FuelCell Energy

Ultra-Clean, Efficient, Reliable Power

Electrochemical Membrane for Carbon Dioxide Capture and Power Generation

DE-FE-0007634

Project Close-Out Meeting
June 10, 2016

Ultra-Clean, Efficient, Reliable Power

Presentation Outline

- Introduction
  - FuelCell Energy, Inc. - Recent Accomplishments
  - Electrochemical Membrane (ECM) Technology Overview
- DE-FE-0007634 Project
  - Task 1. Project Management & Planning
  - Task 2. Preliminary Techno-Economic Analysis Study
  - Task 3. Technology Gap Analysis
  - Task 4. Environmental, Health, and Safety Review
  - Task 5. Bench-Scale Testing
- Summary and Conclusions

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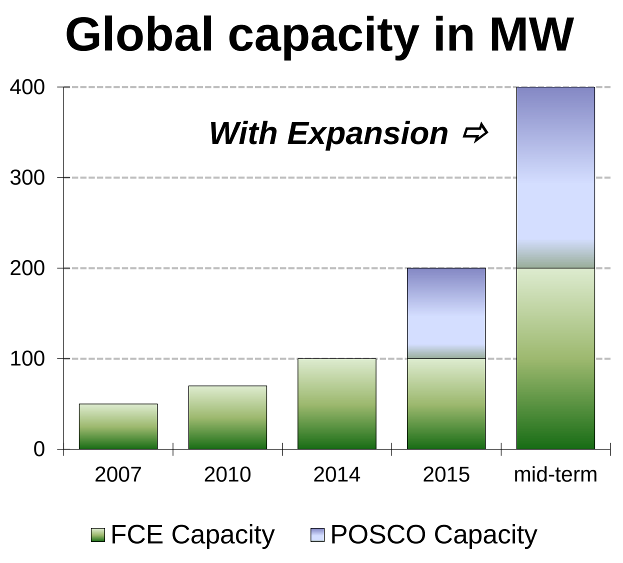
Serving Global Markets



Growth

- **Sizeable market opportunity**
- **Strong global partners**
- **Multiple revenue sources**
- **Global manufacturing footprint**

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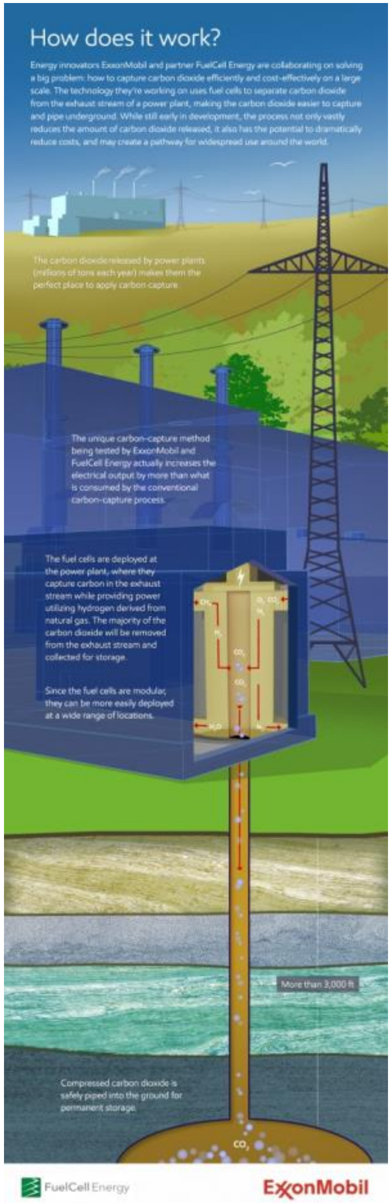
ExxonMobil CCS

- **Global carbon reduction need for gas-fired power**
- **Solution: affordable & scalable carbonate fuel cells**
  - o Carbonate fuel cells consume/capture CO_2
  - o Power generation leads to affordability
  - o Modularity leads to scalability
- **Collaboration partner with extensive resources**
  - o World's largest energy company & public gas producer
  - o Leading expert & experience with sequestration
  - o World-leading research capabilities
- **Opportunity**
  - o Integration with combined cycle gas plants
  - o Global market opportunity measured in Gigawatts

