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Materials Opportunities for Aero-propulsion Efficiency

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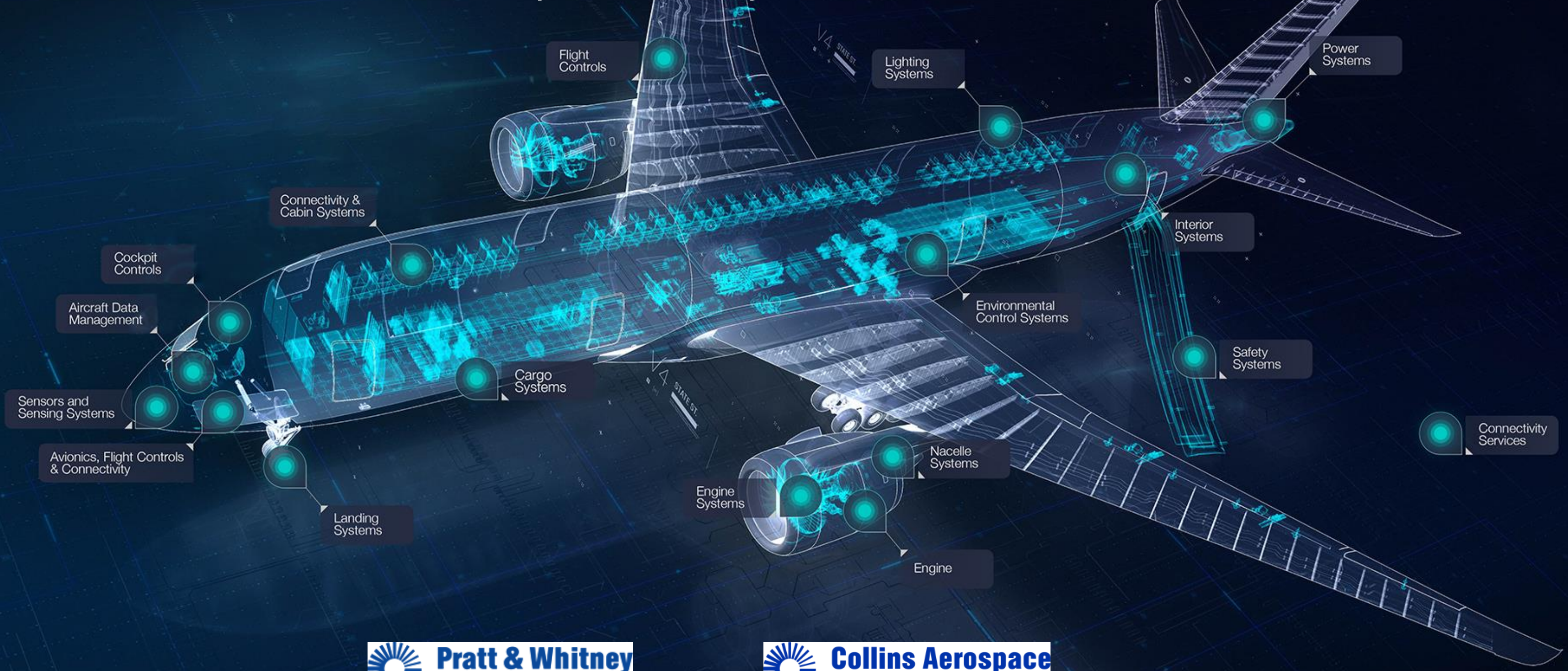
UTC Business Units.

World-wide leader in Aerospace Industry



Pratt & Whitney
A United Technologies Company

Collins Aerospace
A United Technologies Company

An innovation hub.

