A High Efficiency, Ultra-Compact Process For Pre-Combustion CO₂ Capture

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FE0026423

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U.S. Department of Energy
National Energy Technology Laboratory
Office of Fossil Energy
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Presentation Outline

- Project Overview
- Technology Background
- Technical Approach/Project Scope
- Progress and Current Status of Project
- Plans for Future Testing/Development/Commercialization
**Performance Period:** 10-01-2015 – 9-31-2018

**Project Budget:** Total/$1,909,018; DOE Share/$1,520,546; Cost-Share/$388,472

**Overall Project Objectives:**

1. Prove the technical feasibility of the membrane- and adsorption-enhanced water gas shift (WGS) process.

2. Achieve the overall fossil energy performance goals of 90% CO\textsubscript{2} capture rate with 95% CO\textsubscript{2} purity at a cost of electricity of 30% less than baseline capture approaches.

**Key Project Tasks/Participants:**

1. Design, construct and test the lab-scale experimental MR-AR system.-----**USC**

2. Select and characterize appropriate membranes, adsorbents and catalysts.-----**M&PT, USC**

3. Develop and experimentally validate mathematical model.-----**UCLA, USC**

4. Experimentally test the proposed novel process in the lab-scale apparatus, and complete the initial technical and economic feasibility study. .----- **M&PT, UCLA, USC**
Conventional IGCC Power Plant
MR-AR Process Scheme

- Potential use of a TSA regeneration scheme allows the recovery of CO₂ at high pressures.
- The MR-AR process overcomes the limitations of competitive singular, stand-alone systems, such as the conventional WGSR, and the more advanced WGS-MR and WGS-AR technologies.
MR-AR Process Scheme – Advantages over SOTA

Key Innovation:

• Highly efficient, low-temperature reactor process for the WGS reaction of coal-gasifier syngas for pre-combustion CO₂ capture, using a unique adsorption-enhanced WGS membrane reactor (MR-AR) concept.

Unique Advantages:

• No syngas pretreatment required: CMS membranes proven stable in past/ongoing studies to all of the gas contaminants associated with coal-derived syngas.

• Improved WGS Efficiency: Enhanced reactor yield and selectivity via the simultaneous removal of H₂ and CO₂.

• Significantly reduced catalyst weight usage requirements: Reaction rate enhancement (over the conventional WGSR) that results from removing both products, potentially, allows one to operate at much lower W/F₇O (Kgcat/mol.hr).

• Efficient H₂ production, and superior CO₂ recovery and purity: The synergy created between the MR and AR units makes simultaneously meeting the CO₂ recovery/purity targets together with carbon utilization (CO conversion) and hydrogen recovery/purity goals a potential reality.
Field-Testing of CMS Membranes

M&PT test-unit at NCCC for hydrogen separation

CMS membranes and modules
NH₃ ~1000 ppm; S ~1000 ppm; HCl < 5 ppm; HCN ~ 20 ppm; H₂O >10%; high concentrations of napthalenic and other condensable hydrocarbons
Long-Term Stability Testing in Gasifier Off-gas [NCCC]

He or N₂ Test Conditions
Pressure: 20 to 50 psig
Temperature: 230 to 265°C

CMS Membrane Bundle
### A New Generation of CMS Membranes

Original Project Targets:
\[ H_2 \text{ Permeance} \ (350 – 500 \text{ GPU}); \]
\[ H_2/CO > 80 \ (\text{Equivalent to} \ H_2/N_2 > 100) \]

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Adsorbent Preparation and Characterization

High-Pressure Adsorption Isotherm at 250 °C

Excess sorption (wt%/g) vs. Pressure (bar)

- Black squares: Before correcting
- Red circles: After correcting
Co-Mo/Al₂O₃ Sour-Shift Catalyst Characterization
Global Reaction Kinetics- Empirical Model and Comparison with Microkinetic Models

\[ -r_{CO} = A \, e^{-\frac{E}{RT}} \, p_{CO}^a \, p_{H2O}^b \, p_{CO_2}^c \, p_{H2}^d \, (1 - \beta) \]

\[ \beta = \frac{1}{K_{eq}} \left( \frac{P_{CO_2} \cdot P_{H2}}{K_{eq} \cdot P_{CO} \cdot P_{H2O}} \right) \]

