FuelCell Energy

Electrochemical Membrane for CO_2 Capture and Power Generation

DE-FE0007634

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2013 NETL CO_2 Capture Technology Meeting

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Pittsburgh, PA

Ultra-Clean, Efficient, Reliable Power

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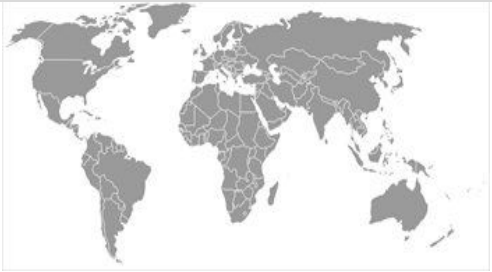
Manufacture	Sell (direct & via partners)	Install	Service



- Premier developer of stationary fuel cell products, with >40 years of experience
- Headquarters in Danbury, CT (USA), international presence in USA, Canada, Germany (Fraunhofer, IKTS) and South Korea (Posco)
- Delivering Direct FuelCell® (DFC®) power plants for On-Site Power and Utility Grid Support
- Over 80 Direct FuelCell plants generating power at more than 50 sites globally

Delivering ultra-clean baseload distributed generation globally

600 kW plant at a food processor

1.4 MW plant at a municipal building

2.4 MW plant owned by an Independent power producer

11.2 MW plant - largest fuel cell park in the world

DE-FE0007634 Project Outline

Overall Project Objectives:

- Demonstrate ability of FCE's electrochemical membrane (ECM)-based system to separate ≥ 90% of CO_2 from a simulated PC flue-gas stream and to compress the CO_2 for sequestration or beneficial use

- Demonstrate that ECM system is an economical alternative for post-combustion CO_2 capture in PC-based power plants, and that it meets DOE objectives for incremental cost of electricity (COE)

Project Participants:

FuelCell Energy Inc. (FCE)	**System design, GAP analysis, ECM fabrication, and bench-scale testing of an 11.7 m^2 area ECM system for CO_2 capture.**
Pacific Northwest National Laboratory (PNNL)	**Test effects of flue gas contaminants on ECM.**
URS Corporation	**Review ECM-based system design, equipment and plant costing, and flue gas clean-up system design.**

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Project Tasks and Schedule

Task	2012				2013				2014				2015			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1 Project Management and Planning																
Task 2 Preliminary Technical and Economic Feasibility Study (PT&EFS)																
PT&EFS Updates																
Task 3 Technology Gap Identification																
Task 3.1 Contaminant Evaluation																
Task 3.2 Membrane Testing																
Task 3.3 BOP Equipment Update																
Task 4 EH&S Review																
Task 5 Bench-scale Testing																

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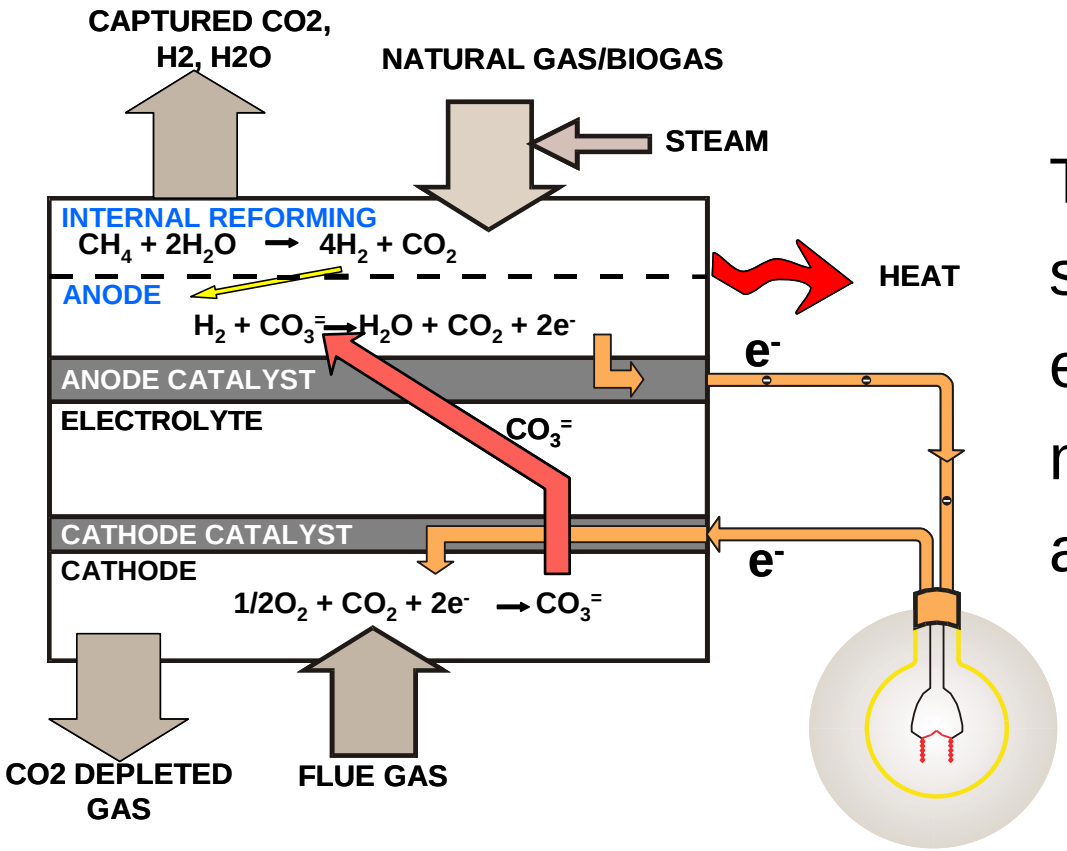
Electrochemical Membrane (ECM) Technology



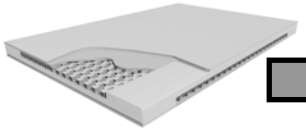
The driving force for CO_2 separation is electrochemical potential, not pressure differential across the membrane

