A NOVEL DE-COUPLED SOFC-GT HYBRID SYSTEM TO POWER COMMERCIAL ALL-ELECTRIC AIRCRAFT

By
Jeff Collins

Overview

- This study considers two variations on existing SOFC-GT power systems and evaluates their potential for use in a variety of existing commercial aircraft

Motivation

- Commercial aircraft generate 3% of all man-made greenhouse gasses, and will reach 5% by the year 2050 [1]
- Proposed solutions include developing light-weight airframe materials and formulating cleaner burning jet fuels [1]
- These proposed solutions will not fully address the problem

[1] GOA, “AVIATION AND Aircraft Emissions Expected to Grow , but Technological and Operational Improvements and Government Policies Can Help Control Emissions Highlights,” *Aviation*, no. June, 2009.

Background

- Companies such as Airbus, Zunum Aero, and Eviation are developing short-range electric aircraft capable of holding 10-30 passengers for near-term deployment [2]
- Power systems consist of lithium-ion batteries and hybrid-electric systems [2]
- Electric aircraft approaching the payload and range of mid-size commercial jets are still projected to be 10-30 years away from deployment [2,3]

[2] Metcalfe, NBC News, 2018, https://www.nbcnews.com/mach/science/electric-planes-promise-big-benefits-air-passengers-planet-ncna862001
[3] M. K. Bradley and C. K. Droney, “Subsonic Ultra Green Aircraft Research: Phase II. N+4 Advanced Concept Development,” *Nasa/Cr-2012-217556*, no. April 2011, p. 207, 2012.

Background

- Mobile power systems are governed by three primary factors:

1) Energy storage density

2) Power density

3) Energy efficiency

Energy Storage Density

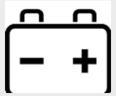
- Lithium-ion batteries used in electric cars and small aircraft have a maximum energy storage density of 1 $MJ \cdot kg^{-1}$ [4]
- Lithium-sulfur batteries have a higher theoretical energy density of nearly 10 $MJ \cdot kg^{-1}$, but have only achieved 1.26 $MJ \cdot kg^{-1}$ in practice [4]

[4] X. Z. Gao, Z. X. Hou, Z. Guo, and X. Q. Chen, “Reviews of methods to extract and store energy for solar-powered aircraft,” *Renew. Sustain. Energy Rev.*, vol. 44, no. 109, pp. 96–108, 2015.

Energy Storage Density

Batteries

~1.26 MJ/kg

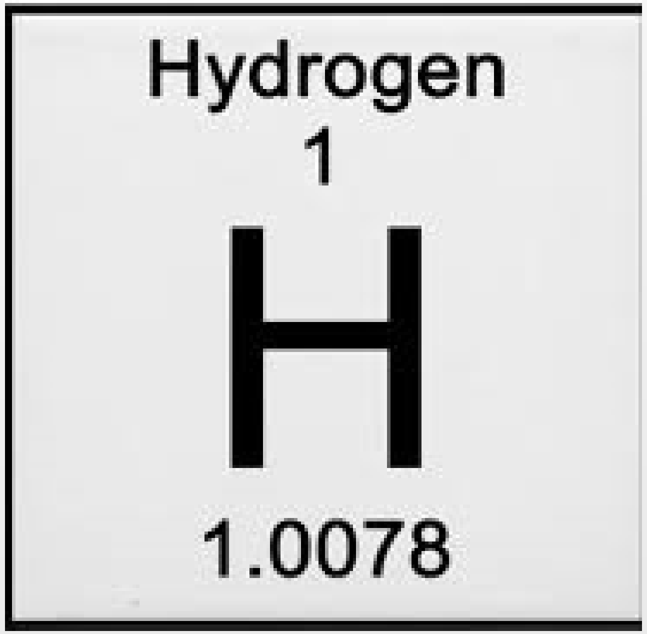


Jet Fuel

~ 40 MJ/kg

Hydrogen

~ 120 MJ/kg



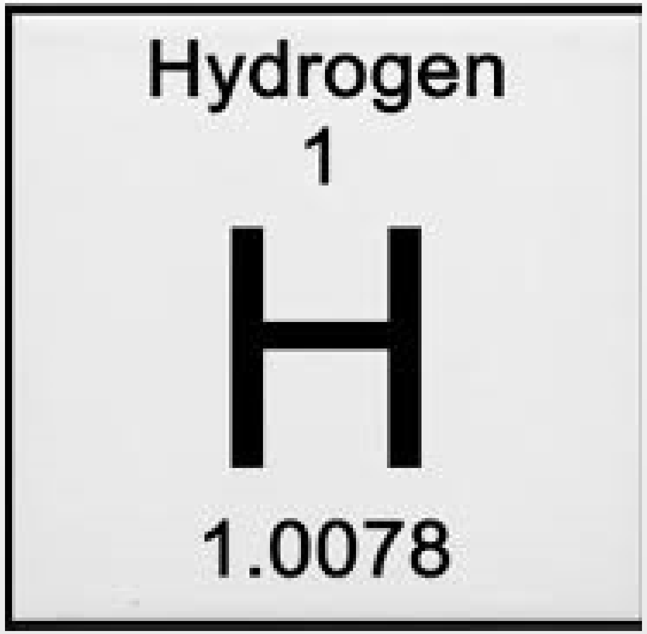
Energy Storage Density

- Benefits
- Zero Carbon Emissions
- High energy storage per mass

- Challenges
- Low mass-to-volume ratio requires storing hydrogen as a cryogenic liquid for use in aircraft [5]

Hydrogen

~ 120 MJ/kg



[5] G. D. Brewer, *Hydrogen Aircraft Technology*, 1st ed. Boca Raton: CRC Press, Inc., 1991.

Power Density

- ➢Fuel Cells have been considered to generated electric power for aircraft
- Heavier than turbine engines

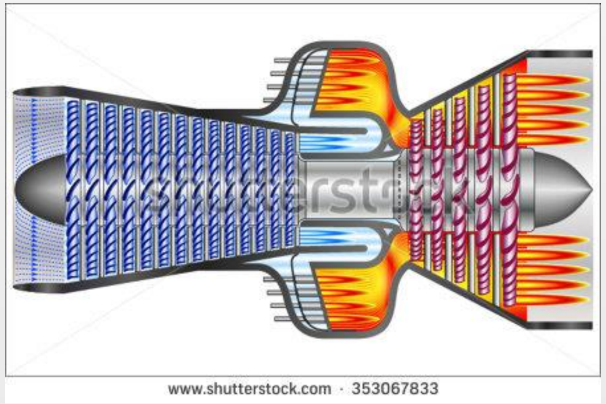


Image courtesy of www.shutterstock.com

Turbine engines
~ 3-8 kW/kg

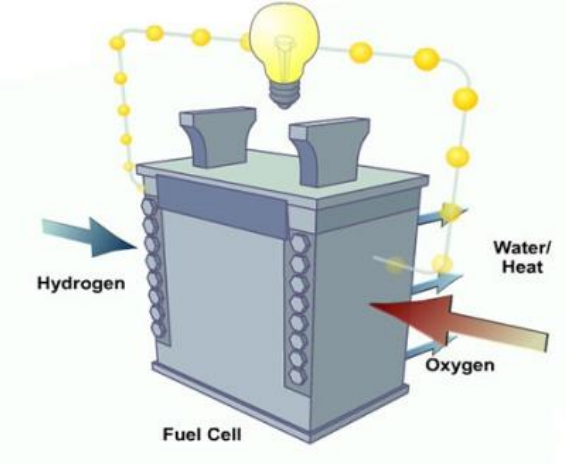


Image courtesy of www.physics.org

~ 0.2-0.94 kW/kg
Depending on Fuel Cell Type and System Requirements

Polymer Electrolyte Membrane (PEMFC)	Solid-oxide (SOFC)
Power density ~ 0.94 kW/kg	Power density ~ 0.2 – 0.35 kW/kg
100ºC	600ºC - 1000ºC
50% efficiency	60% FC efficiency, 75% system efficiency when combined with gas turbine

Fuel Cells in Aviation

- In 2008, Boeing flew a single passenger PEMFC/battery hybrid to an altitude of 1000m, achieved a speed of 100 km/hour for 20 minutes [6]

- Upon project completion, Boeing decided that fuel cells will probably never be a primary power source for commercial aircraft [6]

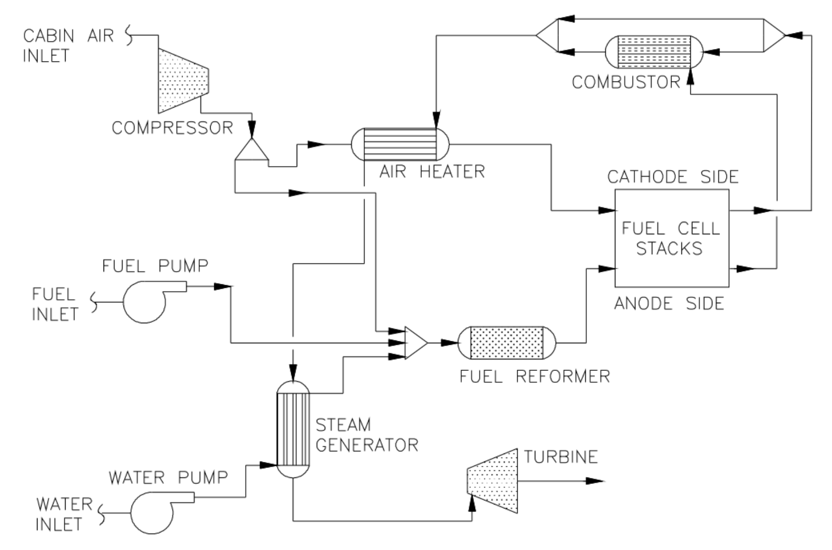
The Boeing aeroplane, powered by an Intelligent Energy fuel cell system, on a test flight. [Boeing]

Image Source: Fuel Cells Bulletin, May 2008

[6] “Feature Story BOEING FRONTIERS A green machine,” *Boeing Front.*, May, 2008.

Fuel Cells in Aviation

- In 2005, NASA estimated the performance and required mass of a proposed SOFC-GT hybrid system for auxiliary power generation [7]



Tornabene et al, *2005*

- Uses reformed jet fuel
- Total system power density $0.315\ \mathrm{kW{\cdot}kg^{-1}}$
- Majority of system mass results from SOFC stack
- Total mass per active fuel cell area was estimated to be $1.55\ \mathrm{g{\cdot}cm^{-2}}$
- Assumed ASR of $0.4\Omega{\cdot}\mathrm{cm}^2$

[7] R. Tornabene, X.-Y. Wang, C. J. Steffen, and J. E. Freeh, "Development of Parametric Mass and Volume Models for an Aerospace SOFC/Gas Turbine Hybrid System," *Vol. 5 Turbo Expo 2005*, vol. M, no. July, pp. 135–144, 2005.

