Solid Oxide Fuel Cell Hybrid System for Distributed Power Generation

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January 2005 to June 2005

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Abstract

This report summarizes the work performed by Hybrid Power Generation Systems, LLC (HPGS) during the January through June 2005 reporting period under Cooperative Agreement DE-FC26-01NT40779 for the U. S. Department of Energy, National Energy Technology Laboratory (DOE/NETL) entitled “Solid Oxide Fuel Cell Hybrid System for Distributed Power Generation”. The main objective of this project is to develop and demonstrate the feasibility of a highly efficient hybrid system integrating a planar Solid Oxide Fuel Cell (SOFC) and a gas turbine. In addition, an activity included in this program focuses on the development of an integrated coal gasification fuel cell (IGFC) system concept based on planar SOFC technology. Also, another activity included in this program focuses on the development of SOFC scale up and stack hybridization strategies.

During this reporting period, further work was performed on analyses of system efficiency improvement opportunities for the integrated gasification fuel cell (IGFC) system. Included in this analyses is work performed by the National Fuel Cell Research Center (NFCRC). To reach 60% efficiency, an IGFC concept could require “revolutionary” performances from an SOFC not under development at this time. Process modifications and improvements were implemented to increase fabrication yields of large area (12” diameter) cells. A set of design of experiments was conducted to correlate process parameters to certain cell properties. From the results obtained to date, it appears that thickness and size were the most significant factors affecting cell surface ripple. Data on root cause analysis strongly suggest that performance loss in large cells is largely an artifact of the test vehicle, and dependent on properties of the cell itself, such as cell size or cell microstructure. Several SOFC stacks built with 6.3” diameter and 12” diameter cells have been tested under hybrid conditions to assess their operating characteristics for hybrid applications. A 3-12” cell stack was tested under pressures up to 60 psia. At 60 psia operating pressure, this stack achieved power density of 0.157 W/cm² at 75% fuel utilization (0.635 V at 0.245 A/cm²) with simulated steam reformate.
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Executive Summary

During this reporting period, further work was performed on analyses of system efficiency improvement opportunities for the integrated gasification fuel cell (IGFC) system. Included in this analyses is work performed by the National Fuel Cell Research Center (NFCRC) on investigating the maximum efficiency of an advanced system reported by NFCRC in the literature; the analyses to date showed an efficiency of ~51%. The GE baseline IGFC system was compared to other concepts identified in the literature, including the NFCRC concept, to identify which system could have the highest potential efficiency. The GE baseline was downselected and a model was created in ASPEN PLUS for the SOFC/Gas Turbine Island to identify key parameters that could result in higher efficiencies. The analyses indicated that if various components, including the SOFC, gas turbine, inverter and system integration, reach a level of performance consistent with what is projected to be the performance entitlement given the success of existing research and development programs, then a system efficiency, with CO₂ isolation of circa-55% is thermodynamically feasible. However, reaching a feasible 60% system efficiency with CO₂ isolation will require significant improvements to the SOFC, beyond what is currently being developed and assumed in the entitlement analysis; even with ‘extreme SOFC’ operating conditions, other constraints could limit the performance estimate to mid to high 50-60% efficiency range. A 60% efficient IGFC concept could require “revolutionary” performances from an SOFC not under development at this time.

In the cell scalability effort, a root cause analysis study was undertaken to identify the reason for lower performance of large cells The potential reasons for the low performance divided into two broad categories: (i) Cell related; and (ii) Stack design and assembly related were evaluated. To isolate the influence of stack design and assembly related issues on performance, two smaller cells (4-3/8” diameter) were laser cut from different areas on a 12.75” cell. The performance of both cells was found to be similar to the performance of standard baseline cells under similar testing conditions and test fixture. Data on root cause analysis strongly suggest that performance loss in large cells is largely an artifact of the test vehicle, and dependent on properties of the cell itself, such as cell size or cell microstructure. Process modifications and improvements were implemented to increase fabrication yields of large area (12” diameter) cells. A set of design of experiments was conducted to correlate process parameters to certain cell properties. From the results obtained to date, it appears that thickness and size were the most significant factors affecting cell surface ripple.

Several SOFC stacks built with 6.3” diameter and 12” diameter cells have been tested under hybrid conditions to assess their operating characteristics for hybrid applications. A 5-cell (6.3”) radial stack achieved power density of 281 mW/cm² (0.588 V @
0.479A/cm²) with 64% H₂, 70% fuel utilization at 800°C under ambient pressure, The
test of this stack under pressure was terminated due to swing in differential pressure
between anode and cathode during stack pressurization. Two 3-12" cell stacks were
tested under pressures up to 60 psia. In addition to pressure, effects of fuel
composition and fuel utilization were also investigated. At 60 psia operating pressure,
one of the stacks achieved power density of 0.157 W/cm² at 75% fuel utilization (0.635
V at 0.245 A/cm²) with simulated steam reformate

Experimental
All experimental work currently performed on the program is conducted under Tasks 2.4
and 2.5. The test procedures and the test methods used to perform the experimental
work for these tasks have been described in previous semiannual reports and in
Sections 2 and 3.

Results and Discussion
1 TASK 1A.5 – IGFC SYSTEM EFFICIENCY IMPROVEMENT STUDY
1.1 Scope and Objective

In 2003 the performance and economics of power generation systems based on SOFC
technology and fueled by gasified coal were analyzed as part of task 1A.4. Two
alternative system configurations were selected in the task that integrated a coal gasifier
with an SOFC, a gas turbine, and a steam turbine. Such systems are referred to as
Integrated Gasified Fuel Cell (IGFC) systems. The two down-selected systems were
projected to have system efficiency of approximately 53% on an HHV basis or
approximately 10 percentage points higher than that of state-of-the-art Integrated
Gasification Combined Cycle (IGCC) systems. While the study showed great promise
for coal-based fuel cell hybrid systems, it assumed currently available gasifier, gas
turbine, and balance-of-plant technology. There are potentially substantial system
efficiency gains that can be realized if advanced technologies, currently in the
conceptual phase or under development, are employed.

Under the current subtask, the IGFC system design as had been created in the original
study is to be used as a starting point to evaluate the potential areas for system
efficiency improvements with the objective of achieving a feasible system with a 60%
system efficiency (AC power/Coal HHV) including carbon dioxide isolation. In addition,
two specific tasks included in this study are to identify opportunities to incorporate Ion-
Transfer Membrane (ITM) and mid-range gas clean-up technology in the IGFC system
design and evaluate their impact on system efficiency and cost.
1.2 Original IGFC Study

A summary of the original IGFC study was given in the July-December 2004 Semi-Annual Report (Ref. 1). It was pointed out in that report that three IGFC concepts were of particular interest:

- Concept A: IGFC Using Cathode Air Recycle, no CO₂ Isolation
- Concept B: IGFC Using Cathode Air Recycle, CO₂ Isolation Using Anode Recycle with Selexol:
- Concept C: IGFC Using Cathode Air Recycle, CO₂ Isolation Using Pure-O₂ Anode Effluent Combustion

These concepts were considered to select the baseline system for the IGFC Extension Study.

1.3 Baseline System for IGFC Extension Study

As described in the July-December 2004 Semi-Annual report, Concept C had been chosen as the baseline (BASELINE-1)

As noted in the July-December 2004 Semi-Annual Report, slight operational modifications (operational pressure and number of stages) to the baseline from that presented in the original January 2004 topical report were made. The improved baseline system efficiency is 52.8%.