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

ECM Module Assembly

Planar Electrochemical Membrane assemblies are stacked and incorporated into MW-scale modules



ECM Assembly

ECM Stack

Four-Stack Module

Enclosed Module

ECM is a modular technology:

- Ease of scale up and transport
- Suitable for incremental phased applications to almost any type of CO_2-emitting plant

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59 MW Fuel Cell Park

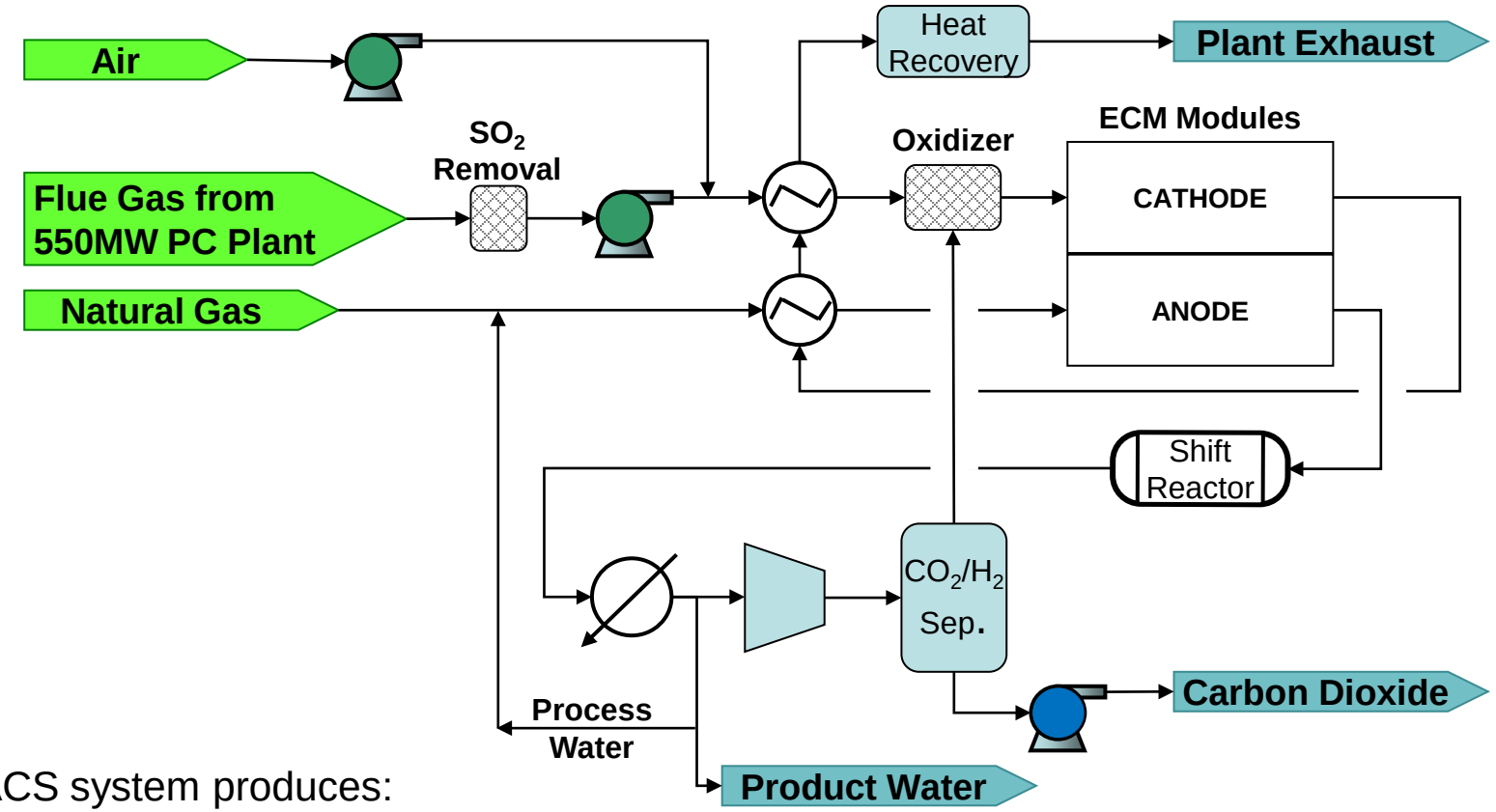
World's largest fuel cell installation

- Located in Hwasung City, S. Korea
- Comprised of 42 modules
- Expected to be fully operational in early 2014

Project being developed by POSCO, Korea Hydro Nuclear Power Co. (KHNP) and Samchully Gas Co in Hwaseong, South Korea

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 CO_2 (90% CO_2 capture from PC Plant)
- Excess Process Water
- Additional 441 MW of clean AC power @ 44.4% 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/NETL-2010/1397, November 2010.