A research model that advances science

Collaboration

- Partner with UTC business units & external research organizations

Innovation

- Expand the boundaries of science & technology through research & innovation

Customer-centricity

- Delivers tech options that meet & anticipate customer needs

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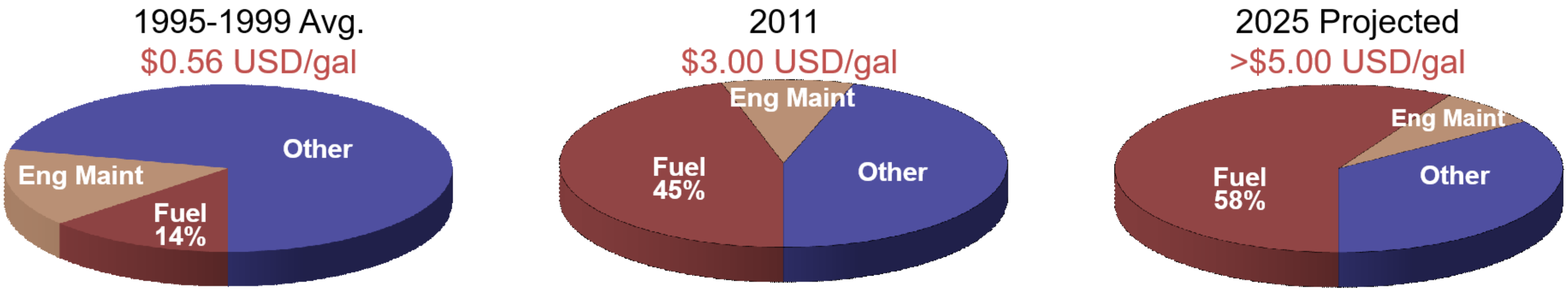
Fuel Drives Aviation Economics



Airline Cash Operating Costs

- Fuel costs can widely fluctuate and drive aviation economics and affordability.
- Reduced fuel consumption provides better value for the customer and the environment.

*adapted from F. Preli, *Aero Engine Challenges*, ASM Summit 2018

Where Can Materials Help…

Breguet Range Equation

V = Velocity

L/D = Lift to Drag ratio

W = weight

h = specific fuel energy

η = turbine efficiency

$$Range = \eta h \left(\frac{L}{D}\right) ln\left(1 + \frac{W_{fuel}}{W_{cargo} + W_{structure}}\right)$$

Turbine Efficiency

Aerodynamics

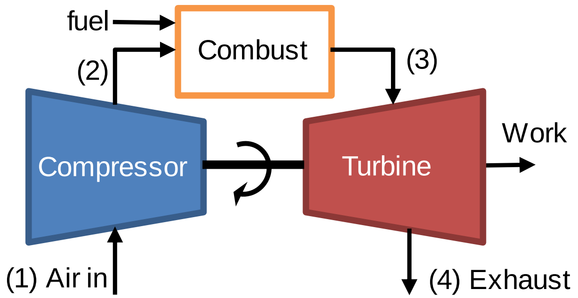
Empty aircraft weight

Opportunities to influence range (or reduce fuel burn) via

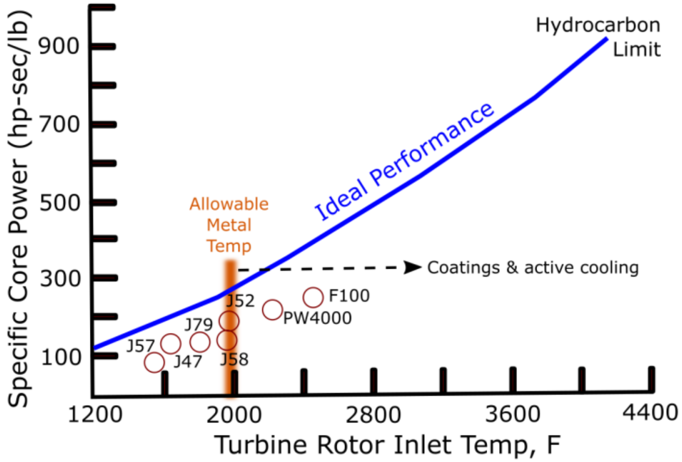
- Reductions in aircraft weight: airframe, wings, turbine, nacelle, etc.
- Improvements in overall turbine efficiency