1.3.1 Performance Assumptions

Assumptions used for the baseline performance were given in the July-December 2004 Semi-Annual Report to include the following:

- Coal, ash, limestone and bitumen compositions
- Gasification/air separation unit (ASU)/Cleanup
- SOFC/Gas Turbine:
- Heat recovery steam generator (HRSG)/steam turbine (ST)

1.3.2 System Efficiency Sensitivity Analysis

Sensitivity of system efficiency to various operating parameters were presented in the July-December 2005 Semi-Annual Report for the following parameters as shown in Table 1
Table 1 Parameters Included in Sensitivity Analyses on Baseline and Prior Study Concepts

<table>
<thead>
<tr>
<th>BASELINE &amp; PRIOR STUDY CONCEPTS</th>
<th>GASIFIER</th>
<th>SOFC</th>
<th>CO2 ISOLATION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Increases in CH4 Yield from Gasifier</td>
<td>Operating Pressure</td>
<td>Fuel utilization</td>
</tr>
<tr>
<td>Prior Study Concept A: IGFC Using Cathode Air Recycle, no CO2 Isolation</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Prior Study Concept B: IGFC Using Cathode Air Recycle, CO2 Isolation Using Anode Recycle with Selexol</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>BASELINE (=Prior Study Concept C: IGFC Using Cathode Air Recycle, CO2 Isolation Using Pure-O2 Anode Effluent Combustion)</td>
<td>x</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1.3.3 Baseline System Rough-Order-of-Magnitude (ROM) Type Cost Estimate Analysis

As the tasks require an estimate of the effects on the baseline system costs, a ROM-type cost estimate was created. The costs of the various islands are shown in Table 2

Table 2  IGFC Extension Study ROM Cost Estimate

<table>
<thead>
<tr>
<th>IGFC EXTENSION STUDY ROM-TYPE COST ESTIMATE</th>
<th>286</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Plant Power (MW)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>IGFC BASELINE ISLAND SUBSYSTEM</th>
<th>Cost (2004, $million)</th>
<th>Cost, $/kW net power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasifier/Air Separation Island</td>
<td>$224</td>
<td>$783</td>
</tr>
<tr>
<td>SOFC/GT Island</td>
<td>$115</td>
<td>$401</td>
</tr>
<tr>
<td>HRSG/ Steam Turbine Island</td>
<td>$33</td>
<td>$168</td>
</tr>
<tr>
<td>CO2 Isolation</td>
<td>$4</td>
<td>$13</td>
</tr>
<tr>
<td>TOTAL on-site cost</td>
<td>$375</td>
<td>$1,313</td>
</tr>
<tr>
<td>TOTALoff-site cost</td>
<td>$113</td>
<td>$394</td>
</tr>
<tr>
<td>TOTALCOST</td>
<td>$488</td>
<td>$1,706</td>
</tr>
</tbody>
</table>

The cost methodology for various components of the islands was based on a size scaling relationship as shown here:

\[ \text{Cost} = \text{Cost }_{\text{ref}} \times \left( \frac{\text{Duty }_x}{\text{Duty }_{\text{ref}}} \right)^N \times CPI \_factor \]

Where

- Cost_ref is a cost value from the literature or generated by GE
• Duty_ref is the size of the referenced unit
• Duty_x is the size of the component or unit being costed
• N is an appropriate cost scaling exponent, usually = 0.7
• CPI_factor is an adjustment to equate costs taken from different years to 2004$ using a Consumer Price Index calculator (Ref. 3)

Costs for the Gasification and Air Separation Island were taken from the literature using a BGL gasification system as described above (Ref. 4) and a previous GE report (Ref. 2).

Costs for the SOFC/GT island were based on a recent study by GE for DOE (Ref. 5) and commercial catalogues. The gas turbine was cost was estimated based on a modified ‘F class’ GE turbine. Some heat exchangers were based on GE cost data (Ref. 6).

Costs for the HRSG/and ST island were based on literature values (Ref. 7) for size ranges similar to this study.

It should be emphasized that the ROM estimate given here was performed for the purpose of completing Tasks 1 and 2 where technologies are inserted into the baseline IGFC concept and a performance and cost impact determined.

1.4 IGFC Extension Study Subtasks

Specific subtasks to be completed in the current study include:

• Subtask 1: Impact of Ion-Transfer Membrane (ITM) on the System Efficiency and Cost: Opportunities to incorporate an ITM into the IGFC system design are to be identified, including options in the gasifier, the fuel cell and the gas turbine subsystems. System analyses are to be performed to quantify effects of introducing an ITM into the baseline IGFC on the system efficiency and cost.

• Subtask 2: Impact of Mid-Range Gas Cleanup on the System Efficiency and Cost: Opportunities to incorporate a mid-range gas cleanup subsystem into the IGFC system design are to be identified. The effects on the system efficiency and cost are to be estimated.

• Subtask 3: Analyses of System Efficiency Improvement Opportunities: Brainstorming is to be performed to identify ideas to improve the system efficiency. Both cycle-level and component level opportunities shall be included. Analyses to quantify these improvements shall be conducted. Recommendations for any necessary future technology improvement efforts shall be made. In addition, impacts on the system cost shall be analyzed.
• **Subtask 4: Impact of Carbon Dioxide Separation**: As the systems to be identified will include CO₂ isolation, the impact of the CO₂ separation on the system efficiency on the down-selected systems will be evaluated.

1.4.1 **Subtask 1: Impact of Ion Transport Membrane (ITM) on System Efficiency and Cost**

ITM performance and costs estimates are based on public literature and telephone conversations with the developer, Air Products; references were provided in the July-December 2004 Semi Annual Report in addition to the following:

- ITM Technology Characteristics:
  - Technology description, testing, and costs
- ITM IGFC Concept Configurations
- ITM Impact on System Efficiency: the best configuration (referred to as B2) increased the system efficiency to 53.5%

1.4.2 **Subtask 2: Impact of Mid-Range Gas Cleanup on System Efficiency and Cost**

Mid-range gas cleanup effects to performance and costs estimates are based on public literature and telephone conversations with the developer, RTI; references were provided in the July-December 2004 Semi Annual Report in addition to the following:

- Technology Characteristics:
  - Technology description, testing, costs, and sulfur recovery options and chemistry
- Mid-Range Gas Cleanup Concept Configurations
- Mid-Range Gas Cleanup Impact on System Efficiency: perhaps 0.2% efficiency increase could be realized; in some configurations, depending on sulfur recovery options and tar removal, the efficiency impact could be negative
- ITM Impact on Cost: not enough information to assess the impact.

1.4.3 **Subtask 3: Analysis of System Efficiency Improvements**

From the July-December 2004 Semi-Annual Report, it was shown that the baseline efficiency could be improved to 53.5% using ITM and perhaps 0.2% from the mid-range gas cleanup processes. Analyses also was shown that the total power generators before subtracting any of the power consumers only adds up to 56%, well below the target 60% efficiency. Hence, for this configuration to reach 60%, the efficiency of the generators would have to be improved significantly.
1.4.3.1 Entitlement Analysis for Baseline Configuration with ITM and Mid-Range Gas Cleanup

An “entitlement analysis” was provided in the July-December 2004 Semi-Annual Report as a means to estimate which selected processes may possibly be improved to affect an overall improvement in the system efficiency. “Entitlement” is a term that implies the maximum possible benefits from engineering and/or technical developments. The following were analyzed that could provide efficiency gains:

- Gasifier entitlement
- Sulfur Removal entitlement
- Oxygen Plant entitlement
- Turbine/Compressor entitlement
- SOFC Power Conversion entitlement
- Fuel Cell Operating Voltage entitlement

The results from the top-level entitlement analysis presented in the previous Semi-Annual Report noted that if the above effects were all realized, and were additive, a 56.3% efficiency might be possible. Hence, given the technologies under development and upper performance estimates form the entitlement analysis, a mid-50% efficiency for the baseline configuration is possible.

1.4.3.2 Brainstorm

Brainstorm was initiated with the objective of generating ideas that would lead to systems with 60% system efficiency within the technologies’ entitlement and feasibility. The problem statement for this brainstorming was as follows:

- Identify technologies which, if developed to their entitlement, can be implemented in an IGFC system and can significantly (>1%) improve the overall system efficiency
- Identify an IGFC system configuration that, if all incorporated technologies are developed to their entitlements’, could be shown by analysis to result in a 60% system efficiency

Several technologies were identified that, if inserted into an IGFC system could have potential efficiency gains to include:

- The use of GE’s Unmixed Fuel Processor (UFP) for coal-based H₂ production in a IGFC configuration (Ref. 8)
- The use of a mid-temperature membrane to separate CO₂ from a H₂ rich stream
• The use of a gasifier designed for higher CH₄ yield, such as a BI-GAS gasifier previously under development by DOE (Ref. 9)

• An intercooler is added to air compressor of the gas turbine to reduce air compression power and potentially increase system efficiency

• Pure or diluted oxygen is added directly into the SOFC; this can improve the cathode voltage performance

• An electrically driven ITM is used to help reduce compression power required to feed pressurized air to the ITM

• Natural gas is added to the anode feed stream of the SOFC to increase the cooling effect via internal reforming SOFC; natural gas may be available as coal bed methane

• Methanation of the gasifier syngas prior to feed to the SOFC

The effects of incorporating these technology ideas in an IGFC concept were not completed in the study.

