Fuel Cell System Modeling and Analysis

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Project ID: FC017

This presentation does not contain any proprietary, confidential, or otherwise restricted information.
Overview

Timeline
- Start date: Oct 2003
- End date: Open
- Percent complete: NA

Barriers
- B. Cost
- C. Performance
- E. System Thermal and Water Management
- F. Air Management
- J. Startup and Shut-down Time, Energy/Transient Operation

This project addresses system, stack and air management targets for efficiency, power density, specific power, transient response time, cold start-up time, start up and shut down energy

Budget
- FY19 DOE Funding: $300 K
- Planned DOE FY20 Funding: $200 K
- Total DOE Project Value: $200 K

Partners/Interactions
- Eaton, Ford, Honeywell, UDEL/Sonijector
- SA, Aalto University (Finland)
- 3M, Ballard, Johnson-Matthey Fuel Cells (JMFC), UTRC, FC-PAD, GM, ElectroCat
- IEA Annex 34
- ANL-Autonomie, U.S. DRIVE fuel cell tech team
Objectives and Relevance

Develop a validated system model and use it to assess design-point, part-load and dynamic performance of automotive (primary objective) and stationary (secondary objective) fuel cell systems (FCS)

- Support DOE in setting technical targets and directing component development
- Establish metrics for gauging progress of R&D projects
- Provide data and specifications to DOE projects on high-volume manufacturing cost estimation

Impact of FY2020 work

- In collaboration with GM and FC-PAD, demonstrated that d-PtCo catalyst supported on high surface area carbon (HSC) can be stabilized by limiting the high potential limit to 0.80-0.85 V in catalyst accelerated stress tests (ASTs)
- Demonstrated that the target of 10% loss in power can be achieved by limiting the electrochemically active surface area (ECSA) loss to 55.3%
- Determined the operating conditions for 55.3% ECSA loss: CEM* turndown = 12 (10), coolant exit temperature = 66°C/70°C for 5000 h/8000 h electrode durability
- Proposed initial metrics for heat rejection in FCS for Class-8 heavy duty trucks: 0.7 V at rated power (275 kW net), 87°C coolant exit temperature
- Showed the relationship between cell voltage, optimum operating temperature and stack power density as determined by heat rejection: 1200 mW/cm² power density at 0.7 V.
- Established FCS duty cycles for Class-8 trucks for regional, multi purpose and urban vocations, specifying time spent at different voltages and temperatures on ARB, mild-55 and mild-65 drive cycles

*CEM: compressor-expander module
Approach

Develop, document & make available versatile system design and analysis tools
- GCtool: Stand-alone code on PC platform
- GCtool-Autonomie: Drive-cycle analysis of hybrid fuel cell systems

Validate the models against data obtained in laboratories and test facilities inside and outside Argonne
- Collaborate with external organizations

Apply models to issues of current interest
- Work with U.S. DRIVE Technical Teams
- Work with DOE contractors as requested by DOE

<table>
<thead>
<tr>
<th></th>
<th>In collaboration with GM, analyze methods of extending the durability of MEAs with SOA d-PtCo cathode catalyst relative to reach the target of 8000 h lifetime.</th>
<th>12/19</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>In collaboration with FC-PAD, establish an initial benchmark for performance and durability of MEAs for medium and heavy-duty trucks.</td>
<td>03/20</td>
</tr>
<tr>
<td>3</td>
<td>In collaboration with SA, update the performance and cost of an automotive FCS with an advanced low-PGM catalyst relative to 2020 targets of 65% peak efficiency, $\frac{Q}{\Delta T} = 1.45 \text{ kW/K}$, and $40/\text{kW}$ cost.</td>
<td>06/20</td>
</tr>
<tr>
<td>4</td>
<td>In collaboration with SA, determine the performance and cost of truck fuel cell systems relative to the FCTO targets.</td>
<td>09/20</td>
</tr>
</tbody>
</table>
Technical Accomplishments: Summary

