A High Efficiency, Ultra-Compact Process For Pre-Combustion CO$_2$ Capture

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Presentation Outline

• Project Overview
• Technology Background
• Technical Approach/Project Scope
• Project Technical Progress and Key Accomplishments and Findings
• Appendix – Technical Publications
**Project Overview**

**Performance Period:** 10-01-2015 – 3-31-2019  

**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% CO₂ capture rate with 95% CO₂ 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
- Use of Partial Pressure Swing Adsorption based regeneration allows CO$_2$ recovery 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/F₇₀ (K₇₀cat/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
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:
- $H_2$ Permeance (350 – 500 GPU);
- $H_2$/CO>80 (Equivalent to $He/N_2$>100)

He/N$_2$ used as $H_2$/CO surrogates in routine permeation tests. He and $H_2$ permeances within 5-10% from each other ($H_2$, typically, faster). CO permeance, typically, 15-20% larger than N$_2$

<table>
<thead>
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<th>Part ID</th>
<th>$He$ [GPU]</th>
<th>$N_2$ [GPU]</th>
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Hydrotalcite (HTC) Adsorbent

- High CO₂ capacity: Over wide range of temperatures and pressures.
- Simple Preparation: Precipitation of Al/Mg from solution in NaOH/Na₂CO₃
- Stable: Unaffected by H₂S and simulated tars at the operating temperature.

**High-Pressure Adsorption Isotherm at 250 °C**

- Excess sorption (wt%/g) vs. Pressure (bar)
- Black squares: Before correcting
- Red circles: After correcting
Lab-Scale Experimental Set-Up
Lab-Scale Experimental Results and Analysis

Co-Mo/Al₂O₃ Sour-Shift Catalyst Characterization
Global Reaction Kinetics- Empirical Model and Comparison with Microkinetic Models

\[-r_{co} = A \ e^{\frac{-E}{RT}} \ p_{co}^a p_{H_2O}^b p_{co_2}^c p_{H_2}^d \ (1 - \beta)\]

\[\beta = \frac{1}{K_{eq}} \left( \frac{P_{CO_2} \cdot P_{H_2}}{K_{eq} (P_{CO} \cdot P_{H_2O})} \right) \ K_{eq} = \exp\left(\frac{4577.8}{T} - 4.33\right)\]

Root-Mean-Square Deviation (RMSD)

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<th>Type</th>
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<td>Direct oxidation</td>
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<td>Associative</td>
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<td>Formate intermediate</td>
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<td>Empirical model</td>
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<table>
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<tr>
<td>a</td>
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<td>b</td>
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<td>c</td>
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<td>d</td>
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Lab-Scale Experimental Results and Analysis, Cont.

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)

\[ X_{CO} = \frac{n_{CO}^E - (n_{CO,exit}^E + n_{CO,exit}^E)}{n_{CO}^E} \]
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/F₇Co=55 g·h/mol.
Experimental Results of Catalyst Robustness During Adsorbent Regeneration

AR pseudo-steady conversion after adsorbent saturation for various regeneration protocols, as shown on the Figure. Temp.=250 °C, pressure=5 bar, $W_c/F_{CO}=121$ g·h/mol, $W_{Ad}/W_c=6.9:1$. 
500-hr Integrated MR-AR Run

Evaluation of Membrane Stability

T= 250 °C, feed pressure of 25 bar with steam sweep (CMS#23).
T=250 °C, feed pressure=25 bar, permeate pressure 3 bar, with steam sweep, \( W_c/F_{CO} = 66 \text{ g·h/mol} \), air-blown gasifier model syngas (CMS#23).
Multi-Scale MR-AR Model for Process Scale-Up

Membrane Reactor (MR)/Adsorptive Reactor (AR) Sequence

\[
\text{Syngas} \quad \xrightarrow{\text{Sweep} (H_2O)} \quad \text{Permeation Zone} \quad \xrightarrow{\text{CO} + H_2O \leftrightarrow CO_2 + H_2} \quad \text{Reaction Zone} \quad \xrightarrow{\text{CH}_4, \text{H}_2, \text{CO}, \text{CO}_2, \text{H}_2\text{O}} \quad \text{Sweep} (H_2O) \quad \text{Water} \quad \xrightarrow{\text{Water} + \text{CO}_2} \quad \text{Water} + \text{CO}_2 \quad \xrightarrow{\text{CO}_2 \geq 20 \text{ bar}} \quad \text{Carbon Dried} \quad \xrightarrow{\text{CO}_2 \text{ Drying andCompression}} \quad \text{CO}_2 \text{ to storage} 150 \text{ bar}
### Pellet-scale Model Equations & Boundary Conditions

