Summary

- RRFCS has developed tools to characterize and improve our fuel cell technology
- Cell technologies are being developed by RRFCS which can meet performance and cost targets
- Scaled tests are demonstrating good performance and durability
Rolls Royce IP-SOFC Technology Development

- Technology and approach
- Cell performance testing and modeling
- Cell design improvements
  - Cell Pitch
  - Cell Materials
  - Primary Interconnect
- Cell performance and degradation
Rolls Royce IP-SOFC Technology Development

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Rolls-Royce integrated planar solid oxide fuel cell tube

Integrated planar series arrangement
Series connected cell design for high voltage low current
Thin layers of active materials minimise cost
Ceramic support material uses low cost MgO+Al₂O₃ powder + low cost extrusion

High voltage low current benefits
Easier hence cheaper for power electronics to convert low current DC to AC
High voltage facilitate direct conversion to 480 V AC grid requirement
Low currents give low Ohmic I²R losses offering greater materials options
SECA

- RRFCS is honored to be selected as an industrial team under the SECA program
- 2010 targets
  - Degradation <2% / 1000 hours in 5000 hours demo test
  - 15kW stack demonstration
  - System cost target for high volume production < $400/kW
Rolls Royce IP-SOFC Technology Development

- Technology and approach
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- Cell performance and degradation
Achieving the goal

- High efficiency and low cost targets require focused optimization
- Detailed understanding of fuel cell performance drives improvements in cost and efficiency
- Cell development for performance improvement
  - Cell pitch
  - Current collectors
  - Electrode overpotential
  - Electrolyte
SOFC Performance Model Development

\[ V_{\text{cell}} = E_{\text{Nernst}} - \eta_{\text{ohmic}} - \eta_{\text{act, cathode}} - \eta_{\text{act, anode}} - \eta_{\text{conc, anode}} - \eta_{\text{conc, cathode}} \]

Over-potentials (losses)

- Electronic Resistance
- E-Chem Reactions
- Mass Diffusion

- Ohmic \( \rightarrow \) based on layer testing, confirmed by EIS
- Cathode activation \( \rightarrow \) based on cathode
- Cathode concentration \( \rightarrow \) symmetric cell testing
- Anode activation \( \rightarrow \) based on cell testing
- Anode concentration

Rolls-Royce data
Testing Performance Envelope

- Temperature (700 – 950ºC)
- Pressure (1 – 6.5 Bar$_a$)
- Cathode composition
  - Oxygen partial pressure (0.08 – 1 Atm)
  - CO$_2$ and H$_2$O additions
- Fuel composition
  - Bundle inlet to bundle outlet
  - Fuel dilution to observe anode mass diffusion limitations
Testing Capability

- 5 pressurized, 8 atmospheric test stands with system relevant gas compositions
- 10 atmospheric tube/bundle test stands
- 2 pressurized bundle test stands
- 4 block test stands under build/commissioning

Block Scale Rig
Located in Derby, UK

5 Pressurized Subscale Rigs
located in Canton, OH
Well Controlled Boundary Conditions

Pressure
Temperature
Current/Voltage
Composition
Detailed Cell Analysis

- Voltage taps to discretize cell losses
- EIS to interrogate e-chem

Rolls-Royce data
Model Development

Electrolyte, 0.060
ACC, 0.028
CCC, 0.069
PIC, 0.038
Cell_Rp, 0.236

Pressurized Cell Testing

Layer Conductivity Tests

Cathode Button Cell Tests
De-convolution of cell performance and degradation contributions

Impossible to de-convolute - only Ohmic and non-ohmic losses

2 features observed

Impedance spectroscopy
With different fuel / oxidant combinations

Quantify individual Electrode layers
And ohmic components

Distribution of relaxation times,
Now see three distinct processes

FFT Analysis

Actively drive and monitor degradation
Target individual degradation processes
Door opened to accelerated testing

Rolls-Royce data
Substrate Characteristics Can Impact Electro-Chemical Performance

- Substrate permeability measured to determine diffusional resistance
- Modeling used to relate measured substrate parameters to cell performance
Impact of Diffusion Resistance