1. Durability of LDV Fuel Cell Systems with State-of-the-Art (SOA), Low-PGM Pt Alloy Cathode Catalyst
   - In collaboration with GM and FC-PAD, demonstrated that d-PtCo catalyst supported on high surface area carbon (HSC) can be stabilized by limiting the high potential limit to 0.80-0.85 V in catalyst accelerated stress tests (ASTs)
   - Demonstrated that the target of 10% loss in power can be achieved by limiting the electrochemically active surface area (ECSA) loss to 55.3%
   - Determined the operating conditions for 55.3% ECSA loss: CEM turndown = 12 (10), coolant exit temperature = 66°C/70°C for 5000 h/8000 h electrode durability

2. Fuel Cell Systems for Heavy-Duty Vehicles
   - Proposed initial metrics for heat rejection in FCS for Class-8 heavy duty trucks: 0.7 V at rated power (275 kW net), 87°C coolant exit temperature
   - Showed the relationship between cell voltage, optimum operating temperature and stack power density as determined by heat rejection: 1200 mW/cm² power density at 0.7 V.
   - Established FCS duty cycles for Class-8 trucks for regional, multi purpose and urban vocations, specifying time spent at different voltages and temperatures on ARB, mild-55 and mild-65 drive cycles

\(^{1}\text{d-PtCo/C: de-alloyed PtCo catalyst on high surface area carbon (HSAC) support}\)
1. Fuel Cell Durability Model Framework using Single Cell Hardware

Degradation Model for ORR Kinetics and O₂ Transport Resistance*
- Degrade cells using catalyst AST protocol for 15k, 30k and 50k cycles
- Vary UPL: 0.95, 0.90, 0.85 V, 0.8 V
- Vary RH: 40%, 100%
- Vary temperature: 95°C, 80°C, 60°C
- Measure cell performance and H₂/N₂ EIS at BOT and EOT for 12 operating conditions; 1-2.5 atm; 60-95°C; 30-100% RH; 5-21% X(O₂)
- Measure and model Pt and Co dissolution using online ICP-MS

*All tests conducted at GM (S. Arisetty Lead), FCPAD-FC156 collaboration (S. Kumaraguru PI)
Controlling Voltage Degradation by Voltage Clipping

Degradation can be controlled by clipping cell voltage

- After 30k AST cycles: $\Delta V(0.85\text{V UPL}) < \Delta V(0.9\text{V UPL}) << \Delta V(0.95\text{V UPL})$
- Smaller voltage losses at higher operating pressures: advantage of pressurized system

Polarization curves in a differential cell at 80°C, 100% RH

Solid symbols: data at BOT
Open symbols: data at EOT for different $X(O_2)$

$\Delta E$: $E(BOT) - E(EOT)$
Open symbols: $\Delta E$ for different $P$
Negligible changes in kinetic parameters denoting reaction order ($\gamma$), activation energy ($\Delta H^c_s$), and RH dependence ($\beta$)

Kinetic losses are nearly proportional to ECSA loss ($S_{Pt}$)

Distributed ORR Kinetic Model

\[ \eta_c = \eta_s^c + i R^c_e \left( \frac{i \delta_c}{b \sigma_c} \right) \]

\[ i + i_x = i_0 S_{Pt} (1 - \theta) e^{-\frac{\omega \theta}{RT} e^{\frac{\alpha n F}{RT} \eta_s^c}} \]

\[ i_0 = i_0 e^{-\frac{\Delta H^c_s}{R} \left( \frac{1}{T} \frac{1}{T_r} \right) P^\gamma O_2 \Phi^\beta} \]
Effect of Ageing on $O_2$ Transport Resistance (d-PtCo/C Catalyst)

Smaller increase in $R_{cf}$ at lower UPL after 30k cycles

<table>
<thead>
<tr>
<th>UPL</th>
<th>$\Delta S_{Pt}$</th>
<th>$\Delta R_{cf}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.95 V</td>
<td>-65%</td>
<td>100%</td>
</tr>
<tr>
<td>0.90 V</td>
<td>-35%</td>
<td>40%</td>
</tr>
<tr>
<td>0.85 V</td>
<td>-20%</td>
<td>50%</td>
</tr>
</tbody>
</table>

$O_2$ Transport Model

$R_m = R_g + R_d + R_{Kn} + R_{cf}$

$R_g$ and $R_d$ are P dependent

$R_{Kn}$ and $R_{cf}$ are P independent
Effect of Ageing on $R_{O_2}$ (d-PtCo/C Catalyst)

