CHANGING WHAT'S POSSIBLE

REEACH Project DOE
H_2 Program Review
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High Power Density Carbon Neutral Electrical Power Generation for Air Vehicles

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Project Vision

"We are solving the electrification of aviation by integrating the propulsion, power, and thermal systems for an energy optimized aircraft."

Economically Viable, Net-Zero Emissions Aviation

- Distributed propulsion shows promise for meeting NASA N+3 metrics
  - High efficiency
  - Low emissions
  - Low cost operation
- Electric power centric propulsion can be an enabler of distributed propulsion

Large Scale Electric Propulsion

Approach

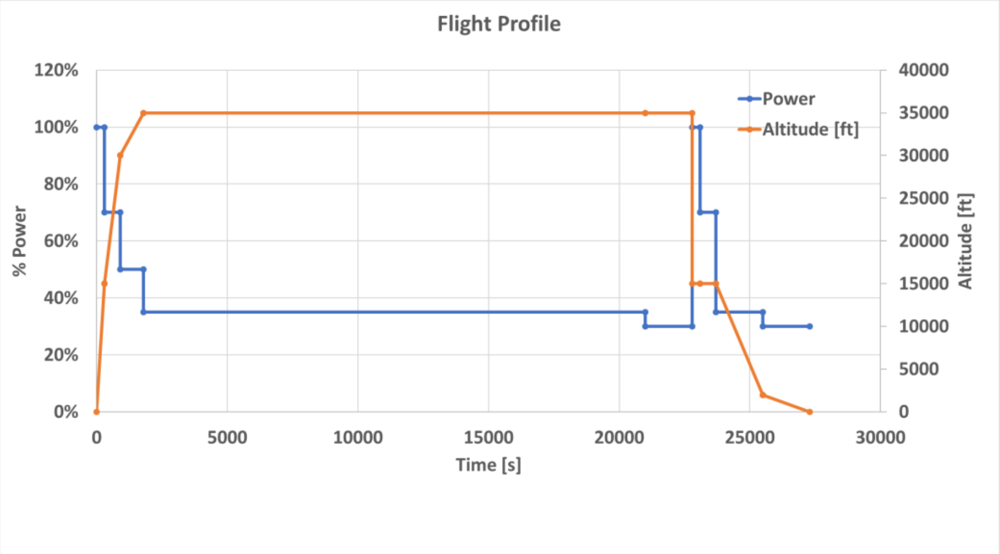
- Requires high conversion efficiency to drive down:
  - $/passenger mile
  - Net zero Emissions
  - Meet current fuel storage requirements
- Vehicle level top-down design approach is required
- Reliability in approach for aerospace standards
- High power density electric centric systems:
  - **<u>Electric power production (REEACH)</u>**
  - Electric propulsors (ASCEND)
  - Electrical distribution system (CABLE)
- **<u>Manage 100's kWs of thermal management</u>**

Large Scale Electric Propulsion

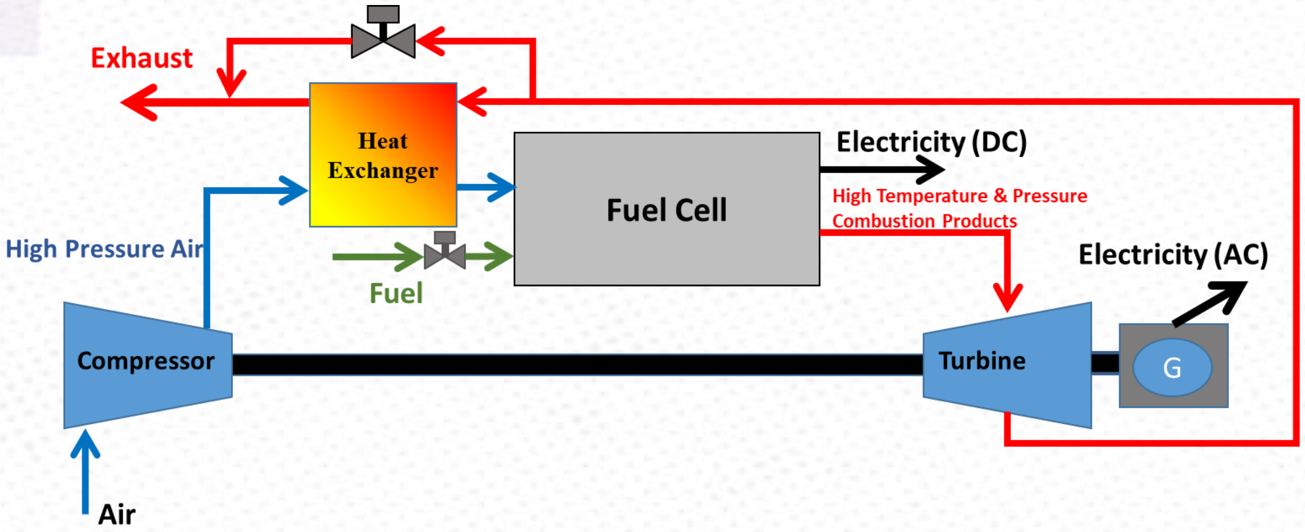
- Challenges
  - Must operate at altitudes of **35,000 ft**
  - Vast range of operating load, pressures and temperatures
    - Temperature range, -54° to 30°C and Pressure range, 23 kPa to 101 kPa
  - Provide high density and high efficiency electrical power
  - Reliability and redundancy
  - Thermal management of the aerospace systems including SOFC

Large Commercial Aircraft Requirements

- 29 MW Take-off Power (Electrical power delivered)
- 9 MW Cruise Power
- > 3 kW-hr/kg
- <0.15 $/kWh
- Electrical Storage and Power Generation System (ESPG)< 25,804 kg (includes fuel)
- 6.5 hours Flight time, 3600 mile range



Conventional Hybrid
Fuel Cell-Gas Turbine (FC-GT)



Pros

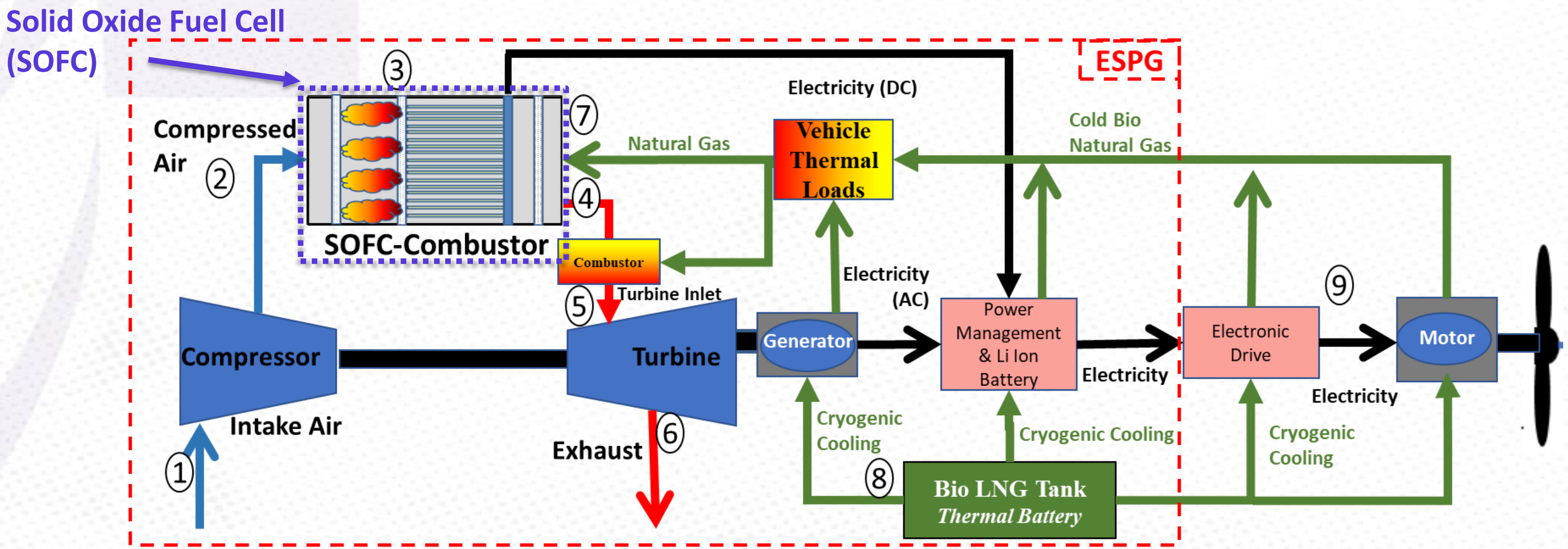
- **FC-GT provides ultra high chemical-to-electrical conversion efficiency**
- **Provides pressurized environment at high altitudes**

Cons

- **Large massive systems with low specific power**
- **Large thermal mass, sluggish response to perturbations**
- **Long cold startup times**
- **Complex thermal management of FC typically with large valves**

Proposed Integrated ESPG Concept

Solid Oxide Fuel Cell Combustor-Turbogenerator system (SOFC-C-TG) is proposed for the ESPG