Fuel Cells in Aviation

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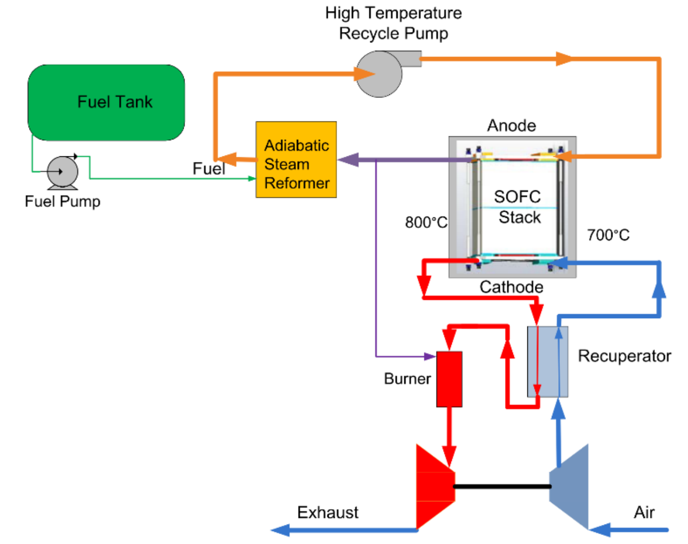


Figure 2.5. Configuration for Anode Recycle Steam Reforming

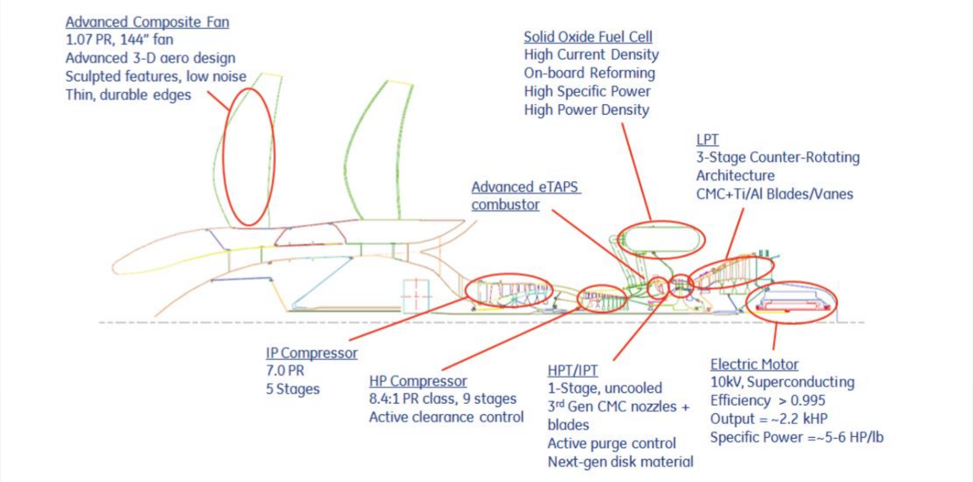
Whyatt et al, *2012* [8]

- Uses reformed desulfurized jet fuel
- Total system power density 0.227 $kW \cdot kg^{-1}$
- 76% of system mass results from SOFC stack and pressure vessel
- FTE efficiency increases from 53% using turbine APU to 70.6% using SOFC-GT
- Added mass of SOFC stack increased total mission fuel consumption
- SOFC mass was 5.9 $g \cdot cm^{-2}$

[8] G. Whyatt and L. Chick, “Electrical Generation for More-Electric Aircraft using Solid Oxide Fuel Cells,” no. April, p. 110, 2012.

Fuel Cells in Aviation

- NASA’s Subsonic Ultra Green Aircraft Research (SUGAR) proposed an advanced airframe design powered by SOFC-GT

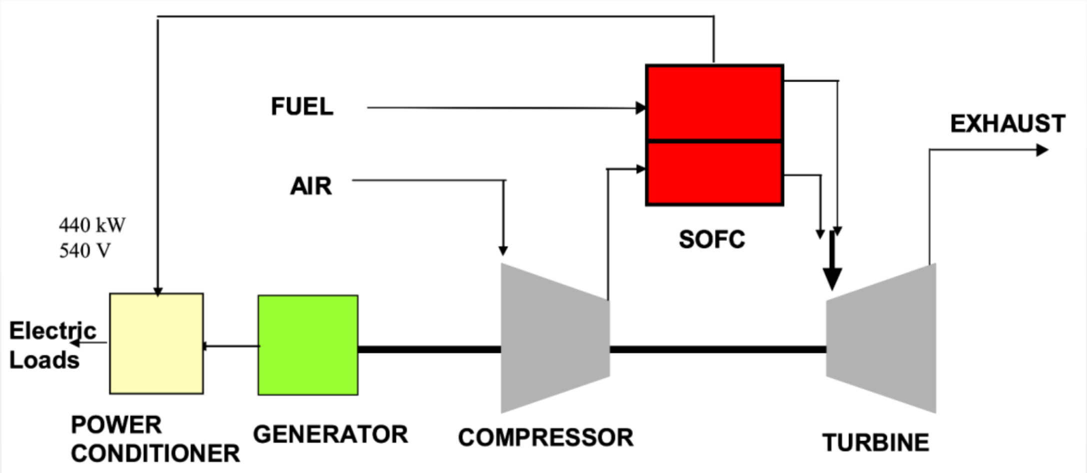


Bradley et al, *2012* [3]

- Uses liquid methane as fuel
- Total system power density 0.356 kW·kg^{-1}
- Uses a combination of lightweight airframe and novel propulsion schemes to be feasible
- Cruise SFC 0.313 lbm·lbf^{-1}·hour^{-1}
- Lower SFC than similar size aircraft:

Boeing 757 = 1.20 lbm·lbf^{-1}·hour^{-1}
Airbus A330 = 1.02 lbm·lbf^{-1}·hour^{-1}

Common Features of SOFC-GT Systems



Simplified SOFC-GT system, Rajashekara et al, *2006* [9]

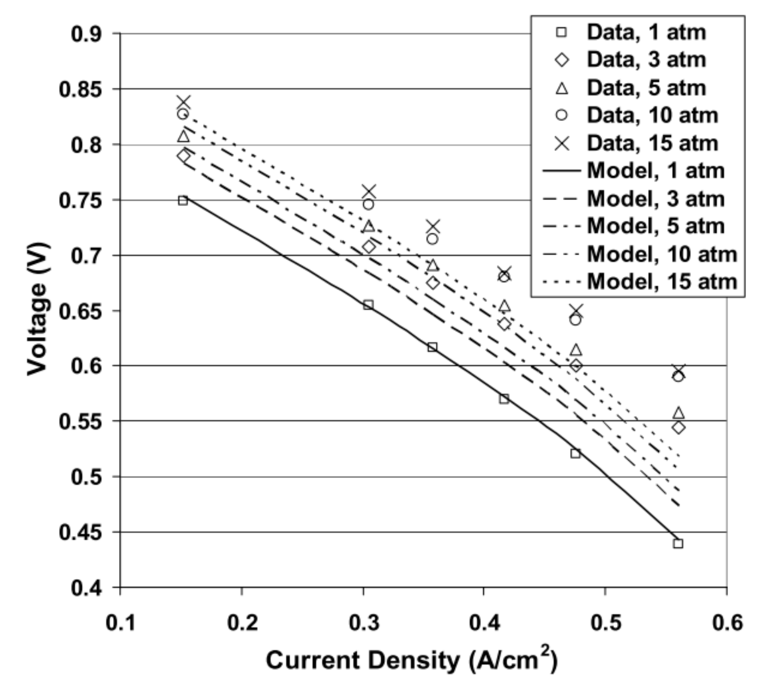
- SOFC cannot achieve 100% single pass utilization (SPU), voltage drop results in lower electrical power and increased waste heat
- Unutilized fuel is mixed with cathode exhaust air and oxidized for additional power generation in turbine
- SOFC waste heat is primarily rejected by flowing excess air across the cathode
- Intake air compressor and gas turbine are directly coupled with SOFC
- Optimal performance requires balancing power generation between SOFC and GT

[9] K. Rajashekara, J. Grieve, and D. Dagget, "Solid oxide fuel cell / gas turbine hybrid APU system for aerospace applications," *IEEE Ind. Appl. Conf.*, vol. 00, no. c, pp. 2185–2192, 2006.

Proposed Variations on SOFC-GT Systems

- Design power plant to maximize SOFC performance
- Pressurized operation increases power density and efficiency
- Anode off-gas recirculation increases fuel concentration and SOFC voltage
- Use pure oxygen in place of atmospheric air increases oxidant concentration and SOFC voltage
- Use lighter-weight materials to construct SOFC stack

Pressurized Operation



Freeh et al, 2004 [10]

- Pressurized operation increases voltage and power density
- Increasing pressure from 1 atm to 10 atm can reduce fuel cell ASR by ~20% [11]

[10] J. E. Freeh, J. W. Pratt, and J. Brouwer, “Development of a Solid-Oxide Fuel Cell/Gas Turbine Hybrid System Model for Aerospace Applications,” *Vol. 7 Turbo Expo 2004*, no. May, pp. 371–379, 2004.

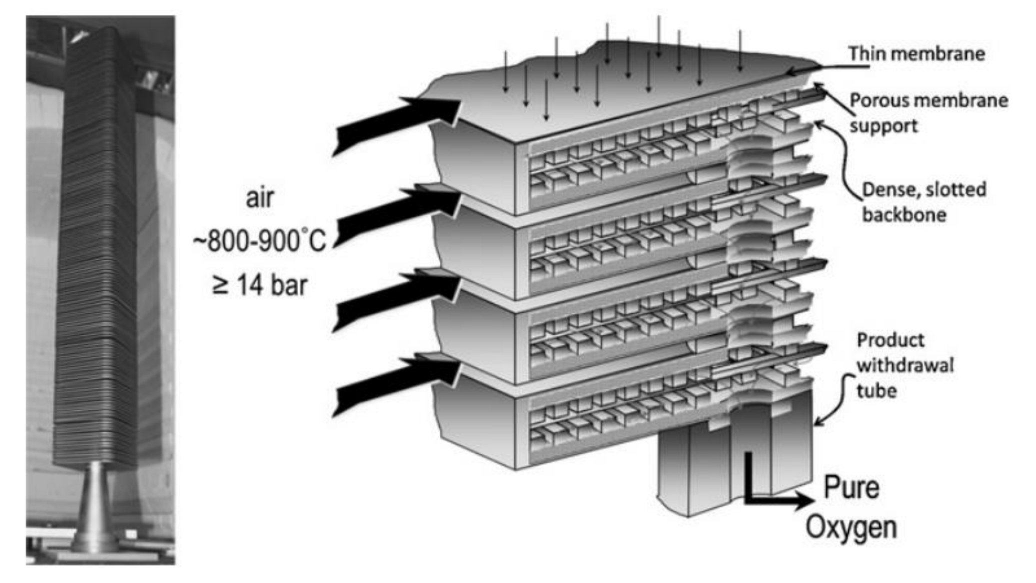
[11] S. H. Jensen, C. Graves, M. Chen, J. B. Hansen, and X. Sun, “Characterization of a Planar Solid Oxide Cell Stack Operated at Elevated Pressure,” *J. Electrochem. Soc.*, vol. 163, no. 14, pp. F1596–F1604, 2016.

Anode Off-Gas Recirculation

- Fuel recirculation increases system efficiency up to 10% [12], eliminates combustion of fuel at turbine inlet
- Anode exhaust must be purified
- Requires hydrogen blower to maintain pressure at fuel cell inlet

[12] R. Peters *et al.*, “Efficiency analysis of a hydrogen-fueled solid oxide fuel cell system with anode off-gas recirculation,” *J. Power Sources*, vol. 328, pp. 105–113, 2016.

Pure oxygen vs. atmospheric air



Baumann et al, 2013 [13]

[13] S. Baumann, W. A. Meulenberg, and H. P. Buchkremer, “Manufacturing strategies for asymmetric ceramic membranes for efficient separation of oxygen from air,” *J. Eur. Ceram. Soc.*, vol. 33, no. 7, pp. 1251–1261, 2013.

- Pure oxygen results in higher Nernst voltage, fuel efficiency and SOFC power density than atmospheric air
- Carrying compressed oxygen would require 8x storage weight of hydrogen
- Oxygen transport membranes (OTMs) could provide a continuous supply from the atmosphere by applying pressure to drive flux across the membrane [13]

Light-weight SOFC stack materials

- SOFC interconnects are primary contributor to stack mass, typically made from steel
- Could be replaced with doped Yttria-stabilized Zirconia, experimentally demonstrated interconnect ASR of $0.07\ \Omega \cdot cm^2$ [14], 22% lower material density
- Thermiculite © compressive seals are 6x lighter than steel [15], can provide internal gas manifold and electrical isolation between components
- Carbon fiber could replace steel for SOFC pressure vessel

[14] W. Z. Zhu and S. C. Deevi, "Development of interconnect materials for solid oxide fuel cells," *Mater. Sci. Eng. A*, vol. 348, no. 1, pp. 227–243, 2003.
[15] S. P. Bond and S. J. Shaw, "Introduction of a low sealing stress vermiculite based compression gasket for SOFCs," *ECS Trans.*, vol. 83, no. 1, pp. 159–170, 2018.