$R_{O_2}$ decreases after ageing – ionomer conditioning

<table>
<thead>
<tr>
<th>UPL</th>
<th>$\Delta S_{Pt}$</th>
<th>$\Delta R_{O_2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.95 V</td>
<td>-65%</td>
<td>-30%</td>
</tr>
<tr>
<td>0.90 V</td>
<td>-35%</td>
<td>-15%</td>
</tr>
<tr>
<td>0.85 V</td>
<td>-20%</td>
<td>-8%</td>
</tr>
</tbody>
</table>

**O$_2$ Transport Model**

$$R_m = R_g + R_d + R_{Kn} + R_{cf}$$

$$R_{cf} = \frac{R_{O_2}}{S_{Pt}}$$

$$R_{O_2} = R_{O_2}(T_c, \Phi_c, N)$$

T: 80°C
RH: 100%

\[
\frac{dS}{dt} = -k(S - S_0), \quad \frac{k}{k_0} = a_k \left( \frac{\dot{r}_d}{\dot{r}_{d,0}} \right) \Phi^\alpha e^{-\frac{\Delta H}{R} \left( \frac{1}{T} - \frac{1}{T_0} \right)}
\]

Data from FCPAD-FC156 collaboration (S. Kumaraguru PI): 50-cm² cell, Trapezoidal wave: 0.6 V LPL, 0.85-0.95 V UPL, 350 mV/s scan rate, 60,000 cycles; 55-95°C; 1-5 s hold time at UPV; 40-100% RH.
Catalyst Durability Study

Default conditions
- Trapezoidal potential: 0.6 (LPL) - 85 V (UPL), 1-s holds at UPL & LPL, 75°C, 50% RH

Main conclusions from parametric and acceptability map analyses
- Limit UPL below 0.85 V (Frame 1)
- Avoid extended holds at UPL (Frame 2)
- Long operation above 80°C is extremely damaging (37.3 kJ/mol) (Frame 3)
- Low RH is preferable but may compromise in membrane stability (Frame 4)
- UPL-T-RH map for 8000-h life with 55% ECSA loss, 1-s holds at UPL & LPL (Frame 5)
Catalyst Degradation on Drive Cycles

**UDDS Drive Cycle**
- Average FCS power: 10 kW
- CEM turndown: 20
- Minimum FCS power: 4 kW
- Average T: 66°C
- Average outlet RH: 111%
- Cell voltage: 760-866 mV

**Pt Dissolution**
- Pt dissolves more as PtOH than as Pt
- PtO$_x$ does not form on UDS

**ECSA loss rate** ~8X faster than the target for 8,000 h durability

*Vehicle demand from Autonomie simulations by Ram Vijayagopal, ANL
Pathways for Reaching 5000-h and 8000-h Electrode Lifetime

**Turndown=12.5:** 849 – 760 mV on UDDS; outlet <RH>: 90%; ~six-fold lower ECSA loss rate

**70°C <T>:** 825 – 760 mV on UDDS; outlet <RH>: 56%

UDDS, 52% HWFET; 26% lower ECSA loss rate

**Conditions for 5,000-h and 8000-h durability on combined EPA UDDS and HWFET cycles.** The combined cycles include 76% time on UDDS and 24% time on HWFET.
Simulations to determine FCS cost with different Pt loadings in cathode

- Constraint 1: Fixed active membrane area as determined for electrode with 0.1 mg/cm² Pt loading in the alloy catalyst
- Constraint 2: FCS produces 72 kW at EOL (5000 or 8000 h) on the EPA combined cycle
- Constraint 3: FCS satisfies the Q/ΔT constraint at BOL and at EOL for 40°C ambient temperature

<table>
<thead>
<tr>
<th>Pt Loading</th>
<th>ECSA</th>
<th>Cell Voltage</th>
<th>Power Density</th>
<th>Current Density</th>
<th>FCS Power</th>
<th>FCS Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>mg/cm²</td>
<td>m²/g</td>
<td>mV</td>
<td>mW/cm²</td>
<td>A/cm²</td>
<td>kWₑ</td>
<td>%</td>
</tr>
<tr>
<td>BOL</td>
<td>0.1</td>
<td>48</td>
<td>682</td>
<td>1024</td>
<td>1501</td>
<td>80.0</td>
</tr>
<tr>
<td></td>
<td>0.125</td>
<td>48</td>
<td>686</td>
<td>1037</td>
<td>1511</td>
<td>81.1</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>48</td>
<td>688</td>
<td>1045</td>
<td>1518</td>
<td>81.7</td>
</tr>
<tr>
<td>EOL</td>
<td>0.1</td>
<td>22</td>
<td>652</td>
<td>930</td>
<td>1426</td>
<td>72.0</td>
</tr>
</tbody>
</table>
2. Fuel Cell Systems for Medium- and Heavy-Duty Trucks