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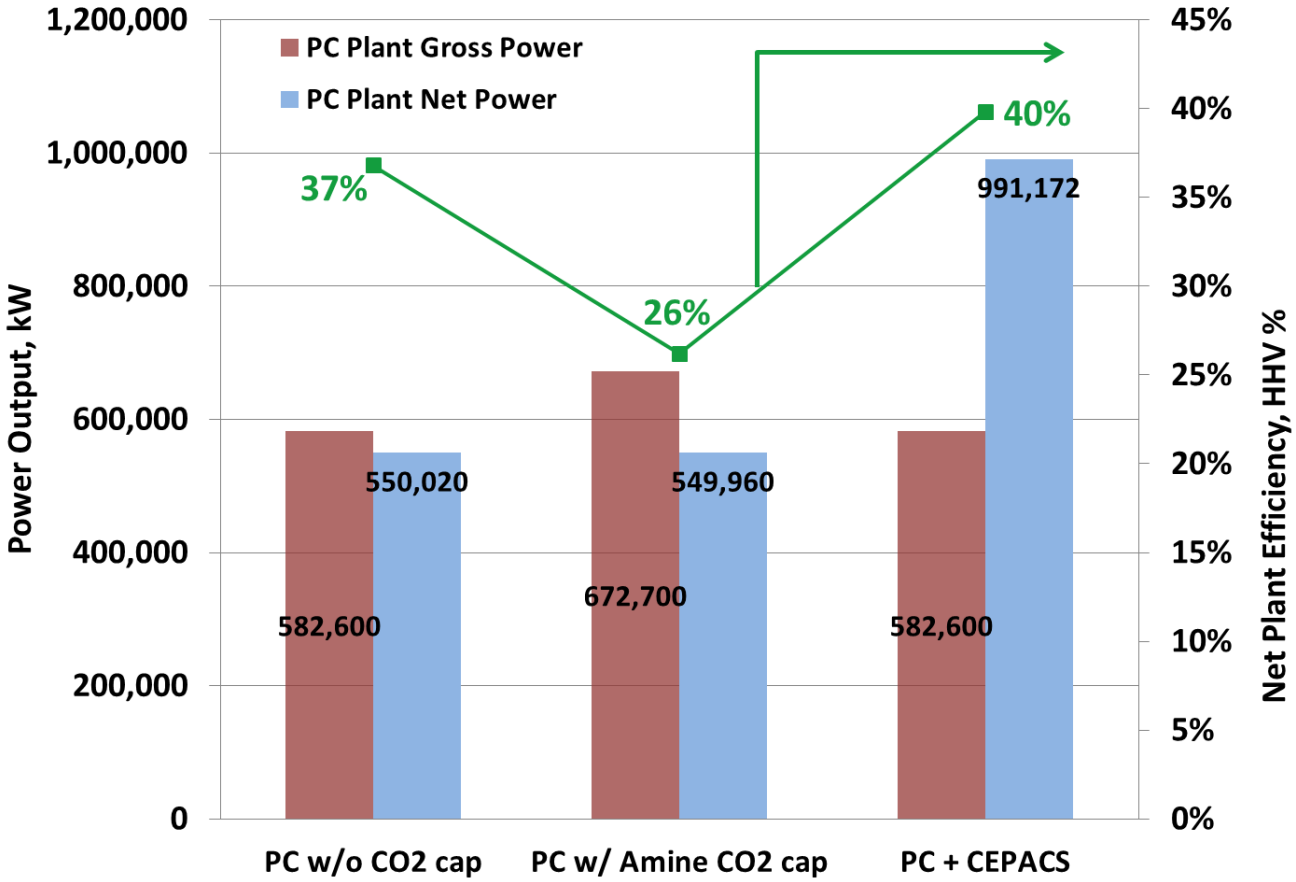
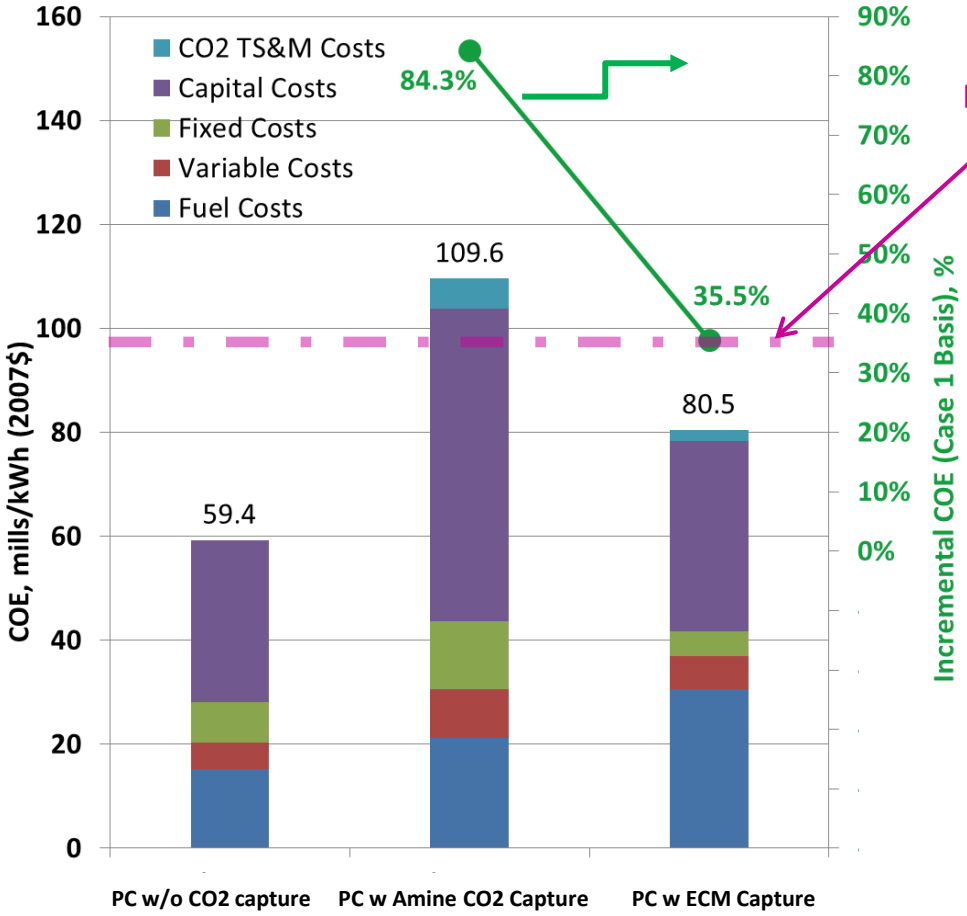
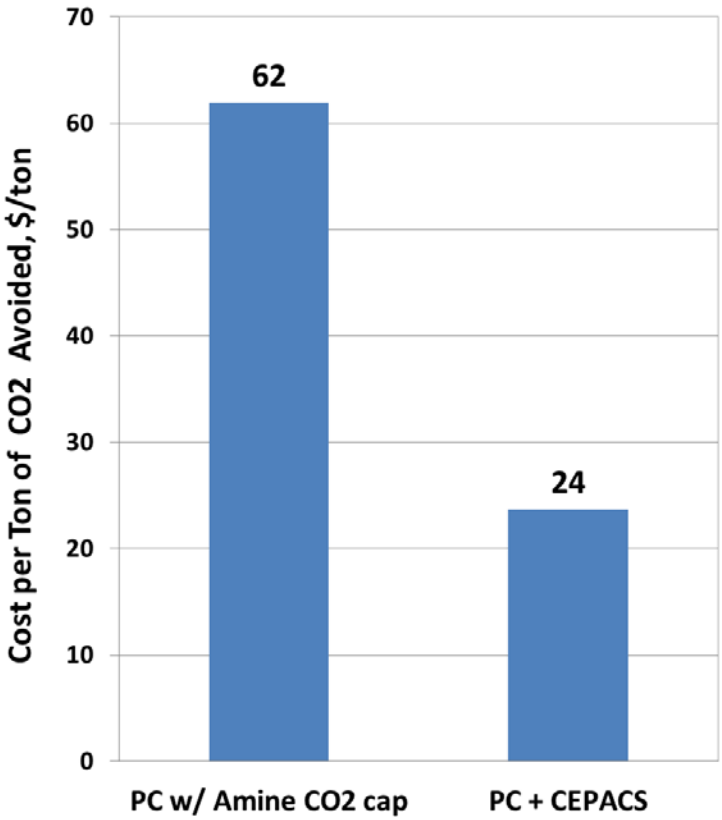
CEPACS System Performance