**Constitutive laws**

**Continuity Equation:**

\[
\nabla \cdot \left( \varepsilon_i^n \rho_i \nabla \right) v_j = \sum_{j=1}^{n} \left( 1 - \varepsilon_i^n \right) \rho_i \sum_{k=1}^{n_k} R_k v_{jk}
\]

**Component mass conservation:**

\[
\nabla \cdot \left( \varepsilon_i^n x_i^n c_i^n v_j^n \right) + \nabla \cdot \left( \varepsilon_i^n n_i^n v_j^n \right) = \left( 1 - \varepsilon_i^n \right) \rho_i \sum_{k=1}^{n_k} R_k v_{jk}
\]

**Energy conservation:**

\[
\left( \sum_{j=1}^{n} \varepsilon_i^n x_i^n c_i^n C_j \right) v_j^n \cdot \left( \nabla T^n \right) = \nabla \cdot \left( \lambda \nabla T^n \right) + \left( 1 - \varepsilon_i^n \right) \rho_i \sum_{k=1}^{n_k} \Delta H_{rk} R_k
\]

**Initial Conditions:**

- \( x_{j}^0 = 0 \)
- \( n_{j}^0 = 0 \)
- \( T^p = T' = T_{m} \)
- \( p^p = 0 \)
- \( Q_r = -\lambda \nabla T^p = 0 \)
- \( \nabla p^p = 0 \)

**Boundary Conditions:**

\[
\begin{align*}
\varepsilon_i^n v_j^n &= 0, \quad Q_r = -\lambda \nabla T^p = 0, \quad \text{for } r = 0 \\
\varepsilon_i^n x_i^n c_i^n C_j^n v_j^n &= \left( 1 - \varepsilon_i^n \right) \rho_i \sum_{k=1}^{n_k} R_k v_{jk} \\
\end{align*}
\]

\[
\begin{align*}
T^r = T_{m} \quad \text{for } t = 0, \forall r \quad (30) \\
p^r = p_{m}^r \\
x_{j}^r &= x_{j}^0 \\
p^r &= p^r
\end{align*}
\]

### Reactor-scale Reaction Zone Model Equations & Boundary Conditions

**Bulk Gas Constitutive laws**

**Continuity Equation:**

\[
\nabla \cdot \left( \varepsilon_i^n c_i^n v_j^n \right) = \sum_{j=1}^{n} \beta_{cm} \left( 1 - \varepsilon_i^n \right) \eta_j \rho_j \sum_{k=1}^{n_k} R_k v_{jk} - \frac{2}{R_{m}^c} \sum_{j=1}^{n} J_{perm}^c
\]

**Component mass conservation:**

\[
\nabla \cdot \left( \varepsilon_i^n x_i^n c_i^n v_j^n \right) + \nabla \cdot \left( \varepsilon_i^n n_i^n v_j^n \right) = \beta_{cm} \left( 1 - \varepsilon_i^n \right) \eta_j \rho_j \sum_{k=1}^{n_k} R_k v_{jk} - \frac{2}{R_{m}^c} J_{perm}^c
\]

**Energy conservation:**

\[
\left[ \varepsilon_i^n \sum_{j=1}^{n} x_i^n c_i^n C_j^n \right] v_j^n \cdot \left( \nabla T^n \right) - \nabla \cdot \left( \lambda \nabla T^n \right) + \frac{A_{SM}^S}{V'} J_{perm}^c \left( H_j^c - H_j^{perm} \right) = \]

\[
\left[ a_w h_{cal} \left( T^r - T_{m} \right) + a_m h_{stm} \left( T^r - T_{m} \right) \right] - \frac{A_{SM}^S}{V'} \left( T^r - T_{m} \right) + \frac{4U}{d_i} \left( T_{for} - T^r \right)
\]

**Initial Conditions:**

- \( x_{j}^r = 0 \)
- \( T^r = T_{m} \) for \( t = 0, \forall z \) (35)
- \( p^r = p_{m}^r \)