Thermal Management

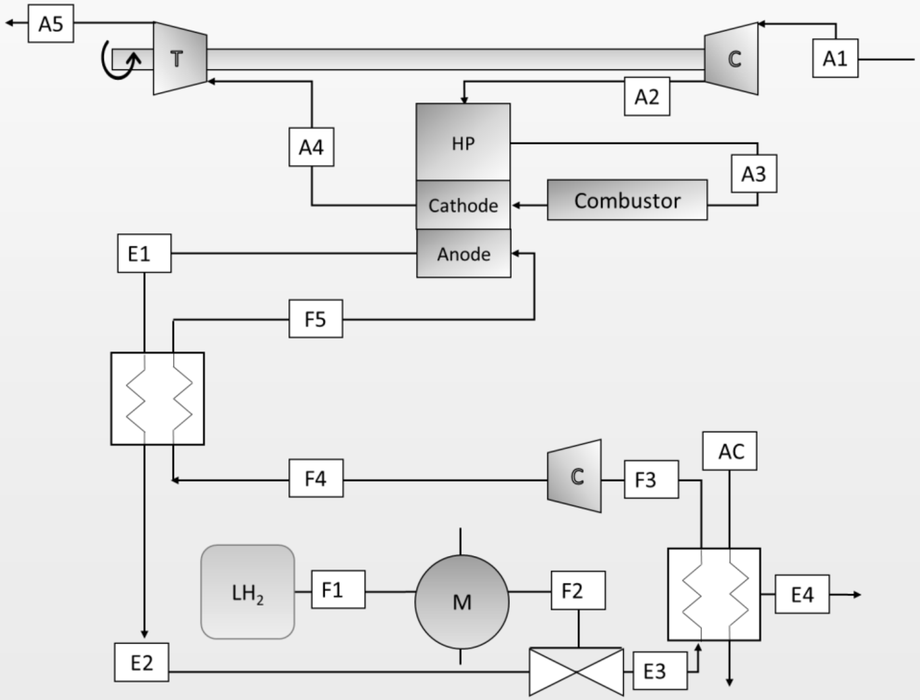
- Heat pipes developed by Dillig et al [16] integrated into the SOFC stack provide high rates of heat rejection at nearly isothermal operation
- Temperature gradients across SOFC were reduced by 75% compared to flowing excess cathode air [16]
- Especially useful in mobile SOFCs with varying power demand and heat generation

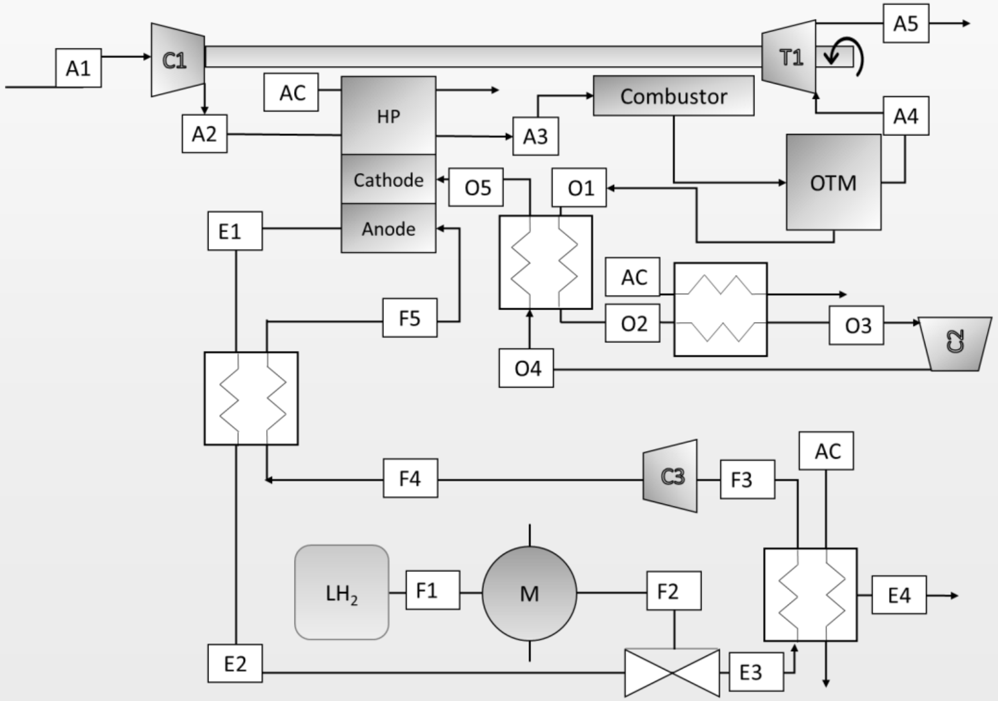
[16] M. Dillig, T. Plankenbühler, and J. Karl, "Thermal effects of planar high temperature heat pipes in solid oxide cell stacks operated with internal methane reforming," *J. Power Sources*, 2018.

Methodology

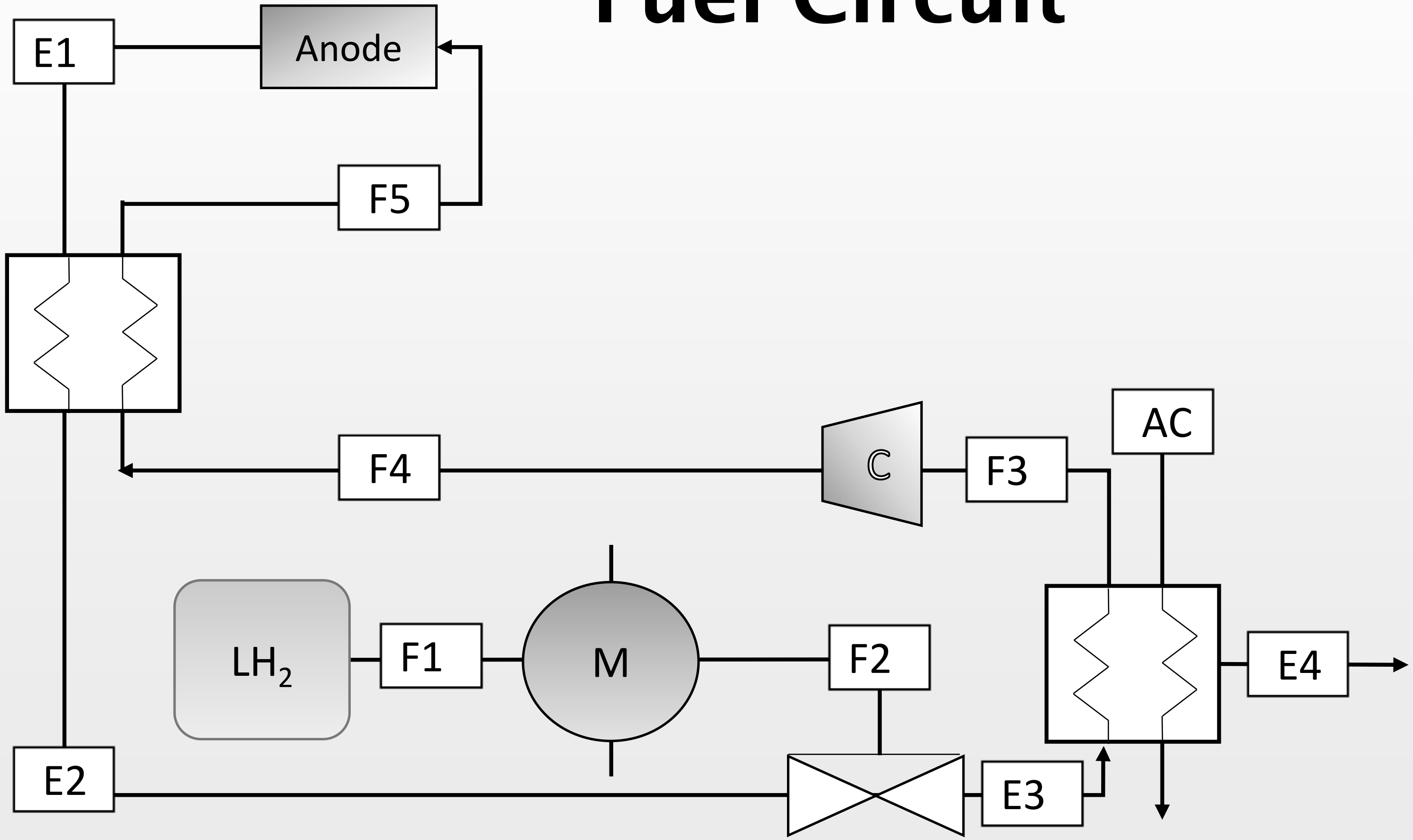
- Power system configurations
- Mass estimates of SOFC and additional power plant components
- Optimize size and efficiency
- Compare resulting payloads