Several concepts reported in the literature were presented in the July-December 2004 Semi-Annual Report. A summary of these concepts is given in Table 3.
<table>
<thead>
<tr>
<th>LITERATURE STUDY</th>
<th>REF. #</th>
<th>CO2 ISOLATION</th>
<th>EFFICIENCY, HHV</th>
<th>NOTES/FEATURES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluor for EPRI</td>
<td>11</td>
<td>No</td>
<td>48%</td>
<td>Texaco gasifier, SOFC @ 200 psia</td>
</tr>
<tr>
<td>Dartmouth College for EPRI</td>
<td>12</td>
<td>No</td>
<td>63%</td>
<td>Air blown 2 stage CO2 Acceptor gasifier, High-Temperature S removal, air recycle (gasifier/fuel cell) system</td>
</tr>
<tr>
<td>UCI for DOE 'Vision 21'</td>
<td>13</td>
<td>No</td>
<td>60.1</td>
<td>Air-blown ATR gasifier, warm-gas cleanup, advanced sulfator system, 19 bar SOFC</td>
</tr>
<tr>
<td>UCI for DOE 'Vision 21'</td>
<td>13</td>
<td>Yes</td>
<td>49.6</td>
<td>O2-blown ATR gasifier, warm-gas cleanup, advanced sulfator system, 19 bar SOFC, CO2 isolated at 140 bar; with CO2 isolated &amp; improved performances of SOFC, efficiency could reach ~ 55%</td>
</tr>
<tr>
<td>Fuel Cell Handbook</td>
<td>14</td>
<td>No</td>
<td>59.7</td>
<td>Hi-cold gas eff. Gasifier, mid-T gas cleanup, 2-stage seal-less SOFC</td>
</tr>
<tr>
<td>Columbia University</td>
<td>15,16</td>
<td>Yes</td>
<td>~ 60%</td>
<td>Hydrogasification, very high SOFC operating temperatures; study evolving</td>
</tr>
<tr>
<td>NETL advanced fossil power system study</td>
<td>17</td>
<td>No</td>
<td>54.4</td>
<td>Destec gasifier, Hot gas cleanup w H2SO4 byproduct, air compressor/cryo ASU integration, gas turbine fired to &gt;2000 F w/ SOFC bypass fuel gas</td>
</tr>
<tr>
<td>NETL advanced fossil power system study</td>
<td>17</td>
<td>Yes</td>
<td>47.9</td>
<td>Destec gasifier, Hot gas cleanup w H2SO4 byproduct, cryo ASU, gas turbine fired to &gt;2000 F w/ SOFC bypass fuel gas, CO2 pumped to 3000 psi</td>
</tr>
<tr>
<td>NETL advanced fossil power system study</td>
<td>17</td>
<td>No</td>
<td>55</td>
<td>Destec gasifier, low T (Rectisol) gas cleanup w S byproduct, SOFC w/ OTM ASU integration, gas turbine fired to &gt;2000 F w/ SOFC bypass fuel gas</td>
</tr>
</tbody>
</table>
**Conventional State-of-the-Art Entrained Bed Gasifiers:** Entrained-bed coal gasifiers that are considered ready for use in an integrated gasification combined cycle plant (IGCC) today would include the following:

- GE (formerly ChevronTexaco)
- E-Gas (or Destec, Conoco-Phillips)
- Shell

Studies by DOE (Ref. 10) have indicated in an IGCC plant, the system efficiencies range in the low- to mid-forty-percent efficiency range (HHV coal to AC power) assuming cold-gas cleanup technology is used. A top-level analysis was performed replacing the BGL gasifier with a GE (Texaco) entrained bed gasifier, assuming similar baseline components downstream of the gasification/cleanup systems are employed. The analysis also assumed the inclusion of ITM technology to generate oxygen. The system efficiency is estimated to be slightly lower than 50%. The analysis results are represented in Figure 1 where intermediate efficiency conversions are illustrated.

**GE (ChevronTexaco) Gasifier**

![Diagram of GE (ChevronTexaco) Gasifier]

**Figure 1 Top-level Efficiency Analysis of Impact of Using Conventional Entrained Bed Gasifier in an IGFC System**

1.4.3.3 System Concept Down Selection

The most promising concepts were compared to the improved baseline and rated using a six-sigma tool, a Pugh matrix. The concepts considered are listed in Table 4.
Table 4 IGFC System Configuration Concepts Considered

<table>
<thead>
<tr>
<th>CONCEPT ID</th>
<th>IGFC CONCEPT/STUDY</th>
<th>Gasifier</th>
<th>Clean Up</th>
<th>Gas Turbine</th>
<th>SOFC</th>
<th>HRSG/ST</th>
<th>CO2 Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL</td>
<td>Improved Baseline</td>
<td>Tex</td>
<td>cold</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Fluor EPRI Study</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Dartmouth Study</td>
<td>CO2 Ac</td>
<td>Hi</td>
<td>small</td>
<td>sealed</td>
<td>conv small</td>
<td>none</td>
</tr>
<tr>
<td>3</td>
<td>UC1 Vision 2i - CO2 capture</td>
<td>ATR</td>
<td>Mid-T</td>
<td>conv</td>
<td>sealed</td>
<td>conv small</td>
<td>H2/CO2 sep</td>
</tr>
<tr>
<td>4</td>
<td>FC Handbook</td>
<td>DESTEC</td>
<td>Tran bed/Mid-T</td>
<td>2-stage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Columbia University</td>
<td>Hydrogas</td>
<td>non-conv</td>
<td>not defined</td>
<td>very H1</td>
<td>not defined</td>
<td>not defined</td>
</tr>
<tr>
<td>6</td>
<td>METL study</td>
<td>DESTEC</td>
<td>mid-T</td>
<td>Conv</td>
<td></td>
<td></td>
<td>H2/CO2 sep</td>
</tr>
</tbody>
</table>

Criteria to compare against the baseline were determined based on judgments as to what conceptual design would have the best chance of creating a feasible system with a 60% efficiency within the resources of this study. From the comparison, none of the other concepts had a positive rating when compared to the baseline.

1.4.3.4 Model Development

To further evaluate the down selected concept, a top-level model was to be developed using ASPEN PLUS for use in evaluating improvements to the baseline system configuration. As the entitlement analysis above indicated that he 60% system efficiency would not be achieved, further improvements of the fuel cell and other components would be investigated using this model. The model would have the following features:

- One model, from coal input to power output
- Top-level, island block approach
  - Gasifier island: use ASPEN’s coal based input feature; simplify island to give cold gas yield as feed to SOFC/GT island
  - SOFC/GT island: use as appropriate SOFC and GT island as modeled in previous IGFC study
- HRSG/ST: simplify HRSG/steam cycle as required
  - Verify performance assumptions using GateCycle
- As a minimum, the input parameters to the model would include
  - Coal gasification / clean up island:
    - Coal composition
    - Pressure
    - Oxygen/coal ratio
- Steam/coal ratio
- Coal feed rate
- Bitumen feed rate

- SOFC/GT
  - SOFC pressure, temperature, SOFC fuel utilization
  - Average cell voltage
  - Air feed rate
  - Inverter efficiency
  - Compressor/ turbine efficiencies

- HRSG/ST island
  - Steam extraction conditions
  - Exhaust temperature
  - Steam turbine efficiencies

At the end of the study, preliminary models had been constructed for the following:
- Coal gasification/clean up island in ASPEN
- SOFC/GT island in ASPEN
- HRSG/ST island in GateCycle

However, further work to validate the models and combine them into one overall system model would have been completed if the study had been completed as initially planned.

