Project Title: **FEASIBILITY EVALUATION OF A DIRECT CARBON FUEL CELL (DCFC) OPERATION ON ILLINOIS COAL**

ICCI Project Number: 06-1/10.1A-3  
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Other Investigators: Dr. Iouri Balachov, SRI International  
Project Manager: Dr. Ronald H.Carty, ICCI

**ABSTRACT**

The objective of this project is the feasibility evaluation of a direct carbon fuel cell (DCFC) operation on Illinois coal. The development of DCFCs offers the potential to greatly improve the economics of power production from Illinois coal in FutureGen plants. The specific objective is to fabricate single tubular DCFCs, 1 cm in diameter x 15 cm long, for evaluation of power production for up to 1000 hours using pulverized Illinois coal. The goal is to establish a power density of greater than 100 mW/cm², comparable to that of commercial MCFCs, for developing a clean power generation system for distributed and centralized electricity generation using Illinois coal. Issues for using Illinois coal, such as the interaction of coal inorganics with the DCFC electrodes and electrolyte and spallation limits of corrosion of metals used for current collection and construction, were also assessed to gauge endurance of DCFCs for power production.

Under this ICCI project, GTI procured Illinois coal samples from Galatia, Freeman and Viper mines and demonstrated a DCFC power density of 115 mW/cm² at 775°C using Freeman coal. It was also determined that composition of the liquid anode containing eutectic mixtures of molten carbonates, coal loading in the melt and inorganics in the coal all contributed significantly to increasing the corrosion rates of the DCFC electrolyte, yttria stabilized zirconia (YSZ) and nickel current collector, thereby curtailing endurance.
EXECUTIVE SUMMARY

DCFCs convert the chemical energy in coal directly into electricity without the need for gasification. The process produces almost pure carbon dioxide (CO₂), which can be contained in a concentrated stream and easily captured for downstream use or disposal. The SRI's DCFC system combines the best features of two demonstrated technologies: solid oxide fuel cells (SOFC) and molten carbonate fuel cells (MCFC) with the use of a liquid-molten salt anode that incorporates a carbon-containing fuel. The molten salt serves as a medium for establishing contacts between the electrolyte surface and the carbon fuel. This one-step, clean, high-efficiency energy conversion process transforms the chemical energy of pulverized coal (and other carbon-containing fuels) directly into electricity through the electrochemical oxidation of carbon. The DCFC concept and its construction is shown in Figure 1. The development of DCFCs offers the potential to greatly improve the economics of power production from Illinois coal in FutureGen plants which supports the ICCI mission.

![Figure 1. DCFC Concept and Construction.](image)

**Overall Reaction:**  \[ C + O_2 \rightarrow CO_2 \]

**Cathode:** Lanthanum Strontium Manganate (LSM)
- Current collector: metallic coil or mesh
- Air (oxygen) supplied to the cathode via a concentric tube

**Electrolyte:** Yttria Stabilized Zirconia (YSZ)

**Anode:** Stagnant molten salt (e.g., Li/Na carbonate) mixed with fuel particles (typically >30 vol.%)  
- Current collector is a mesh or coil made of an alloy stable in molten salt (e.g., Ni)

To evaluate the feasibility of converting Illinois coal directly to electrical power using DCFCs, the proposed project was divided into three tasks: 1) Perform out-of-cell stability tests in molten carbonate, 2) perform single DCFC testing and 3) perform the project management and report submission requirements. Operating conditions for tasks 1 and 2 included the following variables:
- type of coal (Freeman and Galatia).
- coal particle size (fine: 40 μm, coarse: 140 μm).
- temperature (600-800°C).
- composition of molten salt used for the liquid anode.
  - 52Li₂CO₃-48Na₂CO₃ (very basic).
- 50Li₂CO₃-50K₂CO₃ (moderately acidic/basic).
- 34Na₂CO₃-66K₂CO₃ (very acidic).
- coal loading in the melt (10, 20, 30 and 40 vol%).
- gas atmosphere above melt (100% CO₂, 80% N₂+20%CO₂).

In Task 1 of this project, GTI procured two Illinois coal samples: one from the Galatia mine (low sulfur and high chlorine) and one from the Freeman mine (high sulfur and low chlorine) for characterization and use in the out-of-cell DCFC corrosion and stability testing with molten carbonate melts. The out-of-cell tests conducted in this task to determine the effect of molten carbonate composition on DCFC stability indicated that the corrosion of yttria stabilized zirconia (YSZ) electrolyte used in the DCFC, is lowest in Li₂CO₃/ Na₂CO₃ (very basic) and highest in Na₂CO₃/ K₂CO₃ (very acidic) melts. Apparently, corrosion is faster in more acidic melts. In view of this, the less corrosive Li₂CO₃/Na₂CO₃ salt was selected for single DCFC testing in Task 2 of this project.

In Task 2 of this project, SRI performed batch testing of single DCFCs. The objectives of this effort were to: 1) demonstrate a DCFC power density of at least 100 mW/cm², 2) define the factors that control performance and endurance of DCFCs and 3) assess issues for using Illinois coal, such as the interaction of ash and inorganics with the DCFC electrodes and electrolyte and spallation limits of corrosion of metals, such as nickel, used for current collection. As a consequence of the task 1 results, Li₂CO₃/Na₂CO₃ melt was employed for this task.

The project goal of establishing a DCFC power density of >100 mW/cm² was demonstrated as shown below in Figure 2 with coarse Freeman coal (140 micron particle size) with a loading of 40% in the Li₂CO₃/Na₂CO₃ melt. The other key performance and corrosion results from Tasks 1 and 2 testing are summarized below.

![Figure 2. DCFC Performance on Freeman Coal at 775°C.](image)

- Decreasing the operating temperature from 700° to 600°C reduced power density by one order of magnitude.
- Power density generally increased with coal loading in the melt.
• Observed power densities were generally higher for Freeman coal compared to Galatia due to the lower amounts of inorganics contained in Freeman than in Galatia.

• Above 650°C power density was 32% higher for coarse as compared to fine Freeman coal, an important economic benefit because “as is” pulverized coal may be used as fuel for DCFC without any further fine grinding.

• Endurance testing performed with Freeman and Galatia coals at 700°C for 700 hours lowered initial cell voltages by about 20%. The degradation of the YSZ electrolyte is in part responsible for this and possible maldistribution of the fuel in the melt with time may have also affected cell voltages.

