NASA Interests in Superconducting and Cryogenic Technology

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2024 Naval Applied Superconductivity Program Review
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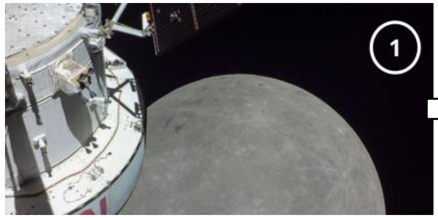
Space Applications

Space – Notable Applications

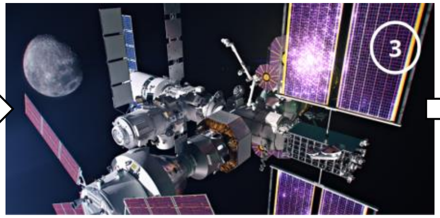
Moon to Mars (incl. Artemis)

- Architecture[1] & objectives[2]



Human Lunar Return

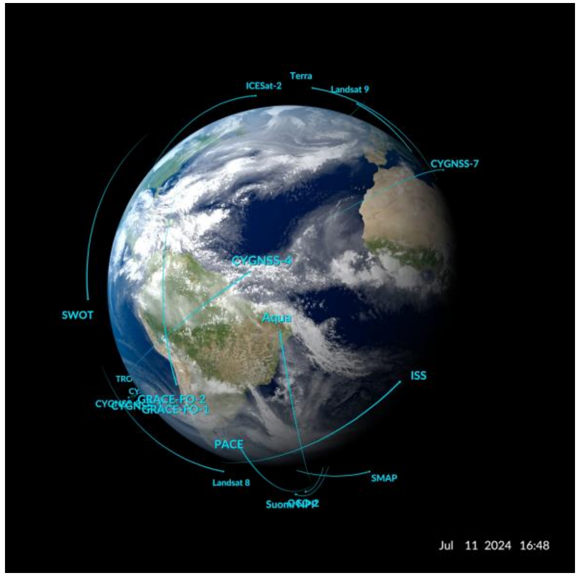
Foundational Exploration



Sustained Lunar Evolution

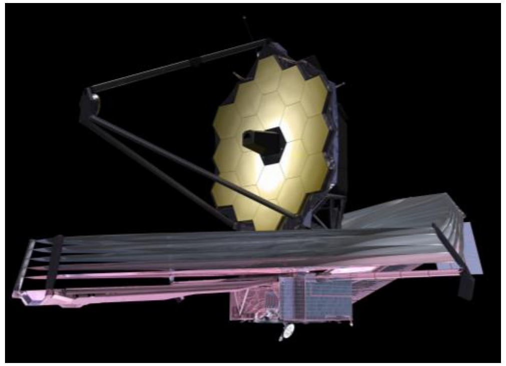
Humans to Mars

Earth science

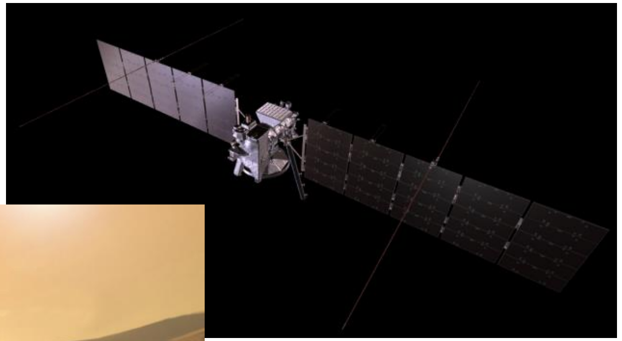


Credit: NASA's Scientific Visualization Studio

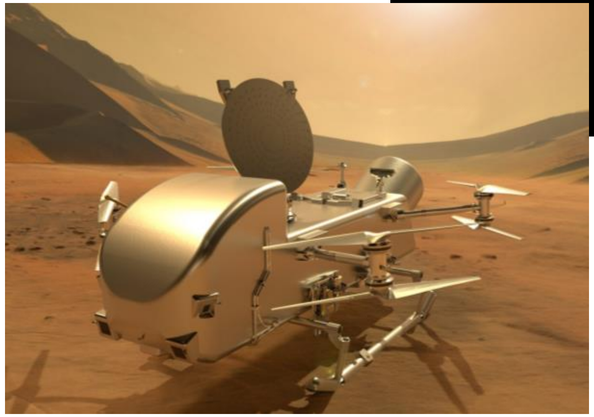
Telescopes



Other solar system exploration



Europa Clipper



Dragonfly

1. https://www.nasa.gov/moontomarsarchitecture/
2. https://www3.nasa.gov/sites/default/files/atoms/files/m2m-objectives-exec-summary.pdf

Space – Technology Needs

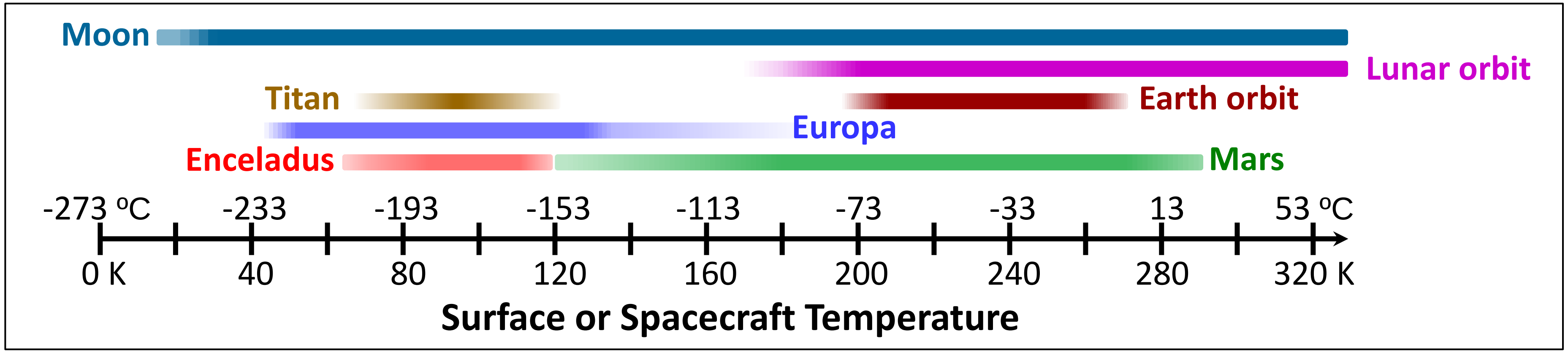
- Identified as 187 technology ‘shortfalls’ released Spring 2024[3]
    - Shortfall rankings released last week