Turbine Efficiency Opportunities

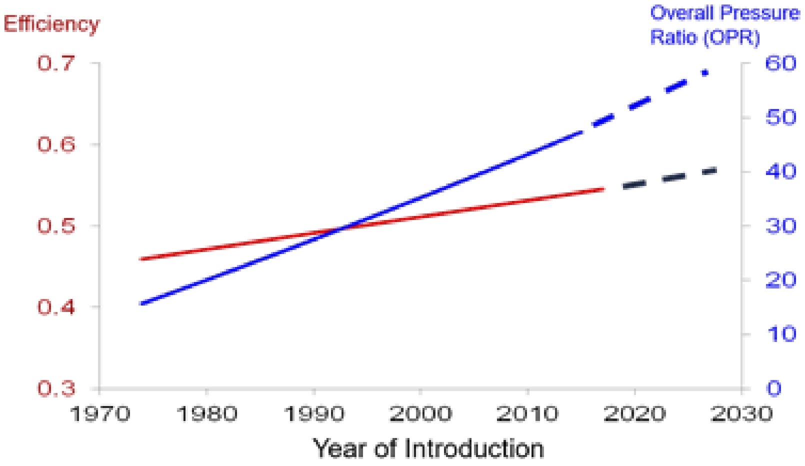
- *Higher temperature materials needed*, efficiency gains via:
  - Increasing OPR → increases compressor exit temperature
  - Increasing turbine inlet temperature → material limited
  - Reducing compressor bleed air for turbine cooling



$$Brayton\ Cycle\ Efficiency, \quad \eta_{thermal} = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{(P_2/P_1)^{\frac{k-1}{k}}} = \frac{W_{net}}{Q_{in}}$$



adapted from Koff, 1991

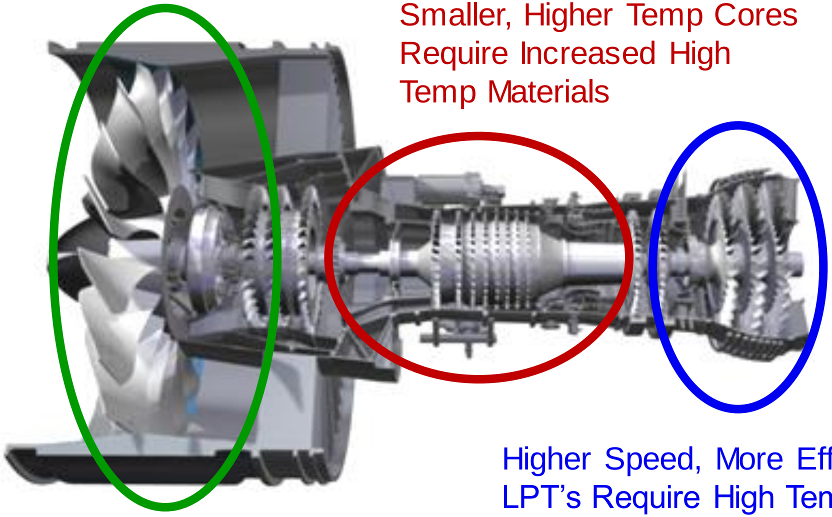


*adapted from F. Preli, *Aero Engine Challenges*, ASM Summit 2018

Light-weighting Opportunities

- *1% reduction in empty aircraft weight reduces fuel burn by 0.725%
- Ni superalloy accounts for over ~ 40% of the engine weight; noteworthy savings possible from a slight reduction in the density of Ni-alloys

**PW4168	lbs	%	Materials
Fan	2,658	25.1	Composite, Ti, Al
LPC	670	6.32	Ti, Ni
HPC	1,161	10.97	
Burner	521	4.92	Ni Superalloy
HPT	1,301	12.29	Ni disk + blades
LPT	2,438	23.02	
Accessories	1,634	15.44	Various
Other	205	1.94	
Grand Total	10,588	100	