- CEPACS System increases power output of Baseline PC plant by 80% while capturing > 90% CO_2 from flue gas
- PC plant retrofitted with CEPACS system is 3 percentage points more efficient than Baseline PC Plant without carbon capture

ECM System Economics

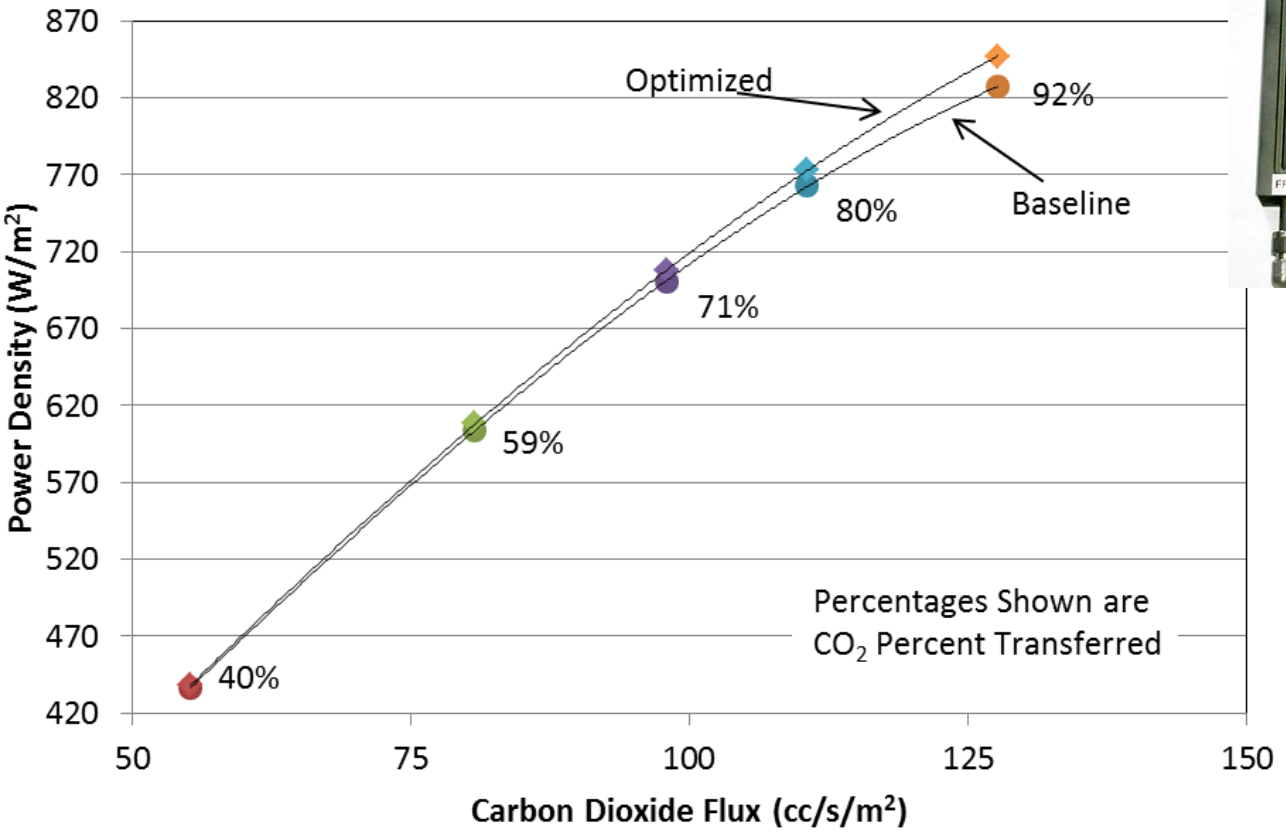


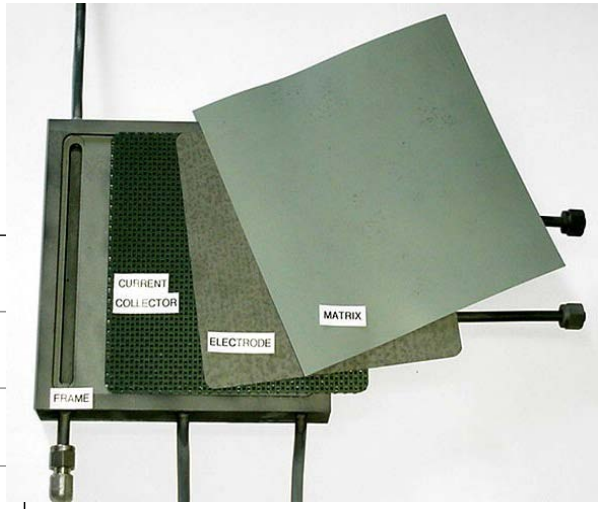


- PC plant retrofitted with ECM system can meet DOE incremental COE target of 35%
- Cost per ton of CO_2 avoided is reduced by more than 50% using ECM instead of Amine scrubber