Relevant shortfalls	Shortfall rank (out of 187)	Relevant critical technology gaps
Cryogenic Liquefaction	76	High Capacity, High Efficiency Cryocoolers 90K
		High Capacity, High Efficiency Cryocoolers 20K
In-space and On-surface, Long-duration Storage of Cryogenic Propellant	17	High vacuum MLI
		Soft vacuum insulation
		Load bearing insulation
		Cryo thermal coating
		Low conductivity structures
High Power, Long Distance Energy Transmission Across Distributed Surface Assets	32	Transmission Cable Systems up to 10 kWe Increment, AC and DC at > 1 kV
		Surface Power Transfer Cables/Connectors/Dust Compliant
		Cabled Power Transmission in Permanently Shadowed Regions

3. https://www.nasa.gov/spacetechpriorities/

Space – Environments

- Temperature

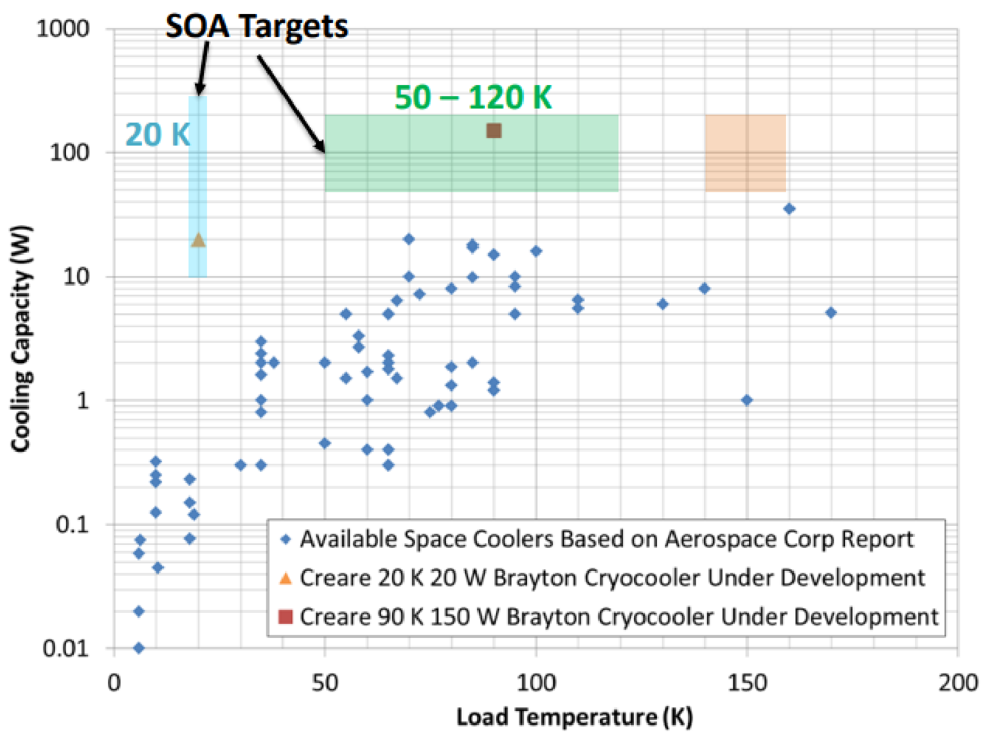


- Atmosphere
  - Pressure ranges from hard vacuum (e.g., Moon) to thin (e.g., Mars) to thick (Titan)
- Radiation[4]
  - <u>Persistent</u>: solar radiation and galactic cosmic rays
  - <u>Erratic</u>: single event effects

4. SLS-SPEC-159 Cross-Program Design Specification for Natural Environment (DSNE) Rev G

Space – Perennial Interests

- Cryocoolers
  - Liquefaction (20 K (LH2), 90 K (LOx)) for nuclear thermal propulsion, IRSU on Moon/Mars, ascent/decent vehicles, etc
  - For science instruments (mK to ~10 K)
  - Needs: higher lift, lower specific mass (kg/W), lower specific power (W/W), lower vibration
- Cryogen storage
  - Passive & active thermal control for reduced & zero boil-off (e.g., broad area cooling)
  - Needs: reduced mass, weeks to 4+ year storage
  - Funded efforts: composite, additive manufactured, & inflatable tanks
- In-space propellent transfer & mass gauging in zero G



SOA & NASA targets circa 2020 [5]