Voltage, V

Current Density, mA/cm²

Bundle Outlet
1 Barₐ, 900°C

More Permeable Tube

Less Permeable Tube

SCT6-26A  PCT21A

SECA Workshop 2009

Rolls-Royce data
Benefit of Pressure

Voltage, V

Current Density, mA/cm²

AO, 1 Bara
AO + 32% N2, 1 Bara

Seaca Workshop 2009

Rolls-Royce data
Benefit of Pressure

Rolls-Royce data
Preliminary Predictions Encouraging

**Table:**

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>41.1%</td>
<td>19.2%</td>
<td>15.2%</td>
<td>11.0%</td>
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</tr>
<tr>
<td>H₂O</td>
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<td>45.3%</td>
<td>41.6%</td>
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<tr>
<td>N₂</td>
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<td>19.8%</td>
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<tr>
<td>CO</td>
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<td>10.8%</td>
<td>7.4%</td>
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<td>1.0%</td>
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<tr>
<td>CO₂</td>
<td>10.8%</td>
<td>20.1%</td>
<td>15.9%</td>
<td>11.5%</td>
<td>5.5%</td>
</tr>
</tbody>
</table>

Points are data, Lines are predictions

**Graph:**

- **Voltage, V:** 0.50 to 1.00
- **Current Density, mA/cm²:** 0 to 1600
- **Cases:**
  - Case 1
  - Case 2
  - Case 3
  - Case 4
  - Case 5

**Legend:**

- **Case 1**
- **Case 2**
- **Case 3**
- **Case 4**
- **Case 5**

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Rolls Royce IP-SOFC Technology Development

- Technology and approach
- Cell performance testing and modeling
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  - Cell Pitch
  - Cell Materials
  - Primary Interconnect
- Cell performance and degradation
Cell Pitch Optimization

60-cell design minimizes conductance requirement for ACC and CCC

195 mm substrate

245 mm substrate

Active area (% of total surface)

35% 37% 46% 48% 63% 53%

Current design
42W

SECA demonstration
55-60W

Rolls-Royce data
Benefits of 60-cell Pitch

- 1.1 mm PIC width selected for lower cost materials
- Targeting ~1S ACC and CCC Conductance
- Power density = 350 mW/cm²

Map to Achieve 60W

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Rolls-Royce data
Rolls Royce IP-SOFC Technology Development

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- Cell performance and degradation
Anode Current Collector

- Minimize CTE mismatch with substrate
- Maximize conductivity within CTE limits

Composition Group 1

<table>
<thead>
<tr>
<th>Volume Fraction Metal (%)</th>
<th>CTE 25-100°C (ppm/K)</th>
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<tbody>
<tr>
<td>50</td>
<td>11</td>
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<tr>
<td>55</td>
<td>11.2</td>
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<tr>
<td>60</td>
<td>11.4</td>
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<tr>
<td>65</td>
<td>11.6</td>
</tr>
<tr>
<td>70</td>
<td>11.8</td>
</tr>
</tbody>
</table>

Group 1: ~ 2S

Group 2

Conductance, S vs. Elapsed Time, hours

Rolls-Royce data
Optimization of CCC Ohmic losses critical to hitting ASR targets

\[ E_a (\text{cell}) = 0.51eV \]
\[ E_a (R_p) = 0.65eV \]

Reduce ASR of CCC from 0.07 to 0.02 ohm-cm\(^2\)

\[ y = 0.0115x - 0.0038 \quad R^2 = 0.9983 \]
\[ y = 0.0033x + 0.0028 \quad R^2 = 0.9991 \]
Lower Cost, Better Performance

Cathode: Dry Air
Anode: Bundle Inlet
Temperature = 900°C
Pressure = 0.98 Bara

Standard Cell
Reduced Width
Latest Material Set
Reduced Width
Standard Cell

ASR, ohm-cm²
Latest Single-Cell Performance

Cathode: 12% O₂, bal N₂

6 Bara, 446 mA/cm²

Anode: 40% H₂, 21% CO, 12% CO₂, 25% H₂O

Temperature, °C

ASR, ohm-cm²

Power Density, mW/cm²

Rolls-Royce data

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Rolls Royce IP-SOFC Technology Development