Root-Mean-Square Deviation (RMSD)
Direct oxidation: 3.38
Associative: 5.12
Formate intermediate: 8.04
Empirical model: 3.32

| \( A \{\text{mol}/(\text{atm}^{a+b+c+d}) \cdot \text{h} \cdot \text{g}\} \) | 18957
|---|---|
| \( E \{\text{J/mol}\} \) | 58074
| \( a \) | 4
| \( b \) | -1.46
| \( c \) | 0.13
| \( d \) | -1.44
Conversion of MR and PBR with three different steam sweep ratios (300 °C, feed pressure of 15 bar, CMS#1)

Conversion of MR and PBR with no sweep (250 °C, feed pressure of 20 and 25 bar, CMS#2)

\[ X_{CO} = \frac{n_{CO}^F - (n_{CO,exit}^F + n_{CO,exit}^F)}{n_{CO}^F} \]
Experimental Results of MR-AR Performance

CO in the AR and total MR-AR conversion, and species molar flow rates. (Left Top) AR I, first cycle, (Right Top) AR II, first cycle, (Left Bottom) AR I, second cycle, (Right Bottom) AR II, second cycle. Temp.=250 °C, pressure=25 bar, H₂O/CO ratio=2.8, W/F₀=55 g·h/mol.
Membrane Reactor (MR)/Adsorptive Reactor (AR) Sequence

Syngas → Reaction Zone (CO + H₂O → CO₂ + H₂) → Permeation Zone (CH₄, H₂, CO, CO₂, H₂O) → Catalyzed Pellet → Adsorbent Pellet → Carbon Depleted Syngas → Water+CO₂ → CO₂ Drying and Compression → CO₂ to Storage

Multi-Scale MR-AR Model for Process Scale-Up
Multi-Scale MR-AR Model for Process Scale-Up – MR System

Pellet-scale Model Equations & Boundary Conditions

Constitutive laws

**Continuity Equation:**

\[ \nabla \cdot \left( \rho_p \varepsilon_v \rho_p \sum_{k=1}^{n_k} R_k \bar{v}_k \right) = \sum_{j=1}^{n_j} \left( 1 - \varepsilon_v \right) \rho_p \sum_{k=1}^{n_k} R_k \bar{v}_k \]

**Component mass conservation:**

\[ \nabla \cdot \left( \rho_p \varepsilon_v \rho_x \sum_{k=1}^{n_k} R_k \bar{v}_k \right) + \nabla \cdot \left( \rho_p \varepsilon_v \rho_x \sum_{k=1}^{n_k} R_k \bar{v}_k \right) = \left( 1 - \varepsilon_v \right) \rho_p \sum_{k=1}^{n_k} R_k \bar{v}_k \]

**Energy conservation:**

\[ \left( \rho_p \varepsilon_v \rho_x \sum_{k=1}^{n_k} R_k \bar{v}_k \right) \nabla \cdot \left( \rho_p \varepsilon_v \rho_x \sum_{k=1}^{n_k} \Delta H_{R_k} R_k \right) \]

**Initial Conditions:**

\[ x_j^p = 0 \]
\[ n_j^p = 0 \]
\[ T^r = T_m \]
\[ p^r = 0 \]

**Boundary Conditions:**

\[ \bar{v}_j = 0 \]
\[ Q_j = -h(T^r - T_m) = 0 \]
\[ \bar{v}_l^r = 0 \] for \( r = 0 \)

Reactor-scale Reaction Zone Model Equations & Boundary Conditions

Bulk Gas Constitutive laws

**Continuity Equation:**

\[ \nabla \cdot \left( \rho_p \varepsilon_v \rho_p \sum_{j=1}^{n_j} R_j \bar{v}_j \right) - 2 \sum_{j=1}^{n_j} J_{perm} = \frac{2}{R_{max}} \sum_{j=1}^{n_j} J_{perm} \]

**Component mass conservation:**

\[ \nabla \cdot \left( \rho_p \varepsilon_v \rho_x \sum_{j=1}^{n_j} R_j \bar{v}_j \right) + \nabla \cdot \left( \rho_p \varepsilon_v \rho_x \sum_{j=1}^{n_j} R_j \bar{v}_j \right) = \beta_{env} \left( 1 - \varepsilon_v \right) \rho_p \sum_{j=1}^{n_j} R_j \bar{v}_j \]