Salient Features

- Multiple stacks 2, 3 or 4
- Pt loading
  - Cathode: 0.2 mg/cm²
  - Anode: TBD
- Membrane thickness: TBD
- Single air system with expander
- Single anode system with recirculation blower
- No cathode humidification
- Rated power: 2.5 atm, 87°C, 0.7 V
- Control valves for startup/shutdown, cold start and OCV
Class 8, Linehaul Heavy-Duty Trucks: Diesel vs. Fuel Cells

- FCS 20% more efficient than diesel at rated power
- Higher radiator heat load (Q) even though FCS is more efficient
- More heat rejected in the tail pipe than the radiator
- 275-kW FCS, 0.7 V cell voltage at rated power
- Double the diesel efficiency at low speeds
- 450-hp turbocharged diesel engine
- Heat rejection in FCS can be an issue
  - Compared to diesel engines, higher Q and smaller ΔT
Fuel cell dominant propulsion system rated at 275-kW\textsubscript{n} net, 35-kWh ESS

- Hill climb at 30 mph, 6% grade, 20-min duration
- 25\textdegree}C ambient temperature

<table>
<thead>
<tr>
<th>Cell Voltage (E)</th>
<th>Coolant T (T\textsubscript{c})</th>
<th>Radiator Heat Load (Q)</th>
<th>Fan Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>\degree}C</td>
<td>kW</td>
<td>kW\textsubscript{e}</td>
</tr>
<tr>
<td>0.675</td>
<td>91 - 94</td>
<td>295 - 275</td>
<td>40 - 20</td>
</tr>
<tr>
<td>0.700</td>
<td>87 - 93</td>
<td>265 - 240</td>
<td>30 - 15</td>
</tr>
<tr>
<td>0.725</td>
<td>84 - 94</td>
<td>240 - 220</td>
<td>30 - 10</td>
</tr>
<tr>
<td>0.750</td>
<td>82 - 93</td>
<td>240 - 220</td>
<td>30 - 8</td>
</tr>
</tbody>
</table>

Cell voltage > 0.750 V at rated power needed for stacks that operate below 80\textdegree}C
Optimum $T_c$ for highest FCS

PD as function of $E$

<table>
<thead>
<tr>
<th>Cell Voltage ($E$)</th>
<th>Optimum Coolant $T$ ($T_c$)</th>
<th>Stack Power Density</th>
<th>Stack Net PD</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.675</td>
<td>92</td>
<td>1220 mW/cm²</td>
<td>1025 mW/cm²</td>
</tr>
<tr>
<td>0.700</td>
<td>88</td>
<td>1200 mW/cm²</td>
<td>1015 mW/cm²</td>
</tr>
<tr>
<td>0.725</td>
<td>86</td>
<td>1120 mW/cm²</td>
<td>965 mW/cm²</td>
</tr>
<tr>
<td>0.750</td>
<td>84</td>
<td>1000 mW/cm²</td>
<td>875 mW/cm²</td>
</tr>
</tbody>
</table>

Lower $E$, higher PD

Higher $T_c$, lower RH, lower PD

PD lower: fan power too high (and electrode flooding)

Optimum $T_c$

PD lower: stack too dry

Optimum $T_c$ for highest FCS

PD as function of $E$
**FCS Performance at Steady State**

### Rated-Power FCS Efficiency at Highest Net Stack Power Density

<table>
<thead>
<tr>
<th>Cell Voltage (E)</th>
<th>Optimum Coolant T (T&lt;sub&gt;c&lt;/sub&gt;)</th>
<th>FCS Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>°C</td>
<td>%</td>
</tr>
<tr>
<td>0.675</td>
<td>92</td>
<td>45</td>
</tr>
<tr>
<td>0.700</td>
<td>88</td>
<td>47</td>
</tr>
<tr>
<td>0.725</td>
<td>86</td>
<td>49</td>
</tr>
<tr>
<td>0.750</td>
<td>84</td>
<td>52</td>
</tr>
</tbody>
</table>