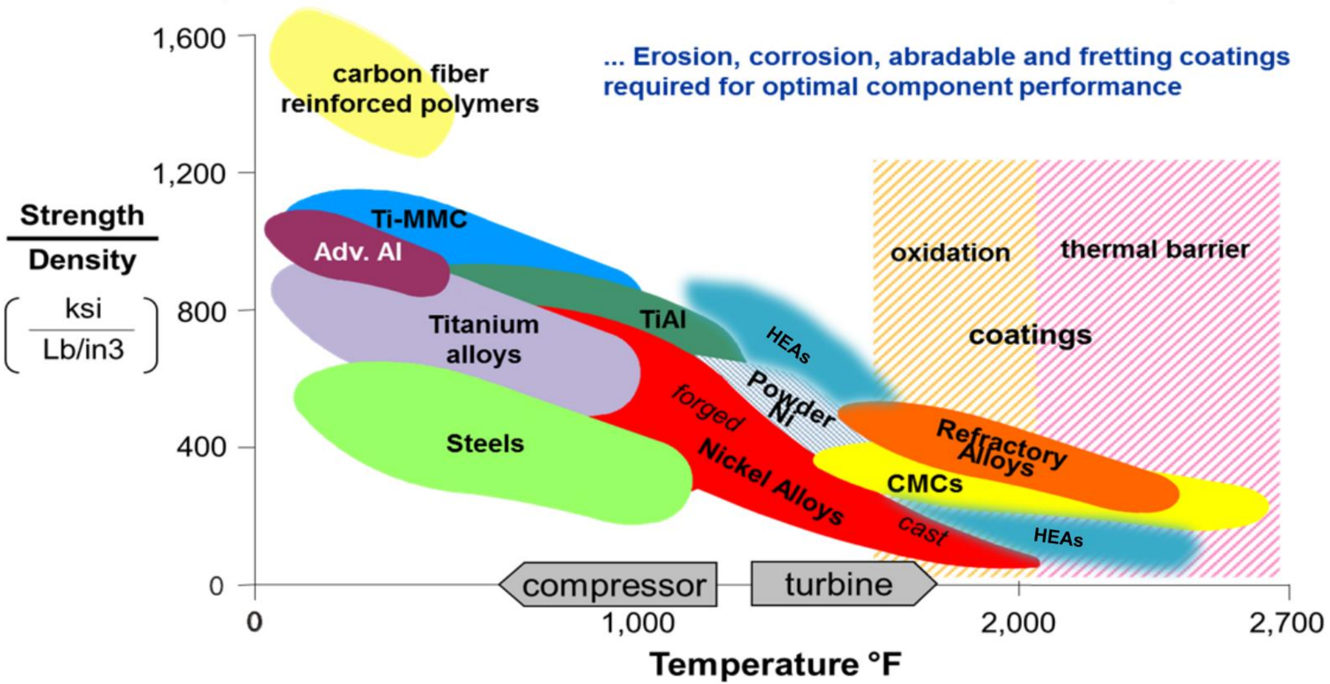


*Lee, J.J, Historical and future trends in aircraft performance, cost and emissions, MS Thesis, Massachusetts Institute of Technology, Cambridge, (2000).

**Data from *N+3 Aircraft Concept Designs & Trade Studies Vol. 2*, NASA cooperative research agreement NNX08AW63A

*adapted from F. Preli, *Aero Engine Challenges*, ASM Summit 2018

Materials & Processing



Of Current Interest

- Ceramic Matrix Composites (CMCs)
- High Entropy Alloys (HEAs)
- Additive Manufacturing

System	Processing Routes
Ceramic Matrix Composites	Melt infiltration, chemical vapor infiltration, polymer infiltration pyrolysis
Metal Alloys	Wrought, cast, powder metallurgy, additive manufacturing