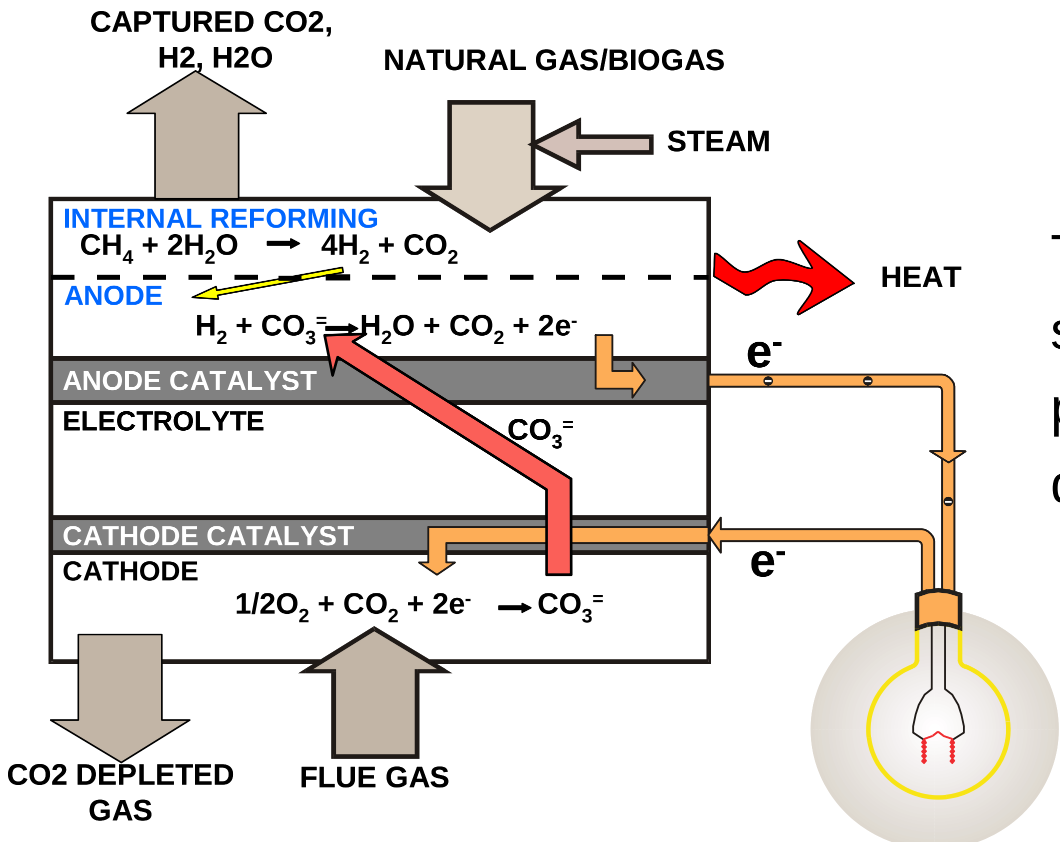


*"And we continue to press forward on innovations such as carbon capture and sequestration. Earlier today, ExxonMobil announced a collaborative research program to pursue the novel application of carbonate fuel cells to capture carbon dioxide from power plants. **Such breakthrough technology could substantially reduce costs**. We are still in the early days, but making carbon capture more economic could lead to **large-scale applications around the world, reducing emissions and mitigating the risks of climate change**."*

- Rex Tillerson, Chairman & CEO, ExxonMobil; May 5, 2016 speech at US Energy Association