• Corrosion of YSZ is lowest in Li₂CO₃-Na₂CO₃ and highest in Na₂CO₃-K₂CO₃ and therefore Li₂CO₃-Na₂CO was used for all DCFC testing.

• Use of 80% N₂+20% CO₂ instead of pure CO₂ as blanket gas above the melt reduced corrosion rates by one order of magnitude at 800°C for Na₂CO₃-K₂CO₃.

• No effect of blanket gas on corrosion was observed for Li₂CO₃-Na₂CO₃.

• An increase in temperature from 750° to 800°C increased corrosion rates by two times for the Li/Na melt, one order of magnitude for Na/K, and two orders of magnitude for Li/K.

• An increase in temperature from 700° to 800°C increased corrosion rate by six times for Galatia coal with Li/Na.

• Coal particle size had no effect on corrosion.

• Corrosion generally increased with increasing coal loading in the Li/Na.

• The high amount of chlorine (4370 ppmw) in the Galatia coal had an adverse effect on the YSZ corrosion.

• State-of-the-art nickel anode interconnect failed in about 300 hours operation indicating a need for other viable materials.

• Of the five alternate interconnect candidate materials studied (platinum, palladium, Incolloy 617, stainless steel 410 and Hastelloy 276) only platinum was stable in the melt suggesting a need to find other viable and cheaper materials.

• DCFC testing with the Freeman and Galatia coals revealed corrosion of the YSZ electrolyte suggesting an interaction of coal inorganics with the DCFC electrodes and electrolyte.

Since this technology has potential to greatly improve the economics of power production from Illinois coal more DCFC testing in a continuous mode (to facilitate coal feeding and discharge of ash and other inerts) is needed both at single cell and stack levels. This allows an assessment of the mechanisms by which inorganics in the coal interact with the YSZ electrolyte and current collector materials to determine if any coal pretreatment is needed to further improve performance and endurance. Also, scalability of the DCFC system to the initial 10s of kilowatt levels is necessary to demonstrate commercial viability in the megawatt levels needed for economic power production.
OBJECTIVES

The objective of this R&D project is to evaluate the feasibility of converting Illinois coal directly to electrical power using SRI’s DCFC and identify issues for using Illinois coal such as the interaction of ash and inorganics with the DCFC electrodes and electrolyte and spallation limits of corrosion of metals used for current collection. To achieve these objectives the proposed ICCI project was divided into two technical tasks: 1) Out-of Cell Stability Tests in Molten Carbonate and 2) Single DCFC Testing.

Task 1. Out-of Cell Stability Tests in Molten Carbonate

This task was performed by GTI.

Subtask 1.1: Illinois Coal Characterization

Samples of Illinois No. 6 coal were procured and selected for testing after discussions with ICCI. The selected sample(s) were characterized with proximate and ultimate analyses along with an ash analysis to identify the inorganics in the coal. The inorganic analyses were used to assess their disposition and any interactions that they may have with the DCFC materials. All this information was used in the effort of the subsequent tasks: out of cell testing with molten carbonate and DCFC testing.

Subtask 1.2: Stability of Cell Element

The stability of DCFC elements in molten carbonate was investigated. Tubular cell elements, which are closed end tubes of LSM cathode supported YSZ electrolyte, were immersed in a bath of molten carbonate maintained at temperatures between 700- 800°C. A blanket gas composition of 20-100% CO₂, diluted with N₂ in certain tests, was maintained over the melt. A test set-up for this effort was fabricated.

The below three compositions representing different acid/base melt conditions were utilized for the DCFC stability testing in the molten carbonate.

- 52Li₂CO₃-48Na₂CO₃                    Very basic
- 50Li₂CO₃-50K₂CO₃                     Moderately acidic/basic
- 34Na₂CO₃-66K₂CO₃          Very acidic

The melting points of these carbonates are 501, 500 and 710°C, respectively. The YSZ coated cell tube was immersed in the melts at temperatures between 700-800°C for up to 250 hours and then analyzed by scanning electron microscopy (SEM) for compositional and microstructural changes. The DCFC tube stability was assessed as a function of melt composition and the best composition was selected for DCFC testing in Task 2.

Subtask 1.3: Stability Tests with Coal Powder in Melt

The tests in Subtask 1.2 were repeated with the selected melt dispersed with pulverized Illinois coal containing impurities such as Al₂O₃, SiO₂, alkalis and alkaline earths, as well as sulfur, chlorides and others. These impurities are likely to react or dissolve in the carbonate melt and influence the acid-base chemistry. The coal sample to be used was
pulverized to less than 200 mesh (275 μm) by ball milling, a common attrition method. After testing, carbonate from the suspended coal was washed off and analyzed by SEM and energy dispersive spectra (EDS) to find out changes in microstructure and elemental composition of the DCFCs. Longer term stability tests were performed in Task 2 based on the melt composition selected.

**Subtask 1.4. Hardware Corrosion**
The cell elements used in the immersion tests under Subtasks 1.2 and 1.3 also contained metallic (e.g., Ni) current collectors. The current collectors were also analyzed for corrosion by SEM to determine surface attacks by the carbonate and assess their stability.

**Task 2. Single DCFC Testing**
This task was performed by SRI.

**Subtask 2.1: Design and Fabrication of the DCFC Test System**
A test system to accommodate testing of single DCFCs was designed and fabricated and included: (1) a DCFC, (2) oxidant (air) system, (3) cell heating system, (4) process control, and (5) a data acquisition system. The heating system consisted of tubular furnace for heating the DCFCs to the operating temperature of 600-800°C. The oxidant system supplied the required amount of oxidant (air) to the cathode side of the cell. The process control system maintained the desired supply of fuel and oxidant flow rates and cell temperature. The DCFCs were equipped with voltage and current take-off leads to monitor performance. The data acquisition system collected and stored process data (e.g., temperature, fuel and oxidant rates, cell voltage and current to estimate power density).

**Subtask 2.2: DCFC Fuel Element Fabrication**
Up to fifteen DCFCs were fabricated for testing using candidate materials-Yttria stabilized zirconia (YSZ) electrolyte and lanthanum strontium manganite (LSM) cathodes. Each DCFC element consisted of a closed-end tube (LSM cathode) coated with thin film electrolyte (YSZ) equipped with anode and cathode current collectors and terminals for DC measurements.