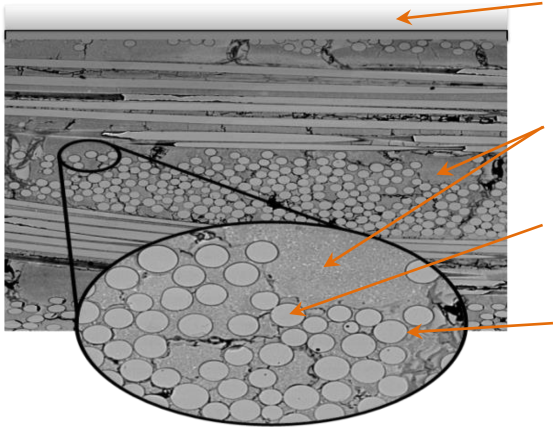
Ceramic Matrix Composites

Benefits

- Higher T capability than Ni-superalloy (+300°F)
- 1/3 the density of Ni-superalloy
- Several % improvement in specific fuel consumption

Challenges

- Oxidation resistance
- CMAS resistant coatings (EBCs)
- Low ductility
- Cost



SiC/SiC Turbine Blade & Vane

* slide from F. Preli, *Aero Engine Challenges*, ASM Summit 2018

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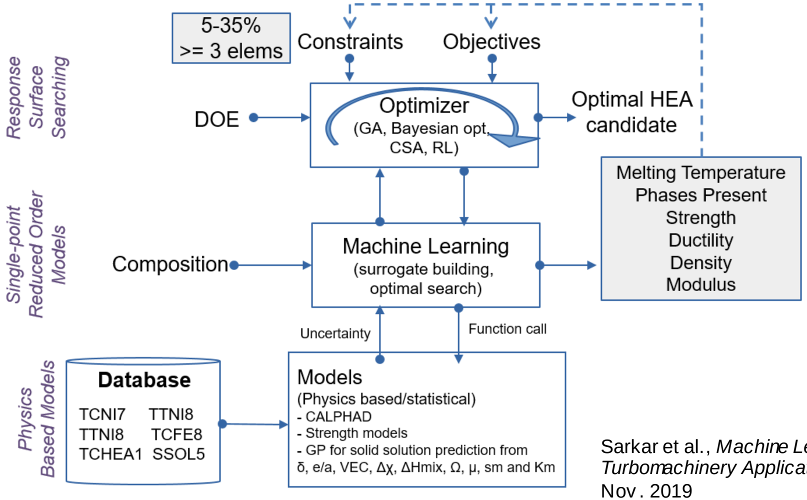
HEA Computationally Guided Materials Discovery

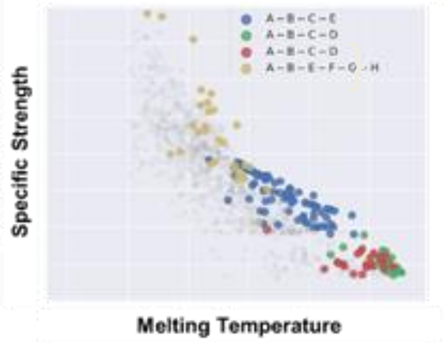
High Entropy Alloys (HEA): 3+ elements present from 5 to 35 at.%

Benefits: potential for lower density & higher strength at temperature compared to Ni-superalloy

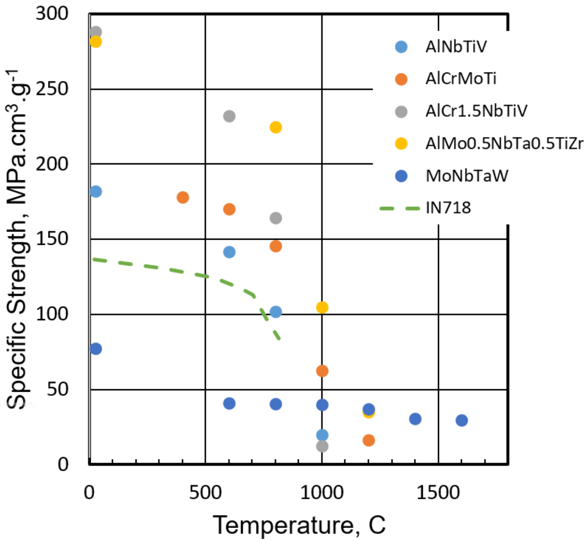
Challenge: a palette of 72 elements results in *billions* of compositions to consider.