Newly Proposed SOFC-GT Systems

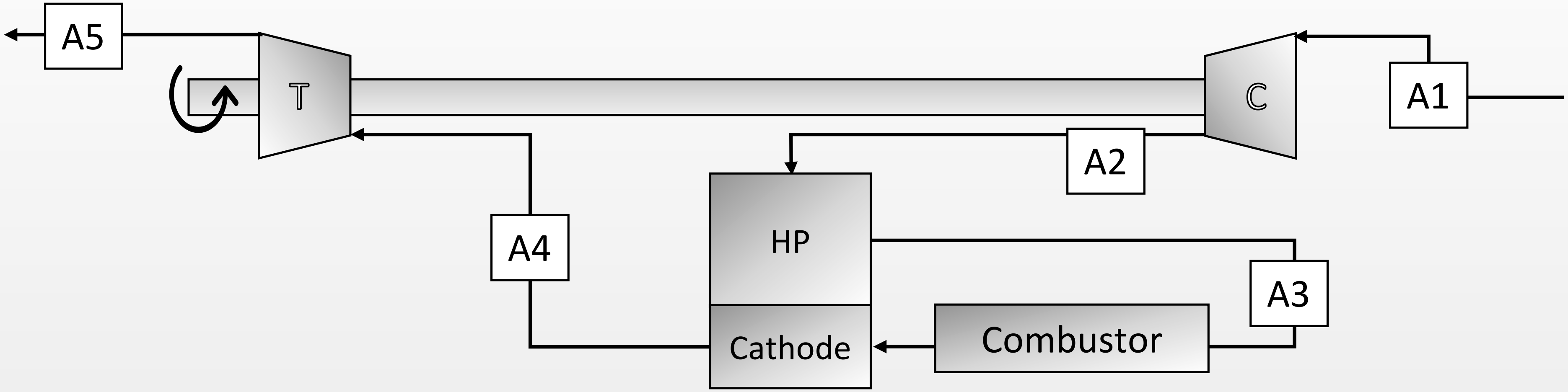




Fuel Circuit

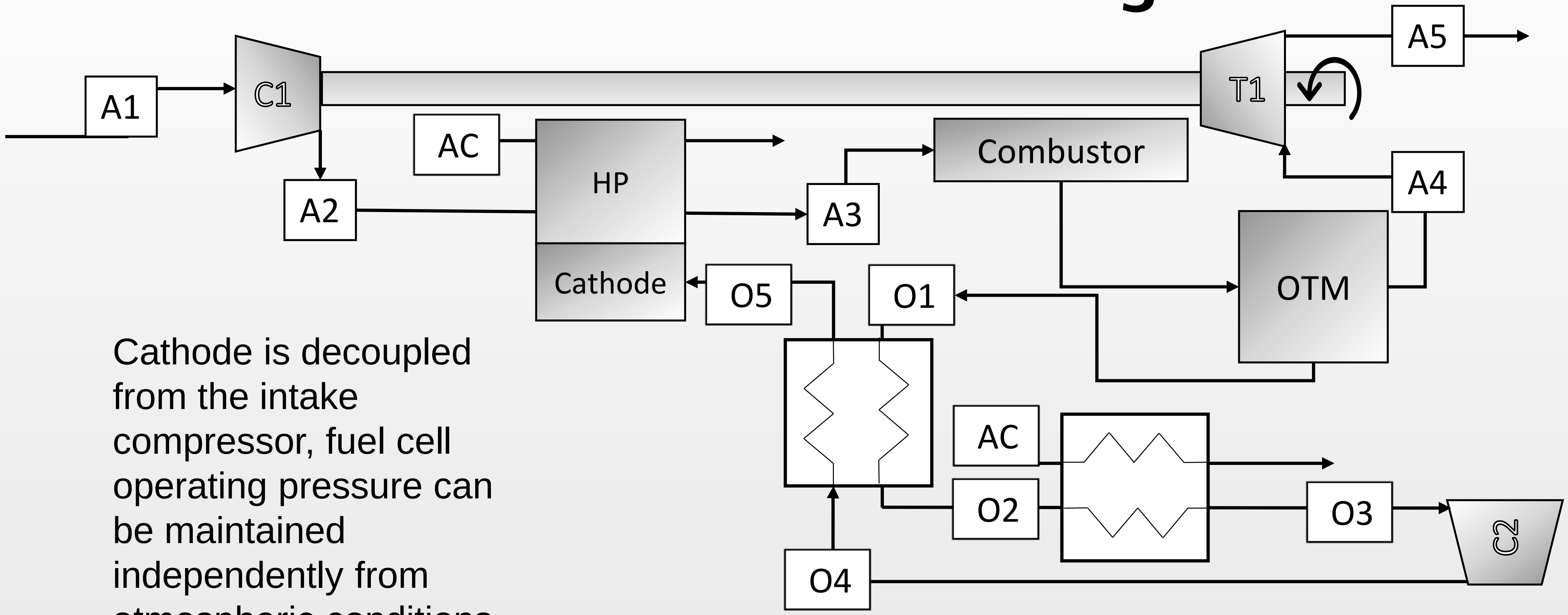


Oxidant Circuit Using Atmospheric Air



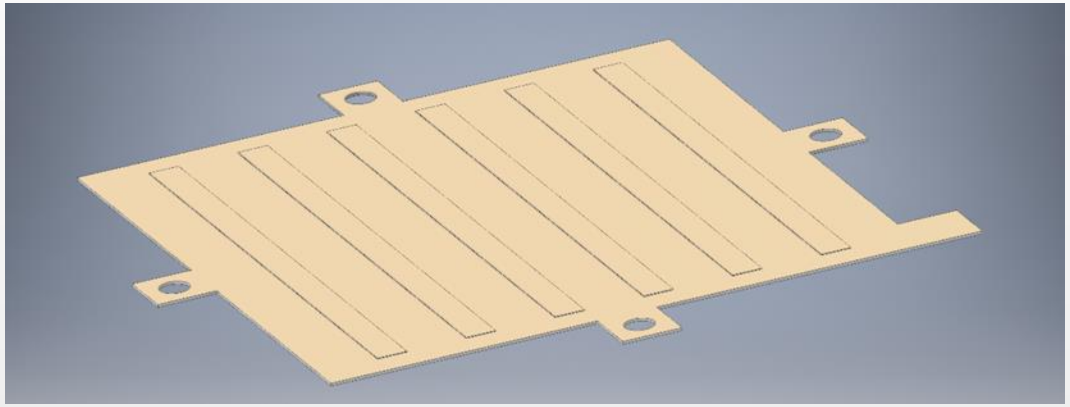
Constant pressure ratio intake compressor requires fuel cell operating pressure to change based on atmospheric conditions at the inlet

Oxidant Circuit Using OTM



Cathode is decoupled from the intake compressor, fuel cell operating pressure can be maintained independently from atmospheric conditions

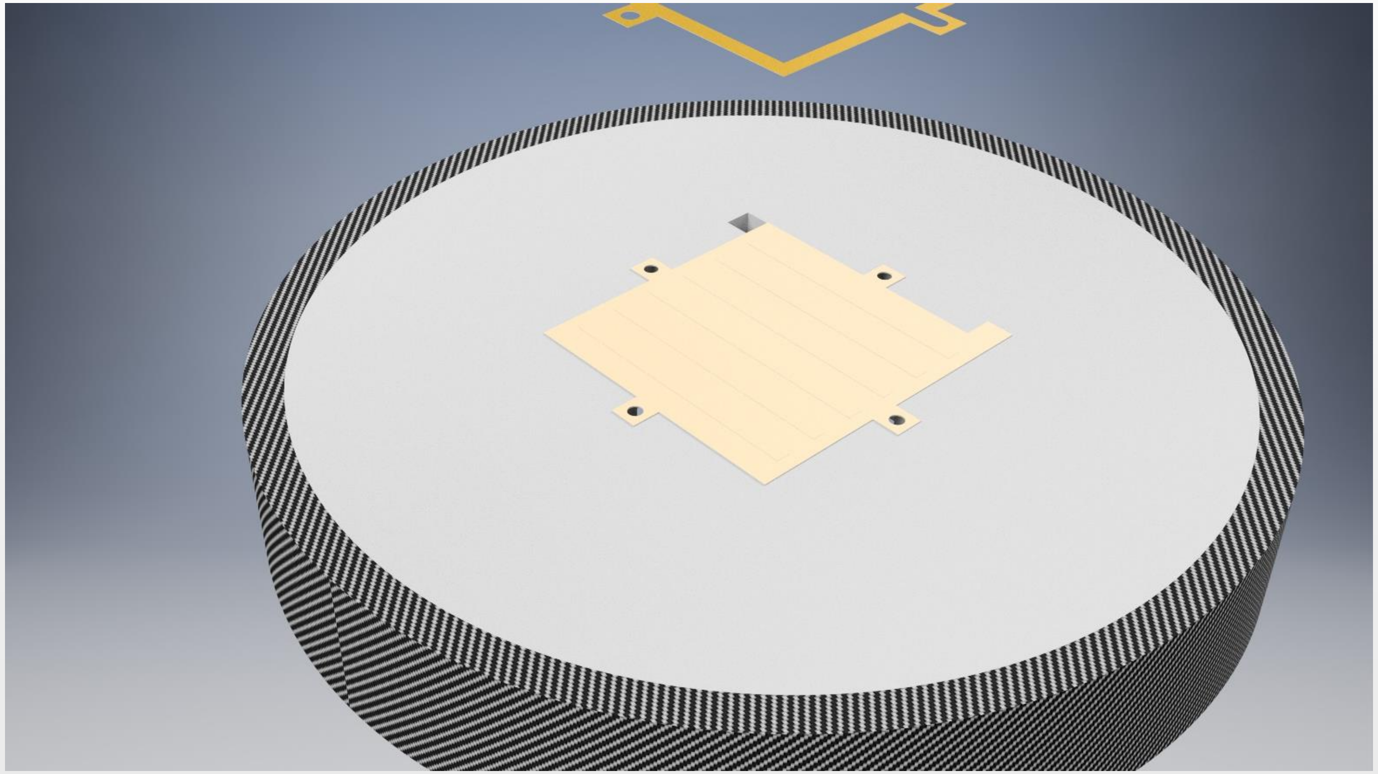
Proposed SOFC Stack Design



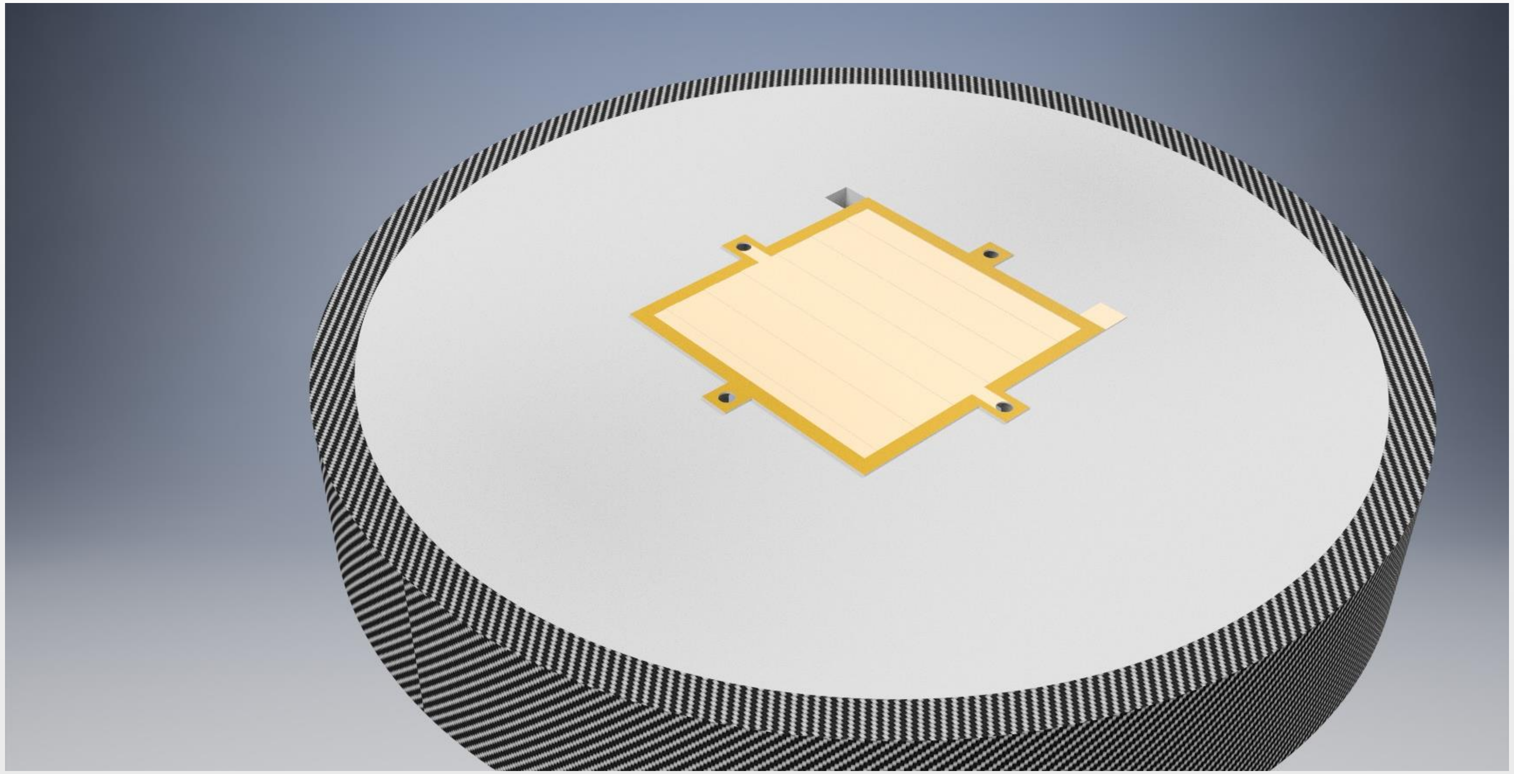
- Total fuel cell membrane area is 10 cm x 10 cm
- Electrolyte supported cells, 150-µm thick with ASR of 0.26 $\Omega\cdot cm^2$ [17]
- Interconnect is 0.5-mm thick
- YSZ material density 6000 $kg\cdot m^{-3}$

[17] E. S. Cells, "KeraCell I Electrolyte Supported Cells Key features," vol. 49, no. 0.