**Cell Voltage (E)**

- **Optimum Coolant T (T<sub>c</sub>)**
- **FCS Efficiency**

- **Below 20-kW<sub>e</sub>**
  - Cell E > 0.9 V

- **Peak η<sub>s</sub> ~ 65%**, depends on CEM performance

- **Higher η<sub>s</sub> during short transients**, fan off

**FCS Efficiency Map at Steady State**
- **Cell Voltage 0.7 V at Rated Power**

**Graphical Components**

- **FCS Efficiency**
- **Cell Voltage (V)**
- **Coolant Temperature, °C**
- **FCS Power, kW<sub>e</sub>**
FCS Performance on EPA Drive Cycles

Instances where vehicle demand > FCS rated power

OCV with anode isolated by shutting-off H₂ supply

FCS idling at 20 kWₑ

Autonomie simulations of vehicle power demand*

*Results from Ram Vijayagopal, ANL

Mild 65

Mild 55

ARB
Simulation methodology

- Fuel cell dominant power train, battery for regenerative braking, hill climb and SOC balance
- Limit high potentials by restricting FCS idle power (20 kW<sub>e</sub>)
- Control OCV by shutting off H<sub>2</sub> supply during deceleration and parked idle
- Attempt to limit high temperatures by operating the fan when coolant exit T exceeds the set target (65°C)
Dynamic FCS Performance

- Dynamic cycle efficiency: ARB > Mild 55 > Mild 65

Radiator fan on: efficiency lower than at steady state

FCS transient power > 275 kW

CEM accelerating, up to 60-kW motor power

CEM decelerating, supplying power to motor/generator, up to 50 kW

Cycle Efficiency: 53%

Mild 55

Cycle Efficiency: 57%

ARB

Cycle Efficiency: 50%

Mild 65
<table>
<thead>
<tr>
<th>Collaboration Area</th>
<th>Collaborations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Management</td>
<td>Honeywell: Cost and Performance Enhancements for a PEM Fuel Cell Turbocompressor (FC27)</td>
</tr>
<tr>
<td></td>
<td>Eaton: Roots Air Management System with Integrated Expander (FC103)</td>
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<tr>
<td></td>
<td>Ballard/Eaton: Roots Air Management System with Integrated Expander (FC103)</td>
</tr>
<tr>
<td>Stack</td>
<td>3M: High Performance, Durable, Low Cost Membrane Electrode Assemblies for Transportation (FC104)</td>
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<td></td>
<td>JMFC and UTRC: Rationally Designed Catalyst Layers for PEMFC Performance Optimization (FC106)</td>
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<tr>
<td></td>
<td>FC-PAD: Fuel Cell Performance and Durability Consortium (FC135, FC136, FC137, FC138, FC139)</td>
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<tr>
<td></td>
<td>GM: Highly-Accessible Catalysts for Durable High-Power Performance (FC144)</td>
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<tr>
<td></td>
<td>GM: Durable High-Power Membrane Electrode Assemblies with Low Pt Loadings (FC156)</td>
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<tr>
<td></td>
<td>ElectroCat: Electrocatalysis Consortium (FC156)</td>
</tr>
<tr>
<td>Water Management</td>
<td>Gore, Ford, dPoint: Materials and Modules for Low-Cost, High-Performance Fuel Cell Humidifiers (FC067)</td>
</tr>
<tr>
<td>Thermal Management</td>
<td>ANL-Autonomie, 3M, Honeywell Thermal Systems</td>
</tr>
<tr>
<td>Fuel Management</td>
<td>3M, University of Delaware (Sonijector)</td>
</tr>
<tr>
<td>Fuel Economy</td>
<td>ANL-Autonomie (SA044), Aalto University (Fuel Cell Buses)</td>
</tr>
<tr>
<td>H₂ Impurities</td>
<td>3M</td>
</tr>
<tr>
<td>Dissemination</td>
<td>IEA Annex 34, Transport Modeling Working Group, Durability Working Group, Catalysis Working Group</td>
</tr>
</tbody>
</table>