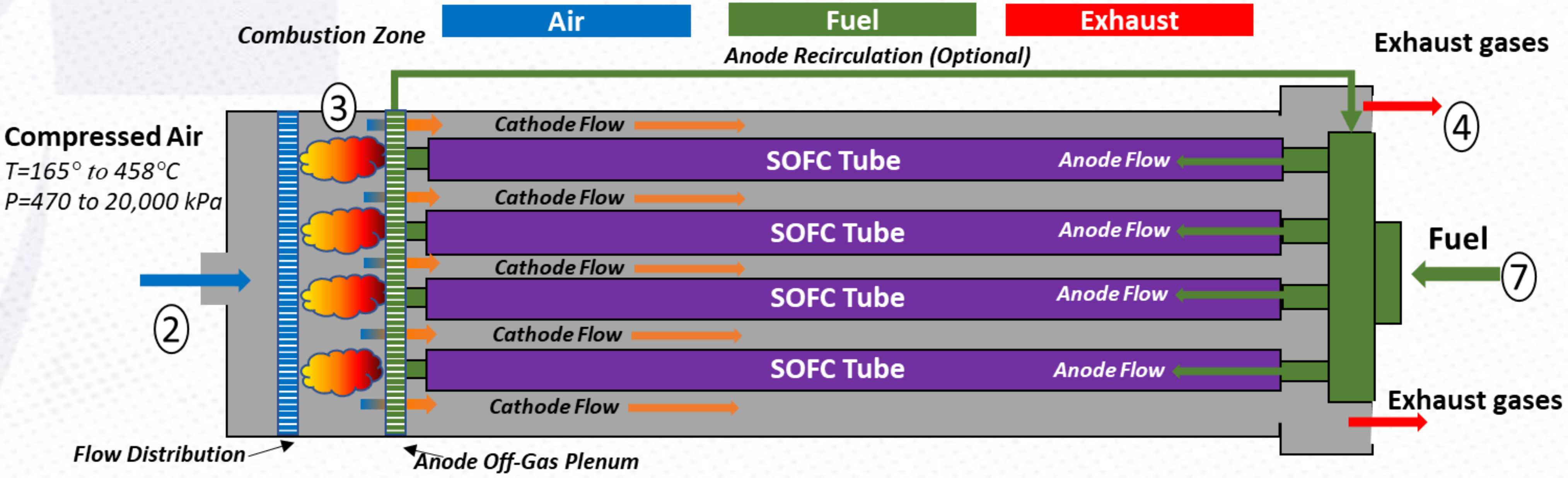
Pros

- SOFC-C-TG provides a simple & elegant solution for electric power generation in air vehicles
- SOFC-C-TG eliminates cathode heat exchangers, large thermal mass. ***Minimum size and weight***
- Provides precise thermal control of SOFC stack at cathode inlet. ***Minimum use of valves***
- Rapid response to perturbations and extreme conditions: load, inlet temperature and pressure.
- Redundancy and reliability

Cons

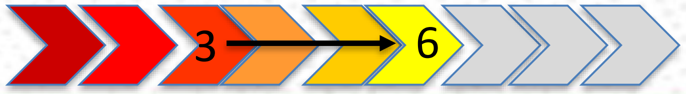
- New concept, never been fully demonstrated

SOFC-C Concept



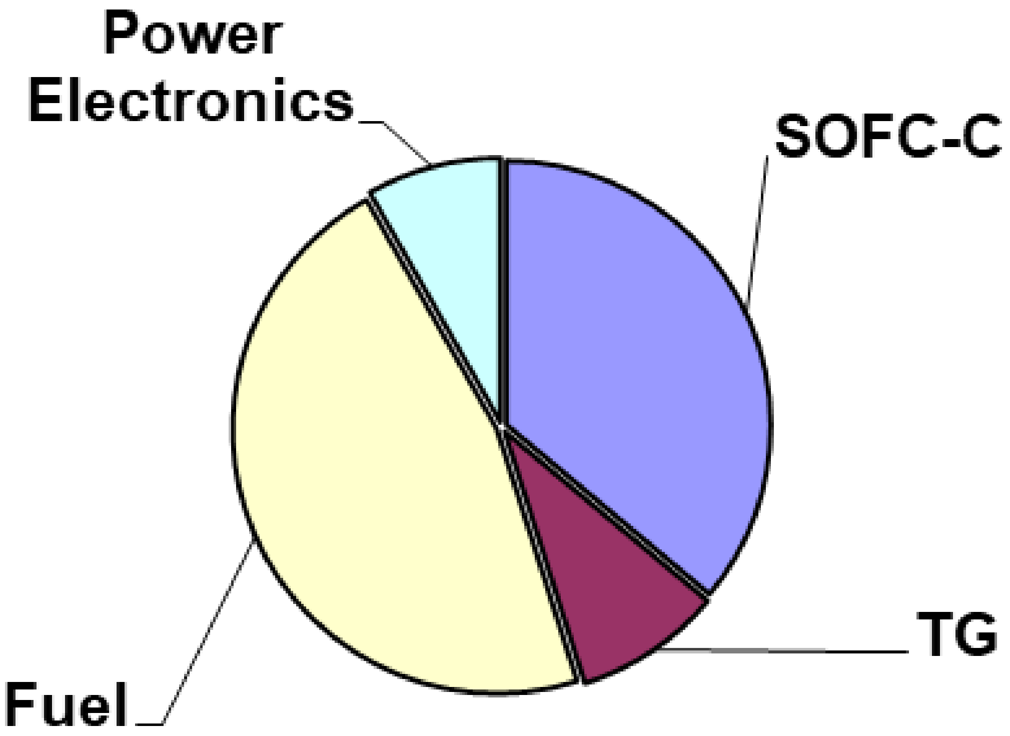
- Eliminates large cathode heat exchangers
- Eliminates external reformers
- Fuel flexible: hydrogen, methane, propane, ammonia, ethanol, methonal
- Increase redundancy in the system
- Minimized sealing requirements
- Resilient to vibration