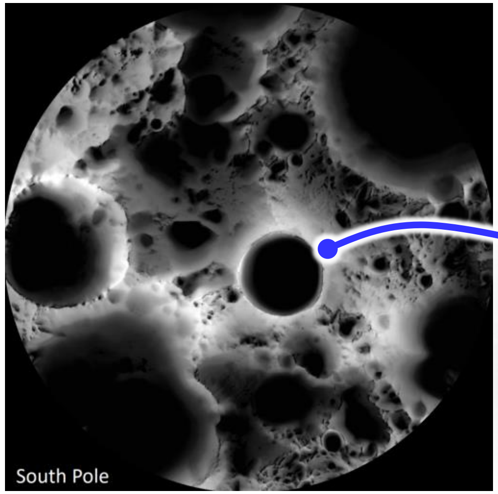
Carbon composite tank

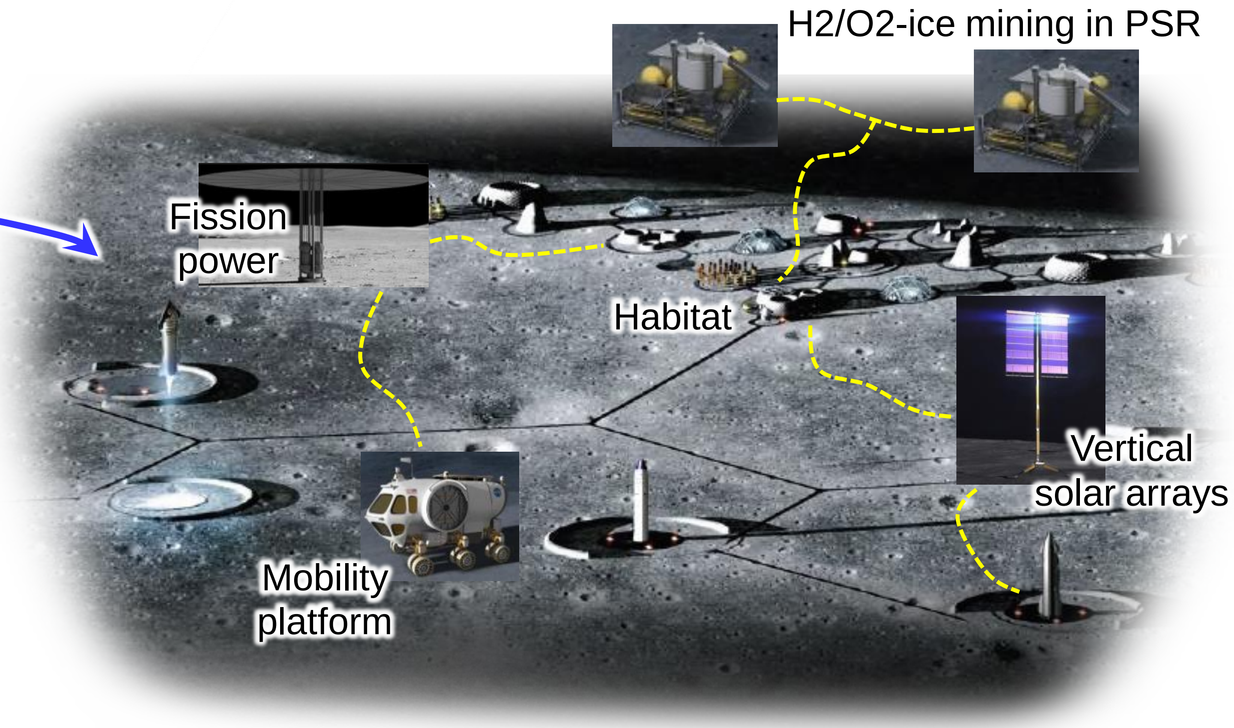
credit: Gloyer-Taylor Laboratories Inc.

5. https://ntrs.nasa.gov/citations/20205010721

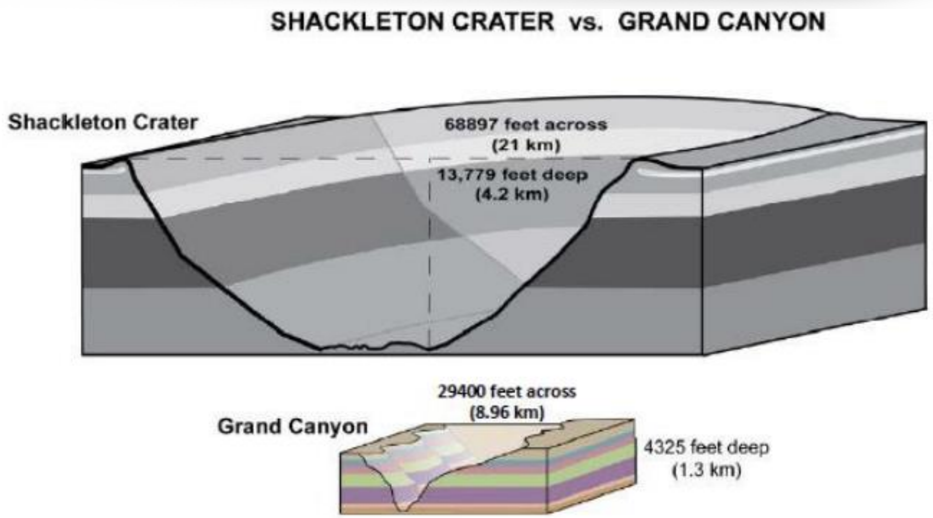
Space – Newer Interests

- Lunar infrastructure for sustained human presence on Moon is of high interest
  - Power generation & distribution within PSRs (extreme cold) and between PSRs and sunlit areas





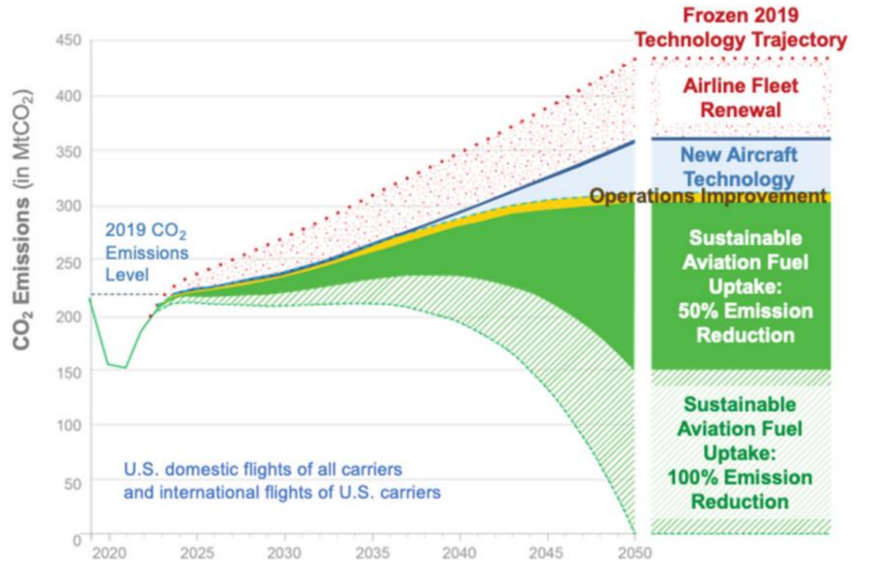
- Shortfall on energy transmission lists need for “superconducting cables of 10 kW capacity and 5 km length for use in permanently shadowed regions (PSR)”
- Surface temperature in PSRs is roughly 20 K to 90 K, but superconducting won’t be a ‘free lunch’