Potential Solution: employ machine learning to rapidly search for & identify ideal alloys





Sarkar et al., *Machine Learning-aided Accelerated Discovery of HEA for Turbomachinery Applications*. (Oral) In 1st World Congress on High Entropy Alloys, Nov. 2019



<u>Data Source(s)</u>
Stepanov et al; J. Alloy. Comp. (2015)
Chen et al.; Metall. Trans. A (2017)
Senkov et al.; Entropy (2016)
Senkov et al.; Intermetallics (2011)

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Additive Manufacturing

Possibilities to impact parts at the meso-, micro-, & nano-levels.

Meso

Potential for new architectures that cannot be cast or machined

Laser powder bed fusion heat exchanger

Conformal, lower weight, less bleed air

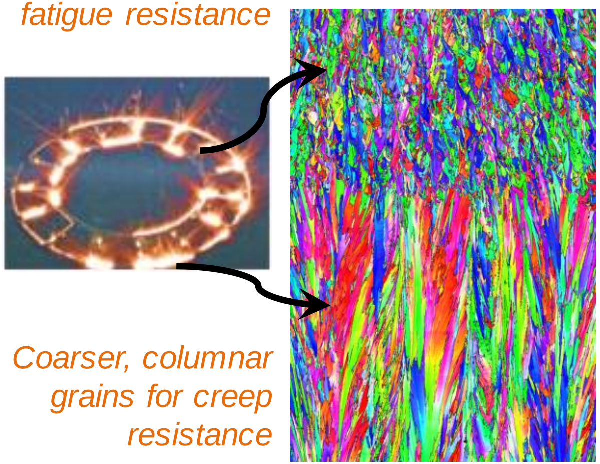
Electron beam powder bed fusion Ti-6-4 synch ring bracket

Lower weight, lower lead time

Micro

Control grain structure for site specific property optimization

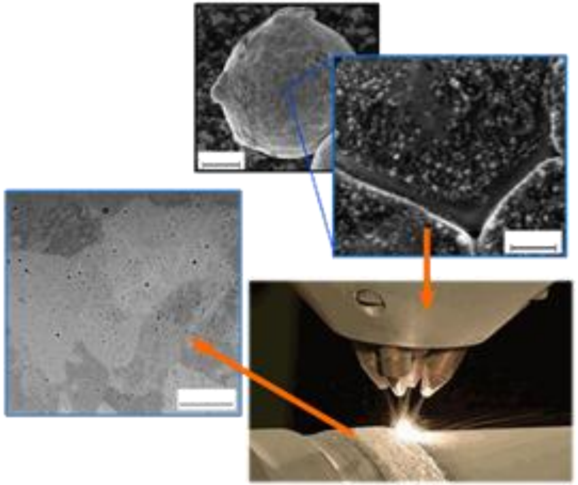
Finer more equiaxed gains for fatigue resistance



Coarser, columnar grains for creep resistance

Nano

New alloys / augment current ones



Incorporate nano reinforcement particles → enhanced creep resistance

Sharon & Sheedy ; *Powder Modification to Enhance Alloys for Laser Based Additive Mfg.* (Oral) In Mat. Sci. & Tech. conference, Oct 2018.

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Enabling Materials Achievements, What's Next?

Propulsion Innovation Enabled by Materials and Processing Technology

DS blades, Cast & Wrought disks, Thermal Spray TBC coatings

Single Crystal blades, Powder metal disk, EB-PVD TBC

Aluminide coatings, PM/fracture tolerant disk

LFW Ti IBR, Dual Property Ni Disk, Burn resistant Ti

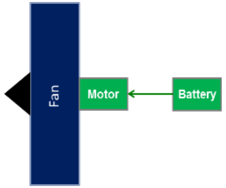
High modulus blade

Hybrid metallic airfoils, γ-TiAl blades

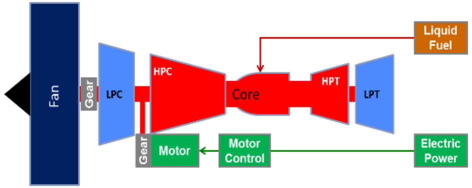
*from F. Preli, *Aero Engine Challenges*, ASM Summit 2018