SOFC-C TRL Level

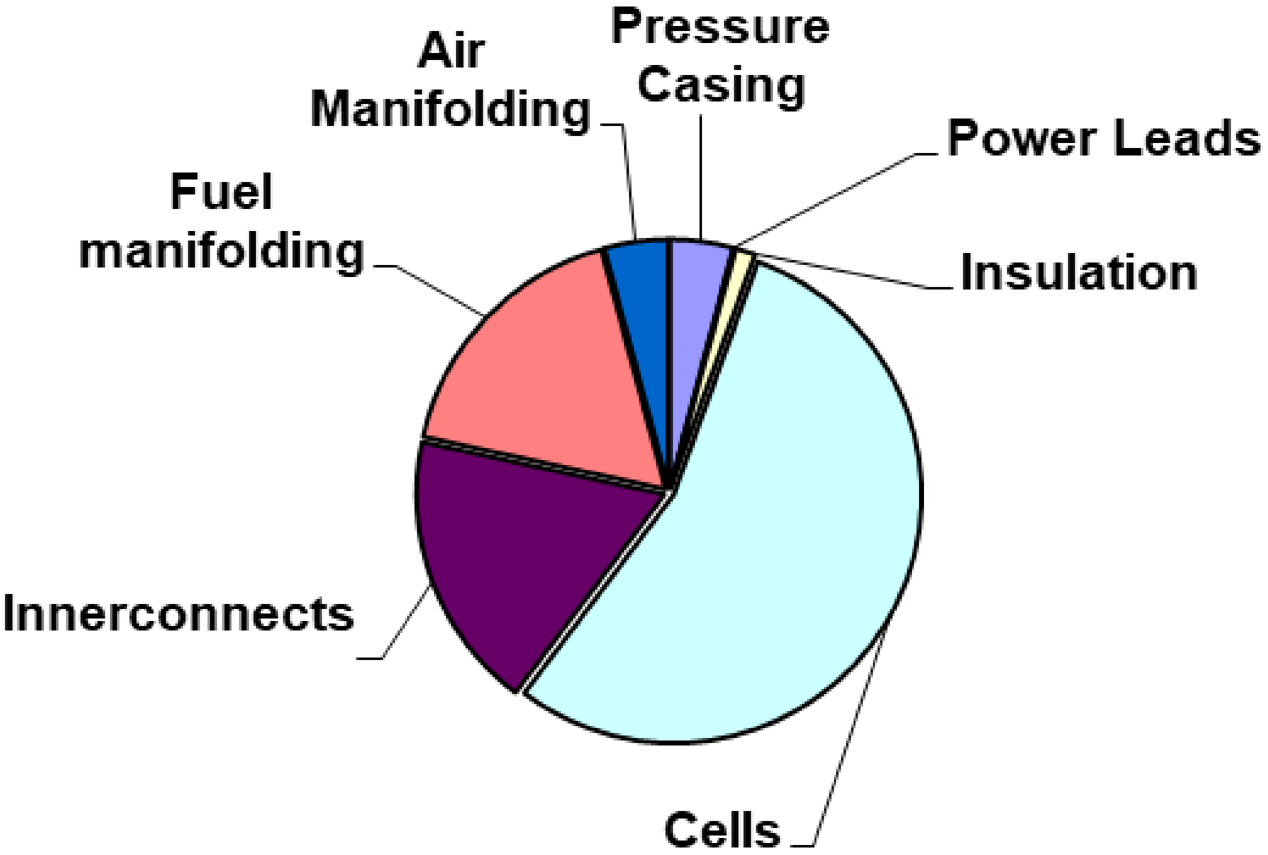


ESPG Mass Breakdown

ESPG Mass Breakdown



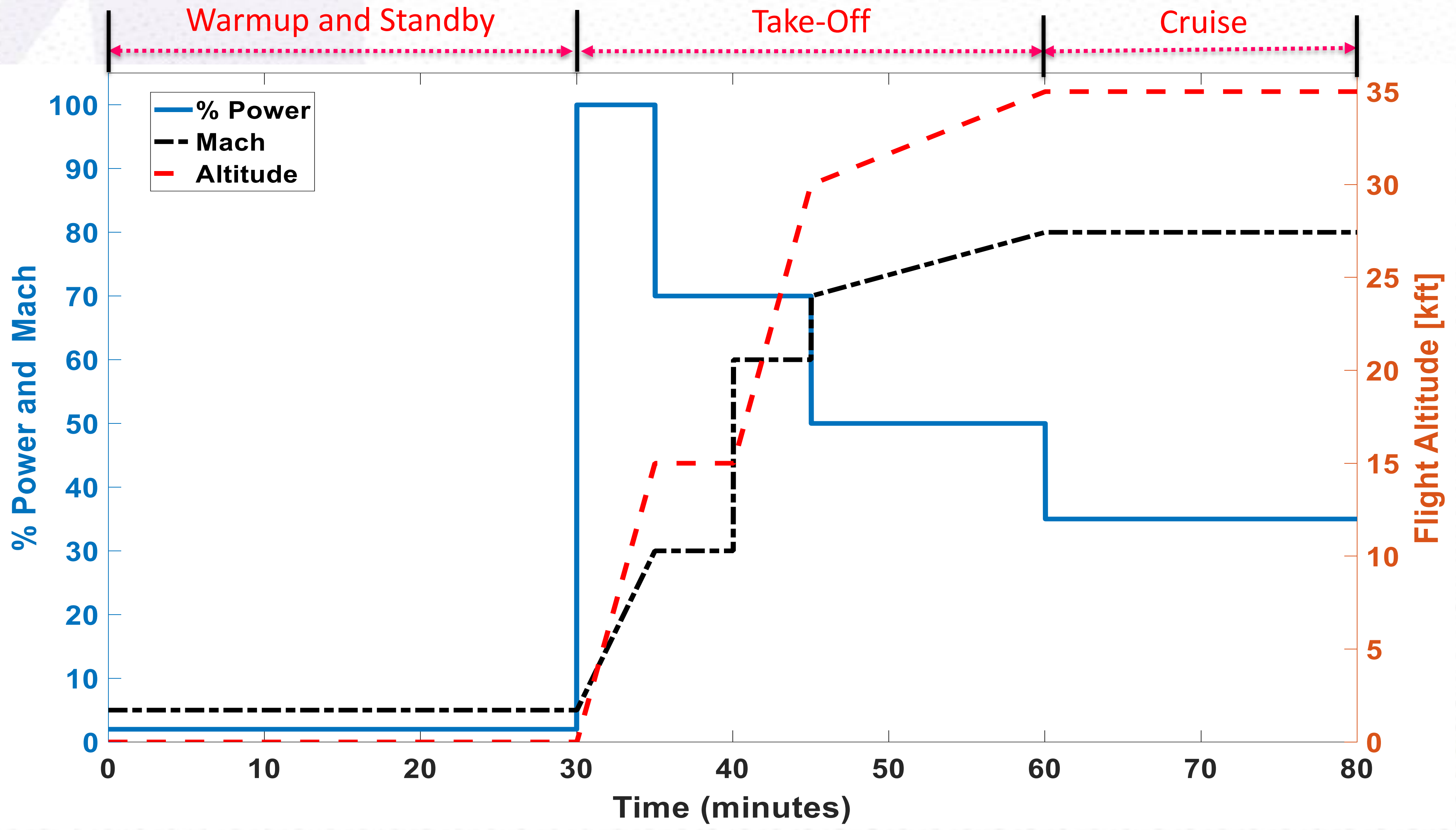
SOFC-C Mass Breakdown



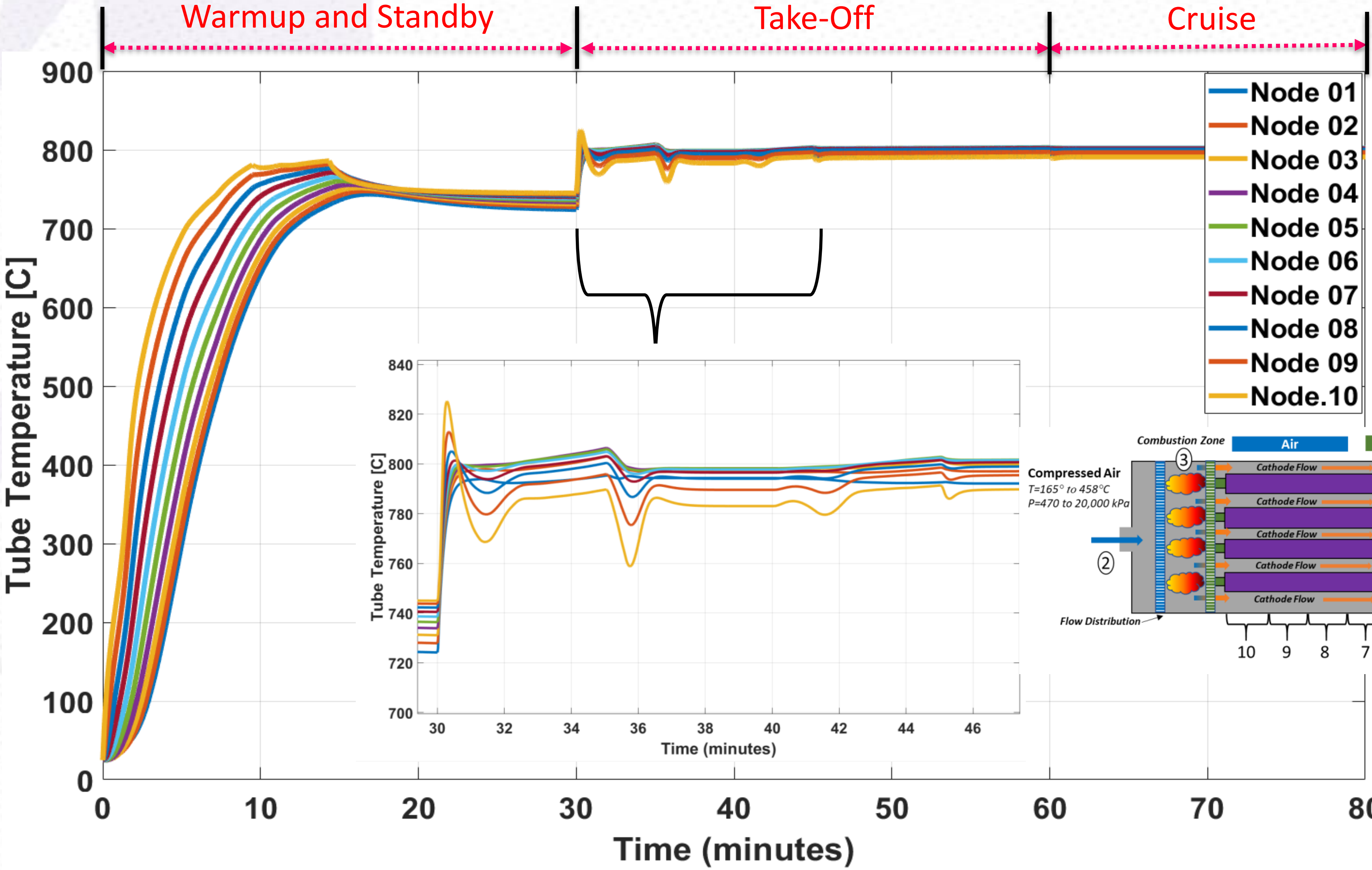
Vehicle Level Transient Analysis

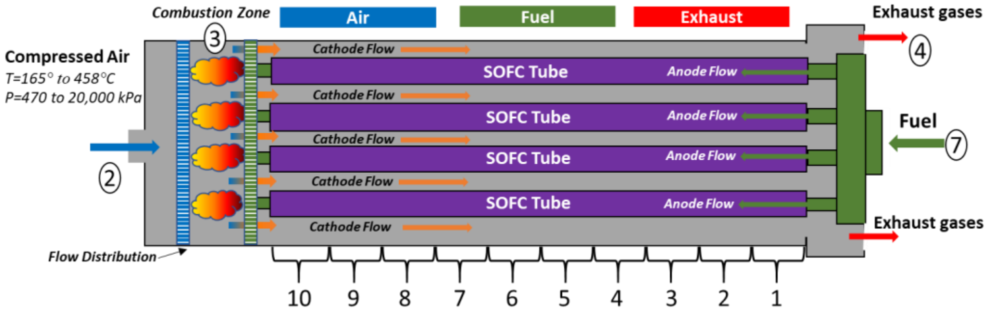
- Objective is to establish detailed boundary conditions and required operational characteristics of the ESPG components
- MATLAB/Simulink detailed transient model with vehicle level controls
  - Quasi-2D SOFC : electrochemistry overpotentials, reformation and electrochemical kinetics, heat transfer included
  - TG includes: performance maps, shaft dynamics, unsteady flow
  - Combustors: combustion reaction and products, heat transfer
  - Electrical Power Conditioning System: Vehicle electrical load balance and control
  - Fuel Thermal Management System: bio LNG tanks, fuel heat exchangers, valves