Aeronautics Applications

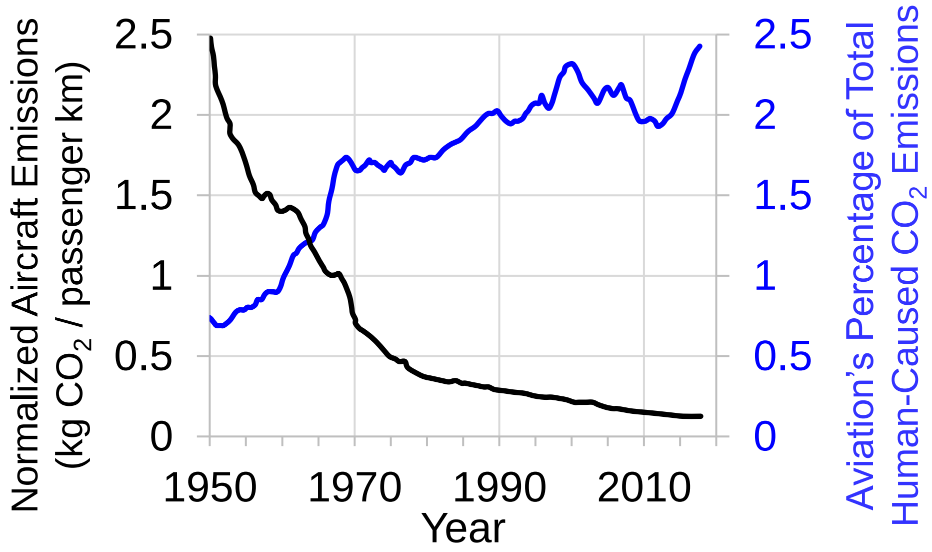
Aero – Technology Needs

- NASA strategy defined in Strategic Implementation Plan[6] (updated 2023)
  - Relevant Strategic Thrust: ultra-efficient subsonic transport
    - Need: propulsion system with increased efficiency, reduced emissions & noise, & targeting alternative energy sources
- US Aviation Climate Action Plan[7] (2021) set goal for net-zero carbon emissions by 2050
- *Status quo won't cut it* – global CO_2 emissions from aviation growing at increasing rate
- *CO_2 not the only problem*
  - Contrails, NO_x, water vapor, soot, sulfur



Aviation Climate Action Plan's path to net-zero

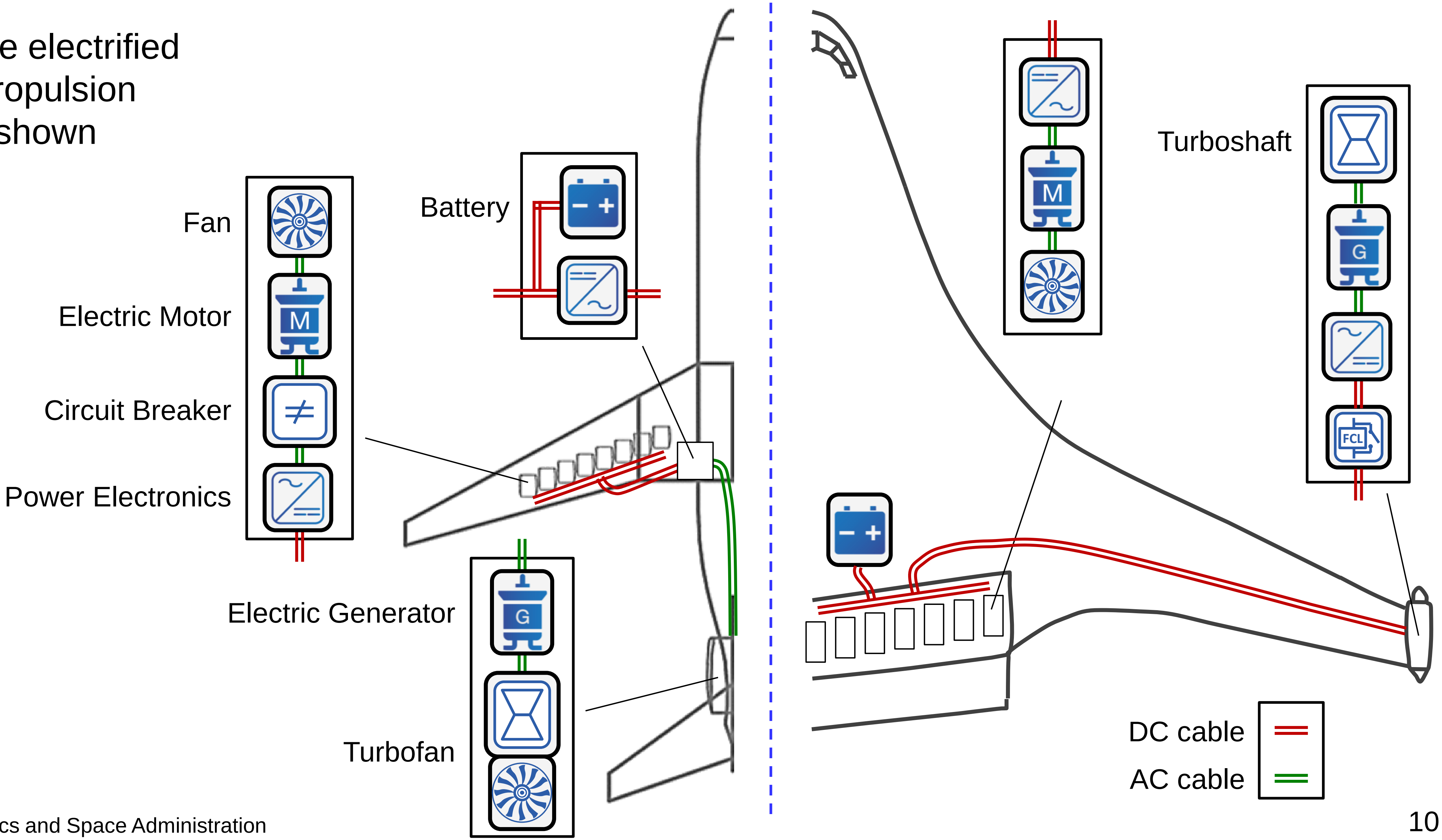
Global aviation's impact on CO_2[8]



