Compact Gasification
Development and Test Status

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Pratt & Whitney Rocketdyne
A United Technologies Company
GTC Annual Conference
October 2011

Leveraging 50 Years of Rocket Engine Experience
to Reduce Cost and Improve Plant Performance
Key Design Features of the Compact Gasification System

- Low Pressure Hopper
- Dry Solids Pump
- Compact Gasifier
- High Pressure Hopper
- Ultra-dense Feed System
- Particulate Removal (Cyclone + Candle Filter)

- Yellow Items are Key Development Items
- Other Items are Commercially Available
• PWR has teamed with ExxonMobil Research and Engineering (EMRE) to develop and commercialize the technology

• Alberta Innovates: Energy and Environment Solutions (EES) is cost-sharing definition of a demo plant for an Alberta location and funding tests with Alberta feedstock

• Zero Emission Energy Plants, Inc. (ZEEP) is a commercial launch customer with a global license for use of PWR technology in gasification plants
Pilot Plant at the Gas Technology Institute
- Started Dec 2009
- 18 tons per day

Test Objectives Completed
- Demonstrated performance
  - 99% carbon conversion
  - High cold gas efficiency
  - Formed protective slag layer
  - Demonstrated particulate removal
- Tested 4 feedstocks
- Verified operating environments
- Validated computer models
- Obtained preliminary life data
- Established operating procedures

764 hours Hot-Fire Testing through April 2011

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Pilot Plant Gasifier Successfully Processed Range of Feedstocks

<table>
<thead>
<tr>
<th></th>
<th>Illinois #6 Coal</th>
<th>Oil Sands Petcoke</th>
<th>Joliet Petcoke</th>
<th>Alberta sub-bit coal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Proximate Analysis (wet)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture Content, %</td>
<td>5.73</td>
<td>0.43</td>
<td>0.23</td>
<td>7.46</td>
</tr>
<tr>
<td>Volatile Matter, %</td>
<td>37.35</td>
<td>13.29</td>
<td>12.26</td>
<td>28.52</td>
</tr>
<tr>
<td>Ash, %</td>
<td>9.32</td>
<td>3.21</td>
<td>0.3</td>
<td>23.86</td>
</tr>
<tr>
<td>Fixed Carbon, %</td>
<td>47.6</td>
<td>83.07</td>
<td>87.21</td>
<td>40.16</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td><strong>Ultimate Analysis (dry)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash</td>
<td>9.89</td>
<td>3.23</td>
<td>0.3</td>
<td><strong>25.78</strong></td>
</tr>
<tr>
<td>C</td>
<td>73.68</td>
<td>84.55</td>
<td>88.66</td>
<td>57.66</td>
</tr>
<tr>
<td>H</td>
<td>4.96</td>
<td>3.47</td>
<td>3.79</td>
<td>3.4</td>
</tr>
<tr>
<td>N</td>
<td>1.32</td>
<td>1.59</td>
<td>1.64</td>
<td>0.85</td>
</tr>
<tr>
<td>S</td>
<td>3.46</td>
<td>6.47</td>
<td>6.45</td>
<td>0.17</td>
</tr>
<tr>
<td>O</td>
<td>6.69</td>
<td>0.69</td>
<td>0</td>
<td>12.14</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100</td>
<td>100</td>
<td>100.84</td>
<td>100</td>
</tr>
<tr>
<td>HHV, Btu/lb (dry)</td>
<td>12,690</td>
<td>14630</td>
<td>15070</td>
<td>9869</td>
</tr>
<tr>
<td>Slag Fluid Temp, °F</td>
<td>2270</td>
<td>2660</td>
<td><strong>2600</strong></td>
<td><strong>2656</strong></td>
</tr>
</tbody>
</table>

PWR gasifier technology successfully gasified very high ash content, high fluid temp Alberta sub-bituminous coal.
Excellent agreement between measured outputs and inputs.
Excellent Raw Mass Balance Data Observed Throughout Testing
Pilot Plant Data Anchors Gasifier Models Over Wide Operating Range

- Models anchored to 53 operating points with 4 feedstocks
- 1-D kinetic model for carbon conversion and heat load predictions
- CFD model as scale-up and design tool
- ~0.1 sec residence time reactor - not optimized for high conversion
Protective Slag Layer Formed on Liner Surface

Slag layer retained after 38 hours on low ash pet coke
(view looking down from gasifier injector)

Coarse slag from Alberta sub-bit

Alberta sub-bit cyclone fines
(magnified 1000x)
<table>
<thead>
<tr>
<th>Objective</th>
<th>Prediction</th>
<th>Results</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Conversion</td>
<td>90% (0.1 sec residence time)</td>
<td>91%</td>
<td>Validates &gt;99% conversion at commercial scale.</td>
</tr>
<tr>
<td>Heat Loss</td>
<td>&lt; 3 MMBTU/hr</td>
<td>&lt; 1 MMBTU/hr</td>
<td>Heat flux within design limits. CGE benefit at comm’l scale.</td>
</tr>
<tr>
<td>Multiple Feedstocks Tested</td>
<td>3</td>
<td>4</td>
<td>Feedstock flexibility demonstrated on petcoke, bituminous, sub-bituminous.</td>
</tr>
<tr>
<td>Test Data Points</td>
<td>&gt;27</td>
<td>53</td>
<td>Supports CFD model validation.</td>
</tr>
<tr>
<td>Component Test Time</td>
<td>&gt;400 hours</td>
<td>&gt;400 hours liner</td>
<td>Slag layer formed. Environments consistent with life goals.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;700 hours injector</td>
<td></td>
</tr>
<tr>
<td>Particulate Removal</td>
<td>Non-leachable fines</td>
<td></td>
<td>Environmentally benign slag/fines streams.</td>
</tr>
<tr>
<td>Operations</td>
<td>&lt; 10 minute start-up time</td>
<td></td>
<td>Fast response. Safety system demonstrated.</td>
</tr>
</tbody>
</table>
Results Validate PWR Compact Gasification System Benefits

Current Market Leaders

Compact Gasification System

- 90% size reduction (gasifier)
- 50% lower capex (gasification system)
- 2 yr burner, 10 yr liner life look feasible
  - Supports > 99% gasifier availability
- > 99% carbon conversion demonstrated
- +3-4% CGE vs. other dry feed gasifiers
- Dry feed system to gasify all ranks of coal, petcoke and biomass blends

Results validate 20%-25% cost of product reduction from NETL, Jacobs studies
Demonstration Plant Gasifier Design Is In Progress

- CFD design tool validated with pilot plant data
- Advancing demonstration plant gasifier design

Pilot Plant 18 TPD
Demo Plant 400 TPD
Commercial Plant 3,000 TPD

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Acknowledgement

• Energy and Environment Solutions is the strategic energy technology arm of the Alberta Government in the Ministry of Advanced Education and Technology. Its mission is to enhance the development of Alberta’s energy resources through investment in research, technology and innovation in partnership with industry.

• The Illinois Department of Commerce and Economic Opportunity provided funding in support of this effort under the Coal Competitiveness Program.

• However, the opinions, findings and conclusions expressed herein are those of the authors

Questions?