Notional Flight-Simulation

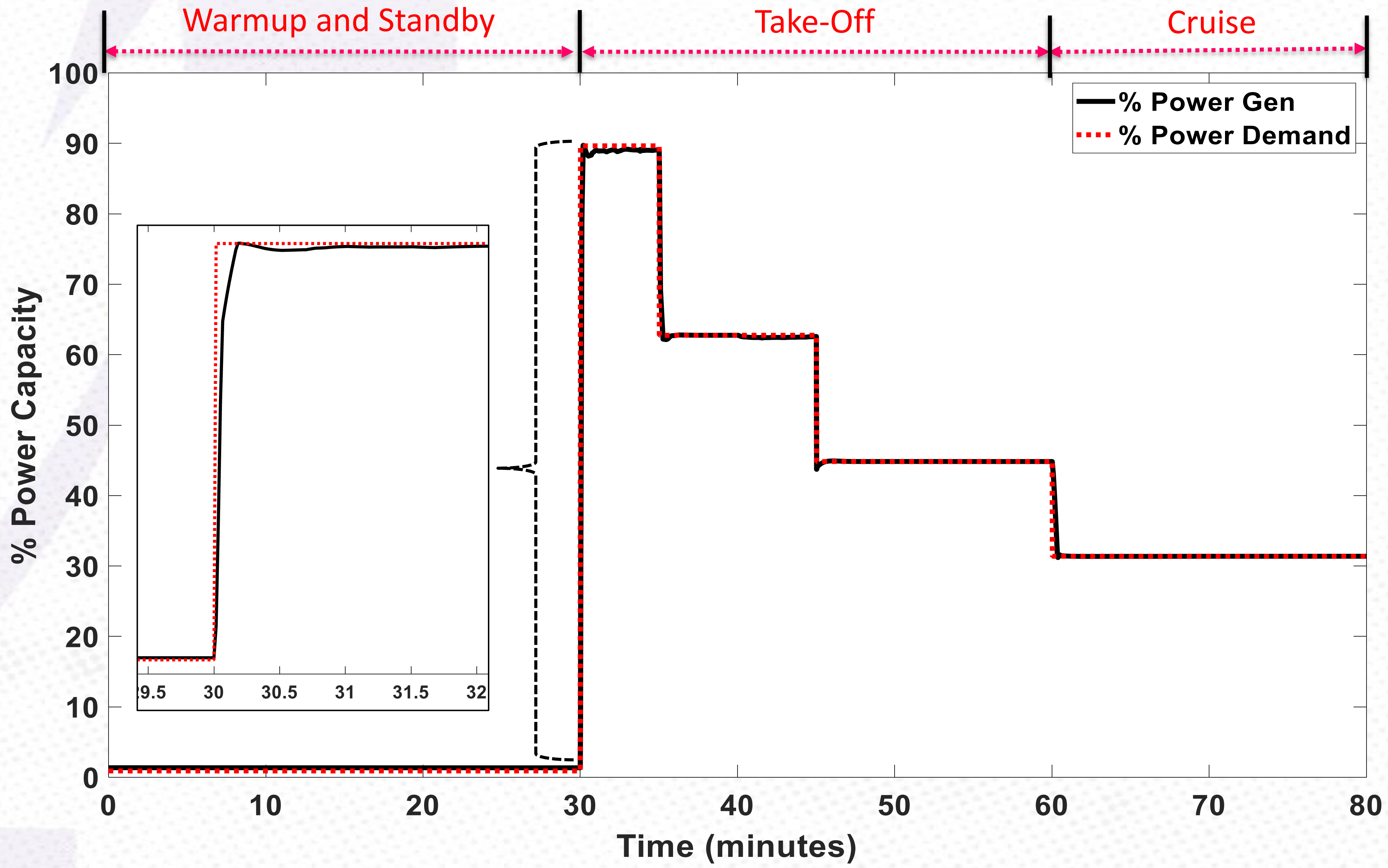


Simulated SOFC Stack Warmup





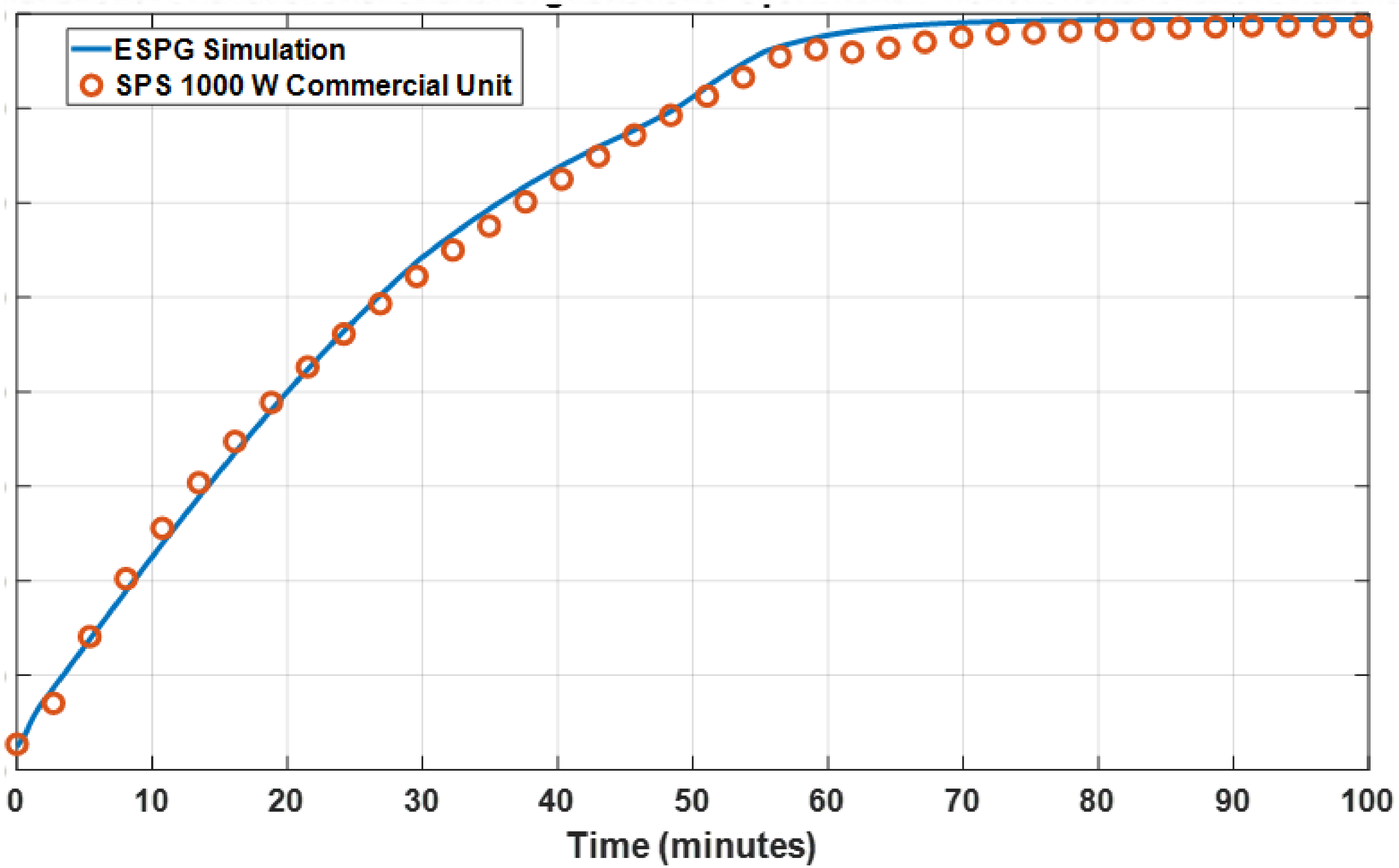
Simulated ESPG Power Load Follow



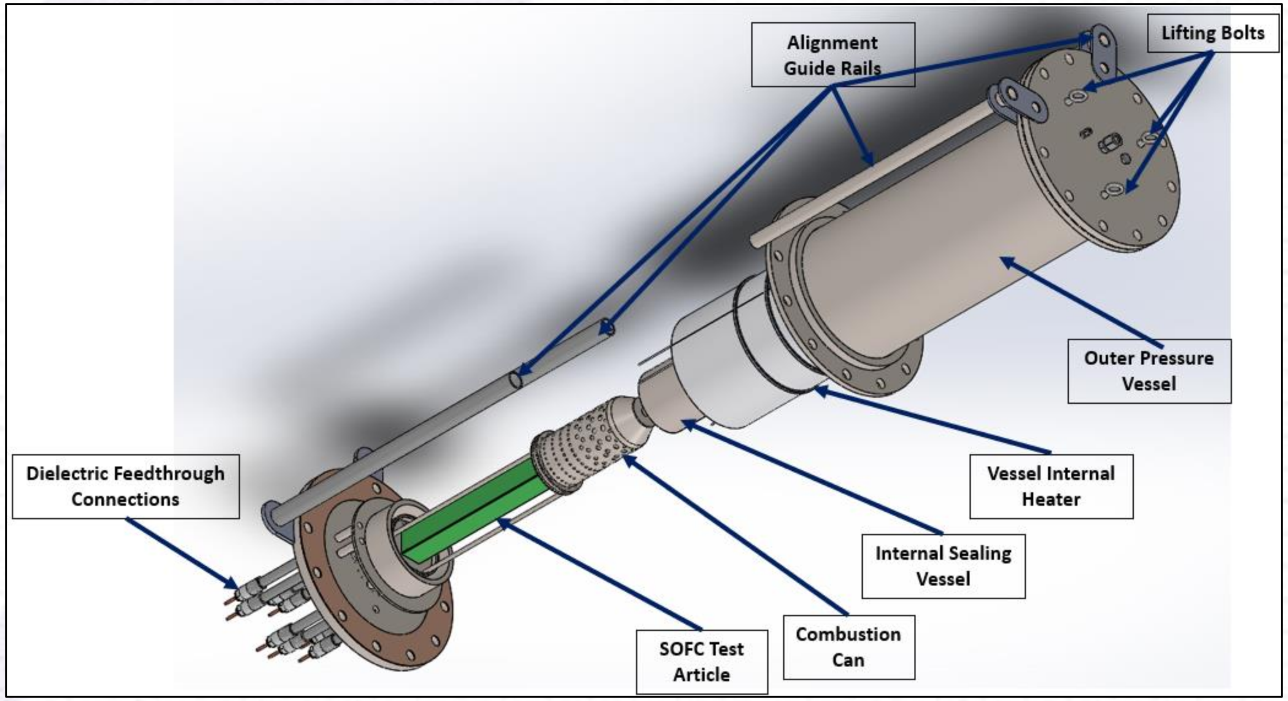
- The ESPG system was able to meet the dynamic vehicle electrical load demands, 90% step change in 1 minute
- Small battery storage (100 kW-hr) would be required to meet the large step change in power demand (worst case)