**Subtask 2.3: Endurance and Performance Testing of the Candidate Fuel Elements**
The DCFCs were tested using the test system described in Subtask 2.1. The single cell test duration lasted up to 1000 hours. During testing pertinent cell operating data (temperature, fuel and oxidant flows, voltage and current density etc.) were acquired and monitored to gauge performance and endurance.

A post-test examination of the DCFCs was performed to obtain information on cell compositional changes after endurance testing.
INTRODUCTION AND BACKGROUND

DCFCs convert the chemical energy in coal directly into electricity without the need for gasification. The process produces almost pure carbon dioxide (CO₂), which can be contained in a concentrated stream and easily captured for downstream use or disposal. The SRI's DCFC system combines the best features of two demonstrated technologies: solid oxide fuel cells (SOFC) and molten carbonate fuel cells (MCFC) with the use of a liquid-molten salt anode that incorporates a carbon-containing fuel. The molten salt serves as a medium for establishing contacts between the electrolyte surface and the carbon fuel. The one-step, clean, high-efficiency energy conversion process transforms the chemical energy of pulverized coal (and other carbon-containing fuels) directly into electricity through the electrochemical oxidation of carbon. The development of DCFCs offers the potential to greatly improve the economics of power production from Illinois coal in FutureGen plants which supports the ICCI mission.

The DCFC’s use of a carbon fuel maximizes the conversion efficiency of carbon chemical energy into electricity by avoiding the Carnot cycle efficiency limitations of heat engines, as well as the efficiency limitations associated with the entropy loss of competing fuel cells. A total conversion efficiency of 80% (based on the heat of combustion of carbon) can be achieved using a wide variety of carbon fuels, including variety of coals. The net fuel cell reaction (C + O₂ = CO₂) has a nearly zero entropy change (Figure 3) and therefore a theoretical efficiency of 100% (Table 1), making DCFC one of the most efficient fuel cells. A comparison of efficiencies for DCFC and the hydrogen-fueled solid oxide fuel cell (SOFC) (Table 1) reveals that nearly 80% efficiency is achievable in DCFC-based systems, whereas the efficiency of the SOFC based system is limited to 50% (at an operating temperature of 800°C). The use of solid fuel also avoids the dilution of fuel by the gaseous fuel oxidation process (as in SOFCs) and makes possible the complete utilization of fuel.
The theoretical efficiency of a fuel cell $\eta_t$ is not limited by the Carnot cycle; instead, it is limited by the ratio of Gibbs energy change $\Delta G$ to enthalpy change $\Delta H$ or, in other terms, the loss of entropy $\Delta S$ in fuel oxidation reaction at operating temperature $T$:

$$\eta_t = \frac{\Delta G}{\Delta H} = 1 - \frac{T\Delta S}{\Delta H} \tag{1}$$

The reaction on the anode side of the DCFC is complete oxidation of carbon by oxygen ions with the release of four electrons and $CO_2$:

$$C + 2O^{2-} \rightarrow CO_2 + 4e^- \tag{2}$$

The reaction on the cathode side of the DCFC is typical SOFC cathode reaction of conversion of oxygen molecules into oxygen ions with consumption of electrons:

$$O_2 + 4e^- \rightarrow 2O^{2-} \tag{3}$$

The overall reaction is

$$C + O_2 \rightarrow CO_2 \tag{4}$$

**Table 1. Comparison of the Energy Conversion Efficiencies of DCFC and Hydrogen Fuel Cells at 800°C.**

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Theoretical limit</th>
<th>Utilization efficiency</th>
<th>Voltage efficiency</th>
<th>Maximal actual efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1.00</td>
<td>1.00</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>H₂</td>
<td>0.76</td>
<td>0.80</td>
<td>0.80</td>
<td>0.49</td>
</tr>
</tbody>
</table>

**Figure 3. Comparison of Theoretical Energy Conversion Efficiency in DCFCs and Gas-Fueled Fuel Cells.**
SRI’s DCFC technology is a composite of two proven technologies: SOFCs and molten carbonate fuel cells (MCFCs), both of which have been scaled up to hundreds of kW. The DCFC cathode and electrolyte are made of typical SOFC materials. The gas diffusion solid cathode is made of lanthanum strontium manganite (LSM), and the solid electrolyte is made of an oxygen-ion-conductive material, such as yttria-stabilized zirconia (YSZ). A distinctive feature of SRI’s DCFC is its liquid anode mixed with solid fuel. Molten salts, such as eutectic mixtures of K₂CO₃, Li₂CO₃, and Na₂CO₃ are used for the liquid anode. The solid fuel consists of carbon in powder form.

As noted, a DCFC generates electricity by the electrochemical reaction associated with the complete oxidation of carbon atoms by O²⁻ ions with the release of four electrons and a CO₂ molecule (Equation 2 above). The fuel oxidation reaction takes place at the interface of the liquid anode and solid electrolyte (Figure 4). Oxygen ions, which are generated from oxygen molecules by the solid cathode on the opposite side of the electrolyte, migrate through the electrolyte to the fuel oxidation zone.

Tubular (cathode-supported) DCFC fuel elements are used (Figure 1) to avoid using sealants. A porous LSM closed-end tube (cathode) is coated with a thin layer (0.02-0.05 mm) of YSZ electrolyte. The anode current collector is in a form of mesh or coil made of an alloy stable in molten salt. The cathode current collector is made of metallic coil or mesh, or consists of a layer of a porous electron-conductive material typically used in SOFCs. The fuel element is immersed in a circulating liquid anode (molten salt) mixed with fuel particles. The oxidant is supplied in the cathode space of the fuel element via a concentric tube. The use of a molten salt liquid anode eliminates temperature gradients, local overheating, and cracking of the solid electrolyte. The fuel cell does not have to be gas tight: because the fuel and oxidant are reliably separated by the solid electrolyte, no high-temperature sealants are required.
EXPERIMENTAL PROCEDURES

Task 1. Out-of-Cell Stability Tests in Molten Carbonate
A test fixture was designed and fabricated for out-of-cell stability and corrosion testing of DCFC elements and associated hardware. A schematic of the test set-up is shown in Figure 5. The setup consists of a 3-inch OD Inconel tube fitted with top and bottom flanges. The top flange contains various ports to accommodate gas inlet and outlets, test thermocouples and a melt stirrer. The Inconel tube also houses three dense alumina crucibles to contain the melts to be tested and hold DCFC tube samples. A typical test consists of placing the setup in a vertical tube furnace and hold at temperature up to 250 hours under a blanket gas composition maintained over the melts. At the end of the test the DCFC tubes are removed, and cross-sectioned for SEM examination to assess corrosion.