**Boundary Conditions:**

\[
\begin{align*}
\varepsilon_i^n v_j^n &= \left( \varepsilon_i^n \right)_m \\
p^r &= p_{m}^r \\
x_{j}^r &= \left( x_{j}^r \right)_m \\
T^r &= T_{m}^r \\
\varepsilon_i^n v_j^n &= 0, \quad \text{for } z = 0 \\
\varepsilon_i^n x_i^n c_i^n C_j^n v_j^n &= \left( 1 - \varepsilon_i^n \right) \rho_i \sum_{k=1}^{n_k} R_k v_{jk} - \frac{2}{R_{m}^c} J_{perm}^c \\
\varepsilon_i^n n_i^n v_j^n &= 0, \quad \text{for } z = L \\
\varepsilon_i^n v_j^n &= 0
\end{align*}
\]
Multi-Scale MR-AR Model for Process Scale-Up – MR System

MR Reactor-scale Permeation Zone Model Equations

Bulk Gas Constitutive laws

**Continuity Equation:**

\[
\vec{\nabla} \cdot \left( c_f \vec{v}_{\text{perm}} \right) = \frac{2}{R_{\text{perm}}} \sum_{j=1}^{N_j} J_{j\text{perm}}
\]

Component mass conservation:

\[
\vec{\nabla} \cdot \left( x_j c_f \vec{v}_{\text{perm}} \right) = \frac{2}{R_{\text{perm}}} J_{j\text{perm}}
\]

Energy conservation:

\[
\left\{ \sum_{j=1}^{N_j} x_j c_f c^\text{perm}_f \frac{\vec{v}_{\text{perm}}}{v_{\text{perm}}} \left( \vec{\nabla} T^\text{perm} \right) = \vec{\nabla} \cdot \left( \lambda \vec{\nabla} T^\text{perm} \right) + \frac{A^\text{SM}}{v_{\text{perm}}} \left( T^r - T^\text{perm} \right) + \frac{A^\text{SM}}{v_{\text{perm}}} J_{j\text{perm}} \left( H^r - H^\text{perm} \right) \right\}
\]

Dusty Gas Model

\[
- \frac{1}{\rho} \sum_{j=1}^{N} \sum_{j'=1}^{N_j} \left( \frac{c_j}{D_{ij}} \vec{N}_j - \frac{c_j}{D_{ij}} \vec{N}_{ij} \right) = \frac{\vec{N}}{D_{ij}} = \vec{\nabla} c_i + \frac{c_i}{\sum_{j=1}^{N_j} c_i} \left( 1 + \frac{p}{D_{ij}} \frac{B_i}{\mu_j} \right) \vec{\nabla} p
\]

The Stefan-Maxwell Equation

\[
x_i = \frac{\sum_{j=1}^{N_j} x_j c_j}{\rho_j} \left( \frac{1}{J_{i}} - \frac{1}{\rho_j} (w_i - x_i) \frac{\vec{\nabla} p}{p} + \frac{\sum_{j=1}^{N_j} x_j c_j}{\rho_j} \frac{D^r_{ij}}{w_i} - \frac{D^r_{ij}}{w_i} \left( \vec{\nabla} T \right) \frac{T}{T} \right)
\]

Momentum Equation

\[
\vec{\nabla} P = -K_D \vec{v} - K_p \vec{v} = \vec{\nabla} p = \left\{ \begin{array}{ll}
-150 \left( 1 - \varepsilon^r \right)^2 & \text{for } z = 0 \\
\frac{\varepsilon^r}{d_p^2} - \mu' \left( 1 - \varepsilon^r \right)^3 & \text{for } z = L
\end{array} \right.
\]

Initial Conditions:

\[
x_f^\text{perm} = 0 \\
T^\text{perm} = T_m^\text{perm} \\
p^\text{perm} = p_m^\text{perm}
\]

for \( t = 0, \forall z \) (47)