Electrochemical Membrane (ECM) Technology Overview

ECM Operating Principle



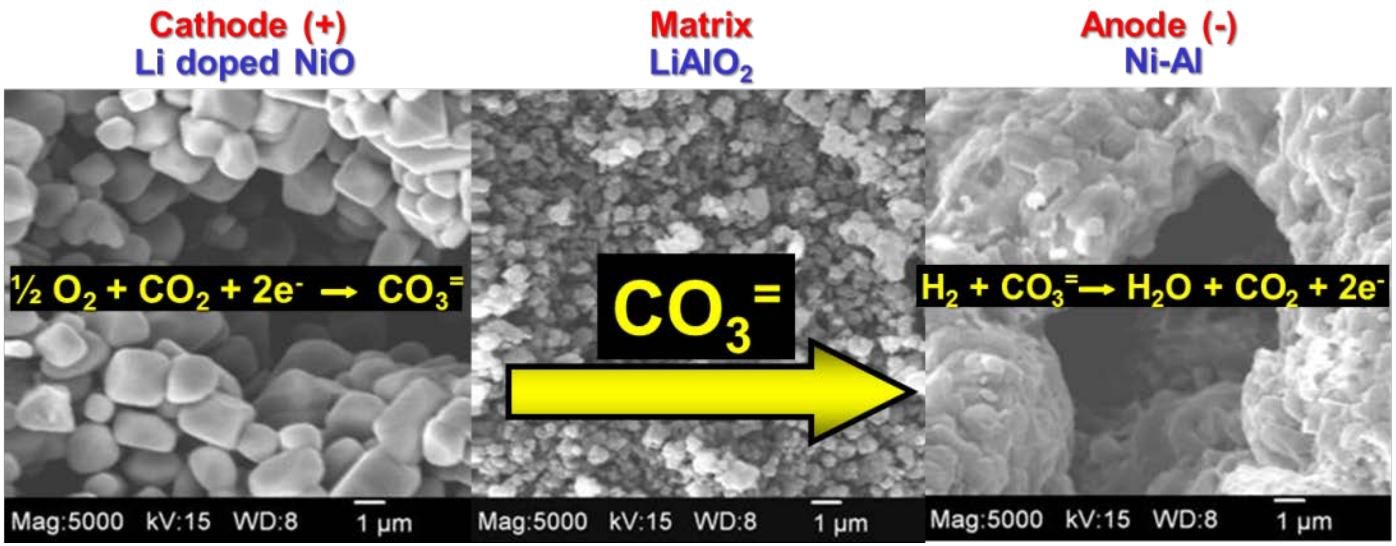
The driving force for CO_2 separation is electrochemical potential, not pressure differential across the membrane

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 Active Components

ECM Structure and Mechanism of CO_2 Transport



- ECM components are fabricated from inexpensive inorganic materials and conventional manufacturing processes
- Because of fast electrode kinetics at the operating temperatures of 550-650^{o}C, ECM is suitable for CO_2 concentration of <15% normally found in the coal or gas-fired power plant flue gases
- Due to the planar geometry and large gas flow channels, ECM can process large gas volumes without significant back pressures (5-8 cm of water)

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Project Objectives

- Demonstrate the ability of FCE's electrochemical membrane (ECM)-based system to separate ≥ 90% of the CO_2 from a simulated PC flue-gas stream and to compress the CO_2 for sequestration or beneficial use
- Demonstrate that the 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)
    - Complete a Preliminary Technical and Economic Feasibility Study on FCE's ECM carbon capture system scaled up for a 550MW PC power plant
    - Perform small-area membrane tests using clean simulated flue-gas
    - Perform contaminant testing to establish maximum permissible concentrations of impurities in flue gas without causing unacceptable ECM degradation
    - Complete design for BOP components, including flue-gas pre-treatment sys.
    - Complete a Technology Gap Analysis to identify any equipment, materials, or other components/processes that may hinder advancement of this technology
    - Perform an EH&S assessment to ensure there are no environmental or safety concerns which would prohibit commercialization efforts for the ECM system
    - Complete bench-scale testing of an 11.7 m^2 area electrochemical membrane system for CO_2 capture, purification, and compression.