Figure 5. Schematic of Out-of-Cell Test Apparatus (a) and Test Setup and Furnace (b).
Task 2. Single DCFC Testing
SRI fabricated a test setup shown in Figure 6 for batch testing of single DCFCs. This setup includes: (1) a DCFC housing, (2) oxidant (air) system, (3) cell heating system, (4) process control, and (5) a data acquisition system. The heating system contains a tubular furnace for heating the DCFCs to the desired operating temperature of 600-800°C. The oxidant system supplies the required amount of oxidant (air) to the cathode side of the cell. The process control system maintains the desired supply of fuel and oxidant flow rates and cell temperature. The DCFCs are equipped with voltage and current take-off leads to monitor performance. The data acquisition system collects and stores process data (e.g., temperature, fuel and oxidant rates, cell voltage and current to estimate power density).

The experiment control and data acquisition system performs a variety of fuel cell tests: current-voltage sweeps (I-V) and power density curves under constant fuel and oxidant flow rates, and impedance measurements to gauge cell internal resistance and polarization losses and monitor cell voltage during endurance testing. Typically up to four cells are tested simultaneously and system has the capability to test up to eight cells at a time. The test setup to accommodate the DCFC testing is shown in Figure 6.

Two types of tubular DCFC elements were used for batch testing of single DCFCs. Generation 1 type, low cost, low performance elements (to stay within budgetary allocations for this project), was employed for parametric studies to maximize data generation for assessing the effects of temperature, coal type and its volumetric loading in the melt on DCFC power density. Generation 2 type, medium cost and high performance elements, was used to demonstrate the DCFC power density target set for this ICCI project.

Generation 1 type elements were 12.5 mm in diameter and 25 cm long, with a YSZ electrolyte thickness of 0.8 mm and a cell active area of 8.7 cm² were developed for 800°-900 °C operation. Cell operating temperature was in 600°-900°C, with Freeman and Galatia coals as fuel and atmospheric air as the oxidizer. The configuration of the Generation 1 type element is shown in Figure 7(a) and a view of it with the black LSM cathode deposited on the outer surface of the YSZ tube is shown in Figure 7(b).
Generation 2 type elements have dimensions similar to type 1, except the cathode was coated on the inside of the DCFC element and YSZ electrolyte was applied onto the outer surface of the tube with a thickness of approximately 70-100 microns. The cathode air was supplied to the inside of the tube, which was immersed into the anode mixture containing molten salt and fuel as shown in Figure 1.

Figure 7. Test Configuration (a) and DCFC Element (b).
RESULTS AND DISCUSSION

To achieve the set objectives for the proposed ICCI project, the effort was divided into two technical tasks: 1) Out-of Cell Stability Tests in Molten Carbonate and 2) Single DCFC Testing. Operating conditions for tasks 1 and 2 included the following variables:

- type of coal (Freeman and Galatia).
- coal particle size (fine: 40 μm, coarse: 140 μm).
- temperature (600–800°C).
- composition of molten salt used for the liquid anode.
  - 52Li₂CO₃-48Na₂CO₃ (very basic).
  - 50Li₂CO₃-50K₂CO₃ (moderately acidic/basic).
  - 34Na₂CO₃-66K₂CO₃ (very acidic).
- coal loading in the melt (10, 20, 30 and 40 vol%).
- gas atmosphere above melt (100% CO₂, 80% N₂+20%CO₂).

The results and accomplishments in these tasks are presented below.

Task 1. Out-of Cell Stability Tests in Molten Carbonate
This task was performed by GTI.

Subtask 1.1. Illinois Coal Characterization
Three samples of Illinois No. 6 coal were procured from Galatia, Freeman and Viper mines and characterized for chemical analyses of both coal ash and particle size distribution. The results are shown in Tables 2 and 3. For testing in Tasks 1 and 2, only two of the three coals, Galatia (low sulfur and high chlorine) and Freeman (high sulfur and high chlorine), were used after consultation with ICCI project manager to stay within the budgetary limits of the program. The inorganic analysis will be used to assess their disposition and any interactions that they may have with the DCFC materials.

### Table 2. Composition of Illinois Coal Samples.

<table>
<thead>
<tr>
<th>Components</th>
<th>Units</th>
<th>Type of Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Viper</td>
</tr>
<tr>
<td>Ash (750°C)</td>
<td>wt%</td>
<td>10.93</td>
</tr>
<tr>
<td>Carbon</td>
<td>wt%</td>
<td>71.9</td>
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<tr>
<td>Hydrogen</td>
<td>wt%</td>
<td>4.99</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>wt%</td>
<td>1.39</td>
</tr>
<tr>
<td>Sulfur</td>
<td>wt%</td>
<td>3.97</td>
</tr>
<tr>
<td>Fluorine</td>
<td>ppm</td>
<td>36</td>
</tr>
<tr>
<td>Chlorine</td>
<td>ppm</td>
<td>2,140</td>
</tr>
<tr>
<td>Oxygen</td>
<td>wt%</td>
<td>6.60</td>
</tr>
</tbody>
</table>
Two average particle sizes 140 microns (designated as coarse) and 40 microns (fine) were generated by grinding and sieving from the two Illinois coals, Galatia and Freeman, for stability, corrosion and DCFC testing in Tasks 1 and 2.

**Subtask 1.2. Stability of Cell Element**

The stability of DCFC elements in molten carbonate was investigated using the test setup shown in Figure 5 and the above test procedures.

Results of tests conducted with the three carbonate melts, 52Li2CO3-48Na2CO3 (very basic), 50Li2CO3-50K2CO3 (moderately acidic/basic) and 34Na2CO3-66K2CO3 (very acidic) at 750° and 800° C under gas atmospheres consisting of 100% CO2 and a mixture of 80% N2 and 20% CO2 to determine DCFC corrosion and material stability are summarized below and shown in Figures 8 and 9 and Tables 4 and 5. The temperature and melt composition effects on YSZ corrosion rates at 750° and 800°C are also summarized in Figure 9 and Table 5.