Boundary Conditions:

\[
\begin{align*}
\vec{v}^\text{perm} &= \vec{v}_m^\text{perm} \\
p^\text{perm} &= p_m^\text{perm} \\
x_f^\text{perm} &= x_f^m \\
T^r &= T_m^\text{perm} \\
\vec{\nabla} T^\text{perm} &= 0 \\
\vec{\nabla} p^\text{perm} &= 0
\end{align*}
\]

for \( z = L \)
Multi-Scale MR-AR Model for Process Scale-Up – AR System

Component Mass Balances

\[
\frac{\partial}{\partial t} \left( \varepsilon_{\text{tot, gas}} c_j^g \right) + \nabla \cdot \left( \mathbf{v}_f^g c_j^g \right) = \varepsilon_{\text{gas-bed}} \nabla D_{z,i} \left( \nabla c_j^g \right) + \left( 1 - \varepsilon_{\text{gas-bed}} \right) \eta_j \beta_{\text{cat}} \rho_{\text{cat}} R_j - \left( 1 - \varepsilon_{\text{gas-bed}} \right) \phi_{\text{ad}} \rho_{\text{ad}} R_{\text{ad}}
\]

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

Energy balance:

\[
\left\{ \left( 1 - \varepsilon_{\text{gas-bed}} \right) \beta_{\text{cat}} \rho_c^c C_c^g + \left( 1 - \varepsilon_{\text{gas-bed}} \right) \phi_{\text{ad}} \rho_{\text{ad}}^c C_{\text{ad}}^g + \left( 1 - \varepsilon_{\text{gas-bed}} \right) \varphi_{\text{qua}} \rho_{\text{qua}}^g C_{\text{qua}}^g + \sum_{j=1}^{n} \varepsilon_j^r c_j^r C_j^r \right\} \frac{\partial T^r}{\partial t} + \nabla \cdot \left( \lambda \nabla T^r \right) + \left( 1 - \varepsilon_{\text{gas-bed}} \right) \eta_j \beta_{\text{cat}} \rho_{\text{cat}} \sum_{j=1}^{n} H_j R_j - \left( 1 - \varepsilon_{\text{gas-bed}} \right) \phi_{\text{ad}} \rho_{\text{ad}} \Delta H_{\text{ad}} R_{\text{ad}} + \frac{4 h_w}{d_t} (T_w - T^r)
\]

Momentum balance:

\[
\nabla P^r = -K_D \mathbf{v}_f^r - K_v \mathbf{v}_f^r \nabla \mathbf{v}_f^r = \nabla P^r = \left\{ -150 \frac{1 - \varepsilon_{\text{gas-bed}}^2}{\varepsilon_{\text{gas-bed}}^3} d_p^2 - \mu_f^r 1.75 \frac{1 - \varepsilon_{\text{gas-bed}}}{\varepsilon_{\text{gas-bed}}^3} d_p \rho_f^r \right\} \mathbf{v}_f^r
\]
Multi-Scale MR-AR Model for Process Scale-Up – AR System

Initial and boundary conditions for the AR model.

**Initial Conditions:**

\[ \begin{align*}
\vec{v}' &= \left( \vec{v}' \right)_{in} \\
\rho' &= \rho'_{in} \\
c'_j &= 0 \\
T' &= T'_{in} \\
P' &= P'_{in}
\end{align*} \]

**Boundary Conditions:**

\[ \begin{align*}
\vec{v}' &= \left( \vec{v}' \right)_{in} \\
\rho' &= \rho'_{in} \\
c'_j &= \left( c'_j \right)_{in} \\
T' &= T'_{in} \\
P' &= P'_{in}
\end{align*} \]

for \( z = 0 \)

\[ \begin{align*}
\vec{v}' &= \left( \vec{v}' \right)_{in} \\
\rho' &= \rho'_{in} \\
c'_j &= \left( c'_j \right)_{in} \\
T' &= T'_{in} \\
P' &= P'_{in}
\end{align*} \]

for \( z = L \)

**Constitutive laws and other property equations.**

**Gas Law:**

\[ c'_{TOT} = \frac{P}{ZRT} \]

**Definitions:**

\[ \sum_{j=1}^{N} x_j = 1, \quad c''_{tot} = \sum_{j=1}^{N} c''_j, \quad P = \sum_{j=1}^{N} P_j, \quad \beta_{tot} + \phi_{tot} + \phi_{aux} = 1 \]

**Heat Flux (Fourier’s Law):**

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

**Dimensionless Groups:**

\[ \text{Nu} = \frac{\beta_{tot}}{\lambda_{tot}}, \quad \text{Re}_f = \frac{\rho_f v_f d_e}{\mu_f}, \quad \text{Pr} = \frac{C_p \mu}{\lambda} \]