- Technology and approach
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Primary Interconnect ASR: Via-based design

Normal interconnect 2nd electrolyte

1st electrolyte

Voltage distribution

Space between CCC and ACC (no current passes)

Ink on electrolyte

“Via” through electrolyte

Conductivity model for PIC ASR
PIC ASR = 0.032 ohm-cm²

Cathode: Air

900°C, 1 Bar, 440 mA/cm²

Anode Gas: 41% H₂, 23% CO, 12% CO₂, 24% H₂O

Bundle outlet

Rolls-Royce data

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Primary Interconnect ASR: Ceramic Strip based design

Cathode CC

Ceramic Interconnect

Anode CC

Cell Power Density, mW/cm²

- Cathode: Air
- 900°C, 1 Bar, 330 mA/cm²

Anode Gas: 41% H₂, 23% CO, 12% CO₂, 24% H₂O

PIC Conductivity, S/cm

ASR, ohm-cm²

- 20 microns thick
- 10 microns thick

Ceramic interconnect showing feasibility but further optimization required
Interconnect Parasitic Losses

- At 60-cell design there is a larger interconnect/cell area ratio
- Must manage local parasitic losses resulting from materials selection, PIC designs and printing accuracy
- Significant improvements achieved through various modifications

\[ \ln(Rate) = \ln \left( \frac{I_{\text{shunt}}}{ZF} \right) \]

Measured OCV

Nernst OCV

\[ \eta_{\text{shunt}} \]

\[ \eta_{\text{shunt}} \]

\[ I_{\text{short}} \]
Rolls Royce IP-SOFC Technology Development

- Technology and approach
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- Cell performance and degradation
40% Improvement in Power

6 Bara, 900°C, Anode Inlet, 12% O₂

60 cell ASR = 0.26 ohm-cm²

30 cell ASR = 0.39 ohm-cm²

Power Comparison at 0.8V

30-cell 331 mW/cm²
60-cell 470 mW/cm²
Single-Cell Degradation Performance

Cathode: Air
12% O₂, bal N₂

Anode: 40% H₂, 21% CO, 12% CO₂, 25% H₂O

Cell Power Density, mW/cm²

Elapsed Time, hours

SCT6-14A&B
Latest Material Sets

Power, Cell A
Power, Cell B

900°C/1 Barₐ
950°C/1 Barₐ
900°C/6 Barₐ

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Rolls-Royce data
Single-Cell Degradation Performance

Cathode: 12% O₂, bal N₂

Anode: 26% H₂, 17% CO, 18% CO₂, 35% H₂O, 4% N₂

900°C, 6 Bar, 430 mA/cm²

SCT6-24A Latest Material Set

Various

Elapsed Time, hours

Rolls-Royce data
Anode+ACC Candidate #1 Durability

Cells can sustain high current density at outlet fuel and 950°C

- Cathode: Air
- 955°C, 1 Bar
- ~0.61V at 943 mA/cm²
- ~0.65V at 848 mA/cm²
- ~0.71V at 704 mA/cm²
- ~0.77V at 457 mA/cm²

Anode: 18% H₂, 13% CO, 23% CO₂, 47% H₂O

Table:

<table>
<thead>
<tr>
<th>Current Density, mA/cm²</th>
<th>Cell Power Density, mW/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>200</td>
<td>100</td>
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<tr>
<td>400</td>
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<tr>
<td>600</td>
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<td>800</td>
<td>400</td>
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<tr>
<td>1000</td>
<td>500</td>
</tr>
<tr>
<td>1200</td>
<td>600</td>
</tr>
<tr>
<td>1400</td>
<td>700</td>
</tr>
</tbody>
</table>

Graph:
- Elapsed Time, hours
- Cell Voltage, Volts
- Current Density, mA/cm²
Anode+ACC Candidate #2 Durability

- This cell displays more diffusive resistance and higher degradation

Cell Power Density, mW/cm²

- Cathode: Air

~0.61V, 740 mA/cm²

Anode: 18% H₂, 9% CO, 19% CO₂, 49% H₂O, 4% N₂

Voltage, Volts

Current Density, mA/cm²

Elapsed Time, hours

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Rolls-Royce data

Rolls-Royce data
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