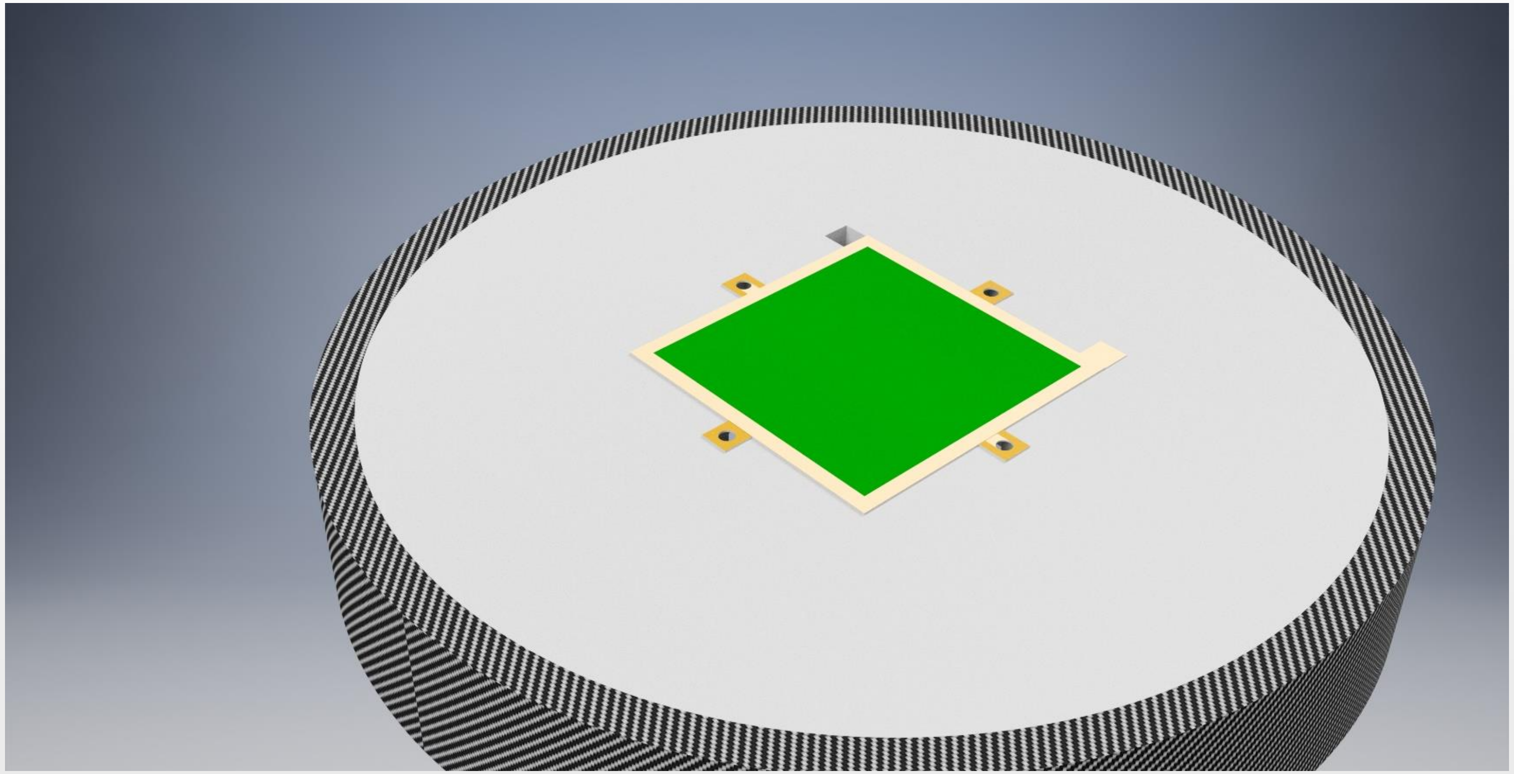
Proposed SOFC Stack Design



Proposed SOFC Stack Design



Proposed SOFC Stack Design

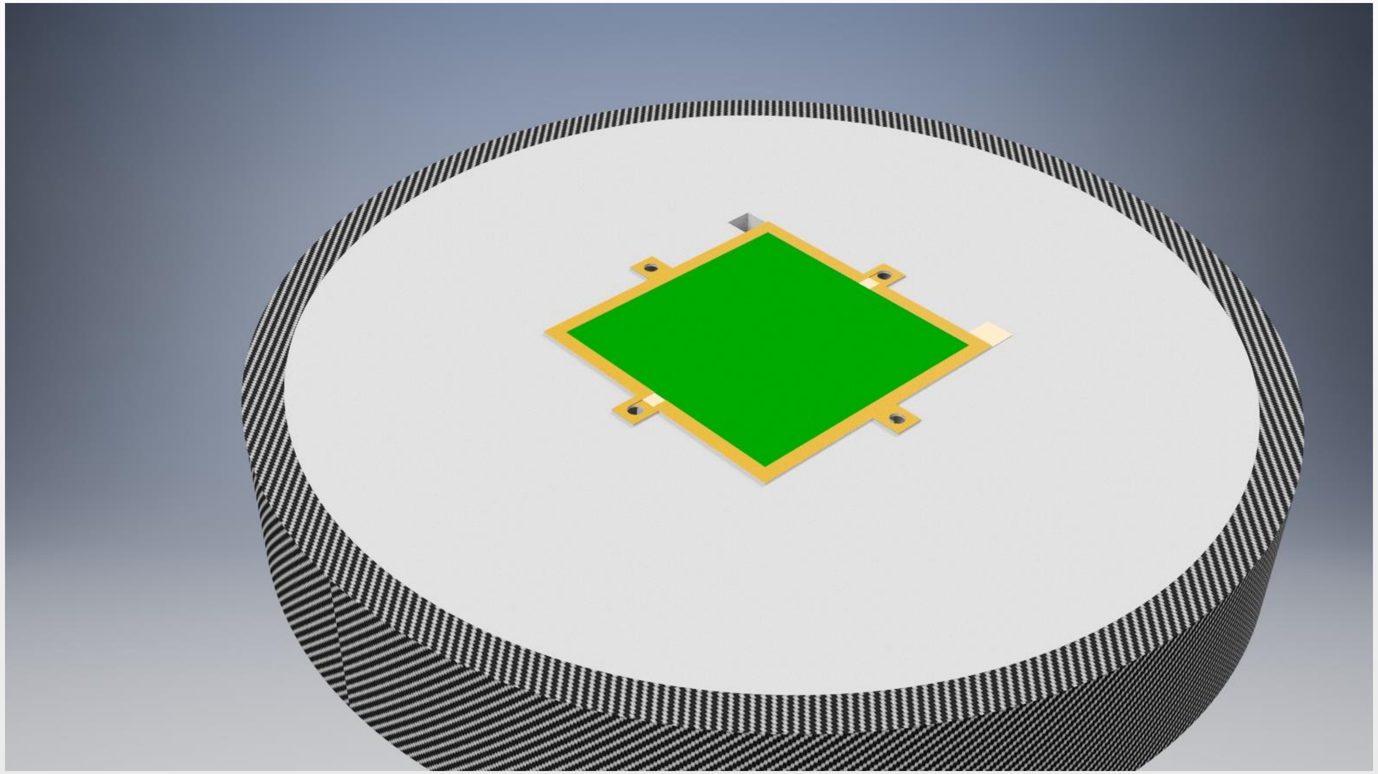


Proposed SOFC Stack Design

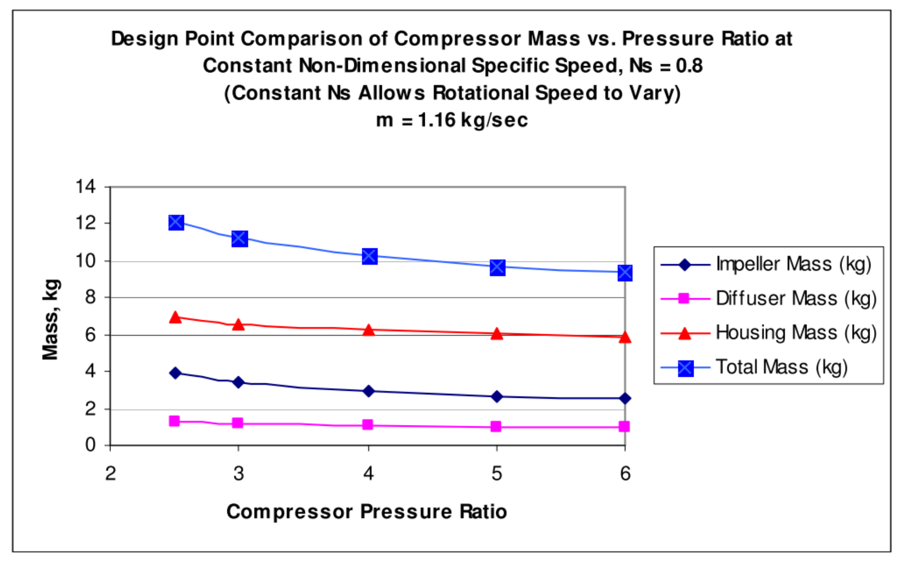
Resulting Mass:

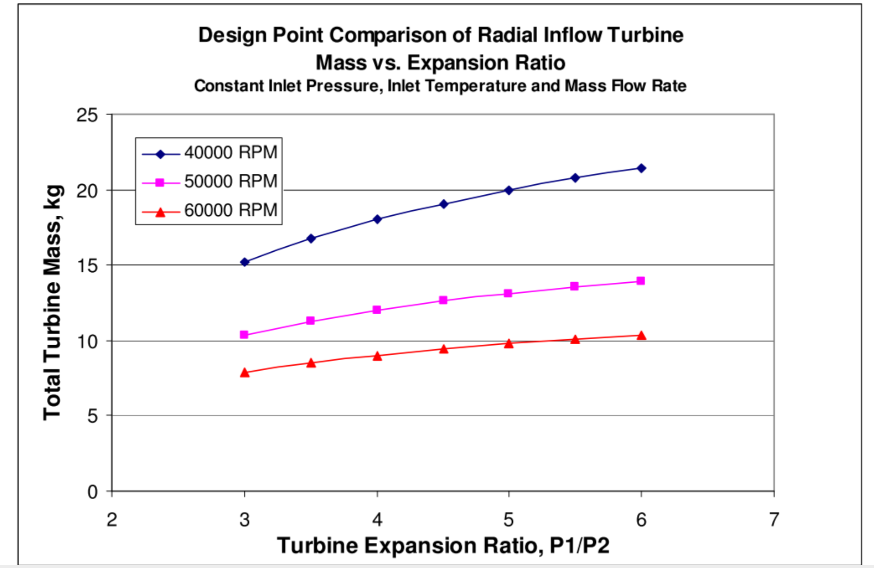
0.855 g·cm^{-2}

Reduces previously estimated fuel cell mass by 45%



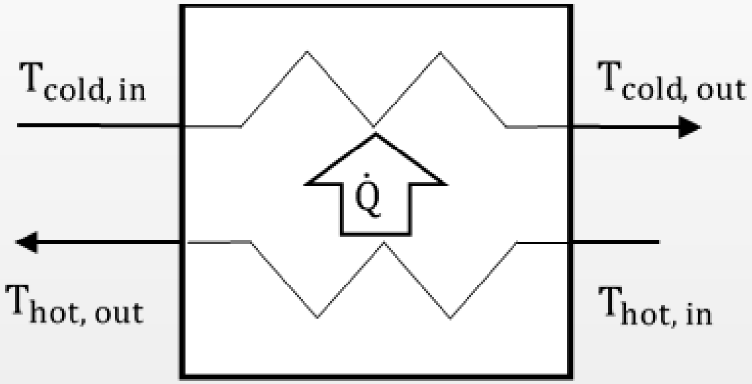
Compressor and Turbine Mass Estimates





Tornabene et al, 2005 [7]