1.4.3.5 Thermodynamic Feasible System Efficiency Discussion
The achievement of a feasible 60% efficiency system requires significant performance improvements of technologies in the baseline configuration. From the entitlement analyses, the baseline configuration with improvements as noted above could result in a system reaching circa-55% efficiency. As the entitlement analysis was constrained to experts opinions as to what would be achieved given the present understanding of technology development, the next step would be to assume technology performances that would be considered extreme, yet thermodynamically feasible, compared to those assumed in the entitlement analysis. The following parameters were to be considered

SOFC:
Increase fuel utilization
Increase delta-T
Increase temperature:
Increase voltage:
Combination of all four

Gasifier
Higher pressure, increased CH₄ yield
Lower steam to syngas saturation
Lower oxygen/coal feed ratio

Others
Inverter efficiency increase
Decrease HRSG exhaust gas temperature

The integrated model would have been used to show the interactions and maximum feasible efficiency of the down selected system. However, the SOFC/GT island model, developed to model the SOFC/GT and HRSG/ST outputs for a system without CO₂ removal and without the use of the ITM technology, is used here to show some of the effects of performance variables that could indicate possible efficiency gains with extreme performances. While the system modeled is not the baseline system described above, it is modeled to be identical in configuration to that described in the previous study (ref. 1) as the Cathode Recycle, no CO₂ isolation. The parameters, system efficiency gains, sensitivities and constraints are noted in Table 5. As noted, a 'calculated' system efficiency of over 60%, without CO₂ isolation, is shown; however, further constraint analysis is required to insure the thermodynamic feasibility of such a system.

Analysis of the baseline CO₂ isolation system as indicated in the preliminary sensitivity analysis above with extreme conditions has not been done.

Key to the thermodynamic feasibility of an IGFC system is the feasibility of the SOFC performance when extreme conditions are assumed as noted above. An Area Specific Resistance (ASR) entitlement analysis addresses part of the thermodynamic constraints
### Table 5 Baseline Sensitivity Analyses

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>X VALUE PERTURBATION</th>
<th>Y VALUE RESPONSE (Note 1)</th>
<th>PARAMETER CHANGE TO EFFECT 1% SYSTEM EFFICIENCY INCREASE</th>
<th>CONSTRAINTS /NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverter efficiency increase</td>
<td>efficiency</td>
<td>0.96 0.98</td>
<td>0.5449 0.028</td>
<td>Inverter for large SOFC devices max TBD</td>
</tr>
<tr>
<td>Fuel utilization increase</td>
<td>fraction</td>
<td>0.8 0.95</td>
<td>0.5610 0.064</td>
<td>Upper fuel utilization &amp; anode stabilization</td>
</tr>
<tr>
<td>Cell voltage increase</td>
<td>voltage</td>
<td>0.7 0.85</td>
<td>0.5644 0.056</td>
<td>Low power density for economic system</td>
</tr>
<tr>
<td>Air flow to air compressor decrease</td>
<td>lb/sec</td>
<td>485.334859 300</td>
<td>0.5462 -218</td>
<td>High cell delta T and operating T</td>
</tr>
<tr>
<td>HRSG exhaust temperature decrease</td>
<td>deg F</td>
<td>250 150</td>
<td>0.5510 -75</td>
<td>Low temperature steam generation &amp; low exhaust dew point</td>
</tr>
<tr>
<td>Mid-point (x1+x2)/2</td>
<td>-- X1</td>
<td>(X1+X2)/2</td>
<td>0.5790 --</td>
<td>Combination of all above constraints &amp; interactive effects</td>
</tr>
<tr>
<td>Best value X</td>
<td>-- X1</td>
<td>X2 for all</td>
<td>0.6315 (Note 2)</td>
<td>Voltage &gt; Exit Nernst; case not possible thermodynamically!</td>
</tr>
<tr>
<td>Exit Nernst voltag constraint</td>
<td>-- X1</td>
<td>X2 for all; volt = 0.79</td>
<td>0.6186 --</td>
<td>Constraints TBD (Note 3)</td>
</tr>
</tbody>
</table>

**NOTES**

1. Y1 for all x perturbations = 0.5377
2. Cell voltage assumed = 0.85 not possible as exit Nernst calculated for conditions = 0.79 volts
3. Constraints as noted above may limit predicted efficiency
of an SOFC system on a cell level and will be presented here. Other thermodynamic constraints, for example on a stack and a module level, are not presented here.

ASR is used in SOFC technology comparisons to report the sum of the resistances in a cell. The total ASR (include both ohmic and non-ohmic resistance) of a cell with current density of \( i \) at the operating voltage \( V_{op} \) may be defined as

\[
ASR = \frac{E - V_{op}}{i}
\]

Where \( E \) is the Nernst potential for the given fuel composition, current density and fuel utilization.

The Nernst potential \( E \) is defined as

\[
E = RT \frac{RT}{4F} \ln \left( \frac{P_{O_2(c)}}{P_{O_2(a)}} \right)
\]

Where \( R \) is the gas constant, \( F \) the Faraday constant, and \( P_{O_2(c)} \) and \( P_{O_2(a)} \) are the equilibrium oxygen partial pressures in cathode and anode streams, respectively. \( P_{O_2(c)} \) and \( P_{O_2(a)} \) often vary with the operating conditions and location within the stack. Ideally, the proper calculation requires knowing local \( E \) and \( i \), however, an arithmetic average value is adequate in practice. Thus the apparent \( ASR \) value in practice can be estimated as

\[
ASR \approx \frac{0.5(E_{in} + E_{out}) - V_{op}}{i}
\]

Where \( E_{in} \) and \( E_{out} \) are Nernst potentials with inlet and outlet stream compositions, \( i \) is average current density.

For purposes discussion and comparison, ASR can be viewed as expressing the slope of the voltage vs. current density (VI) curve, as if it were linear. While the ASR analysis is obviously an over simplification of the VI curve (as the VI curve is non-linear), it is, nevertheless, very useful for comparisons, and, in this report, for SOFC entitlement and feasibility analysis.

For this ASR analysis, the following assumptions are made:

- An ASR in the 0.2 to 0.3 ohm-cm\(^2\) is feasible
• A cell performs at the same voltage from inlet to outlet; hence, it can be limited by the gas compositions at the outlet of the cell

• The temperature used to calculate the inlet Nernst potential for the anode and cathode streams is identical; likewise, the temperature of the exit anode and cathode streams is assumed to be identical

Figure 2 is given here to illustrate the Nernst theoretical constraints that an SOFC would experience if very high fuel and oxygen utilisations (95% fuel and 75% oxygen utilization). The limiting Nernst potential for the baseline system is shown to be about 0.9 volts; for the very high utilization case, the limiting Nernst is shown to be about 0.8 volts. Hence, the case shown in Figure 2 where all the best values for the perturbed values given is not thermodynamically possible. However, if the voltage can be operated near its maximum thermodynamic Nernst constraint, an efficiency of near 60% may be possible as shown in Table xxx; however, other constraints, not fully analyzed here, may have been exceeded. Note also, this calculation did not include CO2 isolation.

Nevertheless, if a high voltage, approaching 0.8 volts, and an ASR in the entitlement range of 0.2 to 0.25 ohm-cm² can be achieved, system efficiencies in the circa 55-60% range may be possible, with further constraint analysis, for the system configuration identified in this report. Note that with an ASR of 0.25 as shown in the plot, voltages circa 0.75 to 0.8 may be possible at current densities of 0.4 A/cm²; the power densities this would represent, in the 0.3 w/cm² range, is not far below present targets of 300 w/cm² for SECA Phase I.

![Figure 2 Example of Exit Nernst Constraints to Extreme SOFC Operating Conditions](image-url)
1.4.3.6 UC Irvine Tasks Supporting IGFC Extension Study

UCI tasks in support of the IGFC Extension study and status are listed in Table 6

Table 6 NFCRC Tasks Supporting IGFC Extension Study

<table>
<thead>
<tr>
<th>NFCRC TASKS SUPPORTING IGFC EXTENSION STUDY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task #</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>1</td>
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<tr>
<td>2</td>
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<td>8</td>
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<td>9</td>
</tr>
</tbody>
</table>

NFCRC Task 1 SUMMARY: Conduct a detailed review/seminar at HPGS on Advanced IGFC Concepts

The purpose of this task was for NFCR to review with HPGS all FutureGen and Vision 21 IGFC analyses to date performed for DOE. This task will support the brainstorming of system concepts for GE's IGFC project.