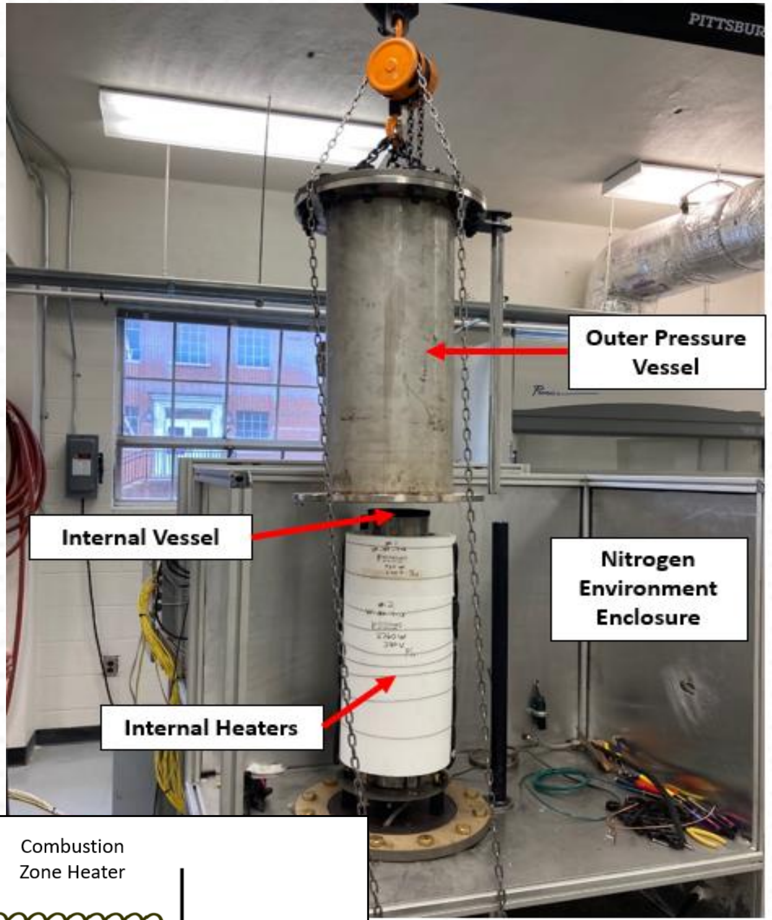
Simulated Warmup Compared to Measured Data

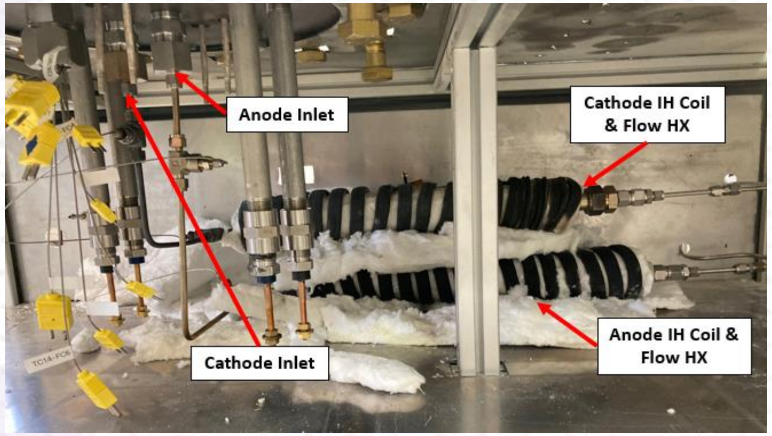
- The ESPG dynamic model was modified to account for corrected air flow and SOFC mass to parametrically match a 1,000 W commercial Special Power Sources SOFC unit.
- The dynamic model was able to predict the warmup sequence.
- 60 minutes was required for this warmup, but < 20 minutes has been demonstrated with commercial units in the field.