Heat Exchanger Mass Estimates

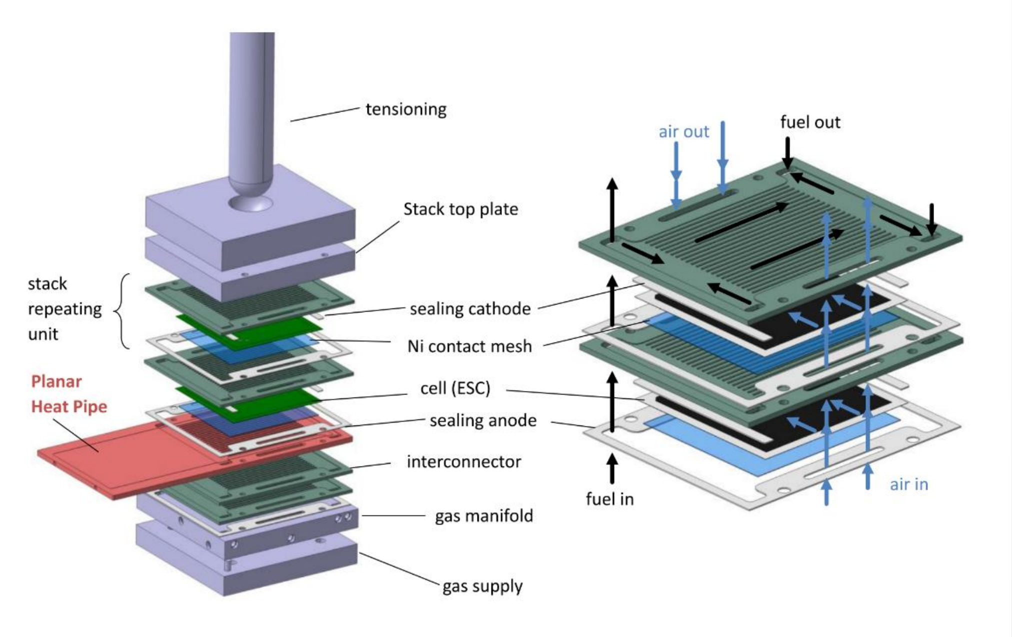


Log mean temperature difference is used to estimate required heat transfer area for a counterflow heat exchanger

Dimensions are based on Tornabene et al [5], plate thickness 0.03 cm, housing thickness 0.15 cm

Using silicon carbide as the construction material, density is 2700 kg·m^{-3}

Heat Pipe Mass Estimates



Dillig et al, 2018 [16]

Based on dimensions and material properties given by Dillig [16], each heat pipe weighs ~ 0.639 kg and rejects up to 740 W

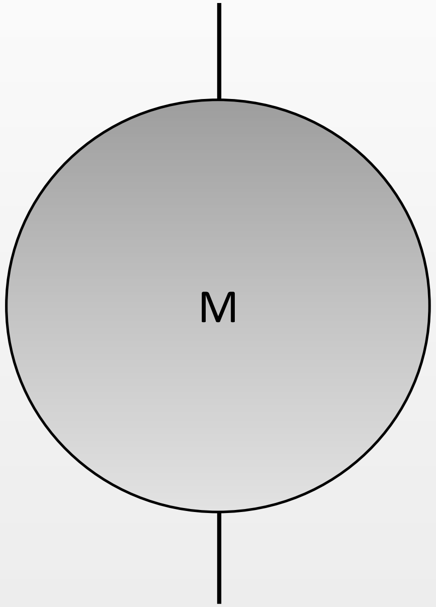
Assuming 35% weight reduction, heat pipes are sized based on maximum heat load and a mass-to-duty ratio of 1.72 $kW \cdot kg^{-1}$

Oxygen Transport Membrane Mass Estimates

- Best reported flux rate was 5.1 $mL \cdot cm^{-2} \cdot s^{-1}$ from a 70-μm thick membrane [13]
- Material for membrane and support structure is BSCF, 5800 $kg \cdot m^{-3}$
- Membrane area, support structure dimensions and insulated pressure vessel are assumed to be same as SOFC stack
- Estimated mass is 0.736 $g \cdot cm^{-2}$

Superconducting Electric Motors

- Constant Efficiency of 98.4 % [18]
- Power density is 24 kW·kg^{-1}[19]
- Operates at 77 K [18]
- Cooled by LH_2 fuel



[18] J. D. Edick, R. F. Schiferl, and H. E. Jordan, "High temperature superconductivity applied to electric motors," *IEEE Transactions on Applied Superconductivity*, vol. 2, no. 4. pp. 189–194, 1992.
[19] C. A. Luongo *et al.*, "Next Generation More-Electric-Aircraft: A Potential Application for HTS Superconductors," *Appl. Supercond.*, vol. 19, no. 3, pp. 1055–1068, 2009.

System Assumptions

- Fuel cell stack ASR can be reduced from the initial 0.33 $\Omega \cdot cm^2$ down to 0.25 $\Omega \cdot cm^2$ under pressure
- Single pass fuel utilization is 20%
- SOFC temperature is maintained at constant 750ºC
- Pressure drop is constant 20 kPa across fuel and oxidant circuits
- Compressor efficiency is constant 80%
- Hydrogen blower efficiency is constant 50%
- Turbine efficiency is constant 88%
- Intake compressor speed is variable from 50-100% of nominal RPM

Performance Modelling

- Turbomachinery is modelled using isentropic efficiency
- Shomate equations of state are used to determine entropy, enthalpy and specific heat
- Fuel cell performance is predicted using the Nernst equation
- Heat exchangers are evaluated using an energy balance and assuming a minimum 10ºC temperature differential to drive heat transfer

Aircraft Models Considered

Model	Takeoff Weight (kg)	Range (km)	Total Fuel Burn (kg)	Reserve Fuel (kg)	Payload (kg)	Engine Type	No. of Engines	Engine Mass (kg)
Airbus A380-800	569000	14408	211418	22356	52725	RR Trent 900	4	6246 [38]
Boeing 787-8	219539	14187	75126	7799	23052	RR Trent 1000	2	6033 [37]
Airbus A300-600	170500	7267	48102	7537	25365	GE CF6	2	5092 [39]
Fokker F70	36741	2020	4917	2136	7167	RR Tay 620-15	2	1501 [40]

System Optimization

- Larger SOFC stacks are heavier but more fuel efficient
- SOFC size can be minimized using supplemental batteries to handle short spikes in power demand
- Batteries are much heavier than fuel
- Optimal tradeoff between SOFC size and battery assist must be determined

Determining Nominal System Size

- Standard Air SOFC-GT Cycle
- Consider intake pressure ratios from 15:1 to 40:1 at a constant rate of airflow
- Apply to SOFC active areas ranging from 1000-5000m^2
- Adjust rates of fuel utilization to find combinations of oxygen utilization and current density that yield thermal balance, generate array of nominal systems across range of sizes and efficiencies
- Scale systems to meet power requirements at a chosen design point in the flight profile

Determining Nominal System Size

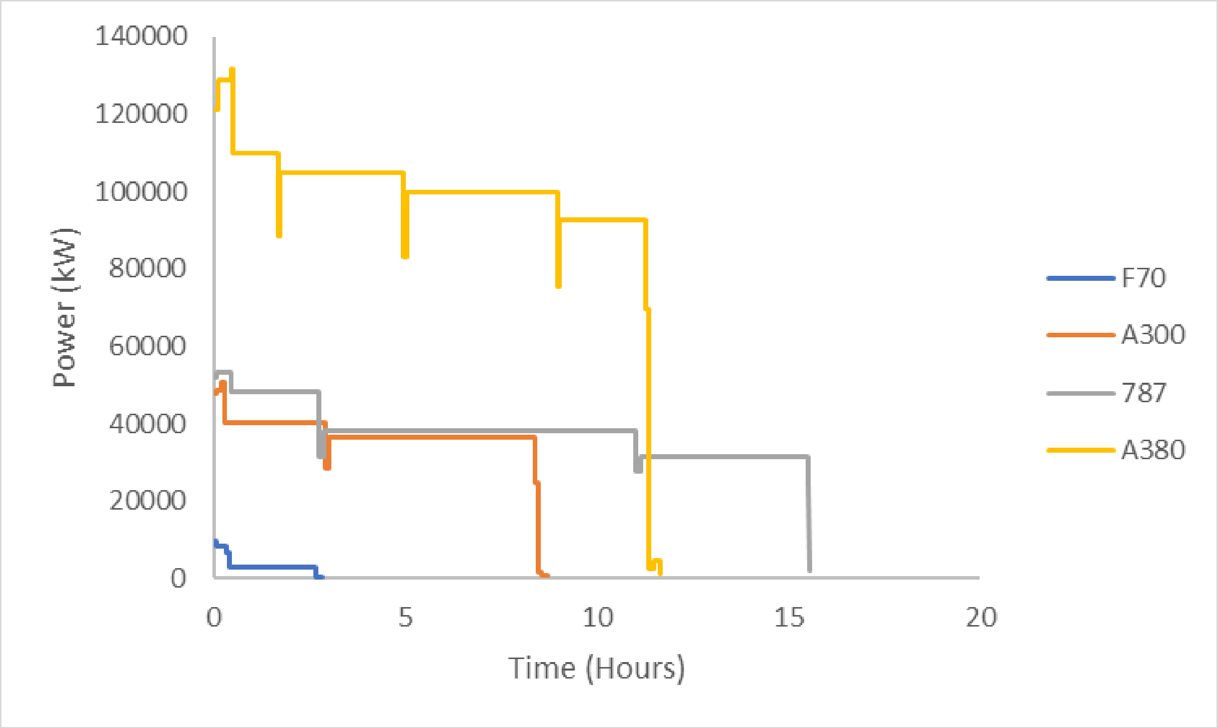
- Pure Oxygen dcFC-GT Cycle
- Consider intake pressure ratios from 18:1 to 50:1 at a constant rate of airflow to calculate resulting oxygen recovery from OTM
- Apply to SOFC active areas ranging from 2000-5000m^2
- Assume 100% oxygen utilization at SOFC to determine fuel consumption, generate array of nominal systems across range of sizes and efficiencies
- Scale to meet power requirements at a chosen design point in the flight profile

Power Demand

Larger systems can be more fuel efficient, but add more mass

Smaller systems require greater battery assist

Must find optimal tradeoff



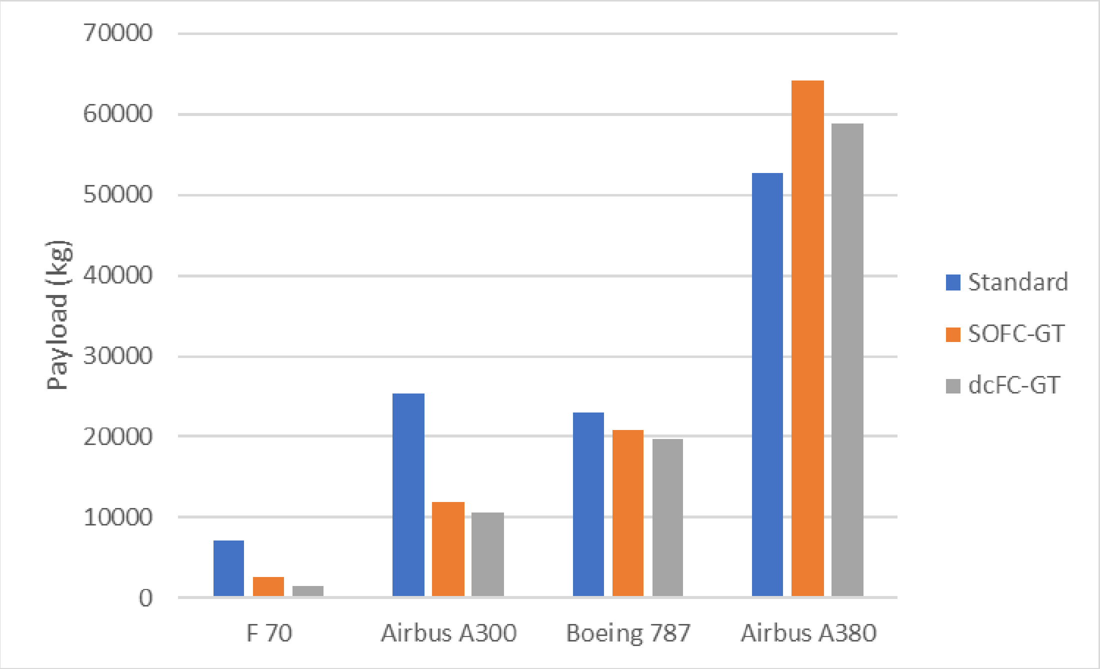
Total Mission Performance

- Consider the performance of each system across entire flight profile
- Off-design performance is controlled by adjusting the volumetric flow rate of intake air. Additional control of oxygen flux through the OTM is achieved by adjusting back pressure
- Power demands that cannot be met by the system are attributed to supplemental batteries with an assumed power density of 1.26 $\mathrm{MJ \cdot kg^{-1}}$
- Integrate total mission fuel consumption across flight profile