Corrosion of YSZ electrolyte in the DCFC element is lowest in Li2CO3/Na2CO3 and highest in Na2CO3/K2CO3 melts. Apparently, corrosion is faster in more acidic melts. In view of this the Li2CO3/Na2CO3 melt was used for all DCFC testing.

A significant effect of gas atmosphere on corrosion of YSZ coated DCFC tubes immersed in the melt was observed. Two compositions were employed: 100% CO2 and a 20/80 mixture of CO2/N2. YSZ corrosion was significantly lower at 800°C for 20/80 mixture of CO2/N2 with melts 50Li2CO3-50K2CO3 and 34Na2CO3-66K2CO3 and slightly lower for 52Li2CO3-48Na2CO3 (Figure 8) as compared to pure CO2.

Also, SEM analyses of the DCFC tube cross-sections from a 235-hour test conducted at 750°C with the above three melts indicated negligible corrosion if any and no major material degradation. In view of this, corrosion testing planned at 700°C was not performed.

**Subtask 1.3. Stability Tests with Coal Powder in Melt**

A test was performed with Galatia coal (low sulfur and high chlorine) with a loading of

<table>
<thead>
<tr>
<th>Element</th>
<th>VIPER Coal</th>
<th>GALATIA coal</th>
<th>FREEMAN coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>3.48 ± 0.27</td>
<td>5.63 ± 0.33</td>
<td>4.34 ± 0.26</td>
</tr>
<tr>
<td>Silicon</td>
<td>15.53 ± 0.29</td>
<td>16.87 ± 0.34</td>
<td>15.25 ± 0.27</td>
</tr>
<tr>
<td>Sulphur</td>
<td>34.01 ± 0.43</td>
<td>17.40 ± 0.39</td>
<td>37.77 ± 0.42</td>
</tr>
<tr>
<td>Chlorine</td>
<td>-</td>
<td>11.70 ± 0.48</td>
<td>1.74 ± 0.37</td>
</tr>
<tr>
<td>Potassium</td>
<td>2.58 ± 0.21</td>
<td>5.46 ± 0.31</td>
<td>3.88 ± 0.22</td>
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<tr>
<td>Calcium</td>
<td>7.98 ± 0.26</td>
<td>3.76 ± 0.28</td>
<td>2.86 ± 0.20</td>
</tr>
<tr>
<td>Titanium</td>
<td>1.83 ± 0.28</td>
<td>3.57 ± 0.40</td>
<td>1.61 ± 0.22</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.12 ± 0.10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Iron</td>
<td>34.48 ± 0.44</td>
<td>36.14 ± 0.56</td>
<td>32.55 ± 0.40</td>
</tr>
<tr>
<td>Strontium</td>
<td>-</td>
<td>0.28 ± 0.09</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3. Ash Analysis of the Illinois Coal Samples.
30% (volume) in the 52Li2CO3-48Na2CO3 melt at 800°C under 100% CO2 atmosphere (to simulate actual DCFC test conditions where CO2 is continuously produced via the electrochemical reaction). Introducing 30%vol of Galatia coal to Li2CO3 – Na2CO3 eutectic increased the corrosion rate of YSZ by an order of magnitude at 800°C as shown in Figure 8 and Table 4. This effect could be significantly mitigated by lowering operating temperature as confirmed in Task 2 single DCFC tests conducted with Freeman and Galatia coals.

Subtask 1.4. Hardware Corrosion
Due to the time constraints of the project, the out-of-cell work in this subtask was conducted as a part of Task 2 in Subtask 2.3, in actual in-cell tests.

Task 2. Single DCFC Testing
This task was performed by SRI.

Subtask 2.1. Design and Fabrication of the DCFC Test System
The design and fabrication of the DCFC system is discussed above.

Subtask 2.2. DCFC Fuel Element Fabrication
SRI fabricated fifteen DCFCs for testing using the candidate materials yttria stabilized zirconia (YSZ) electrolyte and lanthanum strontium manganite (LSM) cathodes and the details are presented above.

Subtask 2.3. Endurance and performance testing of the candidate fuel elements
Single DCFC testing was performed with Gen1 and Gen2 type tube elements to gauge the effect of the above test parameters on performance, endurance, and corrosion and assess the impact of interaction of coal inorganics with DCFC elements and hardware (interconnects). A discussion of the results follows.

PERFORMANCE
DCFC tests were conducted with Galatia (low sulfur and high chlorine) and Freeman (high sulfur and low chlorine) coal samples at temperatures in the range of 600º-700ºC using the 52Li2CO3-48Na2CO3 melt to determine effect of coal type and particle size (40 and 140 microns defined as fine and coarse respectively) on performance. For these tests nickel and silver were employed as baseline anode and cathode current collector materials. In this parametric study (to determine effect of temperature, coal type, particle size and volumetric content of coal fuel in the electrolyte melt) low cost Gen1 type DCFC elements (with thick YSZ electrolyte and designed for operating in the range of 800-900ºC) not optimized for high performance were used to obtain significant information as mentioned above.

Measured I-V data for the two coals (with 30% loading in the melt) is shown in Figure 10 and Table 6 as a function of temperature and particle size. The results indicate that decreasing the operating temperature from 700º to 600ºC reduced the power density by one order of magnitude due to an increase in the area specific resistance (ASR) and the type of coal and particle size did not have a significant effect on power density.
The peak power densities for various volumetric content of Galatia coal are shown in Table 7. Overall, the data indicate that observed peak power density generally increased with the volumetric content of the fuel.

A more advanced thin YSZ-electrolyte-coated Gen 2 type DCFC element was tested next at 775°C with coarse Freeman coal (140 micron particle size) to demonstrate a DCFC power density of greater than 100 mW/cm² on Illinois coal (the goal of this ICCI project). For this test the coal loading was 40% vol in the 52Li2CO3-48Na2CO3 melt and nickel and silver screens were employed as anode and cathode current collectors.