- Argonne develops the fuel cell system configuration, determines performance, identifies and sizes components, and provides this information to SA for high-volume manufacturing cost estimation.
1. Continue to support DOE development effort at system, component, and phenomenological levels

2. Continue to support SA in high-volume manufacturing cost projections, collaborate in life-cycle cost studies
   - Optimize system parameters considering costs at low-volume manufacturing
   - Life cycle cost study for medium- and heavy-duty vehicles (FC-PAD, SA)

3. Fuel cell systems for medium and heavy-duty vehicles and locomotives
   - Heat rejection considerations and impact
   - Low and high-PGM catalysts and MEAs for >1,000,000-mile durability
   - Bipolar plates and flow fields for large stacks (300 kW)
   - Configuring systems with multiple stacks

4. Incorporate durability considerations in system analysis
   - System optimization for cost, performance, and durability on drive cycles (Advanced alloy catalyst systems)

Any proposed future work is subject to change based on funding levels.
1. Even with recent advances in catalysts and MEAs, $40/kW_e$ DOE target for 2020 FCS cost has not been achieved.
   - Recent emphasis on PGM-free catalysts

2. Breakthroughs are needed to achieve $30/kW_e$ ultimate DOE target for FCS cost.
   - Higher activity catalysts
   - Alternate electrode structures to control mass transfer losses at high current densities
   - More fundamental understanding of voltage losses, transport resistances and degradation mechanisms
   - Cheaper bipolar plate substrates and coatings

3. Air management system cost and performance, particularly with an expander

4. Durability of catalysts with low Pt loadings and thin membranes
   - Current generation of fuel cell vehicles on road use high Pt loadings and cannot meet the heat rejection requirement \( \frac{Q}{\Delta T} = 1.45 \text{ kW/}^\circ\text{C} \)

5. Durability models to guide mitigation strategies and system controls

6. System and component simplification for cost reduction
Technology Transfer Activities

Not applicable to this Fuel Cell System Modeling and Analysis Project. However, we are

1. Working closely with FCPAD project partner to jointly develop test protocols to rapidly obtain data on differential cells (goal: 2-3 days testing) that is critical for development of models for performance and durability.

2. Working jointly with partners to develop method to project the performance of integral cells using the model developed for differential cells, determine optimum operating conditions, and control performance degradation.
Backup Slides
Diesel Heat Rejection System

Radiator fan for 450-hp diesel engine, 52°C air-to-boil temperature

<table>
<thead>
<tr>
<th>Heat Exchangers</th>
<th>Dimensions and Details</th>
<th>Heat Loads</th>
<th>Radiator Fan 31 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiator</td>
<td>40” (W) x 42” (H) x 2” (D) Fins: louvered, 12-fpi, 10-mm height Tubes: 2-mm height</td>
<td>174 kW</td>
<td>Vehicle Speed: 38 mph</td>
</tr>
<tr>
<td>CAC</td>
<td>40” (W) x 35” (H) x 2.5” (D) Fins: louvered, 8-fpi, 20-mm height Tubes: 10-mm height</td>
<td>59 kW</td>
<td>Ambient T: 52°C</td>
</tr>
<tr>
<td>AC Condenser</td>
<td>40” (W) x 28” (H) x 0.75” (D) Fins: plain, 12-fpi, 10-mm height Tubes: 2-mm height</td>
<td>12 kW</td>
<td>Air Flow Rate: 8.5 kg/s</td>
</tr>
</tbody>
</table>

Coolant Temperature (°C )