**Energy conservation:**

\[ \left( \rho_p \varepsilon_v \rho_x \sum_{j=1}^{n_j} R_j \bar{v}_j \right) \nabla \cdot \left( \rho_p \varepsilon_v \rho_x \sum_{j=1}^{n_j} \Delta H_{R_j} R_j \right) - \frac{A_{SM}}{V} J_{perm} \left( H_j - H_{perm} \right) = \]

\[ \frac{\sigma_m h_m \left( T^r - (T_{out}) \right) + \sigma_m h_m \left( T^r - (T_{in}) \right)}{V} \left( T^r - (T_{out}) \right) + \frac{4U}{d_i} \left( T^r - T_m \right) \]

**Initial Conditions:**

\[ x_j^r = 0 \]
\[ T^r = T_m \] for \( t = 0, \forall z \)
\[ p^r = p_m \]

**Boundary Conditions:**

\[ \bar{v}_j = \bar{v}_{in} \]
\[ p^r = p_m \]
\[ T^r = T_m \] for \( z = 0 \)
\[ \bar{v}_j = \bar{v}_{out} \]
\[ n_j^r = 0 \] for \( z = L \)
Multi-Scale MR-AR Model for Process Scale-Up – MR System

MR Reactor-scale Permeation Zone Model Equations

**Bulk Gas Constitutive laws**

**Continuity Equation:**

\[ \nabla \cdot (v_{i,\text{perm}} v_{j,\text{perm}}) = \frac{2}{R_{\text{perm}}} \sum_{j=1}^{N_i} J_{j,\text{perm}}^i \]

**Component mass conservation:**

\[ \nabla \cdot (x_{i,\text{perm}} c_{i,\text{perm}} v_{j,\text{perm}}) = \frac{2}{R_{\text{perm}}} J_{i,\text{perm}} \]

**Energy conservation:**

\[
\left\{ \sum_{j=1}^{N_i} x_{j,\text{perm}} c_{j,\text{perm}} (v_j v_{\text{perm}}) \left( \nabla T_{\text{perm}} \right) = \nabla \cdot \left( \lambda \nabla T_{\text{perm}} \right) + \frac{A_{\text{SM}}}{V_{\text{perm}}} (T - T_{\text{perm}}) + \frac{A_{\text{SM}}}{V_{\text{perm}}} J_{j,\text{perm}} (H_j - H_{j,\text{perm}}) \right\}
\]

**Initial Conditions:**

\[
\begin{align*}
x_{i,\text{perm}} &= 0 \\
T_{\text{perm}} &= T_{\text{perm}}^i \\
p_{\text{perm}} &= p_{\text{perm}}^i
\end{align*}
\]

for \( t = 0, \forall z \) \hspace{1cm} (47)

**Boundary Conditions:**

\[
\begin{align*}
v_{i,\text{perm}} &= \left( v_{i,\text{perm}} \right)_m \\
p_{\text{perm}} &= p_{\text{perm}}^m \\
x_j &= x_j^m \\
T &= T_m \\
\nabla T_{\text{perm}} &= 0 \\
\nabla p_{\text{perm}} &= 0
\end{align*}
\]

for \( z = 0 \)

\[
\begin{align*}
v_{i,\text{perm}} &= \left( v_{i,\text{perm}} \right)_m \\
p_{\text{perm}} &= p_{\text{perm}}^m \\
x_j &= x_j^m \\
T &= T_m \\
\nabla T_{\text{perm}} &= 0 \\
\nabla p_{\text{perm}} &= 0
\end{align*}
\]

for \( z = L \)

Dusty Gas Model

\[
- \frac{1}{N_i} \sum_{j=1}^{N_i} \left( \frac{c_j}{D_{\text{eff}}^j} N_i - \frac{c_j}{D_{\text{eff}}^j} N_j \right) \frac{N_j}{D_{\text{eff}}^j} = \nabla c_i + \frac{c_i}{\sum_{i=1}^{N_i} c_i R_T} \left( 1 + \frac{p}{D_{\text{eff}}^i} \frac{B_o}{\mu_j} \right) \nabla p
\]