ECM Project Team Structure

The FCE team is comprised of diverse organizations with expertise in key functional areas:

FuelCell Energy Inc. (FCE), Danbury, CT

- **<u>Key experience</u>:** Manufacturing and commercialization of fuel cell power plant systems in sizes ranging from 300kW to Multi-MW**.**
- **<u>Project Role</u>:** Prime Contractor

Pacific Northwest National Laboratory (PNNL), Richland, WA

- **<u>Key Experience</u>:** Extensive research expertise in characterization of the effects of trace contaminants on high-temperature fuel cells
- **<u>Project Role</u>:** Testing effects of flue gas contaminants on ECM

AECOM (Formerly URS), Austin, TX

- **<u>Key Experience</u>:** Global leader in providing engineering, construction and technical services including pollution control systems
- **<u>Project Role</u>:** Review ECM system design, equipment and plant costing, flue gas clean-up system design

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Work Breakdown Structure

- **Task 1 Project Management And Planning**
  - Task 1.1 Contract Reporting
  - Task 1.2 PMP Update
  - Task 1.3 Final Report
- **BP 1**
  - **Task 2 Preliminary Technical and Economic Feasibility Study**
    - Task 2.1 System Design Study
    - Task 2.2 Economic Feasibility Study
    - AECOM Support (Tasks 2.1 and 2.2)
- **BP 2**
  - **Task 3 Technology Gap Identification**
    - Task 3.1 Contaminant Evaluation — PNNL Lead
    - Task 3.2 Membrane Testing
    - Task 3.3 BOP
- **BP 3**
  - **Task 4 EH&S Review**
    - Task 4.1 Process Emission Review
    - Task 4.2 Technical EH&S Review Report
  - **Task 5 Bench-scale Testing**
    - Task 5.1 Facility Design
    - Task 5.2 Stack Fabrication
    - Task 5.3 Facility Build
    - Task 5.4 Demonstration
    - Task 5.5 Post Test Analysis

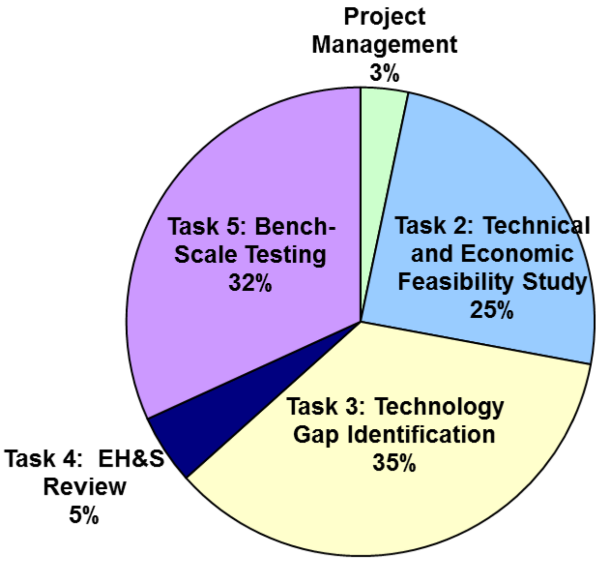
- **The work breakdown structure is designed to ensure success in achieving the program objectives with minimal risk.**

Project Budget vs Cost

	Budget	Actual Cost as of 4/30/2016
DOE Share	$3,034,106	$2,845,953
Participant Share	$758,527	$758,527
Total	**$3,792,633**	**$ 3,604,480**

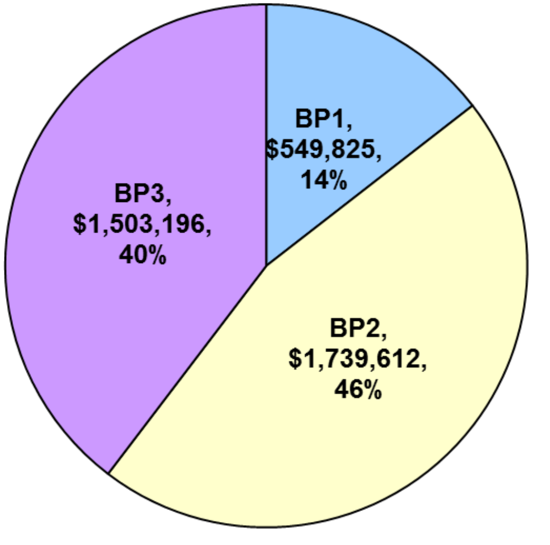
* Includes $50,000 for additional Scope of Work in BP1