IGFC concepts presented are listed in Table 7:

Table 7 NFCRC IGFC Concepts
<table>
<thead>
<tr>
<th>IGFC CONCEPT</th>
<th>GASIFIER</th>
<th>AIR SEP PLANT</th>
<th>SULFUR CLEANUP</th>
<th>SOFC</th>
<th>STEM GEN LEVELS</th>
<th>CO2 ISOLATION</th>
<th>SYSTEM EFFICIENCY (% of HHV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adv. Technology, Power Only</td>
<td>Air blown ATR</td>
<td>none</td>
<td><strong>Warm gas(on syngas)</strong> * Sulfator (on char)</td>
<td>18</td>
<td>1000</td>
<td>0.75</td>
<td>0.85</td>
</tr>
<tr>
<td>Adv. Technology, Zero emission</td>
<td>O2 blown ATR</td>
<td>Combustor/ITM</td>
<td><strong>Warm gas(on syngas)</strong> * Sulfator (on sulfur in char)</td>
<td>18</td>
<td>1000</td>
<td>0.75</td>
<td>0.85</td>
</tr>
<tr>
<td>Zero emission, IGCC</td>
<td>O2, Entrained</td>
<td>Cryogenic</td>
<td>Low T</td>
<td>None</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**NOTES**
1. ATR = Advanced transport reactor under development by DOE
2. ITM = Ion transport membrane

In addition to system concepts, gasification and gas treating characteristics were presented.

Of the advanced technology developments, several were identified as follows:

- Warm (300-400°C) Gas Cleanup (Syngas Suitable for Fuel Cells)
- Ionic Membrane Separation of Air
- Lower Temp ATR Gasifier while Maintaining High Carbon Conversion
- High Temp Shift / Membrane Separation of H₂ for Zero Emission Plant
- Separate Anode / Cathode Exhausts for Zero Emission
NFCRC Task 2 SUMMARY: Verify component models used in Advanced Power Systems Analyses Tools (APSAT) by UCI and ASPEN by HPGS agree

The purpose of this task was to insure several component parameters and models used by NFCRC and HPGS are consistent. The comparison between the two simulation tools was done by selecting the following individual critical components: Compressor, Expander, Reformer, SOFC / Exhaust Gas Combustor System and Heat Exchanger. The results compared well with the compressor, expander, reformer, and the combined SOFC/exhaust gas combustor. For the heat exchangers, simulated as steam generators, there was some discrepancy depending on how the results were interpreted. This is an area where results between the two simulation tools must be carefully compared.

In addition, this task was useful in that SOFC performance parameters, for example stack delta-T rise, needed to be clearly defined so that the use of SOFC parameters were consistent between HPGS and NFCRC.

NFCRC Task 3 SUMMARY: Run ad-hoc sensitivity analyses based on NFCRC IGFC concepts as modeled in APSAT

The purpose of this task was to establish sensitivities of selected technologies to important assumptions for use as screening concepts. This will support the analysis of system efficiency improvement opportunities as stated in the statement of work for GE’s IGFC project.

The baseline ‘Zero Emission, Hybrid’ concept was chosen from which sensitivities would be run. This system, which resulted in 49.6% system efficiency, includes the following advanced technologies and/or novel concepts:

- Oxygen-blown ATR
- Ion Transport Membrane (ITM for gasifier oxygen)
- Warm Gas Clean Up
- Shift and High-Temperature H\textsubscript{2} membrane separator
- SOFC (anode/cathode exit gases separated leaving SOFC block)
- Sulfator to capture warm gas cleanup regenerator off gases in limestone/char
- Methanation reactor before syngas expander
- Steam generated for gasifier via evaporation of condensate by direct contact with O\textsubscript{2} (produced from ITM) in a humidifier
- CO\textsubscript{2} isolation and compression to 140 bars

A summary of sensitivity results are presented in Table 8

Table 8  NFCRC IGFC Concept Sensitivity Analysis
<table>
<thead>
<tr>
<th>PARAMETER (x)</th>
<th>X VALUE PERTURBATION</th>
<th>Y VALUE RESPONSE (system efficiency)</th>
<th>PARAMETER CHANGE TO EFFECT 1% SYSTEM EFFICIENCY INCREASE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UOM</td>
<td>X1</td>
<td>Xb1</td>
</tr>
<tr>
<td>System and/or SOFC operating pressure</td>
<td>bar</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>SOFC average cell voltage</td>
<td>volts/cell</td>
<td>0.65</td>
<td>0.75</td>
</tr>
<tr>
<td>SOFC Fuel utilization (per pass)</td>
<td>fr</td>
<td>0.8</td>
<td>0.85</td>
</tr>
<tr>
<td>SOFC Oxygen utilization (1/stoich ratio/Fuel)</td>
<td>fr</td>
<td>0.24</td>
<td>0.425</td>
</tr>
<tr>
<td>ATR carbon conversion</td>
<td>fr</td>
<td>0.9</td>
<td>0.95</td>
</tr>
<tr>
<td>ATR oxygen use (O2/coal ratio)</td>
<td>fr</td>
<td>0.46</td>
<td>0.56</td>
</tr>
<tr>
<td>CO2 isolation pressure</td>
<td>bar</td>
<td>14.66</td>
<td>140</td>
</tr>
<tr>
<td>Compressor efficiency (isentropic)</td>
<td>eff</td>
<td>0.84</td>
<td>0.88</td>
</tr>
<tr>
<td>Expander efficiency (isentropic)</td>
<td>eff</td>
<td>0.88</td>
<td>0.93</td>
</tr>
<tr>
<td>Inverter efficiency</td>
<td>eff</td>
<td>0.94</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Compared to the HPGS configuration, sensitivities are similar for cell voltage, fuel utilization and inverter efficiency; significant differences exist for the pressure, oxygen utilization, and CO₂ isolation pressure.

An interesting trend was found for the system pressure. From 10 to 12 atm, the effect is quite severe, showing an influence coefficient (the parameter change required to effect a 1% system efficiency change) of 0.52; from 12 to 12, the value increases to 267. This is primarily due to the requirements of the ITM in generating oxygen. As the operating pressure of the system decreases below 13 atm, fuel is required to heat the ITM feed gas to the required operating temperature. At higher pressures, the ITM operates more efficiently and requires less air, and therefore less heat to get the ITM incoming feed air to the ITM operating temperature (~ 700°C). While the NFRC concept takes SOFC air as the feed to the ITM, the stream is relatively cool for an SOFC exhaust stream as it is used to preheat incoming air to the SOFC (similar to the Siemens-Westinghouse SOFC tube-within-a-tube air preheater).

**NFCRC Task 4 SUMMARY:** Determine what effect Pittsburgh #8 and Illinois #6 coals have to BGL gasifier yields

Many DOE studies are based on Illinois No. 6 coal. The coal used for this IGFC study, Pittsburgh No. 8 coal, has a slightly higher heating value and other properties. In order to give an indication of what the effects could be if Illinois 6 coal were chosen as the feed to the IGFC, NFCRC looked at the literature available. An EPRI report (GS-7091) was available that reported test results for various coals. The Illinois No. 6 coal demonstrated a performance similar to the Pittsburgh No. 8 coal. However, its caking and swelling properties limited the gasifier throughput and the amount of fines allowed in the coal feed. However, the fines could be palletized as done in the EPRI report used as a basis for the gasification/cleanup island. While gas compositions were similar, the cold gas efficiency of the Pittsburgh 8 coal was 2-3% higher than the Illinois 6 coal.
NFCRC Task 5 SUMMARY: Review/suggest methods of trace contaminant removal for mid-temperature gas removal systems such as RTI's process.