The Stefan-Maxwell Equation

\[
\nabla x_i = \sum_{j=1}^{N_j} x_i x_j \left( \frac{1}{J_{j,\text{eff}}} - \frac{1}{\rho_j} \right) \left( w_i - x_i \right) \left( \frac{\nabla p}{p} \right) + \sum_{j=1}^{N_j} \frac{x_i x_j}{\rho_j D_{\text{eff}}^j} \left( \frac{D_{\text{eff}}^j}{w_j} - \frac{D_{\text{eff}}^i}{w_i} \right) \left( \frac{\nabla T}{T} \right)
\]

Momentum Equation

\[
\nabla p' = -K_D v_f' - K_v v_f'^2 = \nabla p' = \left( -150 \left( \frac{1 - \varepsilon_f^r}{\varepsilon_f^r} \right)^2 - \mu_f 1.75 \left( \frac{1 - \varepsilon_f^r}{\varepsilon_f^r} \right) \frac{\rho_f}{\rho_p} \left( \lambda f v_f' \right)^2 \right) v_f'
\]
Component Mass Balances

\[
\frac{\partial}{\partial t} \left( \frac{\varepsilon^r_{\text{gas\_bed}}}{\partial t} c_j^r \right) + \nabla \cdot \left( \nu_j \nabla c_j^r \right) = \varepsilon_{\text{gas\_bed}} \nabla D_{z,i} \left( \nabla c_j^r \right) + \left( 1 - \varepsilon_{\text{gas\_bed}} \right) \eta_j \beta_{\text{cat}} \rho_{\text{cat}} R_j - \left( 1 - \varepsilon_{\text{gas\_bed}} \right) \phi_{\text{ad}} \rho_{\text{ad}} R_{\text{ad}}
\]

\[\beta_{\text{cat}} + \phi_{\text{ad}} + \varphi_{\text{qua}} = 1\]

Energy balance:

\[
\begin{align*}
\frac{\partial}{\partial t} \left( \frac{\varepsilon^r_{\text{gas\_bed}}}{\partial t} C_c^r \right) + \frac{\partial}{\partial t} \left( \frac{\varepsilon^r_{\text{gas\_bed}}}{\partial t} \sum_{j=1}^{n} \varepsilon^r_{\text{gas\_bed}} c_f^r C_j^r \right) &= \nabla \cdot \left( \lambda J \nabla T^r \right) + \left( 1 - \varepsilon_{\text{gas\_bed}} \right) \eta_j \beta_{\text{cat}} \rho_{\text{cat}} \sum_{j=1}^{n} H_j R_j - \left( 1 - \varepsilon_{\text{gas\_bed}} \right) \phi_{\text{ad}} \rho_{\text{ad}} \Delta H_{\text{ad}} R_{\text{ad}} + \frac{4h_w}{d_t} (T_w - T^r)
\end{align*}
\]

Momentum balance:

\[
\nabla P^r = -K_d v_f^r - K_v v_f^r = \nabla P^r = \left( -150 \left( 1 - \varepsilon_{\text{gas\_bed}} \right)^2 d_p^3 \rho_f \left( 1 - \varepsilon_{\text{gas\_bed}} \right)^3 \frac{\nu_f}{d_f} \right) v_f^r
\]
Multi-Scale MR-AR Model for Process Scale-Up – AR System

Initial and boundary conditions for the AR model.

**Initial Conditions:**

\[ \begin{align*}
  \text{constitutive laws and other property equations.}
  c_j^r &= 0 \\
  T' &= T_{in}' \\
  P' &= P_{in}' 
\end{align*} \]

**Boundary Conditions:**

\[ \begin{align*}
  u_w &= u'_w \\
  v_j' &= \left( v_j' \right)_{in} \\
  P' &= P'_{in} \\
  c_j^r &= \left( c_j' \right)_{in} \\
  T' &= T_{in}' \\
  \nabla T' &= 0 \\
  n_j' &= 0 \\
  \nabla P' &= 0 \\
  \text{for } z = 0 \\
  \text{for } t = 0, \forall z \\
  \text{for } z = L 
\end{align*} \]

**Gas Law:**

\[ c^r_{\text{tot}} = \frac{P}{ZRT} \]