6. https://www.nasa.gov/directorates/armd/armd-strategic-implementation-plan/
7. https://www.faa.gov/sustainability/aviation-climate-action-plan
8. Lee, D.S. et al., Atmospheric Environment 244, 117834, 2021.

Aero – Applications

- 2 example electrified aircraft propulsion systems shown



Aero – Interests

- Propulsion system components (5-20 MW powertrain)

Superconducting

- Electric machines[9]
- DC cables (multi-kA)
- Fault current limiters

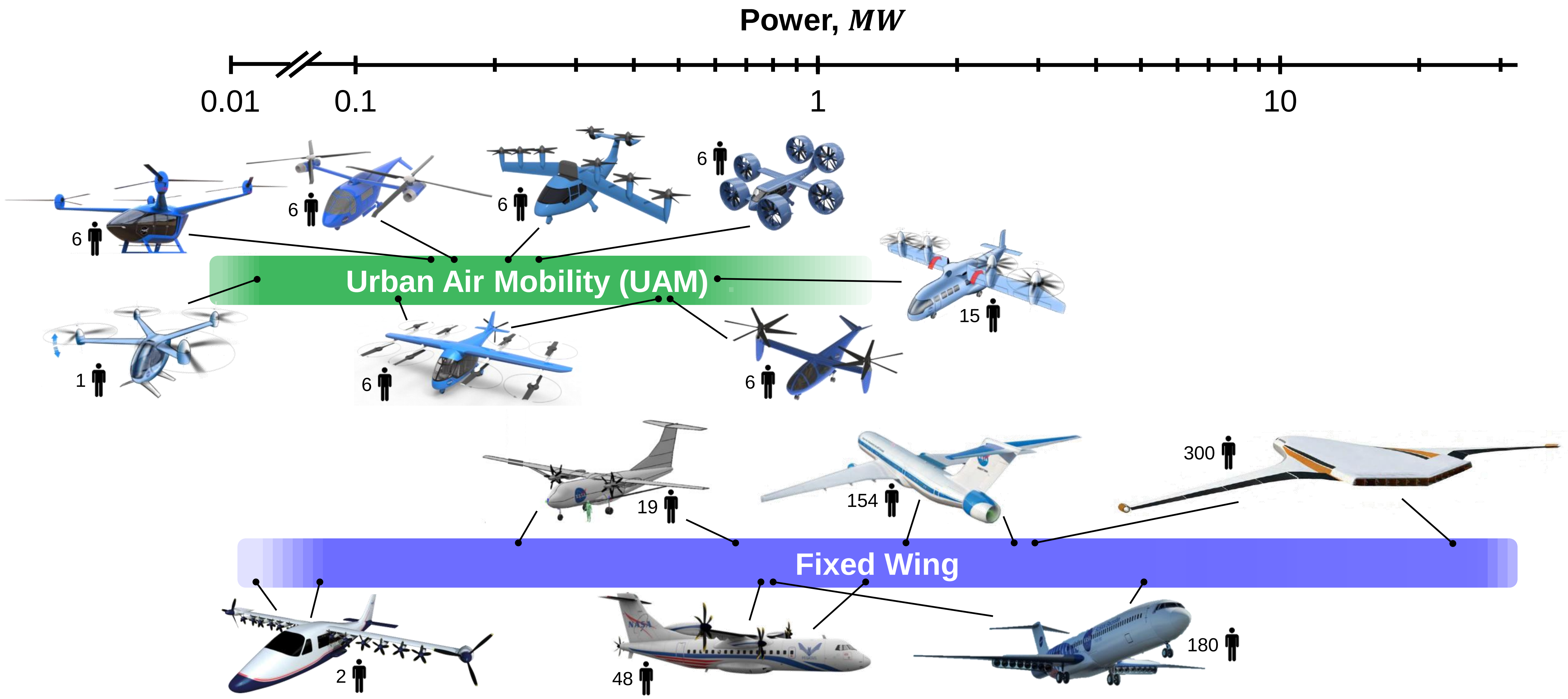
Cryogenic

- MW-class power electronics
- Lightweight, high cycle cryogen tanks
- Fluid loop components (e.g., pumps, valves, HXs)
- Thermal management (< 1 kg/kW)
- Cryocooling