System Performance Validation Tests

Performance of ECM for Carbon Capture from Reference PC Plant at Baseline and Optimized System Conditions

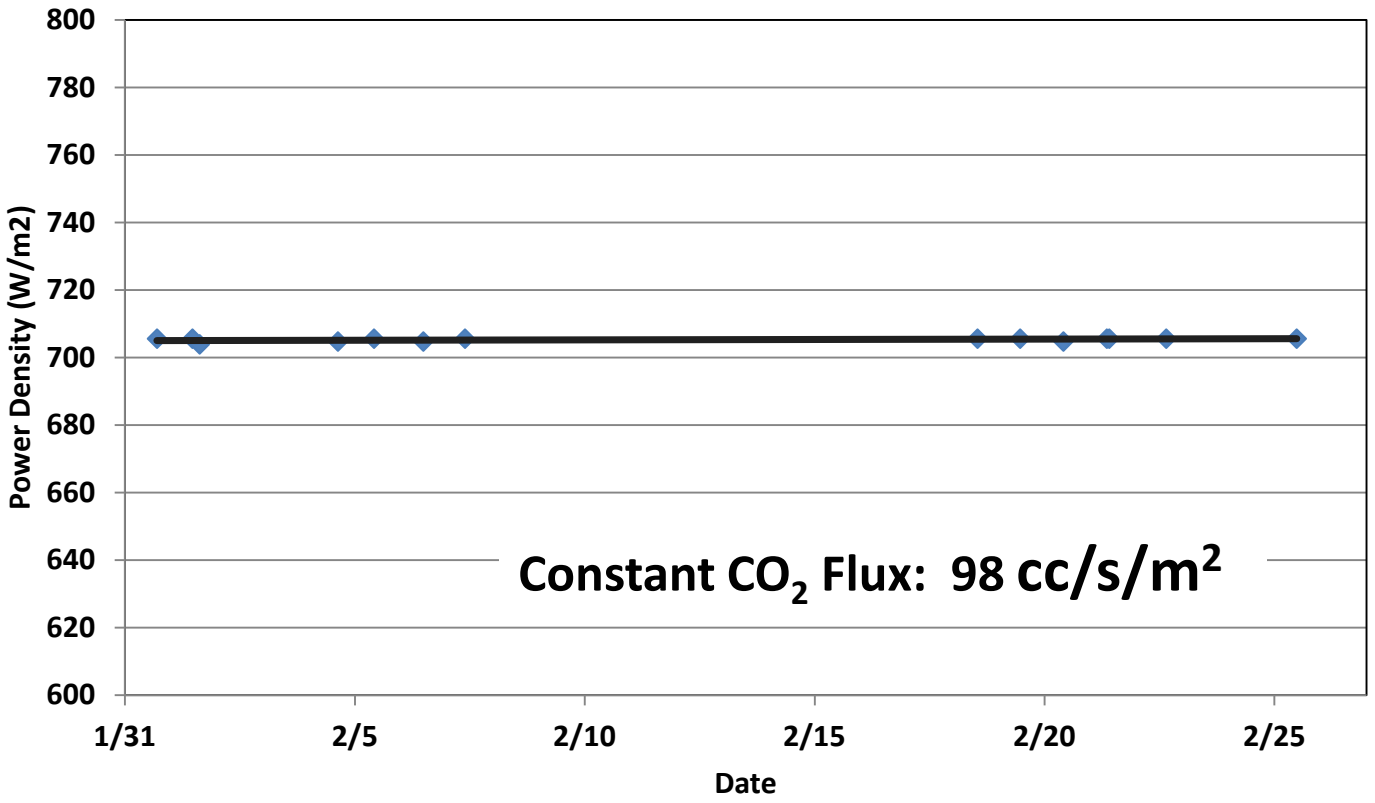




250 cm² ECM utilized to validate CEPACS system performance

ECM can achieve very high flux (>120 cc/s/m²) and substantial power generation at 90+% carbon dioxide capture from PC Plant flue gas

ECM Performance Stability



Verified Stability of ECM Performance for Carbon Capture and Power Production Using Simulated PC Plant Flue Gas during a Month of Testing

Flue Gas Contaminant Effects Testing

Testing Goals:

- Assess physical and chemical interactions of main flue gas pollutants with ECM
- Determine ECM performance effects with S, Cl, Hg, and Se in flue gases
- Enable selection of clean-up technology for CEPACS System