Recently, the DOE has been emphasizing the development of gas cleanup technology operating in the temperature range of 350 to 400°C ("Warm Gas Cleanup"). At these lower temperatures, it may be expected that the 1Warm-Gas Clean-up for BGL Coal Gasification-SOFC Power Generation System metallic compounds such as those of the alkalis formed in the gasifier will be in a condensed state and will be easier to remove from the syngas. Since the British Gas/Lurgi (BGL) coal gasifier typically produces raw syngas at ~750°F (400°C), it is a promising candidate for SOFC power generation. Special challenges with respect to the tars and oil from a BGL gasifier, and its effects on warm-gas cleanup processes is discussed in addition to concepts to handle other contaminants including

- Particulates (entrained particles as well as condensed salts)
- Gaseous sulfur compounds (primarily H₂S, COS and some CS₂, mercaptans)
- Chlorides (primarily HCl)
- Nitrogen compounds (primarily NH₃ and HCN)
- Mercury (Hg) vapor

Two potential processing schemes to remove the contaminants are qualitatively addressed, including a block flow diagram showing how the contaminants would be removed sequentially from the BGL gas. It should be noted that the RTI process mid-temperature sulfur cleanup process is only one of several processes required for cleanup. Cost data are not available. In addition, the RTI regenerator off gas is sent to a sulfur recovery unit where sulfuric acid is produced, not elemental sulfur.

1.4.4 Subtask 4: Impact of Carbon Dioxide Separation

This task was not completed. However, a short discussion is provided here.

- In the original IGFC study, system efficiency for an IGFC system without CO₂ isolation vs one with CO₂ isolation showed a 2.2% efficiency decrease (53.5% vs 51.3%). A similar difference in the efficiencies is expected in the improved baseline; however, as the improved baseline includes an ITM for oxygen removal, the delta is likely to be different, as constraints on the amount of oxygen recovered from the SOFC exhaust must be accounted for.

- The cases discussed here only isolate CO₂. It is possible that in order to sequester CO₂, a high pressure CO₂ pipeline would be required to transport the CO₂ from the IGFC plant boundary to the sequestration facility. The amount of energy required to pressurize CO₂ to a high pressure is significant. In the If this pressurized parasite is CO₂ is to be compressed to a high pressure for a pipeline.
Analysis by NFRC as given in the Appendix notes a power requirement of 156 kW/kg/s to pressurize CO₂ from 14 bar to 140 bar.

- Pressurization of CO₂ from 1 atm to 14 bar could represent over 200 kW/kg/s. The combined effect of taking the isolated CO₂ from 1 atm and pressurizing it to over 140 bar would represent over 3% of the coal feed plant HHV.

2 TASK 2.4 – CELL SCALABILITY

2.1 Scope and Objective

The objective of this task is to demonstrate cell area scaleup based on the tape calendering method. Both theoretical analysis and experimental work were conducted. The theoretical analysis involved literature search to determine fundamental limitations, if any, on the size that can be sintered. Experimental work was performed to identify and optimize key process parameters to demonstrate process scaleup to large area cells (> 10" diameter). Testing was conducted on representative large area cells to determine their performance under typical hybrid operating conditions.

2.2 Root Cause Analysis on Cell Performance

As reported previously, (July-December 2004 Semi-Annual Report) part of the work on the cell scalability task involved testing large-area cells (~12" diameter) and evaluating the effects of hybrid environment on the performance of large cells. Though the testing of cells of this size (~12") was demonstrated, the performance was lower than that observed on smaller cells (0.3 W/cm² vs 0.25 W/cm² at 0.7V, 46% fuel utilization)

A root cause analysis study was undertaken to identify the reason for lower performance of large cells.
The potential reasons for the low performance were divided into two broad categories: (i) Cell related; and (ii) Stack design and assembly related. Each of these categories was further drilled down for all potential causes as explained below.

(i) Cell related: Potential causes in this category include: (a) Cell Microstructure; (b) Cell strength; and (c) Cell flatness/ripples

(a) Cell Microstructure: Potential causes in this sub-category include differences in cell component (electrolyte, anode, and cathode) thickness, porosity, or interfacial microstructure from that of a baseline cell. For instance higher electrolyte thickness may lead to lower performance due to increased ohmic resistance or a denser electrode may experience increased diffusion polarization, and hence, lower cell performance. Cross-section samples from a tested large-area cell were prepared and thickness, porosity, and interfacial microstructure were examined using optical and scanning electron microscope (SEM) at various points along the cells.

For comparison, the microstructure of a baseline cell was also examined. Slight differences in component thickness were seen between the large cell and the baseline cell. These differences, however, may not be significant enough to lead to observed low performance in large cells.

(b) Cell strength: If the cell cracks due to poor strength, it may result in lower than expected performance. However, the fact that both large cells showed lower electrochemical performance but the second cell did not exhibit any cracks in the tested area suggests that cell cracking may not be a significant factor in observed low performance.

(c) Cell flatness/ripples: Presence of ripples or uneven areas on the cells may lead to poor contact of cell with interconnect in those areas, which, in turn, may result in lowered cell performance. A design of experiments, as described below, was performed to get quantitative information on ripples or unevenness in the cell.

(ii) Stack design and assembly related: Potential issues in this category include: cathode and anode bond paste thickness, thickness uniformity, and amount, poor contact between cell and interconnect, flow uniformity issues related to interconnect design.

To isolate the influence of stack design and assembly related issues on performance, two smaller cells (4-3/8” diameter) were laser cut from different areas on a 12.75” bilayer. Cathode was applied by hand painting (as done for large cells) and by the
standard screen-printing process, respectively. The cells were tested on diluted hydrogen fuel stream. The Ni mesh fuel flow field design used especially for the large cells testing was also adopted for the small cell testing. The performance of both tested cells was measured to be similar to the performance of standard baseline cells under similar testing conditions and test fixture (Figure 3).

![Graph showing cell voltage vs current density](image)

**Figure 3** Electrochemical Testing Data on: (i) 12”; (ii) 4.375” Baseline; and (iii) 4.375” Cell Cut from a 12” Cell.

The above results strongly suggest that performance loss in large cells is largely an artifact of the test vehicle, and properties of the cell itself, such as cell size or cell microstructure, may have a small role in the observed lower performance.

2.3 Cell Fabrication Improvements

Fabrication of 12” bilayers was demonstrated in this program. More than 50 large bilayer tapes were produced and fired. The average firing yield on the critical bilayer
firing step was 70%. Since post bilayer firing failures were observed due to presence of large particles and/or foreign impurities, a sieving step on raw material powders was introduced to remove foreign impurities or large particles. This resulted in an improvement in post-firing yields during bilayer cleaning and cathode application from 55% to about 80%.

Due to the presence of an edge curl on the bilayer, cathode application was done on the first few cells using hand painting. Laser cutting the cell removes the edge curl, and hence, facilitates the screen-printing operation for cathode application. The screen-printing process is desirable for the control and uniformity of the layer thicknesses and for having the potential of being a low-cost, high throughput manufacturing process. With the availability of multiple large cells a new fixture was ordered for the lasercutting operation. Over 20 large bilayers were successfully cut to 12” diameter with a lasercutting yield of almost 100%. With the success in laser cutting these cells, screen-printing process development work for cathode application was initiated. A large screen was designed and procured and larger screen print equipment was commissioned. Several process parameters were optimized to overcome debonding issues in the green and fired stages. The optimized process resulted in successful application of cathode on large bilayers using the screen-printing process; thus validating the applicability of screen-printing to fabricate scaled-up cells.

As cell sizes get larger, stiffness of bilayer and its strength become more important for handling and stacking purposes. One of the ways to increase bilayer strength and stiffness is to increase the thickness of anode, and hence, the total thickness. Initial attempt to increase the green tape thickness resulted in severe cracking and delamination of electrolyte during firing. With the modification of the firing process, the firing run was a success (both bilayers 100% intact). Further, the bilayers looked quite flat with very little edge curl. Success in firing these thicker tapes opens up ways to improve the strength, flatness, and edge curl of large-area bilayers. However, any potential decrease in performance with increased cell thickness, especially at high fuel utilizations, needs to be determined.