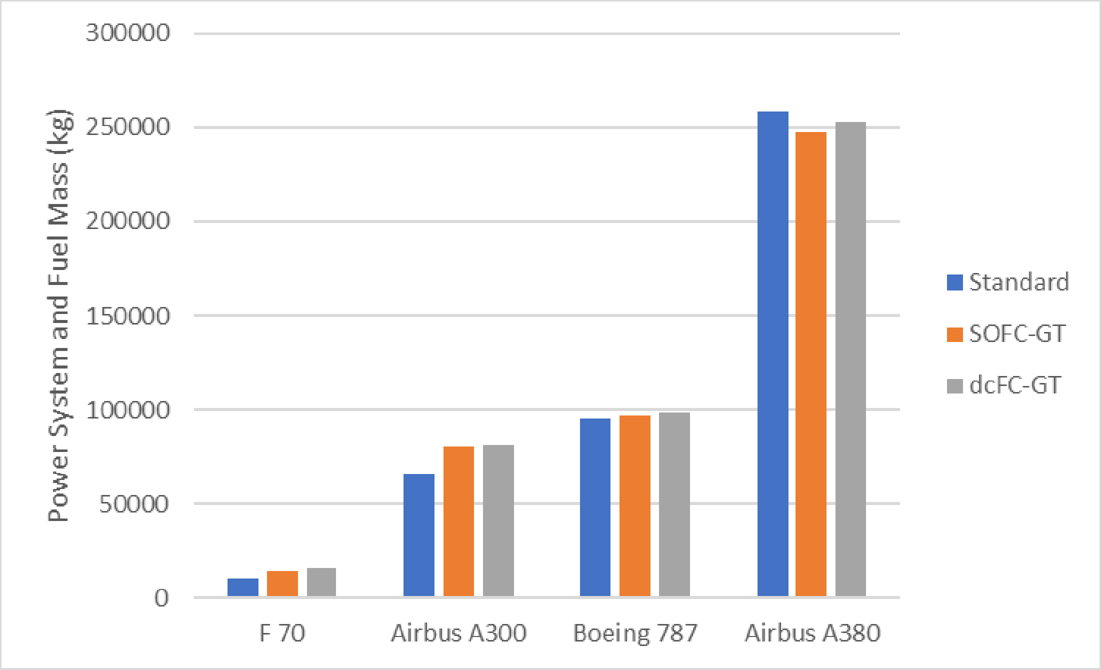
Determining Optimal System Size

- Resulting changes in power plant and fuel mass determine changes in payload
- Size nominal system to a given flight segment and power demand, model performance through entire mission
- Select system resulting in highest payload
- Repeat for all mission segments
- Highest overall payload determines optimal design point and tradeoff between weight and efficiency

Resulting Payloads



Total Mass of Power System and Fuel Storage



Total Mass of Power System and Fuel Storage

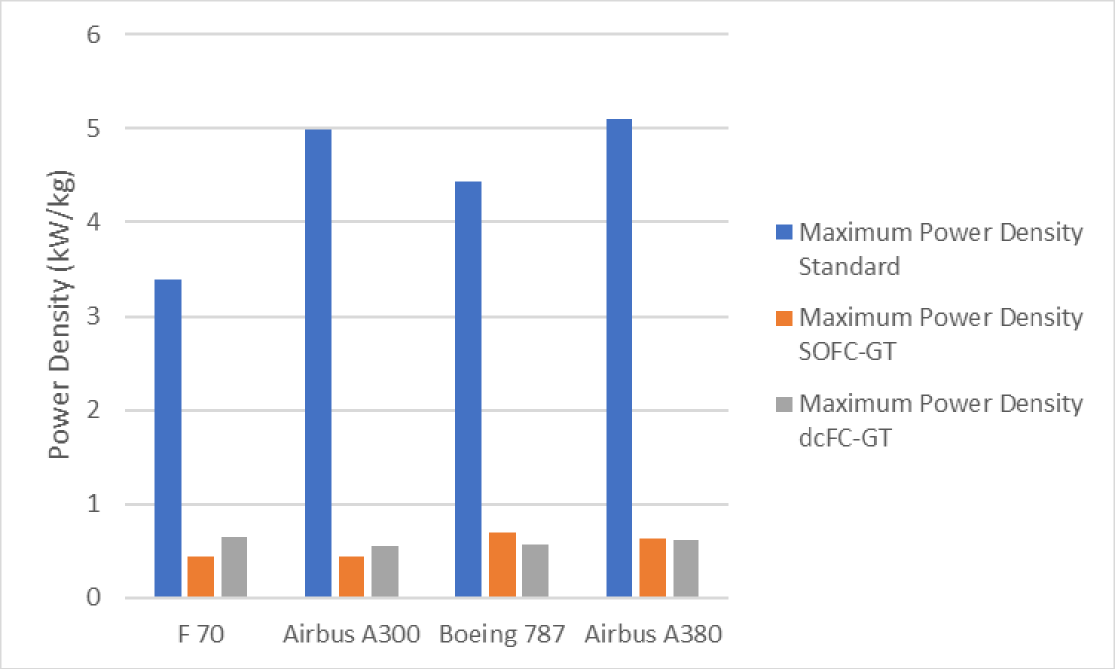
Total savings in fuel storage compensate for weight added by SOFC power system

Power Density

Minimum: 0.44 kW/kg

Maximum: 0.70 kW/kg

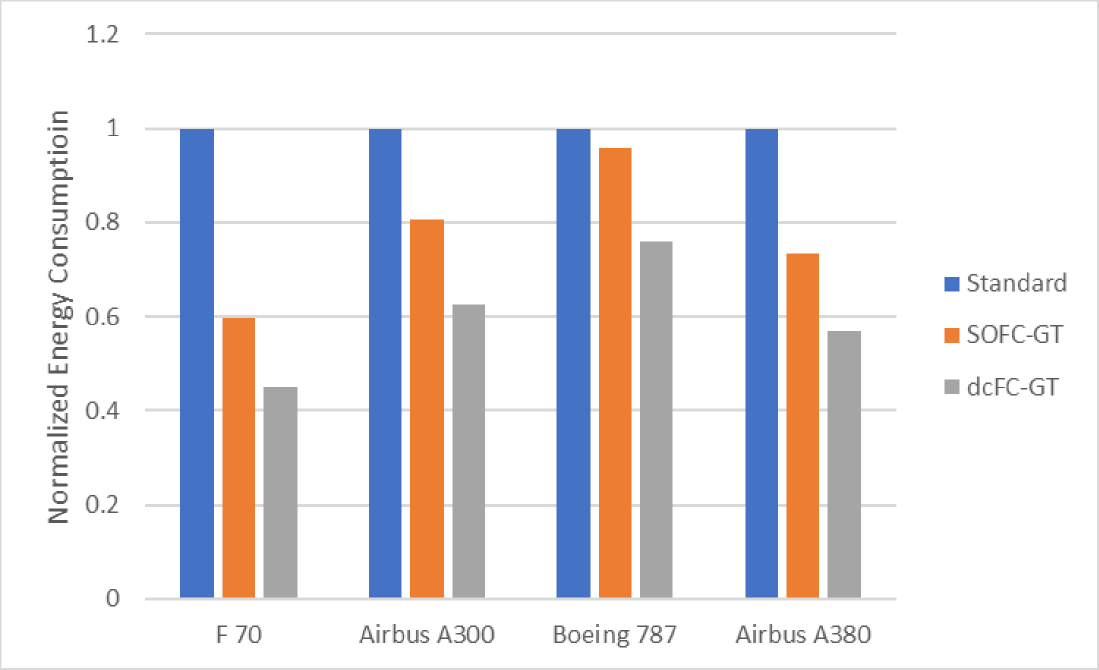
Both exceed NASA SOFC-GT estimate of 0.356 kW/kg [3]



Total Mission Energy Consumption

- dcFC-GT is more energy efficient in all cases

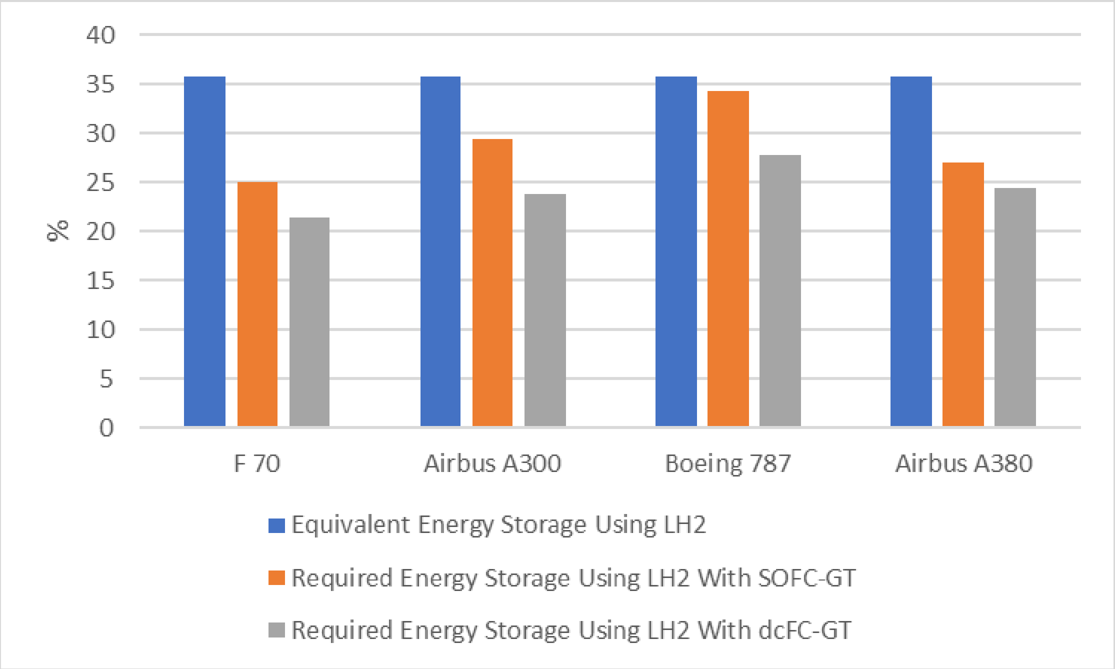
- For Airbus A380, dcFC-GT consumes 13,000 kg less fuel