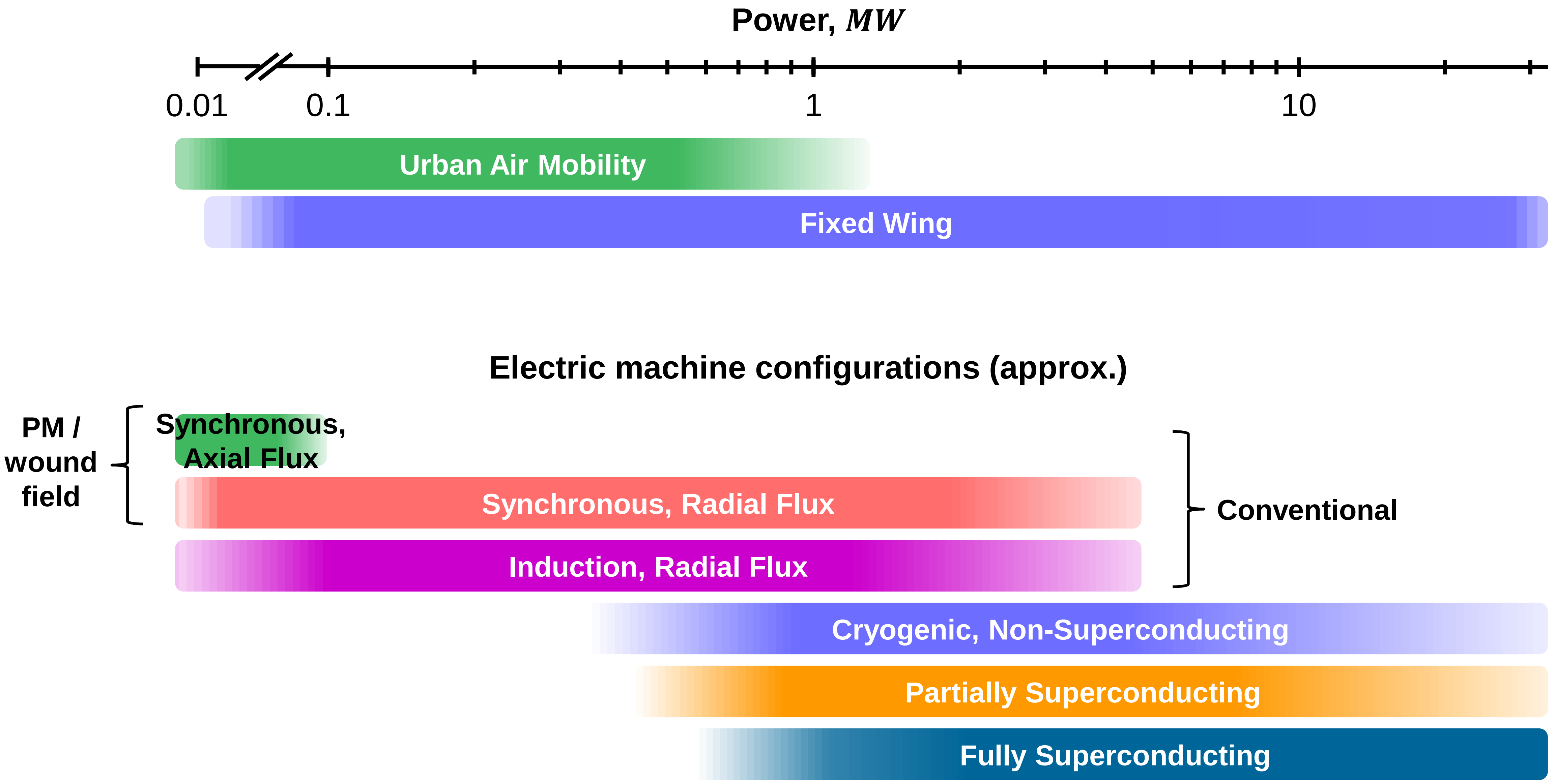
- Multiple fuel sources, including SAF and cryo fuels (LH_2, LNH_3, LNG)
  - Fuel agnostic currently desirable
  - Assume LH_2 will not be allowed to directly cool conductors or electronics
- Fault management
- Aircraft requirements (e.g., DO-160[10])

9. https://ntrs.nasa.gov/citations/20230010027.
10. RTCA standard DO-160G, Environmental Conditions and Test Procedures for Airborne Equipment, 2010.

Aero – What Scale of Electric Machine is Relevant?



Aero – What Types of Electric Machines are Relevant?



Aero – Funded Activities

Component development

Internal

- High efficiency megawatt motor – HEMM (1.4 MW partially superconducting)
- 50 K rotating cryocoolers (50 W lift @ 40 W/W; 20 kW linear motor)
- 5 MW superconducting motor system (more on next slide)

External

- Low AC loss MgB_2 and Bi-2212 superconducting cables & coils[11,12]
- LH2-fueled aircraft design, including detailed propulsion system development
  - CHEETA[13]
  - IZEA[14]
- Composite LH2 dewar-tank & aircraft integration[15]

11. Kovac, J. et al., Supercond. Sci. Technol., 36, 095009, 2003. DOI: 10.1088/1361-6668/ace3fd
12. Otto, A. et al., Proc. of AIAA Aviation Forum, 2023. DOI: 10.2514/6.2023-4129
13. https://cheeta.illinois.edu/
14. http://izea.eng.famu.fsu.edu/
15. https://www.sbir.gov/awards/204010

Aero – Funded Activities

Component development

- New Technical Challenge (Oct 2024 – Sept 2030)
  - ***Develop a 5 MW superconducting motor system and demonstrate at subscale to enable new higher performance airplane architectures (TRL 3)***

Objectives

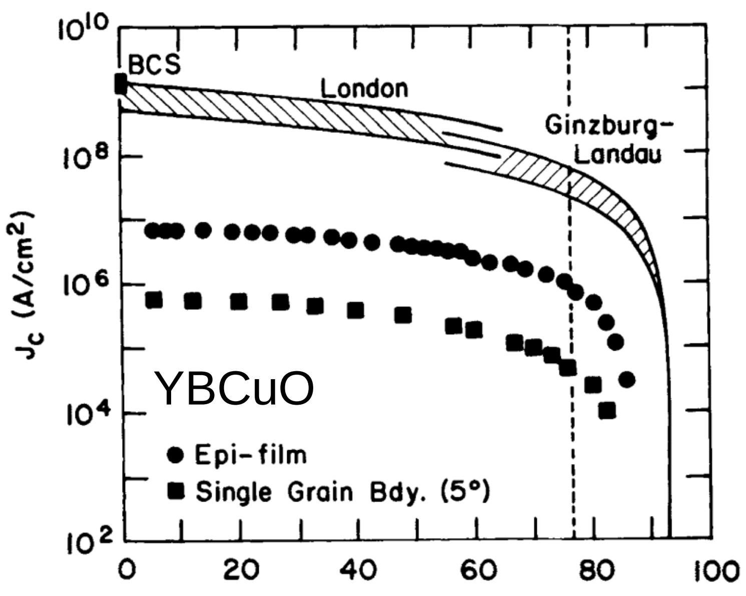
- Develop 5 MW Superconducting Machine Technologies (TRL-3)
- Determine high power EAP aircraft and powertrain architectures