2.4 Design of Experiments

As mentioned earlier, certain cell properties such as flatness affect the stacking behavior and performance of the cells. However, exact correlation between these parameters and cell performance is not known. The stack requirements that are affected by cell properties are: cell edge sealability; electrical contact between the cells and interconnect; and mechanical integrity. It is therefore important to understand the manufacturing process parameters that affect the above-mentioned properties. As part of this task, a design of experiments was initiated to understand bilayer characteristics as a function of size and other parameters.
After sintering, a laser based measurement system (Acugage, Manchester, NH) was used to generate a two dimensional scan of the bilayer surfaces. Line scans were used to measure the edge curl. The output from the program is a series of x, y and z measurements for each location on the cell surface. The measurements were made on the bilayer as it sat freely on the Acugage table. A representative scan is shown in Figure 8.

![Figure 4 Surface Profile of a Scanned Bilayer. (The color scale shows the variation in the z height over the surface.)](image)

A schematic of the circumferential surface ripple and the edge curl are shown in Figure 5. The surface ripple typically spreads out from the center, with the wavelength and amplitude increasing as we move away from the center. As can be inferred, in a fuel cell stack, as the cell and interconnect surfaces mate in the stacking process, the points which are out of flatness in the cell will be the main points of contact, with the other areas having lesser contact. The edge curl is a steep camber at the very edge of the cell, which can severely affect sealing ability. As mentioned earlier, the screen printing operation typically requires removing the edge curl; presently by a laser cutting process.
Figure 5 (a) Surface Ripple and (b) Edge Curl in a Bilayer.

As the extraction of the amplitude and wavelength from the unconstrained laser scan is not straightforward, a Matlab program was developed to analyze the scanned surface profiles for surface ripple using Fast Fourier Transform analysis. The average amplitude for a set of predetermined wavelengths was then calculated (Figure 6). As the values shown are a weighted average over the whole cell, they are lower than localized high ripples that might of more concern. Hence, it should be noted that a direct comparison of these average values may not translate into performance difference between cells. The edge curl values are plotted in Figure 7.

Figure 6. Average Amplitude of Surface Ripple in Different Bilayers
The data was analyzed using GE’s Design for Six Sigma (DFSS) Design of Experiments optimizing tool and a transfer function was generated to correlate the most significant factors affecting surface ripple and edge curl. It was seen that thickness and size were the most significant factors affecting surface ripple. Though the above results provide preliminary trends on variation of bilayer properties with several key process parameters, more detailed studies are needed to generate accurate correlations.

2.5 Literature review on theoretical limitations

Literature review on theoretical models to understand fundamental limitations on the maximum sizes that can be made using the tape calendering process was completed. During the course of review, it became clear that theoretical limitations on cell size couldn’t be predicted using available binder burnout and sintering models. Current models need to be modified to take into account effect of external forces (thermal, gravity, frictional etc.). Though there are no obvious theoretical limitations, practical limitations viz. thermal gradients, uniform binder removal, friction between tape and setter plates, and availability/warpage of setter plates may dictate the upper limit on cells sizes that can be made.

3 TASK 2.5 – STACK HYBRIDIZATION
3.1 Scope and Objective

The objective of this task is to demonstrate operation of planar SOFC stacks and their operating characteristics under hybrid environment and assess scalability of stack design. SECA derived technology will be leveraged in this task. The work will focus on stack testing of various sizes under hybrid conditions, such as temperature, pressure, and gas composition, which are critical to the development of megawatt class hybrid systems. Stack performance as a function of fuel utilization will be determined. Analysis of design features that influence stack reliability, performance, and scalability (area and height) will be performed. Designs and operating procedures to facilitate stack scaleup will be identified.

3.2 Stack Testing

3.2.1 5-cell stack test

During this reporting period, a 5-cell stack, DH-11, was tested under hybrid conditions. The purpose of the 5-cell stack test was to evaluate the performance of the SOFC stack as a function of pressure, temperature, and fuel utilization and the capability of the compliant feed tube manifold system at hybridization conditions. The functionalities and safety of SOFC pressurized test stand were also checked during this test. Simulated steam-reforming fuel was used in the test.

**Setup of 5-cell Compliant Feed Tube Stack, DH-11**

As mentioned in the last Semi-Annual Report (July 2004 to December 2004) the compliant feed tube stack design was used in this 5-cell stack test. Because the root cause analysis indicate that unbalanced glass seal formed during the cell preseal/reduction process may induce cell edge cracks, the 5-cell stack, DH-11 was assembled by using compliant feed tube interconnect and followed the one-step stack assembly process. The cell active area of the 5-cell stack was 142 cm². Preheaters based on a serpentine design of ¼” tubing were also used to heat the air and fuel to the SOFC operating temperature. Both air and fuel preheaters were sized based on their maximum flow rates, the air and fuel could be heated up to 750°C at the stack inlets.

**Test results of 5-cell Compliant Feed Tube Stack, DH-11**

The stack was tested at 800 °C for normal SOFC operations. The anode reduction was started during the stack heating up when stack temperature reached 600 °C. The test plan for the 5-cell stack is given in Table 9

<table>
<thead>
<tr>
<th>Table 9 5-Cell Stack Test Plan</th>
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<td>• Initial polarization curve at fixed flows with dilute hydrogen (64% H₂/balanced with N₂) (at</td>
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14.7 psia. and 800°C);
- Hold for 20 hours under constant current for conditioning (at 14.7 psia. and 800°C);
- Polarization curve at fixed flows with dilute hydrogen (at 14.7 psia. and 800°C);
- Polarization curves at fixed fuel utilization with dilute hydrogen (at 14.7 psia. and 800°C);
- Polarization curve at fixed flows with dilute hydrogen (at pressurized condition and 800°C);
- Polarization curves at fixed fuel utilization with dilute hydrogen (at pressurized condition and 800°C);
- Polarization curves at fixed fuel utilization with simulated steam reforming or SR fuel (at pressurized condition and 800°C);
- Polarization curves at fixed fuel utilization with simulated SR fuel (at 14.7 psia. and 800°C).

a. **Effects of fuel utilization (64% H₂ fuel)**

The performance of individual cells in the 5-cell compliant feed tube stack, DH-11 running on diluted hydrogen fuel (64% H₂, balanced with N₂) fuel stream at 800 °C and 14.7 psia are shown in Figure 9. The fuel flow rate was fixed throughout the whole current density range and therefore, fuel utilization increases linearly with current density as shown in Figure 9. A power density of 307 mW/cm² was achieved at 45% fuel utilization and average cell voltage of 0.607 V. A typical baseline cell performance was achieved in this test.

Performances of individual cells in the 5-cell stack were also measured with 70% fixed fuel utilization at 800 °C and 14.7 psia. During this measurement, fuel flow rates were controlled at given current densities to match fuel utilization specification (i.e., fuel flow increases linearly with current density). The starting current density of these measurements was higher than 260 mA/cm² because the requirement of the low fuel flow rate for low current density reached the limitation of the mass flow controllers.

As shown in Figure 10, this 5-cell compliant feed tube stack achieved power density of 281 mW/cm² (0.588 V @ 0.479A/cm²) with 64% H₂, 70% fuel utilization at 800°C, but, performance of the 5-cell stack at 70% fuel utilization is lower than those obtained with fixed fuel flow. There is about 16% performance difference between fixed flow rate and fixed fuel utilization condition at low current density. However, as anticipated, cell performance with 64% H₂ fuel stream at 70% fuel utilization appears to approach those under fixed flow condition with the increase in current density, which indicates that mass transfer does limit the cell performance.
Figure 8  Performances of Individual Cells in the Compliant Feed Tube Stack, DH-11 with Diluted H₂ and Fixed Flow at 800°C and 14.7 psia.

