Overview

**Federal Railway Administration (FRA) funding:** $500,000

**Previous CARB & SCAQMD funding:** $200,000

**PHASE 1 (October 2015 – March 2016):**
- Develop & apply model to evaluate hybrid SOFC systems
- Evaluate & engage potential technology development partners
- Apply model to a system design for a small prototype
- Identify the path and estimated costs to a line-haul product

**PHASE 2 (July 2016 – December 2017):**
- Select partners for development & testing of hybrid prototype
- Design hybrid SOFC prototype
- Select an experimental test platform
- Design the hybrid SOFC prototype test protocol and test matrix
- Conduct economic analysis
- Establish prototype demonstration budget, approach, schedule
Task 6 – Design Prototype

- **SOFC System Selected – FuelCell Energy Compact Stack Architecture**
- **Compact SOFC Architecture Stack**
- The CSA stack (shown in Figure 33) is a next generation SOFC stack which is suitable for various fuel cell (and electrolysis) applications.

### Selected Operating Parameters

<table>
<thead>
<tr>
<th>Selected Operating Parameters</th>
<th>Nominal</th>
<th>Units</th>
<th>Max</th>
<th>Min</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Density</td>
<td>250</td>
<td>mW/cm²</td>
<td>350</td>
<td></td>
<td>Atm. pressure operation</td>
</tr>
<tr>
<td>Current Density</td>
<td>290</td>
<td>mA/cm²</td>
<td>440</td>
<td></td>
<td>Atm. pressure operation</td>
</tr>
<tr>
<td>Area Specific Resistance</td>
<td>~0.3</td>
<td>Ω – cm²</td>
<td></td>
<td></td>
<td>Function of T and P, see Eq. 3 below for P effect</td>
</tr>
<tr>
<td>Stack Fuel Utilization</td>
<td>65</td>
<td>%</td>
<td>80%</td>
<td>60%</td>
<td>Generally anode recycle desired for water independence and attainment of high system fuel utilization</td>
</tr>
<tr>
<td>Cell Operating Temperature</td>
<td>725</td>
<td>°C</td>
<td>650</td>
<td>800</td>
<td></td>
</tr>
</tbody>
</table>
Task 6 – Design Prototype

CSA Stack Module (simple) – Stacks, Manifolding and Thermal Insulation – Non-Pressure Rated

CSA Stack Module (simple) – Stacks, Pressure Vessel, Manifolding and Thermal Insulation – Pressure-Rated
Task 6 – Design Prototype

- A FuelCell Energy baseline SOFC system design
- As the turbine-hybrid process design will likely lead to a different and more integrated design, a more concise and simple stack module (shaded purple) has been selected for this document and the presented stack module requirements.

**SOFC System Design – FCE Baseline**
Gas Turbine System Selected – Capstone Turbines

- Capstone Turbines (Capstone), the world-leading manufacturer of micro-turbine generator (MTG) technology that is in the size class of the system requirements needed for the prototype system.

- The operating window of the C-250 turbine appears to be at heating rates between 250 and 800kW to produce between 50 and 250kW of electric power.

<table>
<thead>
<tr>
<th>Specification</th>
<th>C-65</th>
<th>C-250</th>
<th>C-370 LP spool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Flow (lb/s)</td>
<td>1.08</td>
<td>3.44</td>
<td>3.2</td>
</tr>
<tr>
<td>Compressor Outlet (°F)</td>
<td>424</td>
<td>469</td>
<td>397</td>
</tr>
<tr>
<td>Compressor Out (psig)</td>
<td>40</td>
<td>58.8</td>
<td>49</td>
</tr>
<tr>
<td>Recuperator Outlet(°F)</td>
<td>1050</td>
<td>1097</td>
<td>960</td>
</tr>
<tr>
<td>Turbine Inlet (°F)</td>
<td>1720</td>
<td>1788</td>
<td>1550</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>31.2</td>
<td>33.25</td>
<td>34.5</td>
</tr>
</tbody>
</table>
Task 6: Prototype SOFC-GT Simulation
Tasks 7&8 – Experimental Platform & Test Plan

- New Route Simulation – Tehachapi loop
Raw Power Demand Curve Bakersfield-Mojave

Locomotive Power Demand

Power [kW]

Time [s]

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System Efficiency along the route
Voltage Losses

Voltage and Overpotentials

- Nernst Voltage
- Cell Voltage
- Activation Overpotential
- Ohmic Overpotential

Voltage (V)

Time [s]
Anode & Cathode Inlet & Outlet Temperatures

![Anode and Cathode Temperatures Graph](image.png)
Considering Small Battery for SOFC-GT Locomotive

Li-Ion Battery Model

Clock

Time

To Workspace

Power Output

Product

Current

Voltage

Voltage

SOC

Gain

Gain1

Gain2

Display

More Info

Scope3

Scope2

Scope1

Current

To Workspace

Voltage

To Workspace

Continuous

powergui

200 volts, 6.6 Ah Ni-MH battery 1

Power Demand

Gain3

Gain11

Load

FC

Excess Current

Controlled Voltage Source

Controlled Current Source

Controlled Current Source1

Gain

Subtract

Integrator

Power Output

1/100

Relay

Gain

Constant1

Gain

Display

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Battery Cycle Data – Bakersfield to Mojave
## Task 9 – Economic Analyses

- **Base Case LCOE and Cents per Revenue Ton-Mile Results (No CO₂ Emissions Cost)**

<table>
<thead>
<tr>
<th>(No CO₂ Emissions Cost)</th>
<th>Tier 4 Diesel-Electric Locomotive</th>
<th>Diesel-Electric Locomotive + Battery Tender</th>
<th>Tier 4 Diesel-LNG Locomotive</th>
<th>SOFC-GT Locomotive (LNG Fuel)</th>
<th>SOFC-GT Locomotive (LH₂ Fuel)</th>
<th>Electric-Only Locomotive (Catenary)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCOE ($/MWh)</td>
<td>$538.20</td>
<td>$1,740.21</td>
<td>$522.78</td>
<td>$535.22</td>
<td>$676.03</td>
<td>$582.38</td>
</tr>
<tr>
<td>Rank Order:</td>
<td>3</td>
<td>6</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Year 1:  ¢/Rev Ton-Mile</td>
<td>2.11¢</td>
<td>11.35¢</td>
<td>2.36¢</td>
<td>2.79¢</td>
<td>3.90¢</td>
<td>2.92¢</td>
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<tr>
<td>Rank Order:</td>
<td>1</td>
<td>6</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Levelized (x 10⁻⁶):  ¢/Rev Ton-Mile</td>
<td>7.31¢</td>
<td>29.31¢</td>
<td>7.28¢</td>
<td>7.64¢</td>
<td>9.90¢</td>
<td>7.91¢</td>
</tr>
<tr>
<td>Rank Order:</td>
<td>2</td>
<td>6</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>
Thank You!