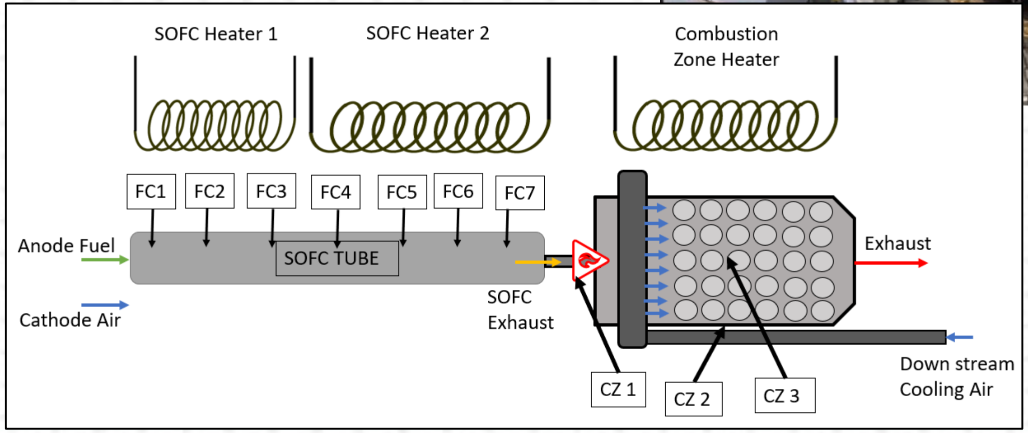


Pressurized Fuel Cell Test Stand

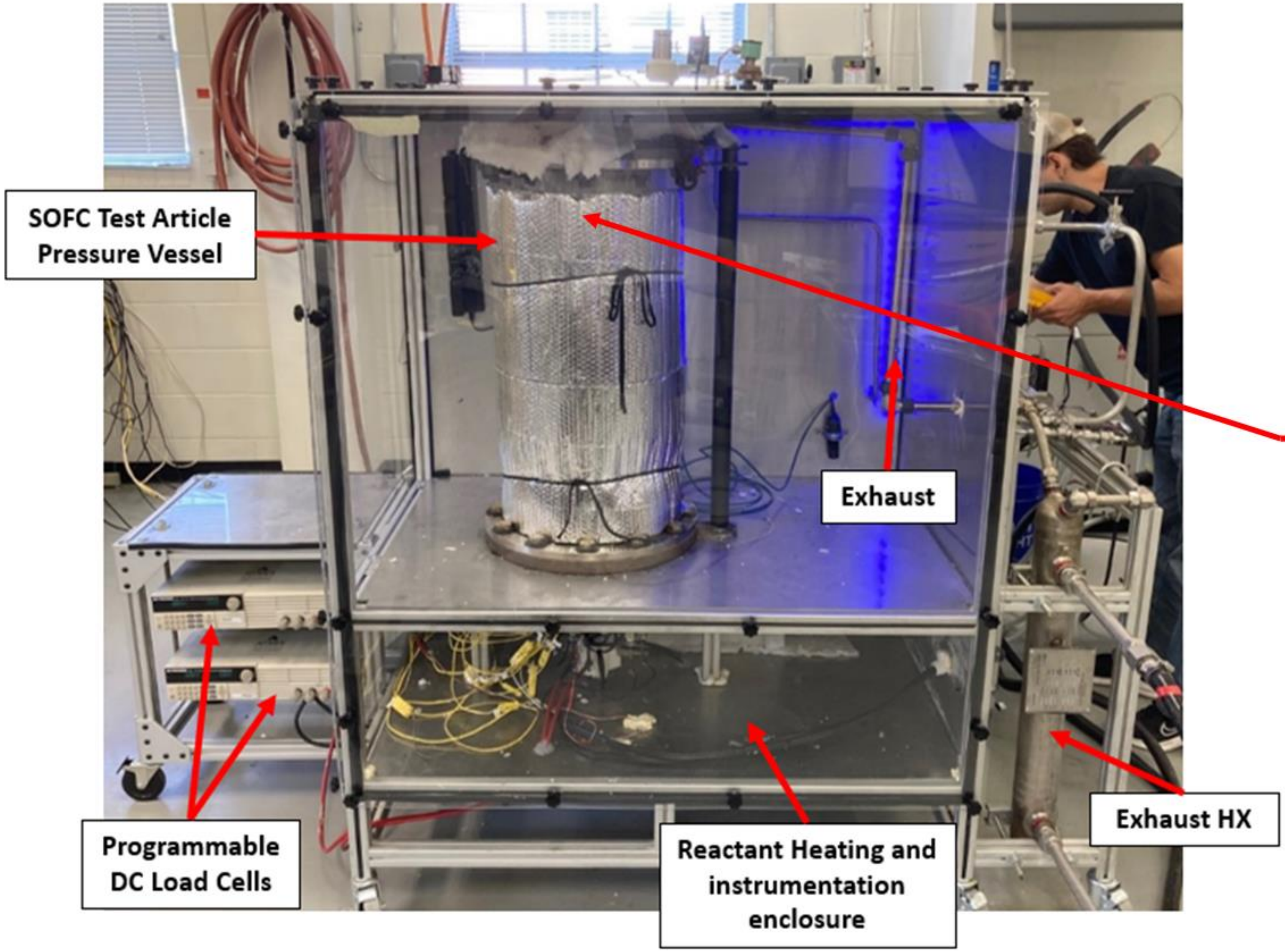


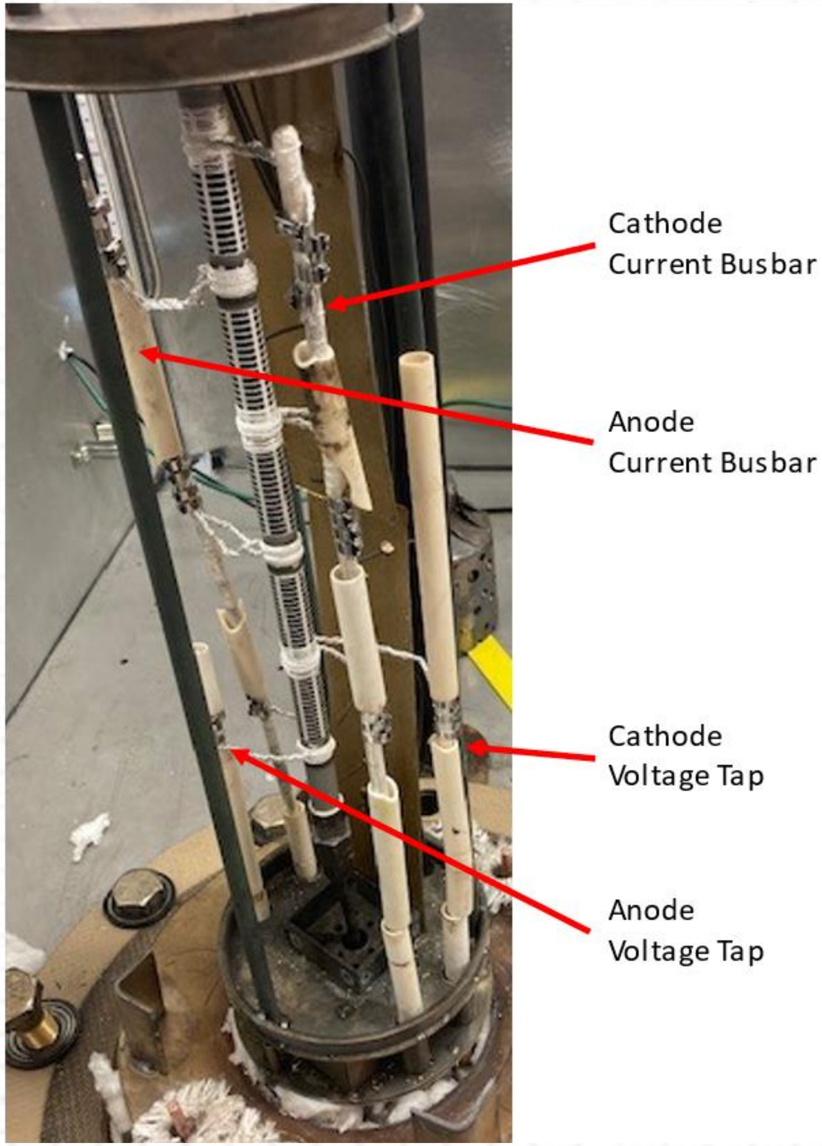




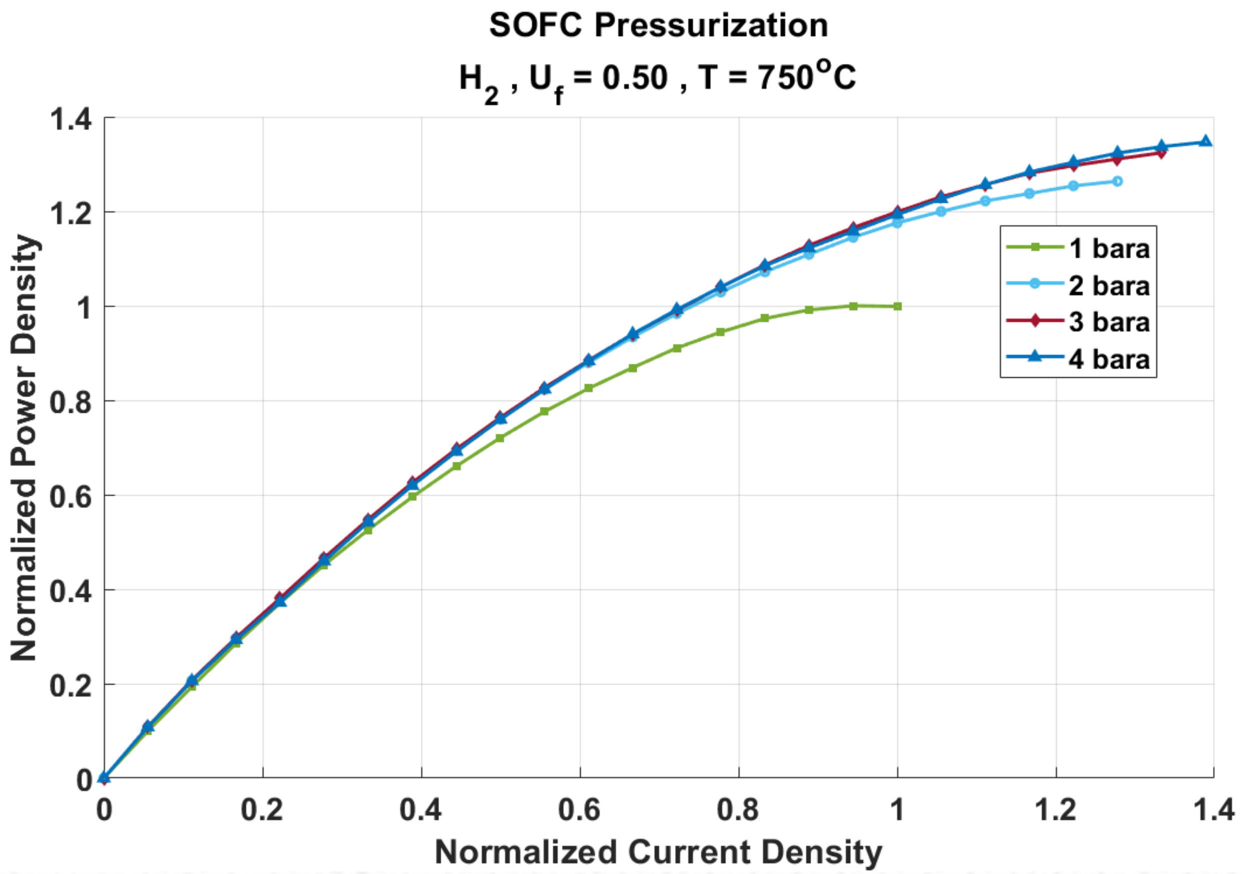


SOFC Test Article

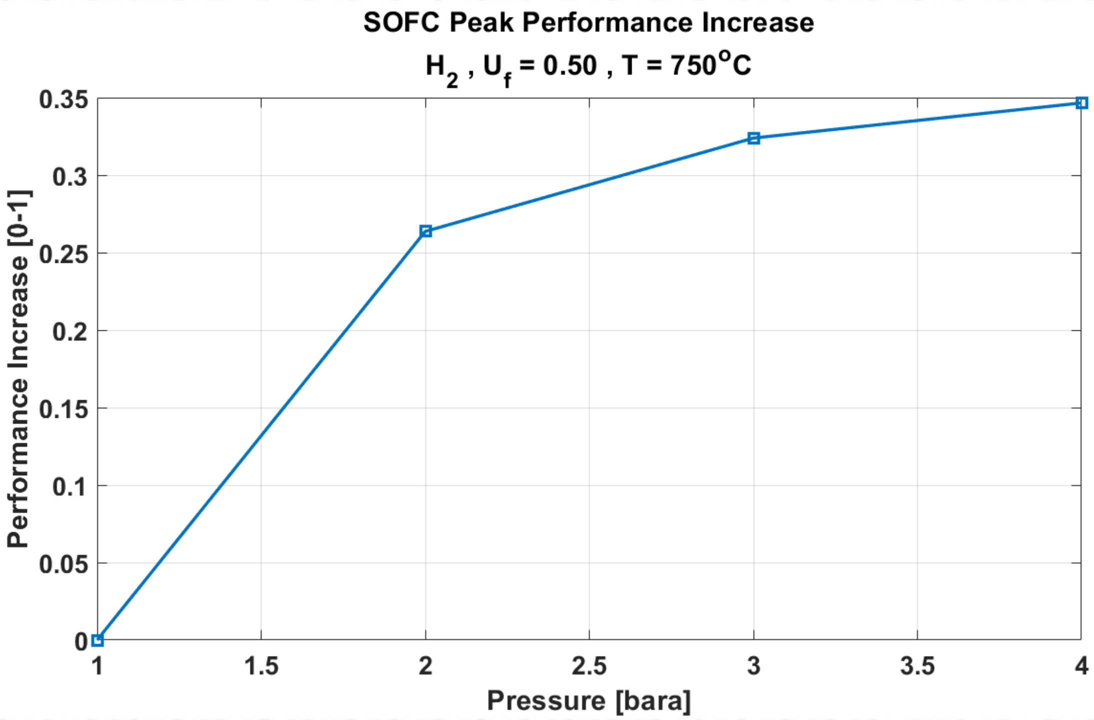