New Engine Architectures: Electric & Hybrid Electric

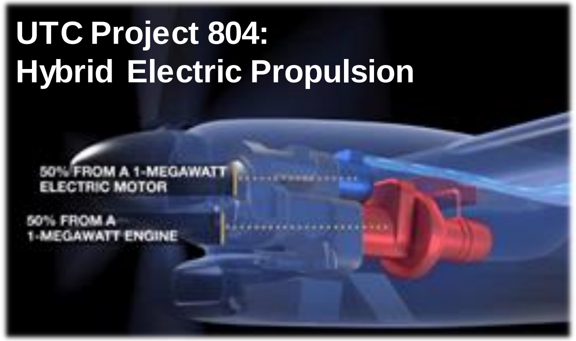
- Storage in current batteries insufficient for long range (regional & commercial) flights. Turbines working in concert with electric motors may enable more efficient systems.

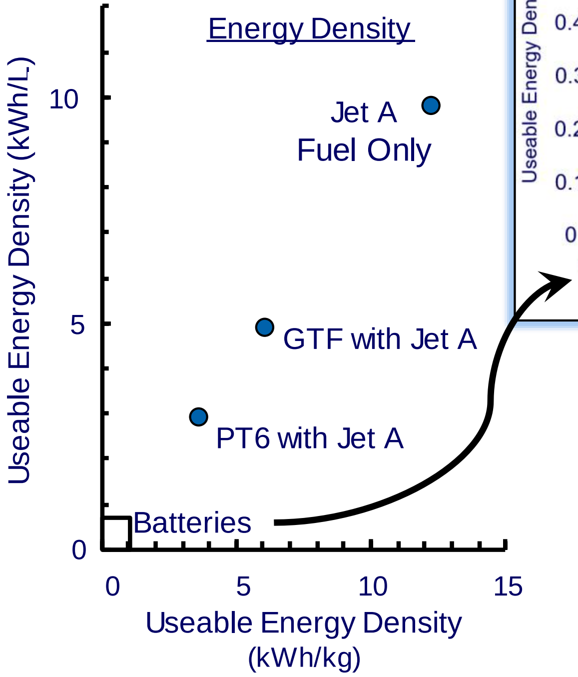


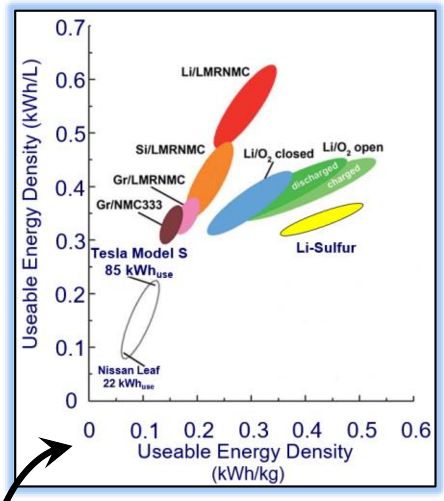
All Electric



Parallel Gas-Electric Hybrid







*adapted from F. Preli, *Turbomachines for Clean Power and Propulsion Systems*, ASME Turbo Expo, 2019

Turboprop optimized for cruise, electric motor assists takeoff & climb → ~30% reduction in fuel for a 1hr flight

https://utap.utc.com/our-projects/project-804

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Summary

- Materials innovation needed to improve turbine efficiency and reduce fuel burn.
- Increasing efficiency requires increasing compressor exit and turbine inlet temperatures while reducing structural weight.
- Additive manufacturing offers opportunities for unprecedented design complexity and microstructure control.
- “Near” term electric propulsion concepts likely to require gas turbines to work in concert with battery powered motors.

Thank you.

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