Walk-in ventilated lab space and multiple work stations are used at PNNL

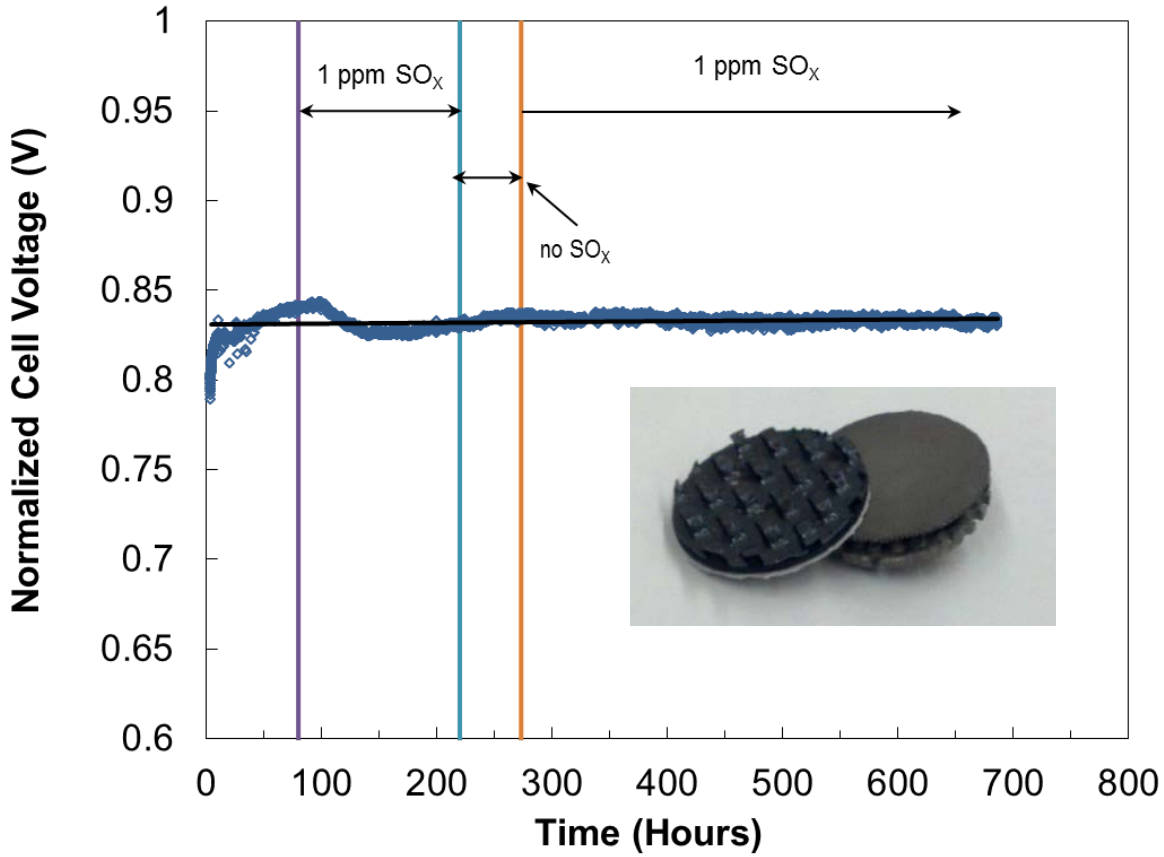
Approach :

- Utilize ECM button cell tests to determine the effect of individual impurities on cell performance.
  - Maintain CO_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

Multiple button cells in furnace, each with individual gas flow and electrical controls

Effects of SO_2 on ECM

- ECM button cells were tested with 1 ppm SO_2 (in feed gas) representing the effluent concentration (0.4ppm) from the polishing Flue Gas Desulfurization (FGD) unit in the CEPACS system
- The test showed stable membrane performance at 1 ppm SO_2 concentration:
  - Constant CO_2 Transport Flux
  - Minimal Voltage degradation impact



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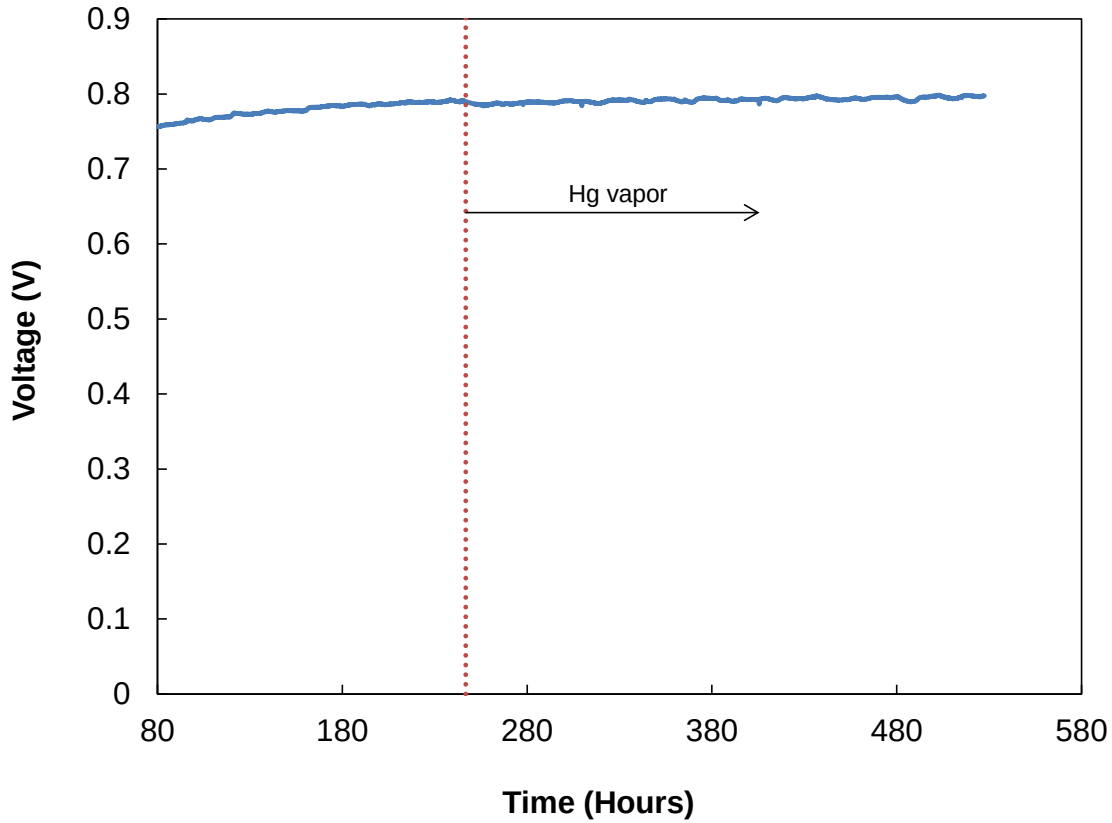
Effects of Mercury on ECM

- An ECM button cell is currently being tested with 750 ppb Mercury (Hg) in feed gas (2-3 orders of magnitude higher concentrations than typical flue gas)
- The test showed stable membrane performance after >280 hours of operation:
  - Constant CO2 Transport Flux
  - No performance loss observed
  - Test is being continued for a longer duration