The data shown in Figure 11 indicate that the cell achieved the theoretical open circuit voltage (OCV) of 1 V shortly after the electrolyte was molten at 480°C. The measured I-V and power density data for the coal are shown in Figure 12. The results exhibit a peak power density of 115 mW/cm² and clearly indicate that the DCFC established a power density of greater than 100 mW/cm² thus achieving the set project goal. Also, this power density is comparable to that of commercial molten carbonate fuel cells (MCFCs) and is suitable for developing a clean power generation system for distributed and centralized electricity generation using Illinois coal. The area specific resistance (ASR) was below 3 ohm-cm² at the cell operating temperature of 775°C (Figure 13).

ENDURANCE
DCFC endurance testing was performed with Freeman and Galatia coals at 700°C using Gen1 elements and 52Li2CO3-48Na2CO3 electrolyte. Four DCFCs were tested with fine (40 micron) and coarse (140 micron) coal particle sizes for a duration of 700 hours. The cell voltages during the 700 hour endurance test are shown in Figure 14. The observed cell voltage decay of ~20% can be attributed to the electrolyte (YSZ) degradation and the spatial variation of the coal fuel content in the stagnant system with time.

CORROSION
Corrosion of the electrolyte and interconnect materials is envisioned as a major life limiting factor for DCFCs. Three major factors affecting corrosion may be identified as: (1) composition of the molten salt, (2) level of impurities in coal, and (3) operating temperature. Only YSZ electrolyte material was tested for stability in molten binary carbonate eutectic mixtures. In order to separate corrosive effect of salt from impact of coal impurities, corrosion tests were performed with and without presence of coal in molten salt.

Corrosion effect of the vapor phase (above the melt) containing Freeman coal (Figure 15 a) was found to be less than the one in the case of Galatia coal (Figure 15b). In the case of Freeman coal, there is an orange spot by the top of the tube and two brownish developing cracks above the melt. With Galatia coal, the YSZ tube had a dark brown layer and the cracks.
<table>
<thead>
<tr>
<th>Temp. (°C)</th>
<th>Fuel(Coal)</th>
<th>Atmosphere above the melt</th>
<th>Salt</th>
<th>Test duration, hours</th>
<th>Corrosion rate, µm/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>750</td>
<td>none</td>
<td>CO₂</td>
<td>Li₂CO₃-Na₂CO₃</td>
<td>235</td>
<td>0.018</td>
</tr>
<tr>
<td>750</td>
<td>none</td>
<td>CO₂</td>
<td>Li₂CO₃-K₂CO₃</td>
<td>235</td>
<td>0.010</td>
</tr>
<tr>
<td>750</td>
<td>none</td>
<td>CO₂</td>
<td>Na₂CO₃-K₂CO₃</td>
<td>235</td>
<td>0.064</td>
</tr>
<tr>
<td>800</td>
<td>none</td>
<td>CO₂</td>
<td>Li₂CO₃-Na₂CO₃</td>
<td>235</td>
<td>0.038</td>
</tr>
<tr>
<td>800</td>
<td>none</td>
<td>CO₂</td>
<td>Li₂CO₃-K₂CO₃</td>
<td>235</td>
<td>1.275</td>
</tr>
<tr>
<td>800</td>
<td>none</td>
<td>CO₂</td>
<td>Na₂CO₃-K₂CO₃</td>
<td>235</td>
<td>1.317</td>
</tr>
<tr>
<td>800</td>
<td>CO₂/N₂ 20/80</td>
<td>Li₂CO₃-Na₂CO₃</td>
<td>235</td>
<td>0.032</td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>CO₂/N₂ 20/80</td>
<td>Li₂CO₃-K₂CO₃</td>
<td>235</td>
<td>0.282</td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>CO₂/N₂ 20/80</td>
<td>Na₂CO₃-K₂CO₃</td>
<td>235</td>
<td>0.116</td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>30% Galatia</td>
<td>CO₂</td>
<td>Li₂CO₃-Na₂CO₃</td>
<td>250</td>
<td>0.364</td>
</tr>
<tr>
<td>800</td>
<td>30% Galatia</td>
<td>salt vapor</td>
<td>Li₂CO₃-Na₂CO₃</td>
<td>250</td>
<td>0.262</td>
</tr>
<tr>
<td>700</td>
<td>Freeman fine, 30%vol</td>
<td>CO₂</td>
<td>Li₂CO₃-Na₂CO₃</td>
<td>700</td>
<td>0.025</td>
</tr>
<tr>
<td>700</td>
<td>Freeman coarse, 30*vol</td>
<td>CO₂</td>
<td>Li₂CO₃-Na₂CO₃</td>
<td>700</td>
<td>0.025</td>
</tr>
<tr>
<td>700</td>
<td>Galatia fine, 30%vol</td>
<td>CO₂</td>
<td>Li₂CO₃-Na₂CO₃</td>
<td>700</td>
<td>0.025</td>
</tr>
<tr>
<td>700</td>
<td>Galatia coarse, 30%vol</td>
<td>CO₂</td>
<td>Li₂CO₃-Na₂CO₃</td>
<td>700</td>
<td>0.025</td>
</tr>
<tr>
<td>700</td>
<td>Galatia fine 10%</td>
<td>CO₂</td>
<td>Li₂CO₃-Na₂CO₃</td>
<td>500</td>
<td>0.069</td>
</tr>
<tr>
<td>700</td>
<td>Galatia fine 20%</td>
<td>CO₂</td>
<td>Li₂CO₃-Na₂CO₃</td>
<td>500</td>
<td>0.051</td>
</tr>
<tr>
<td>700</td>
<td>Galatia fine 30%</td>
<td>CO₂</td>
<td>Li₂CO₃-Na₂CO₃</td>
<td>500</td>
<td>0.061</td>
</tr>
<tr>
<td>700</td>
<td>Galatia fine 40%</td>
<td>CO₂</td>
<td>Li₂CO₃-Na₂CO₃</td>
<td>500</td>
<td>0.119</td>
</tr>
</tbody>
</table>
Figure 8. Summary of Corrosion Tests in Tasks 1 and 2.
Figure 9. SEM Analysis of YSZ Samples for Corrosion in Molten Salt After 235 Hours at 750°C (a) and After Hours at 800 °C (b).

Table 5. Examination of YSZ Samples for Corrosion in Molten Salt After 235 Hours at 705 °C and 800 °C.

