Electrochemical Membrane for CO$_2$ Capture and Power Generation

DE-FE0007634

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Overall Project Objectives:

- Demonstrate ability of FCE’s electrochemical membrane (ECM)-based system to separate ≥ 90% of CO₂ from a simulated PC flue-gas stream suitable for sequestration or beneficial use
- Demonstrate that ECM system is an economical alternative for post-combustion CO₂ capture in PC-based power plants, and that it meets DOE objectives for incremental cost of electricity (COE)

Project Participants:

<table>
<thead>
<tr>
<th>FuelCell Energy Inc. (FCE)</th>
<th>System design, GAP analysis, ECM fabrication, and bench-scale testing of an 11.7 m² area ECM system for CO₂ capture.</th>
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<tbody>
<tr>
<td>Pacific Northwest National Laboratory (PNNL)</td>
<td>Test effects of flue gas contaminants on ECM.</td>
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<td>URS Corporation</td>
<td>Review ECM-based system design, equipment and plant costing, and flue gas clean-up system design.</td>
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## Project Tasks, Schedule and Funding

### Project Funding

<table>
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<tr>
<th></th>
<th>DOE Share</th>
<th>FCE Cost Share</th>
<th>Project Total</th>
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<tbody>
<tr>
<td>Task 1 Project Management</td>
<td>$3,034,106</td>
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<td>Task 2 Technical and Economic Feasibility Study (T&amp;EFS)</td>
<td>$758,527</td>
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<td>Task 3 Technology Gap Identification</td>
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<td>Task 3.1 Contaminant Evaluation</td>
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<td>Task 3.3 BOP Equipment Update</td>
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<td>Task 5 Bench-Scale Testing</td>
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Electrochemical Membrane (ECM) Technology

The driving force for CO$_2$ separation is electrochemical potential, not pressure differential across the membrane.

Net Results

- Simultaneous Power Production and CO$_2$ Separation from Flue Gas of an Existing Facility
- Excess Process Water Byproduct
- Complete Selectivity towards CO$_2$ as Compared to N$_2$
• 59MW power plant consisting of 42 stack modules adequate to power ~ 140,000 homes in S. Korea
• Supplying electric grid and district heating system
• Constructed in only 14 months
Techno-Economic Analysis
CEPACS System Block Flow Diagram

Combined Electric Power and Carbon-dioxide Separation (CEPACS) System Concept Implementation for 550 MW Reference PC Plant*

CEPACS system produces:
- Supercritical CO₂ (90% CO₂ capture from PC Plant)
- Excess Process Water
- Additional 421 MW of clean AC power @ 42.4% Efficiency (based on LHV Natural Gas)

* Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 2, DOE/NELT-2010/1397, November 2010.
Techno-Economic Analysis Results

Cost of Electricity (2007 USD Basis)

- CEPACS System incremental COE meets DOE target of <35%

Cost of CO₂ Captured & Avoided (2011 USD Basis)

- CEPACS System can meet DOE Target of <$40/tonne CO₂ captured (2011 USD)
421MWe CEPACS Plant for >90% Carbon Capture from 550MWe Reference PC Plant requires ~ 12 Acres

CEPACS Plant Layout for Large Systems

CEPACS System modularity allows for isolation of a single enclosure, resulting in near-100% availability with >90% capacity factor.
ECM Testing Results
ECM Components and Single-Cell Testing Facilities

Laboratory facility for testing 250 cm$^2$ electrochemical membranes under a variety of system operating conditions.
Performance Comparison: Effect of Flue Gas Composition

ECM cell performance data for NGCC and PC plant flue gases at 93% carbon capture:

- ECM is capable of operating on flue gases with a wide range of CO₂ partial pressure
- System features (e.g. supplemental air addition, product recycle) allow tuning of cathode-side composition to optimize ECM performance
- High cell power densities at high CO₂ flux is observed in ECM tests
ECM Endurance Testing Results

- ECM cell stability testing at steady state PC flue gas-based system conditions for over 2200 hours of operation:

- The CO₂ flux remained constant through over 2200 hours of testing of a subscale membrane assembly (250 cm² area), indicating constant 90+% CO₂ capture
- The power production remained stable during test duration
Testing Goals:

- Assess physical and chemical interactions of main flue gas pollutants with ECM via experiments and thermodynamic modeling
- Determine effects of most volatile species (S, Cl, Hg, and Se) in flue gases on ECM performance
- Enable selection of clean-up technology for CEPACS System

Approach:

- Utilize ECM button cell tests to determine the effect of individual impurities on cell performance.
  - Maintain CO\textsubscript{2} flux
  - Measure ECM cell resistance and voltage
  - Analyze impurity effects on ECM using Electrochemical Impedance Spectroscopy (EIS)
- Perform post-test analyses using microscopy and surface analytical tools (SEM/EDS, TEM, FIB-SEM, AES, XPS, ToF-SIMS) to determine:
  - Nature of impurity-ECM interactions,
  - Presence of alteration phases formed from any reactions
  - Surface adsorption
Polishing equipment upstream of ECM reduces \( \text{SO}_2 \) concentration in the flue gas (cathode gas) to <1 ppm.

ECM stable operation has been verified with 0.4 - 1 ppm \( \text{SO}_2 \) in the cathode without significant performance loss in two 600+ hour tests.
ECM Flue Gas Contaminant Tolerance: Hg

- Stable operation was observed with 250 ppb Hg in ECM cathode gas (500 times higher than typically present in coal plant flue gas) during ~1,100 hour test
- Test data analysis confirmed no accumulation of Hg in ECM components
ECM Flue Gas Contaminant Tolerance: Selenium

- ECM displayed stable operation with 10 ppb Selenium (20-30x higher than expected levels) for over 860 hours of exposure
ECM Flue Gas Contaminant Tolerance: Chlorine

- ECM displayed no performance loss with exposure to 200 ppb HCl (10-20x higher than expected levels) for over 900 hours
ECM NO$_x$ Removal Mechanism

- Based on FCE’s prior experience:
  - ECM materials are not expected to be degraded by NOx in flue gas
  - CEPACS system offers co-benefit of NOx reduction

Reaction Mechanism by which NOx is removed from the Flue Gas (cathode-side), transferred to the anode-side along with CO$_2$, and subsequently destroyed
- ECM Capability for NO$_x$ Destruction Remains > 70% at High Inlet NO$_x$ Concentration (200 ppm) During Carbon Capture under System Conditions
CEPACS Demonstration system designed, assembled, and ready for testing

- 100 tons/year liquid CO₂ product
- Approximately 9 kW power production
The Technical and Economic Feasibility Study (T&EFS) of a CEPACS system to separate 90% of CO₂ from the flue gas of a Reference Plant (550 MW PC) has verified:

- Incremental cost of electricity (COE) of 35% and cost of CO₂ captured of $38/tonne CO₂ (2011 USD)
- Excess water available for export

Large-area ECM laboratory tests verified:

- High CO₂ flux (>120 cc/m²/s) while separating >90% of CO₂ from simulated PC or NGCC plant flue gas
- Capability to destroy 70-80% of NOₓ from flue gases
- Stability of CO₂ flux as the membrane ages

Contaminants tests indicated ECM is stable in the presence of S, Se, Cl, and Hg levels expected from a conventional wet-FGD polisher.

The Technology Gap analysis indicated that available commercial equipment can be used in CEPACS system with no R&D needed for BOP.

ECM is suitable for a wide range of carbon capture applications: Enhanced oil recovery, SAGD Tar Sands, coal and natural gas power plants, and industrial sites (cement factory & refineries).

Next step: Complete bench-scale CEPACS demonstration system for 100 tons/year carbon capture.
ECM Carbon Capture from Coal Plants supported by DOE/NETL (Award Number: DE-FE0007634)

Guidance from NETL team: Michael Matuszewski, Shailesh Vora, José Figueroa, Lynn Brickett, and others at NETL