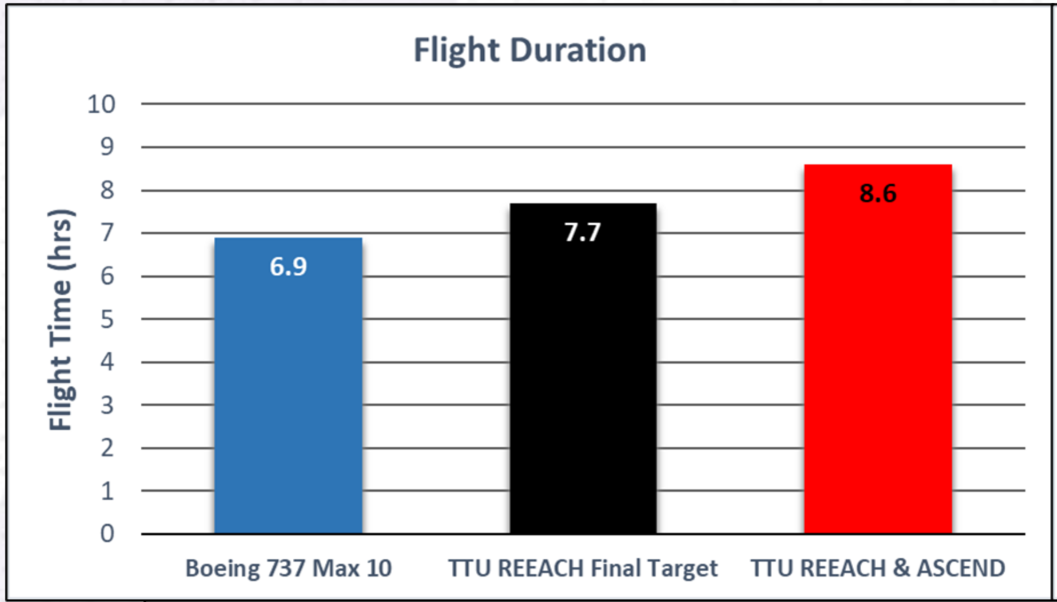
Anode Supported SOFC Pressurization

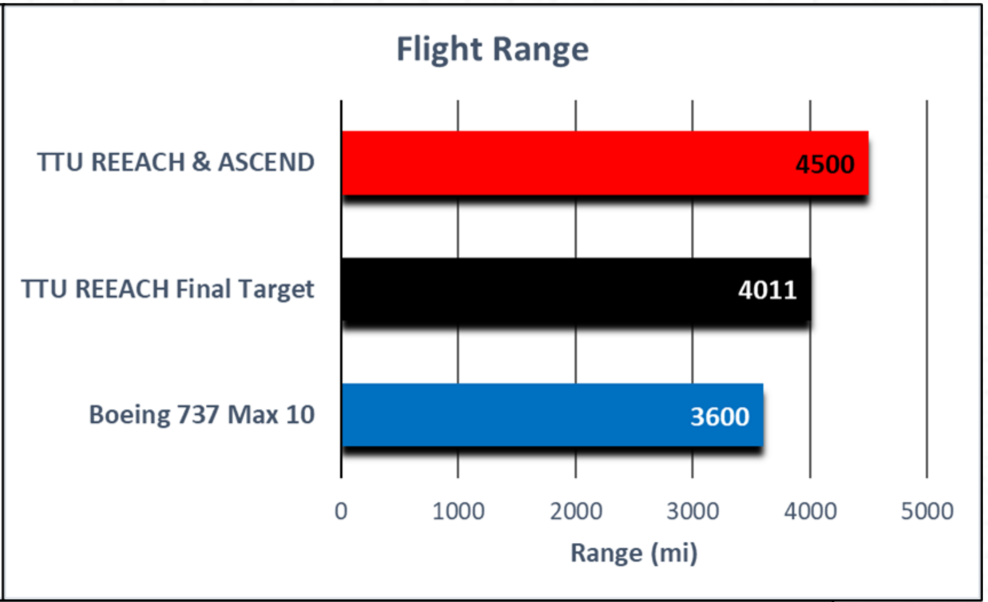


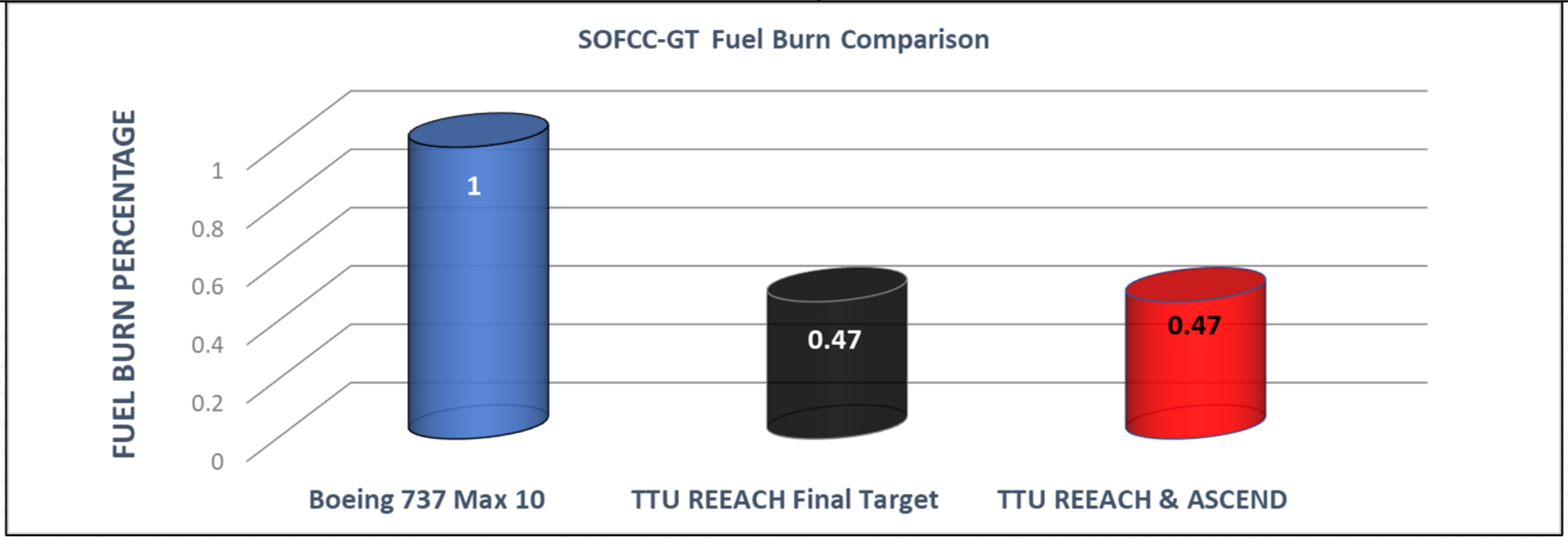
- SOFC performance was normalized using the peak ambient power density and current density
- 35% increase from 1 to 4 bara