<table>
<thead>
<tr>
<th>Salt</th>
<th>Corrosion at 750°C</th>
<th>Corrosion at 800°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>50/50 Li₂CO₃/Na₂CO₃</td>
<td>Negligible corrosion if any. No major changes observed in the texture or the smoothness at the inner and outer wall YSZ surfaces</td>
<td>Negligible corrosion if any. No major changes observed in the texture or the smoothness at the inner and outer wall YSZ surfaces</td>
</tr>
<tr>
<td>50/50 Li₂CO₃/K₂CO₃</td>
<td>Negligible corrosion if any. The texture has not changed at the surface of both inner and outer walls.</td>
<td>The tube is brittle. The sample as received was both alumina vessel and YSZ tube cracked. There is not a clear corroded area by the edges on the cross section but the molten salt attacked the tube since we got shattered pieces.</td>
</tr>
<tr>
<td>34/66 Na₂CO₃/K₂CO₃</td>
<td>K diffused in the YSZ although there is no substantial textural change on the cross section</td>
<td>The tube is brittle. The sample as received was both alumina vessel and YSZ tube cracked. There are differences on texture on the cross section but is random and non-uniform thickness of the attacked layer.</td>
</tr>
</tbody>
</table>
Figure 10. DCFC Performance Summary with Gen1 Type Elements as a Function of Temperature, Coal Type, and Particle Size.
Table 6. Absolute Peak Power Densities for Galatia Coal as a Function of Volumetric Content of Fuel in Molten Salt Anode During Initial 100 Hours of Testing.

<table>
<thead>
<tr>
<th>T, C</th>
<th>YSZ 800 micron thick electrolyte, LSM cathode</th>
<th>Cell Area</th>
<th>ASR, ohm-cm²</th>
<th>Peak Power Density, mW/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>Galatia fine</td>
<td>8.7 cm²</td>
<td>358</td>
<td>0.66</td>
</tr>
<tr>
<td>600</td>
<td>Galatia coarse</td>
<td>8.7 cm²</td>
<td>417</td>
<td>0.82</td>
</tr>
<tr>
<td>600</td>
<td>Freeman coarse</td>
<td>8.7 cm²</td>
<td>325</td>
<td>0.82</td>
</tr>
<tr>
<td>650</td>
<td>Galatia fine</td>
<td>8.7 cm²</td>
<td>105</td>
<td>2.89</td>
</tr>
<tr>
<td>650</td>
<td>Galatia coarse</td>
<td>8.7 cm²</td>
<td>101</td>
<td>2.94</td>
</tr>
<tr>
<td>650</td>
<td>Freeman fine</td>
<td>8.7 cm²</td>
<td>61</td>
<td>2.97</td>
</tr>
<tr>
<td>650</td>
<td>Freeman coarse</td>
<td>8.7 cm²</td>
<td>61</td>
<td>4.18</td>
</tr>
<tr>
<td>700</td>
<td>Galatia fine</td>
<td>8.7 cm²</td>
<td>40</td>
<td>6.95</td>
</tr>
<tr>
<td>700</td>
<td>Galatia coarse</td>
<td>8.7 cm²</td>
<td>35</td>
<td>7.45</td>
</tr>
<tr>
<td>700</td>
<td>Freeman fine</td>
<td>8.7 cm²</td>
<td>34</td>
<td>7.84</td>
</tr>
<tr>
<td>700</td>
<td>Freeman coarse</td>
<td>8.7 cm²</td>
<td>27</td>
<td>9.88</td>
</tr>
</tbody>
</table>

Table 7. Absolute Peak Power Densities for Galatia Coal as a Function of Volumetric Content of Fuel in Molten Salt Anode During Initial 100 Hours of Testing.

<table>
<thead>
<tr>
<th>Volumetric content of fuel</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time, h</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4.9</td>
<td>6.4</td>
<td>3.9</td>
<td>6.0</td>
</tr>
<tr>
<td>7</td>
<td>3.0</td>
<td>6.4</td>
<td>4.6</td>
<td>6.4</td>
</tr>
<tr>
<td>10</td>
<td>3.2</td>
<td>5.6</td>
<td>4.6</td>
<td>6.6</td>
</tr>
<tr>
<td>48</td>
<td>3.0</td>
<td>2.3</td>
<td>5.6</td>
<td>5.7</td>
</tr>
<tr>
<td>100</td>
<td>3.1</td>
<td>3.9</td>
<td>8.9</td>
<td>6.2</td>
</tr>
</tbody>
</table>
Figure 11. Voltage and Temperature During DCFC Start Up.

Figure 12. DCFC Performance with Gen 2 Type Element on Freeman Coal at 775 °C.
Figure 13. ASR of the DCFC Tested with Freeman Coal at 775 °C.

Figure 14. DCFC Endurance of Freeman and Galatia Coals at 700 °C with Gen 1 Type Elements.
INTERCONNECTS
Corrosion testing was performed on five anode interconnect (current collector) candidate materials- platinum (Pt), palladium (Pd), Inconel 617, Stainless steel 410 and Hastelloy 276 for use in DCFCs. These were exposed to the 52Li_{2}CO_{3}-48 Na_{2}CO_{3} melt at 700 °C under 100% CO_{2} atmosphere for 250 hours to assess stability. Pure carbon was used as fuel in these tests in order to separate the effect of impurities in the Illinois coals on corrosion and identify best performing materials for use in the envisioned phase 2 work of this project. The nickel employed as the anode interconnect material in the previous long term DCFC tests with Freeman and Galatia coals at 700 °C was found to be unstable and therefore considered not a viable interconnect material. Results are presented below.

Palladium wire was not dissolved in the molten salt. Also, inner texture of cross section remained unchanged after exposure to the melt (Figure 16a). The surface layer had high level of porosity (Figure 16 a and b). The estimated corrosion rate (based on the holes as a consequence of the corroding molten salt) is about 0.219 ± 0.068 µm/h. The samples were found to be extremely brittle. For this reason, Pd was found to be not suitable for anode interconnect.

The platinum wire was not dissolved in the molten salt. The texture of the wire was not changed (Figure 17a). The texture of its surface (Figure 17) is different from that on Pd wire where holes can be seen. In view of this, platinum was found to be suitable as anode interconnect material.
Inconel 617 samples (main components by wt%: 22 Cr; 2 Fe; 12 Co; 52 Ni and 11 Mo) were mostly dissolved in the melt. Therefore, no SEM analyses were performed for these samples.