Air Temperature (°C )
# Project Summary

<table>
<thead>
<tr>
<th>Relevance:</th>
<th>Independent analysis to assess design-point, part-load and dynamic performance of automotive and stationary FCS</th>
</tr>
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</table>
| Approach: | Develop and validate versatile system design and analysis tools  
Apply models to issues of current interest  
Collaborate with other organizations to obtain data and apply models |
| Progress: | In collaboration with GM and FC-PAD, demonstrated that d-PtCo catalyst supported on high surface area carbon (HSC) can be stabilized by limiting the high potential limit to 0.80-0.85 V in catalyst accelerated stress tests (ASTs)  
Demonstrated that the target of 10% loss in power can be achieved by limiting the electrochemically active surface area (ECSA) loss to 55.3%  
Determined the operating conditions for 55.3% ECSA loss: CEM* turndown = 12 (10), coolant exit temperature = 66°C/70°C for 5000 h/8000 h electrode durability  
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Showed the relationship between cell voltage, optimum operating temperature and stack power density as determined by heat rejection: 1200 mW/cm² power density at 0.7 V.  
Established FCS duty cycles for Class-8 trucks for regional, multi purpose and urban vocations, specifying time spent at different voltages and temperatures on ARB, mild-55 and mild-65 drive cycles |
| Collaborations: | 3M, Eaton, GM, Gore, JMFC, SA, UTRC, UDEL/Sonijector |
| Future Work: | Extending durability of low-PGM FCS for light-duty vehicles  
Fuel cell systems for heavy-duty vehicles and locomotives  
System analysis with durability considerations on drive cycles |
Sample comments and feedback

- The project is progressing well towards the set objectives and the diversity of its studied aspects. It also progresses well towards the DOE goals. The modeling methodology and procedures are highly developed.
- ANL's accomplishments are relevant, and the team provides excellent data.
- Additional details on the methodology for reaching DOE targets in performance and cost would be helpful.
- The addition of HDVs to the analysis framework is interesting and needed.
- A complete system dynamic model would be valuable for explaining barriers related to system thermal management and transient operation.
- Evaluating the impact of different materials, designs, and some operations is needed to achieve the overall objectives of the project. Increased emphasis on Pt dissolution/impact on ECSA would be beneficial.

Work scope consistent with above recommendations

- On-going work on performance and durability of PtCo/C catalysts in collaboration with FC-PAD and an industrial partner.
- In collaboration with GM and FC-PAD, evaluated the durability of d-PtCo catalyst supported on high surface area carbon (HSC).
- Determined the operating conditions for LDVs to reach 10% rated power loss for 5000 h / 8000 h electrode durability. Demonstrated the concept of managing CEM turndown and coolant exit temperature for meeting the durability target.
- Initial metrics for heat rejection in FCS for Class-8 heavy duty trucks.
- Established FCS duty cycles for Class-8 trucks for regional, multi purpose and urban vocations, determined time and energy spent at different voltages and temperatures on ARB, mild-55 and mild-65 drive cycles.
**FCS with d-PtCo/C Cathode Catalyst: Critical Assumptions**

### PEFC Stack
- Membrane: 12-µm, 850 EW, PFSA. Mechanically reinforced, with chemical additive.
- Cathode Electrode: GM d-Pt₃Co/C catalyst, 0.1 mgₚt/cm², high surface-area carbon support, 825 EW ionomer, I/C=1.0.
- Anode Electrode: Pt/C catalyst, 0.025 mgₚt/cm², Vulcan carbon support.
- Cathode/Anode GDL: Non-woven carbon paper with microporous layer (MPL), SGL 25BC, 235 µm nominal uncompressed thickness.
- Seals/Frame: PET subgasket (3M patent).
- Bipolar Plates: 3-mil (0.075 mm) 316 SS substrate with Treadstone coating, 0.5 mm land, 0.7 mm channel, 0.4 mm depth. 62.5% active area, 15 mΩ.cm² 2X ICR*.

### Air Management System
- Integrated centrifugal compressor-expander-motor module (Honeywell), airfoil bearings (AFB).
- Mixed axial flow compressor.
- Inflow radial expander, variable area nozzle.
- 3-phase brushless DC motor, liquid and air cooled; liquid-cooled motor controller.
- Efficiencies at rated power: 71% compressor, 73% expander, 89.5% motor, 89.5% controller.
- Turn-down: 20
- 5 psi ΔP between compressor discharge and expander inlet at rated power.

### Heat Rejection System
- Two circuits: 75-95°C HT, 10°C ΔT. 65°C LT coolant, 5°C ΔT.
- 55% pump + 92% motor efficiency.
- 45% blower + 92% motor efficiency.
- 10 psi ΔP in stack and 5 psi in radiator.

### Water Management System
- Planar cross-flow humidifier with Gore’s M311.05 membrane.

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*2X ICR: two-sided interfacial contact resistance.*
Journal Publications


Conference Presentations


<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>a</td>
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