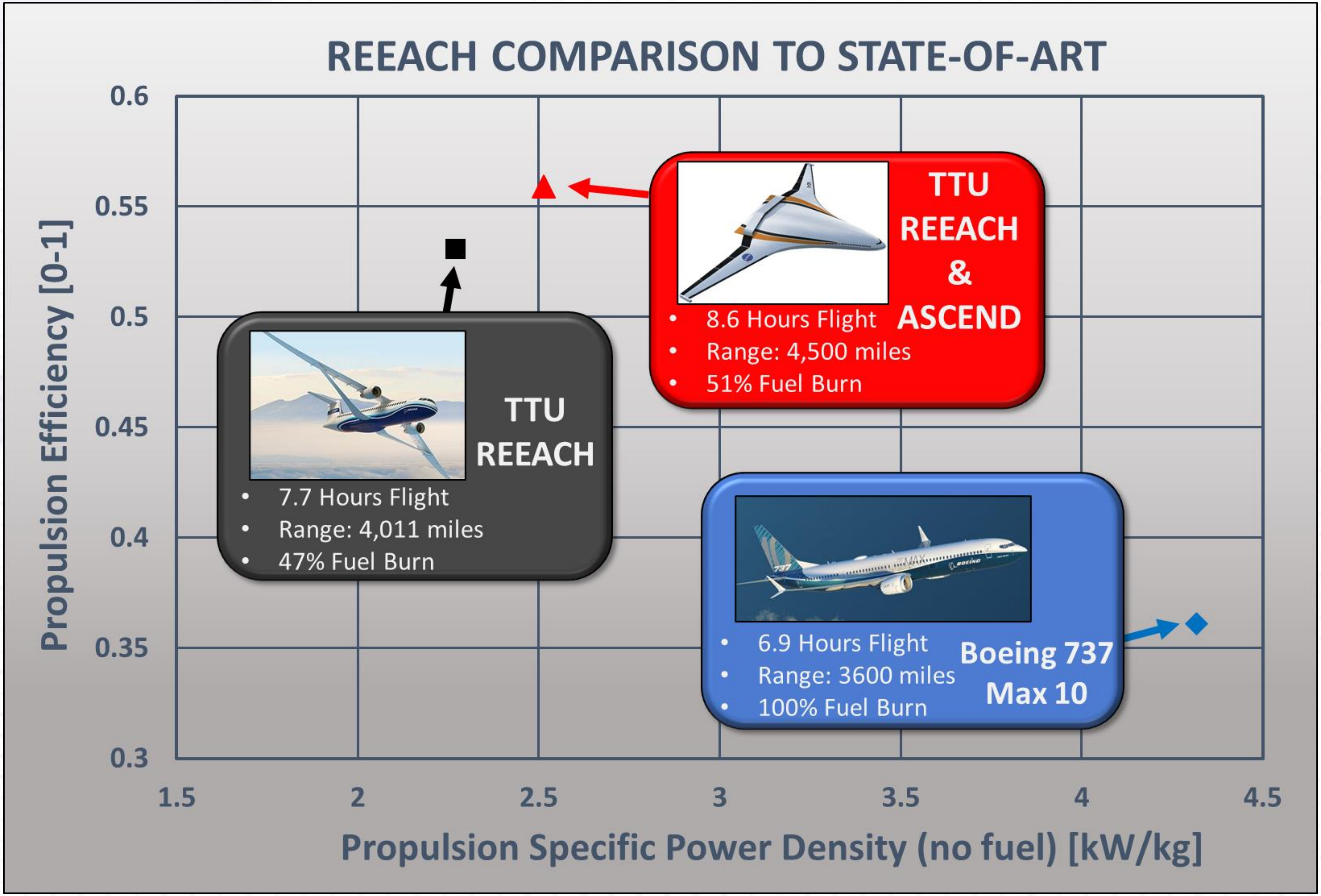


TTU REEACH Comparison to State-of-Art








REEACH COMPARISON TO STATE-OF-ART
0.6
0.55
0.5
0.45
0.4
0.35
0.3
Propulsion Efficiency [0-1]
1.5
2
2.5
3
3.5
4
4.5
Propulsion Specific Power Density (no fuel) [kW/kg]
TTU REEACH & ASCEND
8.6 Hours Flight
Range: 4,500 miles
51% Fuel Burn
TTU REEACH
7.7 Hours Flight
Range: 4,011 miles
47% Fuel Burn
Boeing 737 Max 10
6.9 Hours Flight
Range: 3600 miles
100% Fuel Burn

Summary

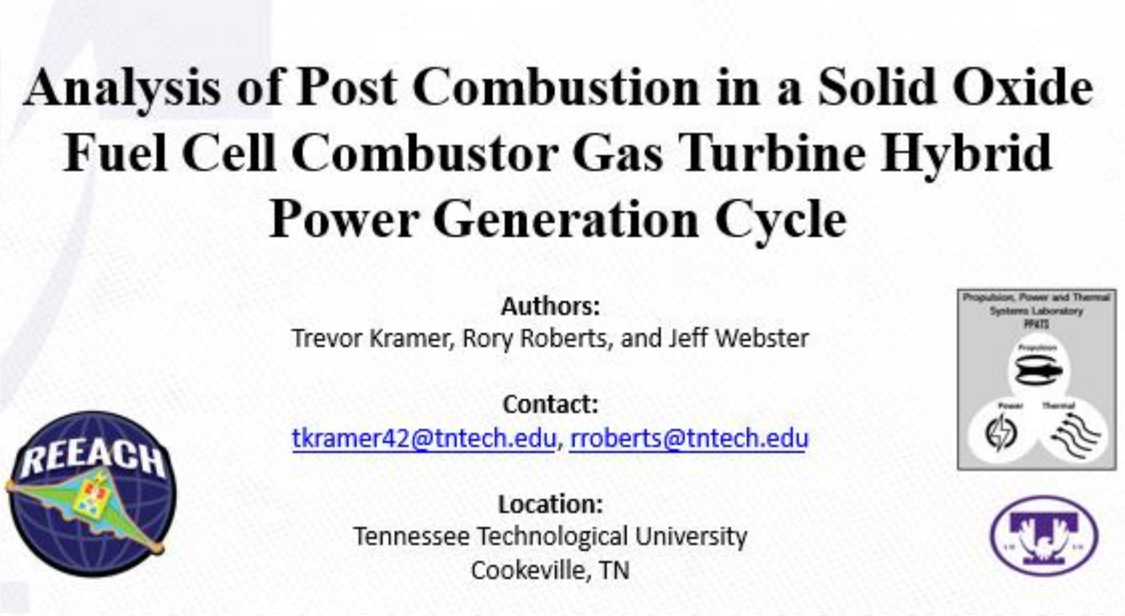
- ESPG projected to achieve 65% efficiency, 3.6 kW/kg specific power density
  - For a Boeing 737 Class aircraft this translates to 4,500 miles range
- Demonstrated ESPG concept's capability to respond to rapid perturbations such as load and environmental boundary conditions
- SOFC rapid startup has been demonstrated numerically and experimentally
- SOFC tubes have been successfully tested at 4 bar with a demonstrated performance gain for pressurized operation
- Demonstrated on-anode CH_4 internal reforming

Future Work

- SOFC-C thermal- hydraulic modeling for detailed analysis of a SOFC-C module
- Continue vehicle level trades studies as technology progresses
- Transient analysis at the vehicle for subsystem and component design requirements and system integration evaluated for notional flights
- SOFC-C will be testing under time dependent load and fuel scheduling for comparison of simulated and experimental performance during a notional flight

Published Paper

- T. Kramer, R. Roberts, and J. Webster, “Analysis of Post Combustion in Solid Oxide Fuel Cell Combustor Gas Turbine Hybrid Power Generation Cycle,” *AIAA Sci. Technol. Forum Expo. AIAA SciTech Forum 2022*, pp. 1–14, 2022, doi: 10.2514/6.2022-0315.



Analysis of Post Combustion in Solid Oxide Fuel Cell Combustor Gas Turbine Hybrid Power Generation Cycle

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Tennessee Technological University, Cookeville, TN, 38501, United States

A hybrid Solid Oxide Fuel Cell (SOFC) gas turbine cycle is being suggested to provide sufficient power generation on an electric aircraft. A Boeing 737 style commercial aircraft is estimated to require ~28 MW of electrical power for stable flight and operation. Electric ducted fans will serve as the propulsion for the aircraft with bio-liquefied natural gas (BIO LNG) serving as the fuel and coolant for the thermal management system. A Solid Oxide Fuel Cell Combustor (SOFCC) will take the place of the combustor in a traditional power generating Brayton Cycle. The tubular SOFC stack will operate in a counter-flow configuration allowing the anode off gas to combust with the compressed air and preheat the cathode air in the SOFC stack. The power density and efficiency are tracked when the cycle is modified to include post combustion of SOFCC exhaust gas before the turbine inlet.

I. Nomenclature

β	Nonlinear regression independent variable coefficient
E_o	Theoretical fuel cell potential [V]
ESPG	Electrical Storage and Power Generation
F	Faraday's Constant [96485 C / mol e$^-$]
GT	Gas Turbine
H	Enthalpy [kJ/kmol]
h_f^o	Heat of formation [kJ/kmol]
i	Fuel cell current load [A]
n	Number of molar equivalent of electrons per mole of reactant [mol e$^-$ / mol]
LHV_{CH4}	Lower Heating Value of Methane [kJ/kg]
$\dot{N}$	Molar flow rate [kmol/s]
$\dot{N}_{CH4}$	Molar Flow Rate of Fuel to Anode inlet [kmol/s]
$\dot{N}_{PC}$	Molar Flow Rate of Fuel to Post Combustor [kmol/s]
η_{comp}	Compressor Isentropic Efficiency [0-1]
η_{gen}	Generator Efficiency [0-1]
η_{plant}	Plant Efficiency [0-1]
η_{turb}	Turbine Isentropic Efficiency [0-1]
P	Pressure [kPa]
PR	Gas turbine pressure ratio
ρ_{plant}	Plant Specific Power Density [kW/kg]
$Q_{cathode}$	Heat of Cathode inlet flow [kW]
Q_{fuel}	Cooling of fuel cell with BIO LNG [kW]
Q_{gen}	Heat generated from fuel cell overpotentials [kW]
Q_{ref}	Endothermic heat absorption due to reformation [kW]

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[2] Associate Professor, Department of Mechanical Engineering.
[3] Graduate Research Assistant, Department of Mechanical Engineering.

1

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Thank You

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- Special Power Sources
- Raytheon Technologies Research Center
- Oak Ridge National Laboratory
- Boeing
- Wright State University

Acronyms

- A- Amps
- A/cm^2-Amps per square centimeter
- BC- Boundary conditions
- BoP- Balance of Plant
- CAD – Computer aided design
- CFD- Computational Fluid Dynamics
- $PPM- Dollars per passenger mile
- $/kW- Dollars per kW of capacity
- dP – Pressure drop between compressor and turbine
- ESPG – Electrical Storage and Power Generation
- FC-GT - Fuel Cell –Gas Turbine hybrid system
- hr-Hour
- kW- kilowatt
- RTRC - Raytheon Technologies Research Center
- SOFC-C- Solid Oxide Fuel Cell Combustor
- SOFC-C-TG - Solid Oxide Fuel Cell Combustor-Turbogenerator System
- SPS – Special Power Sources
- SWaP – Size, weight and power
- T2M- Technology-to-Market
- TG - Turbogenerator
- TTU- Tennessee Tech University
- TiT – Turbine inlet temperature
- V-Voltage
- WSU - Wright State University
- W/cm^2-Watts per square centimeter
- YSZ-Yttra-stabilized zirconia