**Definitions:**

\[ \sum_{j=1}^{N} x_j = 1, \quad c_{\text{tot}}^r = \sum_{j=1}^{N} c_j^r, \quad P = \sum_{j=1}^{N} P_j, \quad \beta_{\text{tot}} + \phi_{\text{tot}} + \phi_{\text{gas}} = 1 \]

**Heat Flux (Fourier’s Law):**

\[ Q = -\lambda \nabla T \]

**Dimensionless Groups:**

\[ Nu = \frac{h_d}{\lambda}, \quad Re_v = \frac{v_d d_m}{\mu}, \quad Pr = \frac{C_{\text{vis}} \mu_s}{\lambda_s} \]

**Viscosity of Gas Mixture:**

\[ \mu_s = \sum_{i=1}^{N} x_i \mu_i, \quad \phi = \left[ \frac{1 + \left( \mu_i / \mu_j \right)^{1/2} \left( M_j / M_i \right)^{1/4}}{8 \left( 1 + \left( M_j / M_i \right) \right)^{1/2}} \right] \]

**Thermal Conductivity:**

\[ \lambda' = (1 - \epsilon'') \beta_{\text{tot}} \lambda_{\text{tot}} + (1 - \epsilon') \phi_{\text{gas}} \lambda_{\text{gas}} + (1 - \epsilon') \phi_{\text{out}} \lambda_{\text{out}} + \epsilon' \lambda_s \]

**Thermal Conductivity of Pure Gases:**

\[ \lambda_s = A_T + B_T + C_T^2 + D_T^3 \]

**Thermal Conductivity of Gas Mixture:**

\[ \lambda_s = \sum_{i=1}^{N} x_i \lambda_i, \quad \phi = \left[ \frac{1 + \left( \mu_i / \mu_j \right)^{1/2} \left( M_j / M_i \right)^{1/4}}{8 \left( 1 + \left( M_j / M_i \right) \right)^{1/2}} \right] \]

**Specific Heat Capacity of Pure Gases:**

\[ C_i = a_{i0} + a_{i1} T + a_{i2} T^2 + a_{i3} T^3 + a_{i4} T^4, \quad t = \left( \frac{T}{1000} \right) \]

**Specific Heat Capacity of Gas Mixture:**

\[ C_{\text{gas}} = \sum_{i=1}^{N} x_i M_i \]
Experimental conversion for the MR with different sweep ratios and the corresponding MR model fits using both the empirical and microkinetic models. (300 °C, feed pressure of 15 bar, CMS#1)

\[ X_{CO} = \frac{n_{CO}^F - (n_{CO,exit}^F + n_{CO,exit}^P)}{n_{CO}^F} \]
Experimental hydrogen recovery and the corresponding MR model fits using both the empirical and microkinetic models. (300 °C, feed pressure of 15 bar, CMS#1)
Lab-Scale Experimental Results and Model Fits - AR

Temperature = 250 °C, Pressure = 15 bar.
(W_{cat}/F_{CO}=55 on MR)

Temperature = 250 °C, Pressure = 15 bar.
(W_{cat}/F_{CO}=66 on MR)
Axial Profiles of Catalyst Effectiveness Factors in MR (Top) and PBR (Bottom)

Key Results

- Catalyst effectiveness factors in PBR and MR vary significantly along reactor length.
- Catalyst pellets of same diameter exhibit different effectiveness factors.
- Sweep gas pressure/temperature and membrane area have a significant impact on MR behavior.
- The adiabatic MR gives higher conversion values as compared to the wall-isothermal MR for the same operating conditions.
Model Predictions for Industrial-Scale Systems

Catalyst Effectiveness Factor Profiles in AR

AR→r_catalyst=0.035 cm (lab scale)

AR→r_catalyst=0.5 cm (industrial scale)

Axial Averaged Effectiveness Factor

Time (s)
Model Predictions for Industrial-Scale Systems

Adsorbent Effectiveness Factor Profiles in AR

Graphs showing adsorbent effectiveness factor profiles for different reactor conditions.
Preliminary TEA - MR-AR IGCC Process Scheme
Preliminary TEA - CAPEX/OPEX of the MR-AR Process

Capital Cost Analysis of the MR-AR IGCC Process

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Operating Cost Analysis of the MR-AR IGCC Process