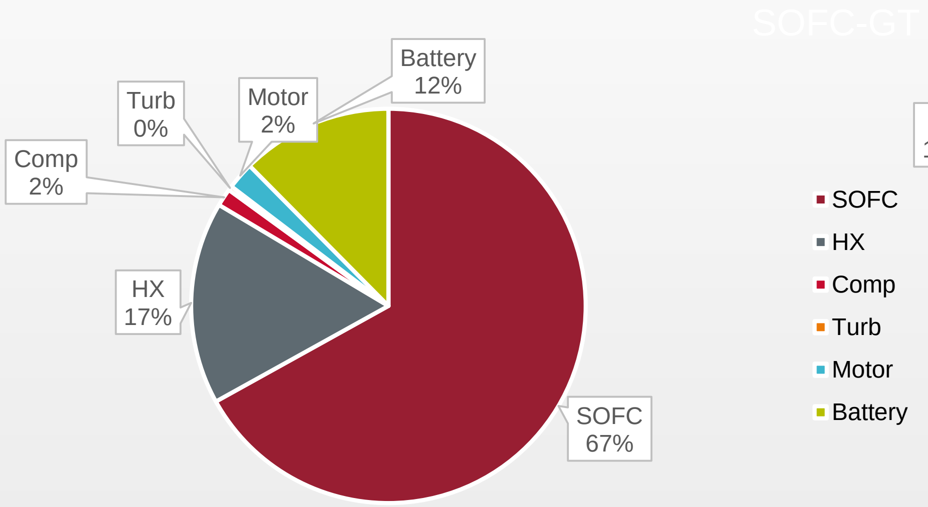
Reduced Energy Storage Mass: Density vs Efficiency

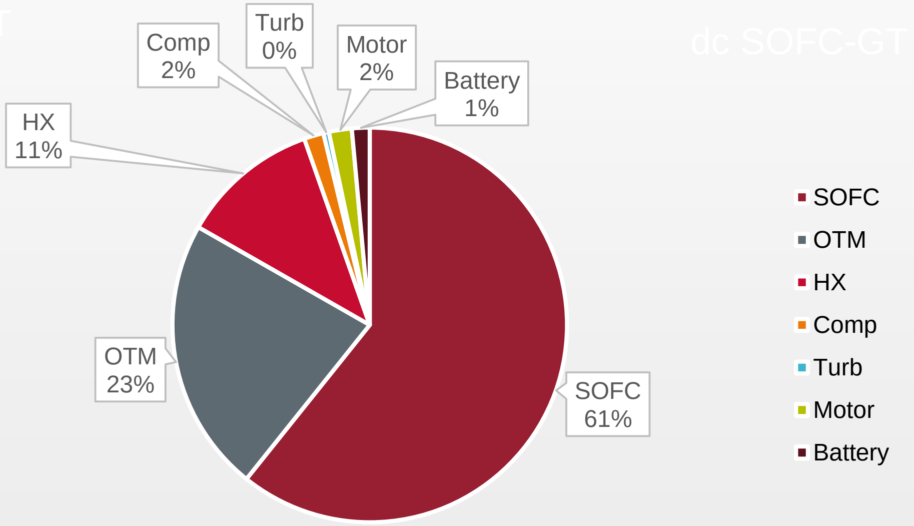
Assuming equivalent energy efficiency after replacing jet fuel with hydrogen, total fuel storage mass would be 35.8% of current levels

Reducing energy consumption with high efficiency SOFC-based system, total fuel storage requirements are further reduced to 24%-34% of current levels



Mass Contributions by Component



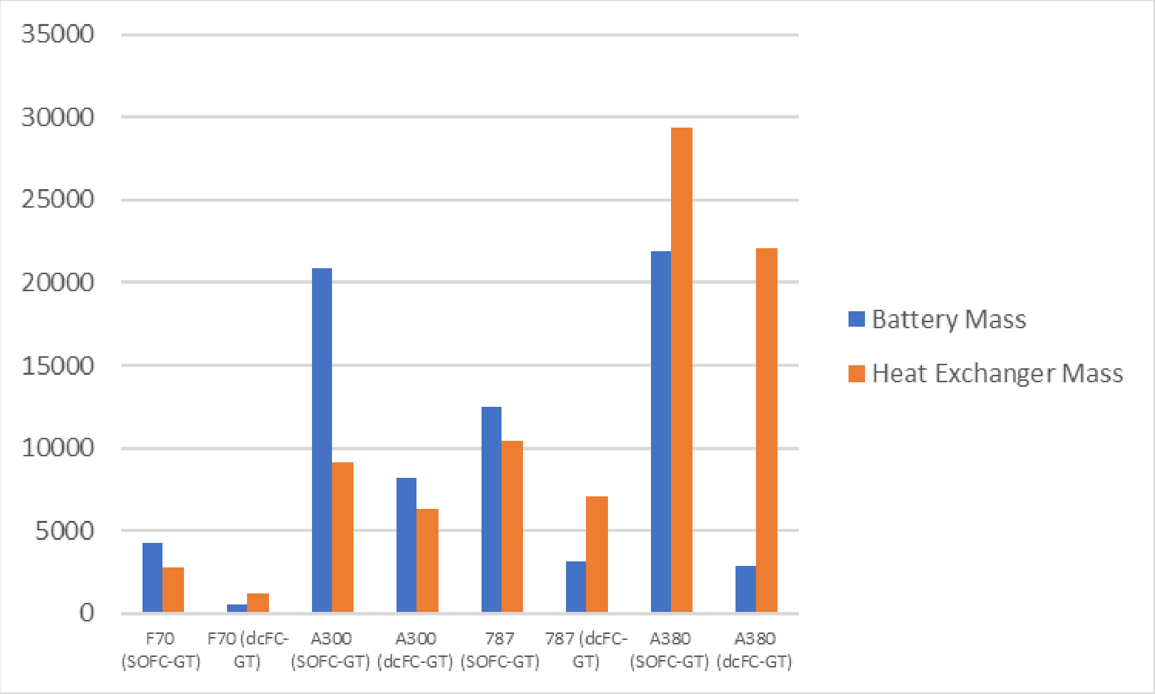


SOFC-GT: 176,700 kg

dcFC-GT: 194,595 kg

Comparison of Heat Pipe And Battery Sizes

Pure oxygen generates less waste heat, larger range of power generations reduces battery assist for nearly identical SOFC stack sizes

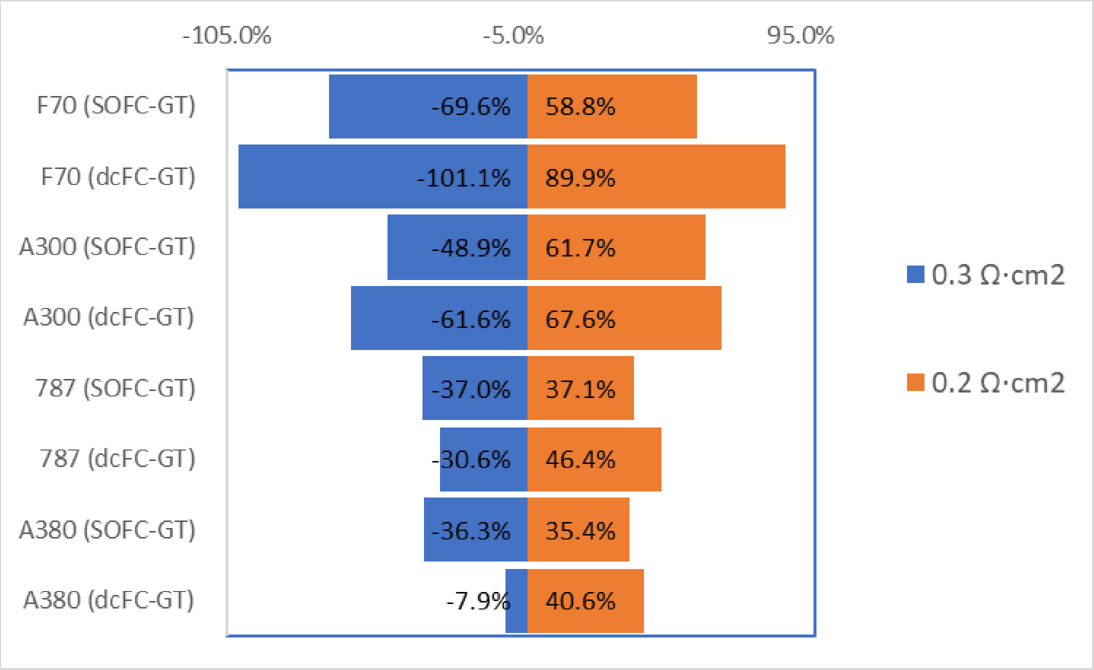


Comparison of System Configurations

- dcFC-GT is consumes less total energy, requires less battery assist during takeoff, and requires lighter heat pipes due to lower waste heat generation
- OTM mass outweighs any savings realized through higher efficiency
- Reducing OTM by 15% would allow dcFC-GT to achieve same payload as SOFC-GT for the A380

Sensitivity to Fuel Cell ASR

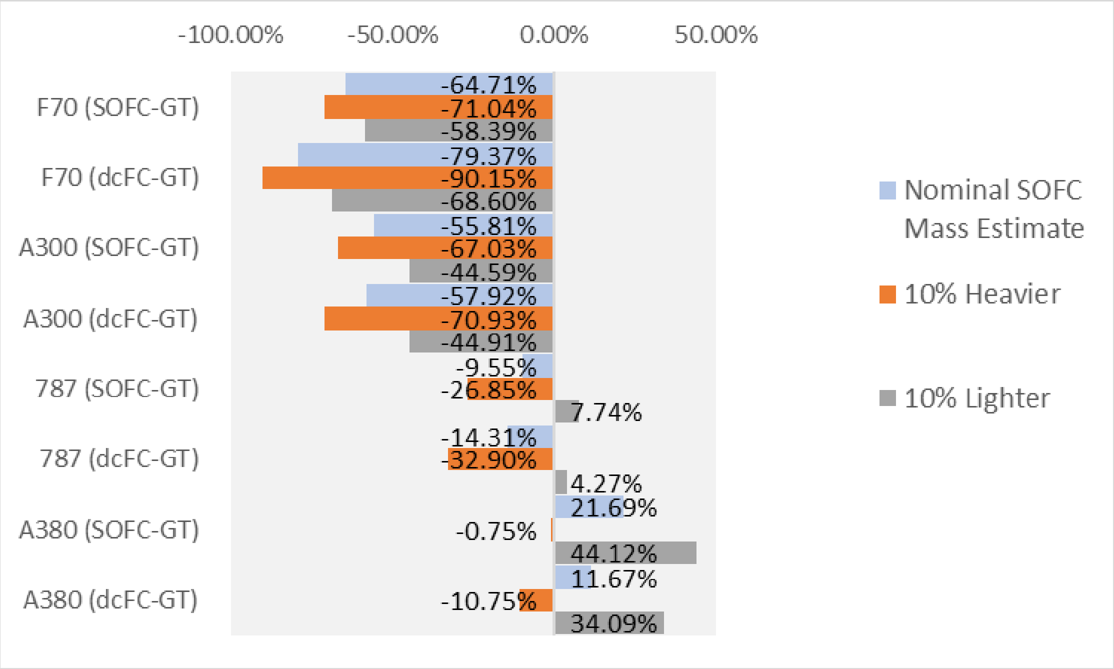
Lower ASR allows Boeing 787 to exceed standard payload, expands the size of aircraft that may benefit



Sensitivity to SOFC Mass

Reducing initial mass estimate by 10% allows 787 to exceed standard payload

Increasing estimate by 10%, SOFC-GT breaks even with standard A380 payload



Summary

- Developed performance models for two alternate SOFC-GT configurations that have not been previously considered
- Combined materials to construct lighter SOFC stack, resulting in higher system power density than has been previously estimated
- Applied SOFC-GTs as a primary mover for existing commercial aircraft with no changes to propulsion system
- Developed method for optimizing tradeoffs between weight and efficiency
- Found that larger, long-range aircraft can increase payload and reduce total energy consumption using hydrogen powered SOFC-GT systems

Conclusions

- Hydrogen powered SOFC-GTs can achieve power-to-weight ratios necessary to power large, long-range aircraft, although
- Converting existing turbine engines to use pure hydrogen would likely be a more practical near-term solution for eliminating aircraft emissions
- Assuming hydrogen powered jet engines with equivalent energy efficiency to those currently in use, SOFC-GTs could potentially complete the same flight mission using only 60% of the fuel.
- The benefits of operating SOFCs on pure oxygen are significant, further research into lightweight oxygen separation for mobile applications is warranted

- Questions?

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