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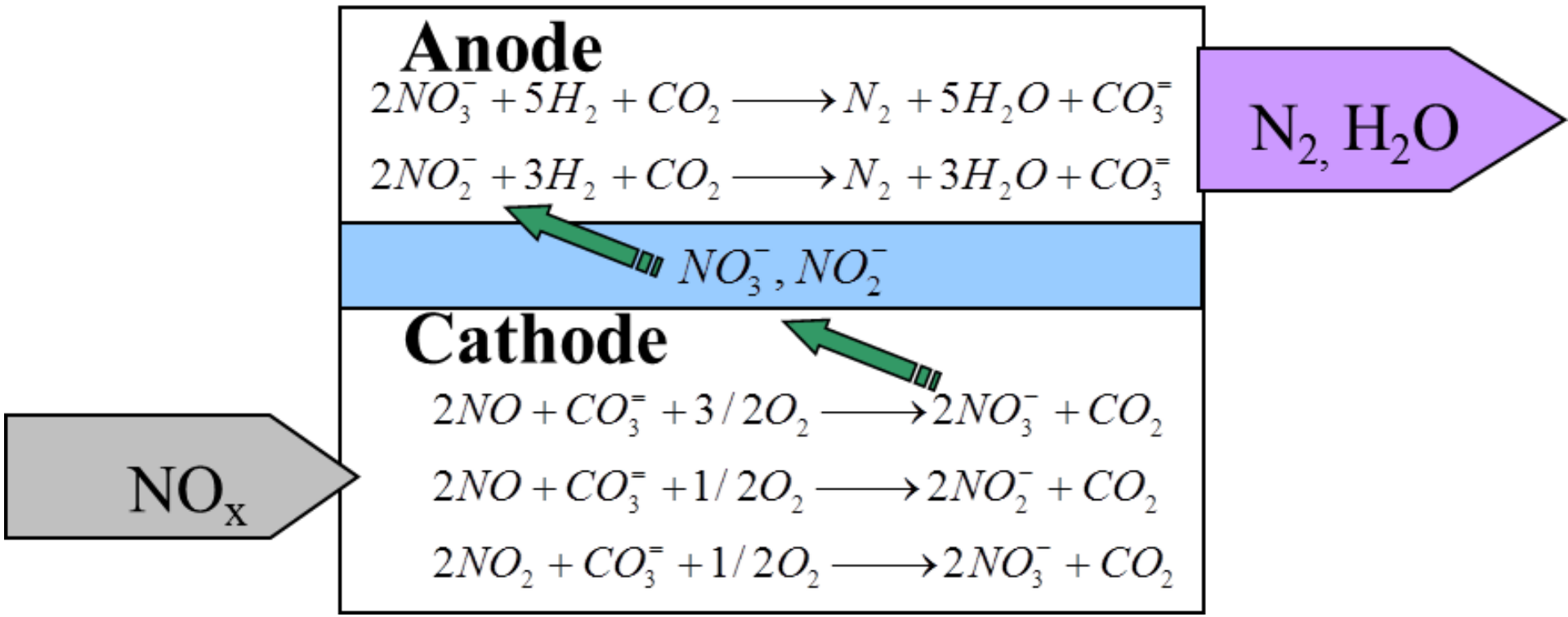
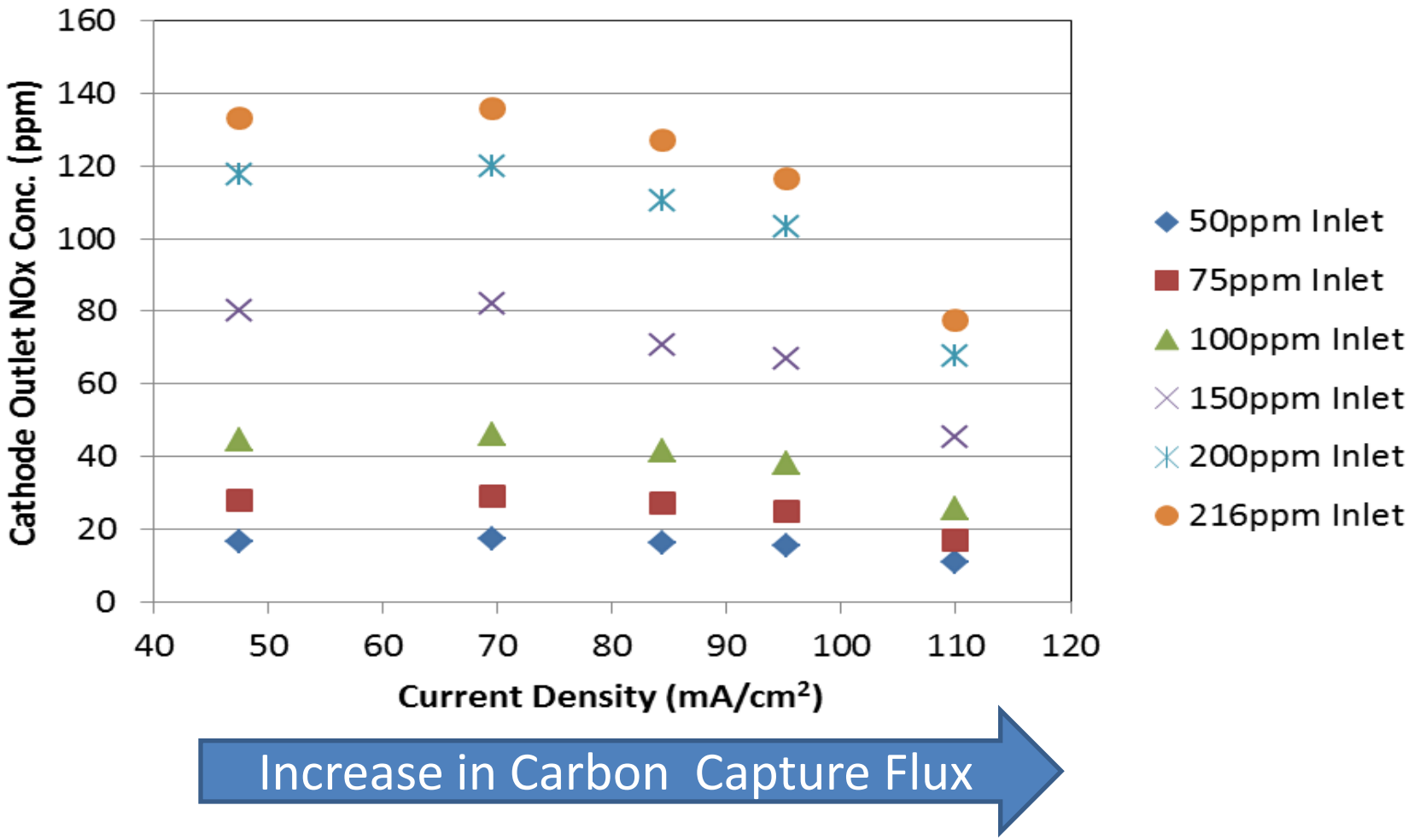
ECM NOx Destruction Capabilities