Figure 9  Performances of Individual Cells in the Compliant Feed Tube Stack, DH-11 with Diluted H₂ at 800°C and 14.7 psia. Fixed Flow vs 70% Fuel Utilization.

b. Effects of the differential pressure between anode and cathode

The test of the 5-cell compliant feed tube stack, DH-11 at pressurized condition was terminated due to the abnormal rising of the temperature (up to 850 °C) in fuel exhaust manifold and the open circuit voltage (OCV) drop of cell #5 during the stack pressurization.
The analysis of the recorded temperature, pressure, and cell voltage data and events showed that the initiation of cell #5 OCV drop and the temperature rise in the fuel exhaust manifold were associated with the change of differential pressure between anode and cathode. Because the inlet pressure control scheme was used during the operation of the stack pressurization and the sealless design was used in the cathode flowfield of the compliant feed tube stack, this phenomenon (cell OCV drops and the temperature of the fuel exhaust manifold raises when cathode pressure is higher than anode pressure) implied that there was leak path between anode of the cell #5 and the cathode. When the anode pressure was higher than the cathode pressure, the fuel leaked into the cathode and caused fuel combustion in the cathode or pressure vessel. This type of fuel leakage affected stack performance at high fuel utilization condition, but did not damage stack and cause catastrophic failure of the stack since the heat was quickly carried out by rapid flow of air functioning as an oxidant and a thermal management medium. The cell OCV was not dramatically affected. However, when the anode pressure is lower than the cathode pressure, the air will leak into the anode and cause fuel combustion in the anode compartment. The consequences of this type of air leakage are cell OCV drop temperature of the fuel exhaust rising, and catastrophic failure of the stack.

After the test, post-mortem test was performed to determine the root causes of the abnormal rising of the fuel exhaust temperature and the OCV drop of cell #5. A burning mark was found near the seal area cell #5. This finding confirms the leak path hypothesis. It is believed that this edge leakage caused the low OCV and high fuel exhaust temperature at pressurized conditions.

A root cause analysis was performed to identify causes of the swing of the differential pressure between anode and cathode during stack pressurization. An issue associated with the setup of the pressure control hardware was identified. The pressurized test stand was then modified to ensure that there is always a ± 0.25 offset pressure add to the anode pressure to avoid the air leaks into the anode compartment.
3.3 Large-area Cell Test

After the successful test of the two large-area single cell modules during the last reporting period. Two 3-large area cell stacks were tested under hybrid conditions. The purpose of the tests of 3-large area cell stack was to evaluate the performance of the large area cell as a function of pressure, temperature, and fuel utilization. The cell flow uniformity and the capability of the compliant feed tube manifold system (compliant feed tube and manifold sealant) were also examined at hybridization conditions. Simulated steam-reforming fuel was used in the tests.

Test Results of 12” 3-cell Radial Stack, DH-12
The 12” 3-cell radial stack was tested down to 800 °C for normal SOFC operations. The anode reduction was started after the 3-cell stack temperature reached 800 °C. The test plan for the 12” 3-cell radial stack is given in Table 10.

Table 10 3-Cell (12”) Radial Stack Test Plan

- Initial polarization curve at fixed flows with dilute hydrogen (37% H₂/balanced with N₂) (at 14.7 psia. and 800 °C);
- Hold for 20 hours under constant current for conditioning (at 14.7 psia. and 800 °C);
- Polarization curve at fixed flows with dilute hydrogen (at 14.7 psia. and 800°C);
- Polarization curves at fixed fuel utilization with dilute hydrogen (at 14.7 psia. and 800°C);
- Polarization curve at fixed flows with dilute hydrogen (at pressurized condition and 800°C);
- Polarization curves at fixed fuel utilization with dilute hydrogen (at pressurized condition and 800°C);
- Polarization curves at fixed fuel utilization with simulated SR fuel (at pressurized condition and 800°C);

a. Cell performance with diluted hydrogen fuel at fixed flow rate
The performance of 12” 3-cell radial stack running on fixed flow with 37% H₂ fuel stream is shown in Figure 17 at different pressurization levels. The peak power density at ambient pressure (14.7 psia) was measured to be 213 mW/cm² and it reached 290 mW/cm² at 61.5 psia. From ambient pressure condition, the power density at similar operation condition (36.4% fuel utilization and 0.342A/cm²) is calculated to increase about 4% at 30 psia, 10% at 45 psia and 19% at 60 psia, respectively. At 60 psia, the stack achieved total power of 532 W (0.592 V at 0.489 A/cm², power density of 0.290 W/cm³) at 52% fuel utilization with 37% H₂ fuel stream.

![Figure 10](image-url)

**Figure 10** Performances of the Average Cell in the 12” 3-Cell Radial Stack, DH-12 as a Function of Operation Pressure with 37% H₂ and Fixed Flow at 800°C

**b. Effects of fuel composition (37% H₂ vs. simulated SR fuel steam)**

The performance of 12” 3-cell radial stack running on 37% H₂ fuel stream at 60% fuel utilization and 60 psia operation pressure was compared with that on simulated SR fuel in Figure 18. The peak power density measured on SR fuel was 216 mW/cm² and this is lower than that measured on 37% H₂ fuel stream (247 mW/cm²). However, at same operation condition the difference of the performance between operated at 37% H₂ fuel stream and simulated SR fuel steam is less than 6%.
Figure 11  Average Cell Performance of 3-Cell (12”) Radial Stack, DH-12 with Diluted H₂ and SR Fuel and 60% Fuel Utilization at 800°C

c. Effects of fuel utilization

Cell performance was also measured with fixed fuel utilization. Fuel flow rates were controlled at given current densities to match fuel utilization specification (i.e., fuel flow increases linearly with current density). Figure 19 shows cell voltages measured with 60 %, 70%, and 75% fuel utilization on simulated SR fuel streams at 60 psia operation pressure. The starting current density of these measurements was higher because the requirement of the low fuel flow rate for low current density reached the limitation of the mass flow controllers. As anticipated the average cell performance decrease as the increase of fuel utilization due to the limitation of the mass transfer. At 60 psia operation pressure, the stack achieved power density of 0.157 W/cm² at 75% fuel utilization (0.635 V at 0.245 A/cm²) with simulated SR reformate (stack efficiency: 38%).

The performance of this 3-cell stack is much better than the large area single cell module tested before (about 28% performance increase, 0.229 W/cm², 0.672 V/cell at 340 mA/cm², vs. 0.179W/cm², 0.665V at 268.7 mA/cm² under similar operating conditions); However, the performance of this 3-cell stack is still lower than the performance of 6.3” cell stack (0.335 W/cm² at 75% fuel utilization with 64% hydrogen), the possible causes for the these may be due to the contact resistance and poor flow distribution.
Figure 12  Average Cell Performance of 3-Cell (12”) Radial Sealless Stack, DH-12 as a Function of Fuel Utilization with Simulated SR Fuel at 800°C

Test Results of 12” 3-cell Half Seal Stack, R-14

The 3-cell (12”) half seal stack was tested at 800 °C for normal SOFC operations. The anode reduction was started after the 3-cell stack temperature reached 800°C. The anode flowfield used in this stack was designed to improve the fuel flow uniformity. To explore the effect of cell microstructure on the cell performance, three different type of 12” cells were used, (1) cell made of 0.025” thick baseline bilayer tape, (2) cell made of 0.017” thick baseline bilayer tape (this is GE HPGS's baseline cell thickness), and (3) “Option 1” cell made of 0.025” thick “Option 1” bilayer tape, were used in this stack.

The initial performance of 12” 3-cell half seal stack running on fixed flow with 64% H₂ fuel stream is shown in Figure 23. After 18 hours of conditioning, the performance of the 3-cell half sealed stack achieved power density of 0.273 W/cm² (0.675 V/cell at 405 mA/cm²) with 64% dilute hydrogen and 35% fuel utilization at ambient pressure (14.7 psia), which is better than the 1st 3-large area cell radial stack tested before (241 mW/cm², 0.592V at 408 mA/cm²) under similar operating conditions. This is about 13% of performance improvement. However, the stack cannot perform stably at pressurized condition due to the issue of pressurized test stand. The pressure regulator of anode side was unable to stabilize the anode pressure. The fluctuation of differential pressure between cathode and anode (up to 2 psid at pressurized condition) caused or accelerated the reactants crossover in the 3-cell stack and damaged cells due to internal combustion. This issue has been resolved by retuning the pressure regulator and setting new control parameter for the pressure regulator.
Figure 13  Individual Cell Performance of 3-Cell (12") Half Seal Stack, R-14 with 64% H₂ and Fixed Flow at 800°C

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