Approach

- Explore fully superconducting and fully cryogenic machines to increase percentage electrification and meet weight targets at the airplane level
- Design a 5 MW machine and drive
- Demonstrate key tall poles for high power superconducting (stator cooling, non-contact rotor current supply, low AC loss, cost, flight-like requirements, etc.)
- Support component-level work with system studies at all levels (power quality, thermal management, airplane performance)
- Focus on solutions that support SAF and Hydrogen

Material development

- Computing superconducting critical currents (POC: NASA Ames / Zhigang Wu, zhigang.wu@nasa.gov)
  - Find new superconductors that can carry stronger current at higher temperature with reduced weight
  - Combine the Ginsburg-Landau and BCS theories, we can compute the theoretical limit of $J_c(T)$ for conventional superconductors
  - Find the numerical correlation between the coherence length ξ_0 and the energy gap Δ in high-T_c superconductors
  - Optimize the flux vortex pinning to increase $J_c(T)$ in high-T_c superconductors



Example scope[11]

11. Tsuei, et al., AIP Conf. Proc. 182, 194-205 (1989)

Acknowledgements

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THANK YOU


Glenn Research Center
Lewis Field
RESEARCH AND TECHNOLOGY
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Summary of Select NASA Efforts

Electric Machines (In-House)

Development / experimental projects

- High efficiency megawatt motor – HEMM (1.4 MW partially superconducting)
- Cryocooler compressor motors (2 kW & 20 kW)
- Stator winding reliability / partial discharge

Design projects

- 5 MW partially superconducting machine

= application to fixed wing aircraft (1+ MW components)

= application to vertical lift aircraft (~100 kW components)

Electric Machines (External)

Development / experimental projects

- [OSU / U. Wisconsin] Fault-tolerant integrated modular motor drive – IMMD (1 MW, 2 kV, 20,000 rpm)
- [CGC Ultramarin] Single fluid tuned winding induction motor (200 – 500 kW, 5,000 rpm)
- [Hinetics] Integrated magnetics, insulation, and cooling architecture for robust eVTOL motors – MAGICA
- [Hinetics] Tail propulsor generator for NASA SUSAN demonstrator (150 kW)

Design projects

- [U. Illinois] CHEETA electric machine (2.5 MW, 4,500 rpm fully superconducting)
- [FL. St. U.] IZEA turbogenerator & motor

Summary of Select NASA Efforts

Electrical power system

Development / experimental projects

- 250 kW inverter (1 kV)
- Resonant inverter (14 kW, 500 V)
- Immersion liquid cooled inverter – MAGIC (40 kW, 270 V)
- DC bus power quality & related standards

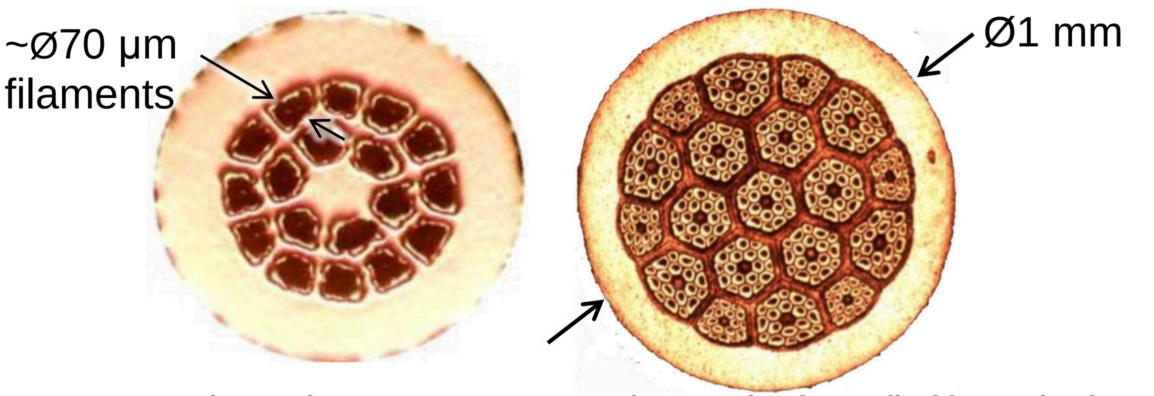
Design projects

- Resonant inverter with very low THD output for low inductance, loss-sensitive superconducting machines

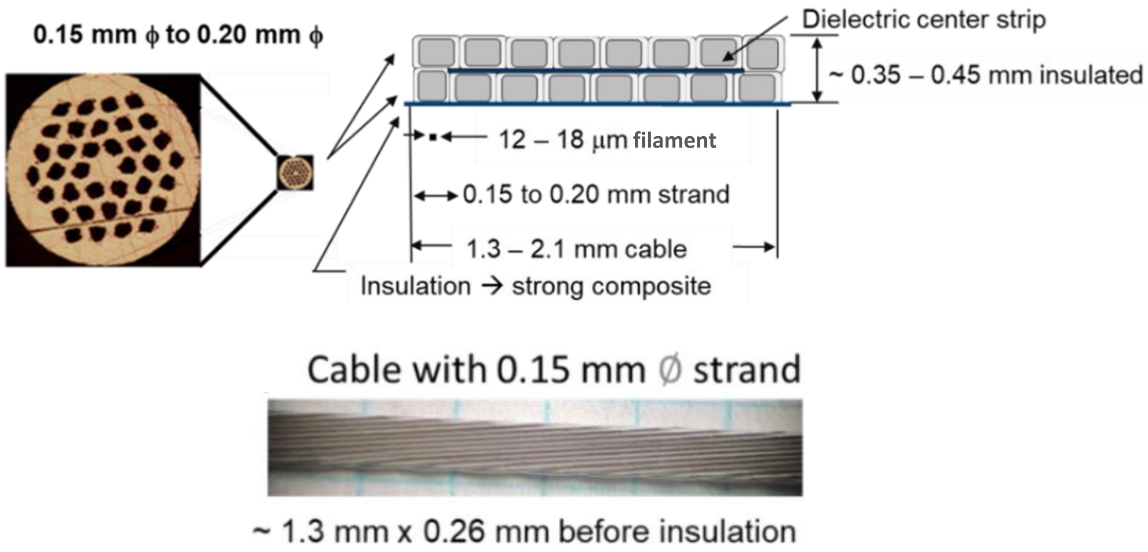
(green)	= application to fixed wing aircraft (1+ MW components)
(purple)	= application to vertical lift aircraft (~100 kW components)