**Viscosity of Gas Mixture:**

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

**Thermal Conductivity:**

\[ \lambda' = (1 - \epsilon') \beta_{tot} \lambda_{tot} + (1 - \epsilon') \phi_{tot} \lambda_{tot} + (1 - \epsilon') \phi_{aux} \lambda_{tot} + \epsilon' \lambda_{tot} \]

**Thermal Conductivity of Pure Gases:**

\[ \lambda_i = A_i + B_i T + C_i T^2 + D_i T^3 \]

**Thermal Conductivity of Gas Mixture:**

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

**Specific Heat Capacity of Pure Gases:**

\[ C_i = a_{i0} + a_{i1} T + a_{i2} T^2 + a_{i3} T^3 + a_{i4} T^4 \]

**Specific Heat Capacity of Gas Mixture:**

\[ C_{tot} = \sum_{i=1}^{N} x_i C_i \]

22
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)

\[ X_{CO} = \frac{n_{CO_{exit}}^F - (n_{CO_{exit}}^F + n_{CO_{exit}}^P)}{n_{CO_{exit}}^F} \]
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_{\text{cat}}/F_{\text{CO}}=55 \text{ on MR})

Temperature = 250 °C, Pressure = 15 bar.
(W_{\text{cat}}/F_{\text{CO}}=66 \text{ 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
## Preliminary TEA - MR-AR IGCC Process

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<th>Designs</th>
<th>Net Power Production (MWe)</th>
<th>CO$_2$ Capture (%)</th>
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<td>0</td>
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<tr>
<td>Shell IGCC w/ CCS – 2 Stage Selexol</td>
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<td>90</td>
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<tr>
<td>MR-AR IGCC Plant</td>
<td>593</td>
<td>92</td>
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### Preliminary TEA - MR-AR IGCC Process

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<th>Conversion</th>
<th>Catalyst Amount (ft³)</th>
<th>Adsorbent (kg)</th>
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<td>MR-AR Combined System</td>
<td>99%</td>
<td>4,064* (2,553**)</td>
<td>606,912</td>
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<tr>
<td>IGCC WGS Reactor</td>
<td>97%</td>
<td>6,246</td>
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<tr>
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<th>% CO Conversion</th>
<th>% H₂ Recovery</th>
<th>% CO₂ Purity</th>
<th>% CO₂ Recovery</th>
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<td>&gt;90</td>
<td>&gt;95</td>
<td>&gt;90</td>
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<td>MR-AR Realization</td>
<td>99%</td>
<td>99</td>
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<td>92</td>
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</tbody>
</table>

*Initial Purchase Catalyst*: Amount of catalyst needed to initially load all MR-AR reactors (which contributes to the catalyst capital cost) is 4,064 ft³

**Operating Purchase Catalyst**: AR is operated periodically and catalyst is not exposed continuously to reaction, and thus catalyst’s lifetime is longer than baseline design. Amount of catalyst for replacement (which contributes to the catalyst operating cost) is 2,553 ft³
## Preliminary TEA - MR-AR IGCC Process

<table>
<thead>
<tr>
<th>Process</th>
<th>Capital Cost ($/1000)</th>
<th>Variable Operating Cost ($)</th>
<th>Net Power (MWe)</th>
<th>N₂ Product (ton/h)</th>
<th>COE (No N₂ sale/ N₂ Sale) ($)</th>
<th>% COE reduction vs Baseline (No N₂ sale/ N₂ Sale)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGCC CCS</td>
<td>$1,840,115</td>
<td>$46,580,032</td>
<td>543</td>
<td>0</td>
<td>135.4</td>
<td>0</td>
</tr>
<tr>
<td>MR-AR Realization</td>
<td>$1,539,820</td>
<td>$47,672,487</td>
<td>593</td>
<td>619</td>
<td>113.1 / 86.3</td>
<td>16.4% / 36%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>Net Power (MWe)</th>
<th>COE (No N₂ sale/ N₂ Sale) ($)</th>
<th>CO₂ Captured Cost (No N₂ sale/ N₂ Sale) ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGCC CCS</td>
<td>543</td>
<td>135.4</td>
<td>63.2</td>
</tr>
<tr>
<td>MR-AR Realization</td>
<td>593</td>
<td>113.1 / 86.3</td>
<td>39.3 / 5.1</td>
</tr>
</tbody>
</table>
### Sensitivity Analysis – Membrane Reactor Lifespan