Reaction Mechanism by which NOx is Removed from the Cathode and Destroyed in the Anode

NO_x Removal Tests



Cathode Outlet NO_x Concentration with Increased CO_2 Flux for Carbon Capture at Various Cathode Inlet NO_x Concentrations

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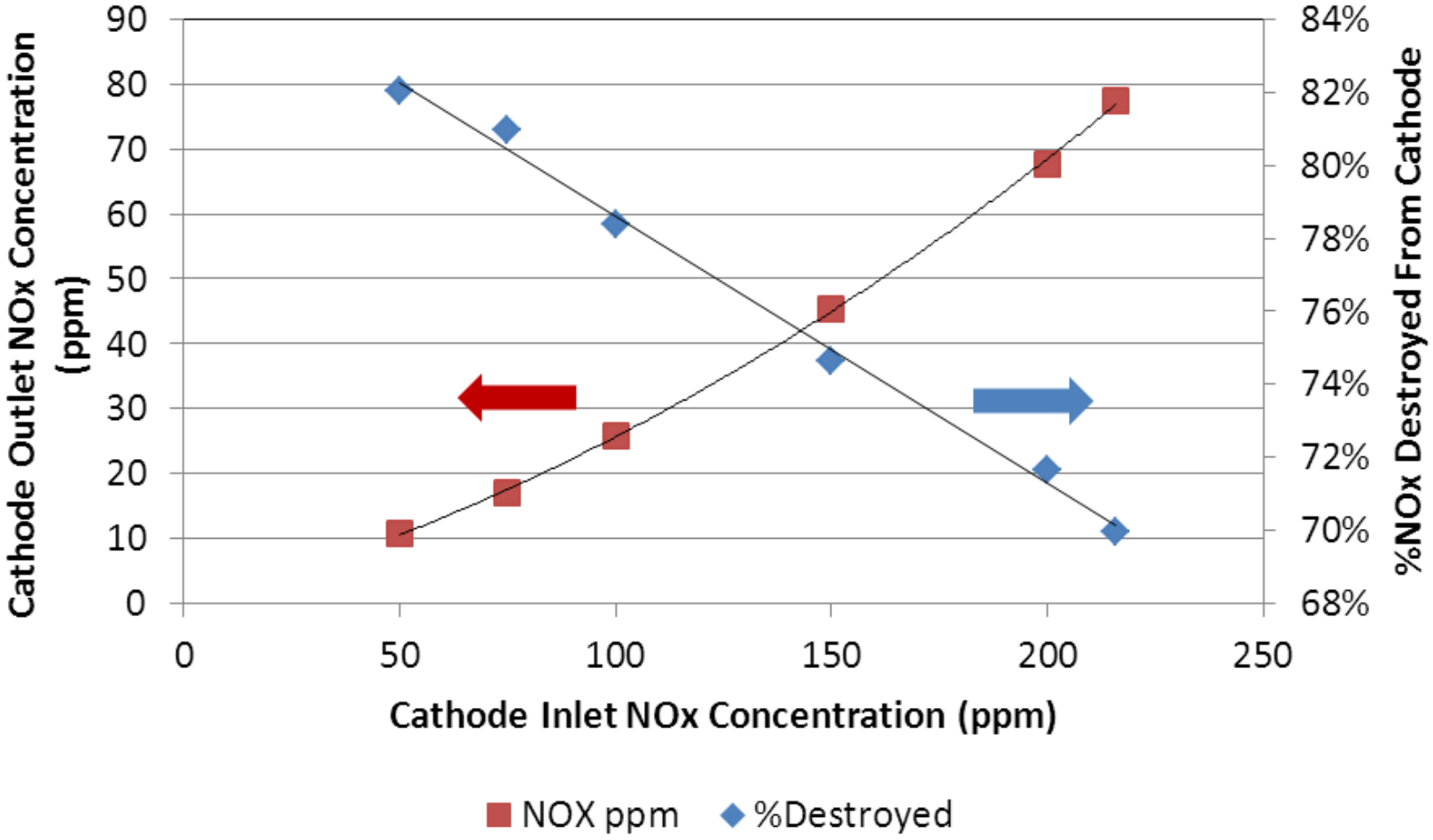
NO_x Removal Efficiency



ECM Capability for NO_x Destruction Remains > 70% at High Inlet NO_x Concentration (200 ppm) During Carbon Capture under System Conditions

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Summary of ECM Benefits

Benefits

- Commercially proven fuel cell technology repurposed for carbon capture
- Allows separation of >90% of carbon dioxide from flue gas of coal plants
- ~ 35% increase in cost-of-electricity (COE) for post-combustion CO_2 capture
- Produces additional electric power using a supplemental fuel, rather than consuming power
- Increases the net efficiency of coal plant by ~ 8 percentage points
- Capabilities to reduce NOx emissions leading to potential elimination of SCR
- Modular technology suitable for incremental applications (phased addition)
- Generates excess clean water as part of the electrochemical separation process

Acknowledgements

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Guidance from NETL team: Shailesh Vora, Jose Figueroa, and Lynn Brickett