Recent Progress on Superconductor Development

- Superconductors only loss-free under DC current and magnetic field
  - Existing superconductors are suitable for the field windings of a machine (often on the rotor) but not for the armature windings (often on the stator)
- NASA funded multiple SBIR projects to develop low AC loss versions of MgB_2 and Bi-2212 superconductors [13,14]
  - Performance is now viable for superconducting machines, but further experimental validation is required



Cross-section of MgB_2 superconductor before (left) and after (right) NASA-funded development to reduce AC loss [13]



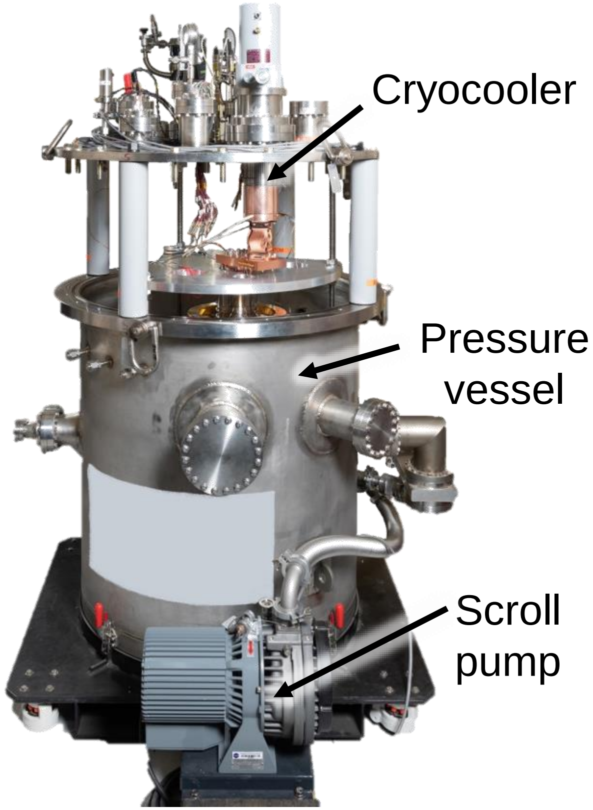
16 wire Bi-2212 superconducting cable [14]

13. Brown, G.V. et al., NASA/TM-20205005815, 2020.
14. Otto, A. et al., Proc. of AIAA Aviation Forum, 2023.

Multi-purpose cryogenic vacuum chambers

ICE-Box

- Wide range of test articles – single wires to components or assemblies up to about Ø0.75 m x 1 m
- Current vacuum capability: ~10^{-3} torr (warm) to ~10^{-5} torr (cold)
- Cryocooler Lift Capacity
  - Primary AL-325: 79W @ 20K or 100W @ 25K
  - Designed for secondary / cold wall cryocooler, but not currently installed
- Inert gas backfill capable

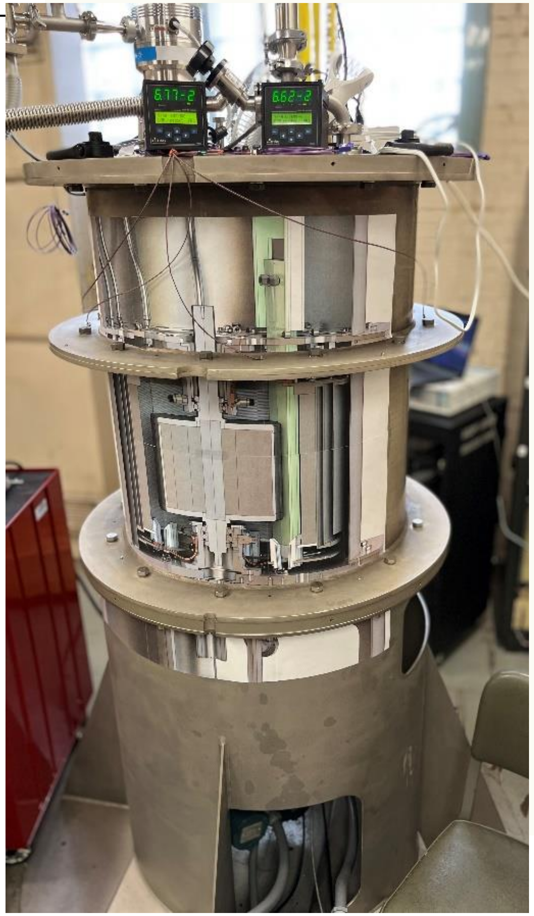


VF-15

- Test articles up to about Ø0.4 m x 0.4 m
- Vacuum capability: 10^{-6} torr (warm)
- Cryocooler Lift Capacity: 79W @ 20K or 100W @ 25K

NASA's Superconducting Test Facilities

AC loss test rig



- Superconducting Coil Tester creates realistic environment for a stator coil
  - ~20 K and up
  - 0-400 Hz electrical frequency
  - 0.4-0.5 T magnetic field produced by spinning rotor
  - Test article cooled with cryocooled gaseous He (GHe)
  - Loss target: ~5 – 50 W
  - Expected tare: < 2 W