<table>
<thead>
<tr>
<th>Consumption</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Fill</td>
<td>Per Day</td>
</tr>
<tr>
<td>Membrane Packs (m²)</td>
<td>w/equip</td>
</tr>
<tr>
<td>Total Variable Cost:</td>
<td></td>
</tr>
<tr>
<td>Total COE:</td>
<td></td>
</tr>
</tbody>
</table>

#### 10-Year MR Lifespan

<table>
<thead>
<tr>
<th>Membrane Packs (m²)</th>
<th>w/equip</th>
<th>n/a</th>
<th>$650</th>
<th>$0</th>
<th>$1,071,560</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Variable Cost:</td>
<td></td>
<td></td>
<td>$10,074,435</td>
<td>$48,208,277</td>
<td></td>
</tr>
<tr>
<td>Total COE:</td>
<td></td>
<td></td>
<td></td>
<td>86.5</td>
<td></td>
</tr>
</tbody>
</table>

#### 5-Year MR Lifespan

<table>
<thead>
<tr>
<th>Membrane Packs (m²)</th>
<th>w/equip</th>
<th>n/a</th>
<th>$650</th>
<th>$0</th>
<th>$2,678,900</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Variable Cost:</td>
<td></td>
<td></td>
<td>$10,074,435</td>
<td>$49,815,607</td>
<td></td>
</tr>
<tr>
<td>Total COE:</td>
<td></td>
<td></td>
<td></td>
<td>86.8</td>
<td></td>
</tr>
</tbody>
</table>

#### 2-Year MR Lifespan

- **MR Lifespan utilized in TEA is 10-year lifespan**
  - *A 5-year lifespan increases total COE by 0.2%*
  - *A 2-year lifespan increases total COE by 0.6%*
Sensitivity Analysis for Critical Technology Parameters

<table>
<thead>
<tr>
<th>Sensitivity Analysis – Nitrogen Sale Price</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumption</td>
<td></td>
</tr>
<tr>
<td>Initial Fill</td>
<td>Per Day</td>
</tr>
<tr>
<td>$30/ton Nitrogen Price</td>
<td></td>
</tr>
<tr>
<td>Nitrogen (tons)</td>
<td>0</td>
</tr>
<tr>
<td>Total COE ($/MWh)</td>
<td></td>
</tr>
<tr>
<td>$1/ton Nitrogen Price</td>
<td></td>
</tr>
<tr>
<td>Nitrogen (tons)</td>
<td>w/equip</td>
</tr>
<tr>
<td>Total COE ($/MWh)</td>
<td></td>
</tr>
<tr>
<td>$414/ton Nitrogen Price</td>
<td></td>
</tr>
<tr>
<td>Nitrogen (tons)</td>
<td>w/equip</td>
</tr>
<tr>
<td>Total COE ($/MWh)</td>
<td></td>
</tr>
</tbody>
</table>

- **Baseline COE 135.4 $/MWh**
- A \( N_2 \) sale price of $30/ton reduces COE from the baseline by 36.3%
- A \( N_2 \) sale price of $1/ton reduces COE from the baseline by 17.1%
- A \( N_2 \) sale price of $414/ton yields a negative COE
Compact Process Advantages

- **Simultaneous CO conversion and H₂ and CO₂ separation**

- **MR-AR Compression Work:** <20% of IGCC w/CCS compression work

- **Catalyst Amount:** <50% of IGCC w/CCS catalyst amount

- **High-Purity Hydrogen Product**

- **Low-Grade Quality Nitrogen Product**

- **CO₂ capture cost ($/ton)**
  - IGCC w/CCS Baseline: 63.2
  - MR-AR with no N₂ Sales: 39.3
  - MR-AR with N₂ Sales (30$/ton): 5.1

- **COE Reduction target approached/met**
  - Target: Proposed Technology COE 30% lower than IGCC w/CCS COE
  - No N₂ Sales: MR-AR COE 16.5% lower than IGCC w/CCS COE
  - N₂ Sales (30$/ton): MR-AR COE 36% lower than IGCC w/CCS COE


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