Coupons made of 410SS (main components are Cr/Fe 12/87 and Al 0.1-0.3 % as minor component) were tested for corrosion. The estimated corrosion rate of $0.355 \pm 0.017 \mu m/h$ was found to be unacceptable. Also a thick surface layer was detected (Figure 18). The outer layer corresponds to Fe (as LiFeO$_2$). The Cr also diffuses out and may form LiCrO$_2$.

Hastelloy 276 wire (main components by wt%: 15 Cr; 6 Fe; 62 Ni and 16 Mo) formed a thick porous surface layer leading to the enlargement of the wire diameter (Figure 19). This material was also found not to be suitable for anode interconnects.
Figure 18. Corrosion analysis of 410SS: SEM (a) and Element Mapping for Na (b), Fe (c), and Cr (d).
Figure 19. Corrosion Analysis of Hastelloy 276: SEM (a) and Element Mapping for Na (b), Fe (c), Cr (d), Mo (e), Co (f), and Ni (g).
INTERACTIONS OF COAL INORGANICS WITH DCFC ELEMENTS AND HARDWARE

Five DCFC post-test samples were subjected to an in-depth analysis for gauging the effect of inorganics contained in the coals tested on the corrosion of YSZ electrolyte. These were from tests conducted with Galatia (low sulfur and high chlorine) and Freeman (high sulfur and low chlorine) coals at 700°C using the 52Li2CO3-48Na2CO3 melt to determine effect of coal type and particle size (40 and 140 microns) on performance. Results showed that the high amount of chlorine (4370 ppmw) in the Galatia coal appeared to have attacked the YSZ electrolyte. The scanning electron microscopy (SEM) image in Figure 20a shows large particles adhering to the electrolyte. The energy dispersive spectra (EDS) presented in Figure 20b indicates that they are sodium chloride (NaCl) particles formed by the reaction of chlorine in the coal with Na2CO3 in the melt.

![Figure 20. a) Adhering NaCl Particles on YSZ Electrolyte Exposed to the Melt Containing Coarse Galatia Goal and b) EDS of the Particles in a) Indicating Na and Cl as Major Elements.](image)

Freeman Coal

Figure 21 is a micrograph of the electrolyte cross section with the edge exposed to the anode (52Li/48Na carbonate containing fine Freeman coal). The corrosion layer did not have a uniform thickness and the corrosion product appears to have penetrated the electrolyte by more than 10 μm deep. The energy dispersive spectra (EDS) of the corrosion product shown in Figure 22 indicates the presence of zirconia (Zr), the major element of the electrolyte, sodium(Na) from the melt and other coal elements such as Al, Si, Mg, Ca, Fe, S, Cl, C and O as contaminants. Obviously, the anode melt and contaminants in the coal have attacked and corroded the electrolyte surface.

Galatia Coal

Figure 23 is a micrograph of the electrolyte cross section with the edge exposed to the anode, which was coarse Galatia coal in 52Li/48Na carbonate melt. The 5-8μm thick corrosion layer has a granular structure similar to that observed for coarse Freeman coal.
The EDS of this layer is shown in Figure 24 and the results are similar to those obtained with fine Freeman coal where the coal contaminants attacked and corroded the electrolyte.

Figure 21. Electrolyte Exposed to the Melt Containing Fine Freeman Coal.

Figure 22. EDS Spectra of the Corrosion Product Shown in Figure 21.
Figure 23. Electrolyte Exposed to the Melt Containing Course Galatia Coal.

Figure 24. EDS of the Corrosion Product Shown in Figure 23.
CONCLUSIONS AND RECOMMENDATIONS

The following observations can be made from the tests, which are reported above:

- Decreasing the operating temperature from 700° to 600°C reduced power density by one order of magnitude.
- Power density generally increased with coal loading in the melt.
- Observed power densities were higher for Freeman coal compared to Galatia due to the lower amounts of inorganics contained in Freeman than in Galatia.
- Above 650°C power density was 32% higher for coarse as compared to fine Freeman coal, an important economic benefit because “as is” pulverized coal may be used as fuel for DCFC without any further fine grinding.
- Endurance testing performed with Freeman and Galatia coals at 700°C for 700 hours lowered initial cell voltages by about 20%. The degradation of the YSZ electrolyte is in part responsible for this and possible maldistribution of the fuel in the melt with time may have also affected cell voltages.
- Corrosion of YSZ is lowest in Li₂CO₃-Na₂CO₃ and highest in Na₂CO₃-K₂CO₃ and therefore Li₂CO₃- Na₂CO₃ was used for all DCFC testing.
- Use of 80% N₂+20% CO₂ instead of pure CO₂ as blanket gas above the melt reduced corrosion rates by one order of magnitude at 800°C for Na₂CO₃-K₂CO₃.
- No effect of blanket gas on corrosion was observed for Li₂CO₃-Na₂CO₃.
- An increase in temperature from 750° to 800°C increased corrosion rates by two times for the Li/Na melt, one order of magnitude for Na/K, and two orders of magnitude for Li/K.
- An increase in temperature from 700° to 800°C increased corrosion rate by six times for Galatia coal with Li/Na.
- Coal particle size had no effect on corrosion.
- Corrosion generally increased with increasing coal loading in the Li/Na.
- The high amount of chlorine (4370 ppmw) in the Galatia coal had an adverse effect on the YSZ corrosion.
- State-of-the-art nickel anode interconnect failed in about 300 hours operation indicating a need for other viable materials.
- Of the five alternate interconnect candidate materials studied (platinum, palladium, Incolloy 617, stainless steel 410 and Hastelloy 276) only platinum was stable in the melt suggesting a need to find other viable and cheaper materials.
- DCFC testing with the Freeman and Galatia coals revealed corrosion of the YSZ electrolyte suggesting an interaction of coal inorganics with the DCFC electrodes and electrolyte.

Since this technology has potential to greatly improve the economics of power production from Illinois coal more DCFC testing in a continuous mode (to facilitate coal feeding and discharge of ash and other inerts) is needed both at single cell and stack levels. This allows an assessment of the mechanisms by which inorganics in the coal interact with the YSZ electrolyte and current collector materials to determine if any coal pretreatment is needed to further improve performance and endurance. Also, scalability of the DCFC system to the initial 10s of kilowatt levels is necessary to demonstrate commercial viability in the megawatt levels needed for economic power production.
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