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<th>Variable Operating Costs</th>
<th>Consumption</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
<td>Daily</td>
</tr>
<tr>
<td>Water (/1000 gallons):</td>
<td>0</td>
<td>4,201</td>
</tr>
<tr>
<td>Makeup and Waste Water Treatment Chemicals (lbs):</td>
<td>0</td>
<td>25,026</td>
</tr>
<tr>
<td>Carbon (Mercury Removal) (lb):</td>
<td>135,182</td>
<td>231</td>
</tr>
<tr>
<td>Shift Catalyst (ft³):</td>
<td>5,452</td>
<td>3.39</td>
</tr>
<tr>
<td>Adsorbent (lb):</td>
<td>910.368</td>
<td>0.81</td>
</tr>
<tr>
<td>Selexol Solution (gal):</td>
<td>242,554</td>
<td>36</td>
</tr>
<tr>
<td>Claus Catalyst (ft³):</td>
<td>w/equip</td>
<td>2.01</td>
</tr>
<tr>
<td>Subtotal:</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Differences in Performance between MR-AR and Baseline IGCC Plants

### Performance Summary

<table>
<thead>
<tr>
<th></th>
<th>Baseline IGCC with CCS (Case B5B)</th>
<th>MR-AR IGCC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Combustion Turbine Power, MWe</strong></td>
<td>464</td>
<td>464</td>
</tr>
<tr>
<td><strong>Sweet Gas Expander Power, MWe</strong></td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td><strong>Steam Turbine Power, MWe</strong></td>
<td>264</td>
<td>264</td>
</tr>
<tr>
<td><strong>Total Gross Power, MWe</strong></td>
<td>734</td>
<td>731</td>
</tr>
<tr>
<td><strong>CO₂ Compression, kWe</strong></td>
<td>31,160</td>
<td>2,997</td>
</tr>
<tr>
<td><strong>Hydrogen Compression, kWe</strong></td>
<td>0</td>
<td>5,692</td>
</tr>
<tr>
<td><strong>Water Pump, kWe</strong></td>
<td>0</td>
<td>150</td>
</tr>
<tr>
<td><strong>Acid Gas Removal, kWe</strong></td>
<td>19,230</td>
<td>2,590</td>
</tr>
<tr>
<td><strong>Total Auxiliaries, MWe</strong></td>
<td>191</td>
<td>152</td>
</tr>
<tr>
<td><strong>Net Power, MWe</strong></td>
<td>543</td>
<td>579</td>
</tr>
</tbody>
</table>

### COE Breakdown for the MR-AR and Baseline IGCC Plants

<table>
<thead>
<tr>
<th></th>
<th>Baseline IGCC with CCS (Case B5B)</th>
<th>MR-AR IGCC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>COE Component</strong></td>
<td>Value, $/MWh</td>
<td>Value, $/MWh</td>
</tr>
<tr>
<td>Capital Cost</td>
<td>74.2</td>
<td>60.3/(56.1)</td>
</tr>
<tr>
<td>Fixed Operating Cost</td>
<td>18.2</td>
<td>17.1/(15.9)</td>
</tr>
<tr>
<td>Variable Operating Cost</td>
<td>12.2</td>
<td>9.8/(9.1)</td>
</tr>
<tr>
<td>Fuel Cost</td>
<td>30.7</td>
<td>28.8/(26.8)</td>
</tr>
<tr>
<td>Total COE</td>
<td>135.4</td>
<td>51.4/(43.3)</td>
</tr>
</tbody>
</table>

### Comparison in Performance between MR-AR and Baseline IGCC Plants

<table>
<thead>
<tr>
<th>Designs</th>
<th>Net Power Production (MWe)</th>
<th>CO₂ Capture (%)</th>
<th>CO₂ Purity</th>
<th>COE ($/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGCC w/o CCS (Case B5A)</td>
<td>622</td>
<td>0</td>
<td>n/a</td>
<td>102.6</td>
</tr>
<tr>
<td>IGCC w/ CCS–Dual Stage Selexol (Case B5B)</td>
<td>543</td>
<td>90</td>
<td>99</td>
<td>135.4</td>
</tr>
<tr>
<td>MR-AR IGCC Plant</td>
<td>588</td>
<td>90.6</td>
<td>99</td>
<td>51.4/(43.3)</td>
</tr>
</tbody>
</table>
# Milestone Log – BP2

