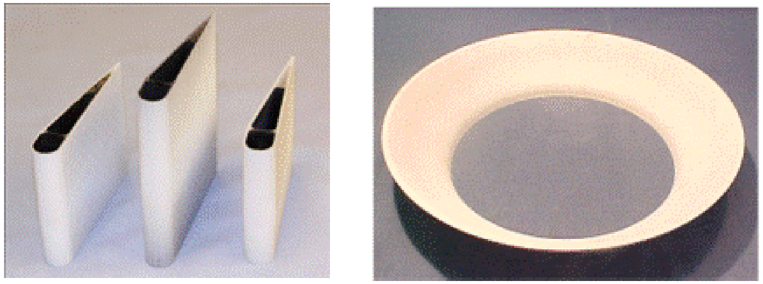
Benefits of Ceramic Matrix Composites in Propulsion Systems

CMCs are enabling materials for aero-propulsion and other high temperature extreme environment applications



Jim DiCarlo

SiC/SiC CMCs offer significant advantage over superalloys at 1/3 density



Coated CMC Components from NASA Programs

Additive Manufacturing of CMCs

Additive Manufacturing of CMCs

Conventional Manufacturing

- Customized parts in small volumes are time consuming and expensive to produce.
- Complex shape fabrication issues: mold design, dimensional tolerances, etc..
- Manufacturing of multifunctional parts are challenging.

Additive Manufacturing

- Small series of ceramic parts can be manufactured rapidly and cost-effectively.
- Specific molds are not required.
- Different designs can be optimized (no major cost of changes)
- Parts with significant geometric complexity.

Material and Process Challenges

- Property and behavior of starting materials
- Sintering and densification challenges
- Process modeling
- Mechanical behavior
- NDE and in-situ damage characterization
- Material and property databases

Long term research efforts have now resulted in various applications.

Efforts in this very promising field are now underway.

Materials and processing challenges are quite similar

Applications of Additively Manufactured SiC

- SiC is a lightweight (3.2 g/cc), thermally conductive (~40 w/mK) material with high temperature capability (>1200°C).

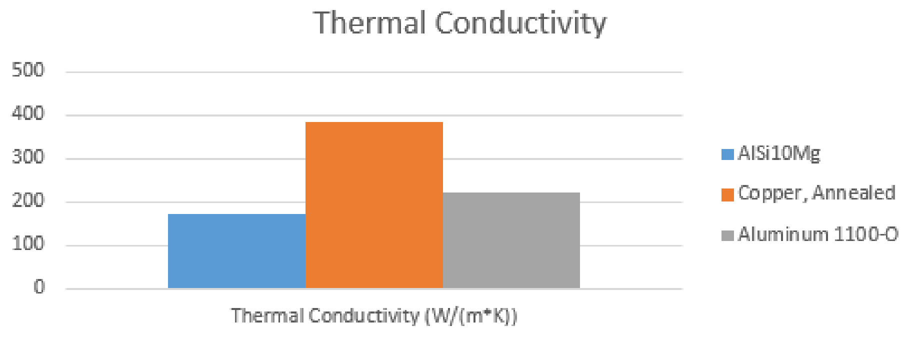
- Innovative manufacturing development of SiC could enable heat exchangers with up to 50% weight reduction, compared to metals.

- Lightweight heat exchangers can be used to improve the efficiency small of hybrid electric aircraft- such as the ones envisioned for On-Demand Mobility.

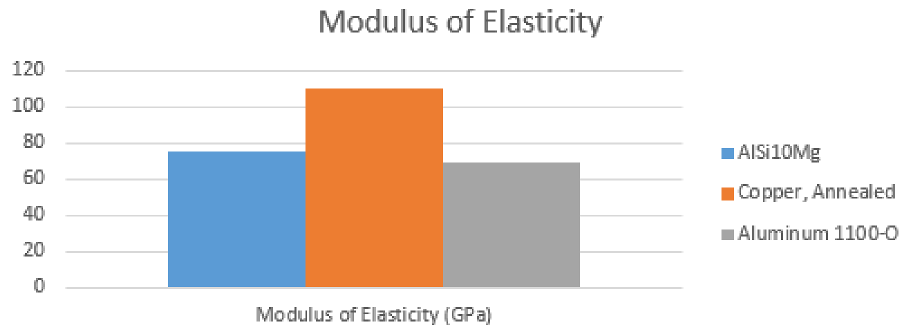
- Initial studies have shown that ceramics, such as SiC can be printed, but extensive studies on the material optimization and durability have yet to be explored.

Metals for Additively Manufactured Heat Exchangers and Heat Sinks

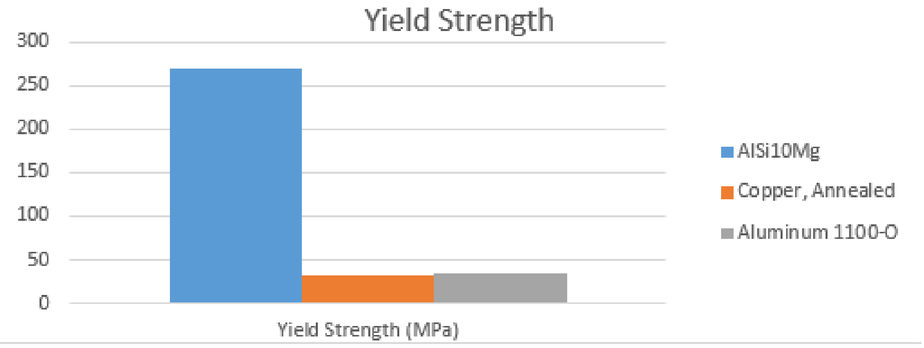
- Due to the multiple properties involved in selecting the material with which to construct the heatsink, sometimes the best material is not one which is necessarily the strongest in any one property.
- Sometimes constraints such as use temperature over-ride otherwise attractive properties.
- In this way, a high performance aluminum alloy may be ideal for certain applications (like a structural heatsink for thermal management of electrical systems) by non-ideal in others (such as a high temperature jet turbine recuperator).
- Metals often excel where impact resistance and toughness are required with lightweight alloys becoming feasible for lower use temperatures.
- Metals (instead of ceramics) are also useful where both thermal management and mechanical strength are desired in the same part, such as this structural heatsink:



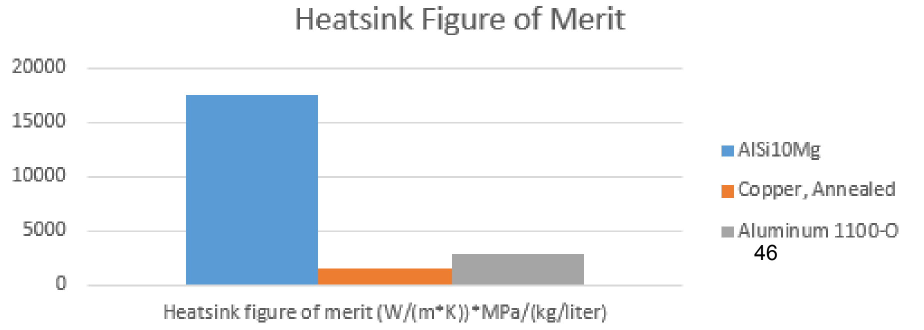
Thermal Conductivity



Modulus of Elasticity



Yield Strength

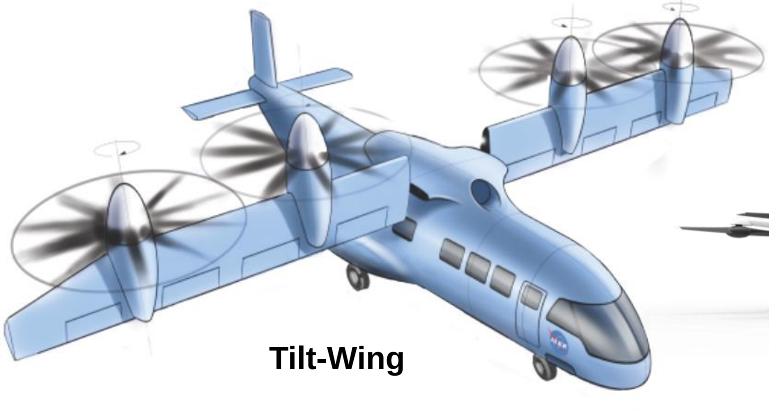


Heatsink Figure of Merit

Possible Application: Thermal Structural Management for Enabling Electrified Aircraft

The Problem:

Component inefficiencies produce low-grade waste heat generated in motors, batteries, and power electronics for electrified aircraft.



Tilt-Wing

Lift+Cruise

Side-by-Side Helicopter

X-57

Ref: Silva, Christopher, et al. "VTOL Urban Air Mobility Concept Vehicles for Technology Development." *2018 Aviation Technology, Integration, and Operations Conference*. 2018.
Ref: https://www.nasa.gov/aeroresearch/X-57/technical/index.html

Need: A Multifunctional Aircraft Skin Panel

- Can a <u>system-level light-weight benefit</u> be shown for a structurally/thermally optimized aircraft skin panel*?

- Can <u>an efficient path to manufacturability</u> be shown for a structurally/thermally optimized aircraft skin panel*?

*Aircraft skin panel includes stiffened structure.

Can a system-level light-weight benefit be shown for a structurally/thermally optimized aircraft skin panel?

- Heat Exchanger Design Space
  - Lightweight topologies
  - e.g. lattice frame materials, branching structures?
- Aircraft Location: wing, fuselage, nacelle
- Heat exchanger integrated Into the aircraft skin
- Meets structural requirements
- Optimized for weight
- Demonstrated light-weight benefit at a system-level

Can an effective path to manufacturability be shown for a structurally/thermally optimized aircraft skin panel?

- Material Selection
  - High thermal performance
  - High mechanical performance
  - Low density
  - Manufacturability by advanced additive methods
- Additive Manufacturing
  - Prototyping
  - Complex topology
  - Scalability
  - Maintaining performance
  - Path to certification

Q&A and Introductions

- You are welcome to ask questions but please be aware of the guidance/rules

- When speaking, you are welcome (but not mandated) to introduce yourself and your company/institution if you so choose for the awareness of all of those participating

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Guidance/Rules:

- This is an educational brief and includes discussions of general programmatic goals
  - NASA will not discuss if/how any of these goals are included in a given ongoing or forthcoming solicitation
  - For any solicitation, please refer to the goals/metrics stated within those requests for proposals (RFPs)/solicitations; proposals must be responsive to the stated requirements of those specific solicitations and not to any other stated or perceived need
  - Forthcoming solicitations may also contain other guidance, technical needs, and or challenge areas; please review solicitations fully

- Because of pending/formulating proposals, NASA will not assess, prioritize, discuss, or answer questions on proposed or ongoing technologies/solutions by those in this forum
  - Also note that this is an open forum with others in attendance