<table>
<thead>
<tr>
<th>Budget Period</th>
<th>ID</th>
<th>Task</th>
<th>Description</th>
<th>Planned Completion Date</th>
<th>Actual Completion Date</th>
<th>Verification Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>i</td>
<td>5</td>
<td>Parametric testing of the integrated, lab-scale MR-AR system and identification of optimal operating conditions for long-term testing completed</td>
<td>9/30/2017</td>
<td>9/30/2017</td>
<td>Results reported in the quarterly report</td>
</tr>
<tr>
<td>2</td>
<td>j</td>
<td>5</td>
<td>Short-term (24 hr for initial screening) and long-term (&gt;100 hr) hydrothermal and chemical stability (e.g., NH₃, H₂S, H₂O, etc.) materials evaluations at the anticipated process conditions completed</td>
<td>3/31/2018</td>
<td>3/31/2018</td>
<td>Results reported in the quarterly report</td>
</tr>
<tr>
<td>2</td>
<td>k</td>
<td>5</td>
<td>Integrated system modeling and data analysis completed</td>
<td>3/31/2018</td>
<td>3/31/2018</td>
<td>Results reported in the quarterly report</td>
</tr>
<tr>
<td>2</td>
<td>l</td>
<td>5</td>
<td>Materials optimization with respect to membrane permeance/selectivity and adsorbent working capacity at the anticipated process conditions (up to 300°C for membranes and 300-450°C for adsorbents, and up to 25 bar total pressure) completed</td>
<td>12/31/2018</td>
<td></td>
<td>Results reported in the quarterly report</td>
</tr>
<tr>
<td>2</td>
<td>m</td>
<td>5</td>
<td>Operation of the integrated lab-scale MR-AR system for at least 500 hr at the optimal operating conditions to evaluate material stability and process operability completed</td>
<td>12/31/2018</td>
<td></td>
<td>Results reported in the quarterly report</td>
</tr>
<tr>
<td>2</td>
<td>n</td>
<td>6</td>
<td>Preliminary process design and optimization based on integrated MR-AR experimental results completed</td>
<td>3/31/2019</td>
<td></td>
<td>Results reported in Final Report</td>
</tr>
<tr>
<td>2</td>
<td>o</td>
<td>6</td>
<td>Initial technical and economic feasibility study and sensitivity analysis completed</td>
<td>3/31/2019</td>
<td></td>
<td>Results reported in Final Report</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,2</td>
<td>QR</td>
<td>1</td>
<td>Quarterly report</td>
<td>Each quarter</td>
<td></td>
<td>Quarterly Report files</td>
</tr>
</tbody>
</table>
**Success Criteria - BP2**

<table>
<thead>
<tr>
<th>Decision Point</th>
<th>Basis for Decision/Success Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Completion of Budget Period 2</td>
<td>Successful completion of all work proposed in Budget Period 2.</td>
</tr>
<tr>
<td></td>
<td>Completion of short-term (24 hr) and long-term (&gt;100 hr) hydrothermal/chemical stability evaluations. Membranes/adsorbents are stable towards fuel gas constituents (e.g., NH₃, H₂S, H₂O) at the anticipated process operating conditions. Target &lt;10% decline in performance over 100 hr of testing.</td>
</tr>
<tr>
<td></td>
<td>Completion of integrated testing and system operated for &gt;500 hr at optimal process conditions.</td>
</tr>
<tr>
<td></td>
<td>Results of the initial technical and economic feasibility study show significant progress toward achievement of the overall fossil energy performance goals of 90% CO₂ capture rate with 95% CO₂ purity at a cost of electricity 30% less than baseline capture approaches</td>
</tr>
<tr>
<td></td>
<td>Submission of updated membrane and adsorbent state-point data tables based on the results of integrated lab-scale MR-AR testing</td>
</tr>
<tr>
<td></td>
<td>Submission of a Final Report</td>
</tr>
</tbody>
</table>
Acknowledgements

The financial support of the US Department of Energy, the technical guidance and assistance of our Project Manager Andrew Jones, and helpful discussions with Ms. Lynn Brickett are gratefully acknowledged.