** Includes $600,000 for Pacific Northwest National Laboratory (PNNL)



By Task

Budget Breakdown



By Budget Period

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Milestones

Budget Period	Task-Subtask No.	Milestone Description	Planned End Date	Actual End Date	Verification Method	Comments/Progress
1	2.1	Demonstrate the potential of the ECM-based system to achieve 90% carbon capture from the Reference PC Plant, based on results of a system study.	5/30/2012	3/31/2012	Preliminary Techno-Economic Analysis Report	Current technology scaled up to 550 MW PC plant (reference case) with ≥ 90% CO_2 capture
1	2.2	Demonstrate potential to achieve incremental COE of <35%	5/30/2012	5/30/2012	Preliminary Techno-Economic Analysis Report	Cost estimates for carbon capture ≤ 35% increase in COE
2	3.2	Verify that ECM CO_2 flux can meet the target identified in the Technical and Economic Feasibility Study.	7/31/13	12/31/2012	BP2 Q2 Quarterly Report	Small-area ECM testing verified that a CO_2 flux of >127cc/s/m^2 is achievable for >90% CO_2 capture
2	3.2	Demonstrate >50% NO_x Destruction Capability of ECM	12/13/13	6/30/2012	BP2 Q2 Quarterly Report	Small area membrane tests will demonstrate >50% NO_x destruction within the fuel cell.
2	3.1	Verify that ECM contaminant tolerances can be met by cost-effective flue gas pretreatment technologies.	12/23/13	9/30/2013	BP2 Q4 Quarterly Report	Button cell testing has confirmed cell performance is within ECM operating window.
3	5.4	Verify CO_2 Flux at 100 cc/m^2/s	9/31/14	7/30/2014	BP3 Q1 Quarterly Report	A CO_2 flux of 116 cc/m^2/s was achieved which is 16% higher than the targeted Milestone value.
3	5.4	Complete 9 Months of Endurance testing with degradation in Carbon Capture Efficiency based on the value identified in the Technical and Economic Feasibility Study.	6/19/15	5/30/2015	BP3 Q4 Quarterly Report	Bench-scale endurance testing showed zero degradation in carbon capture efficiency and only 0.05%/1000 hours decay in power production over 9 months.
3	5.4	Demonstrate 3 deep Thermal Cycles between ambient and operating temperatures with <2% Degradation in Carbon Capture Efficiency	8/16/15	8/14/15	Report	Parametric testing will confirm the durability of the membrane to undergo thermal cycles.

→ Project Milestones were successfully achieved

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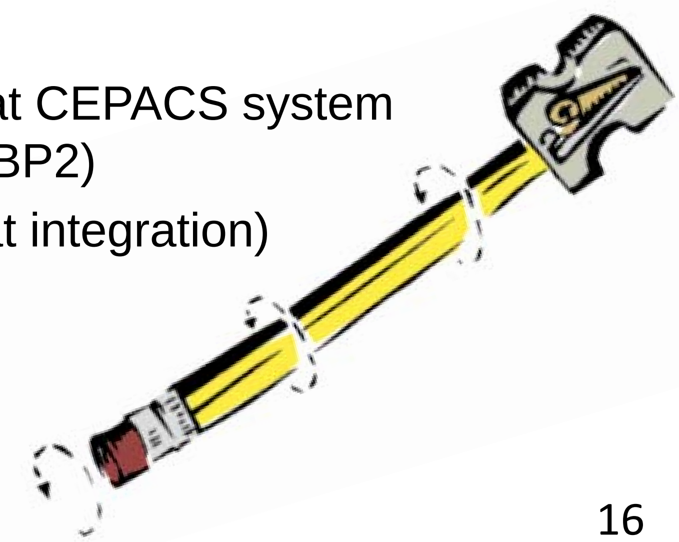
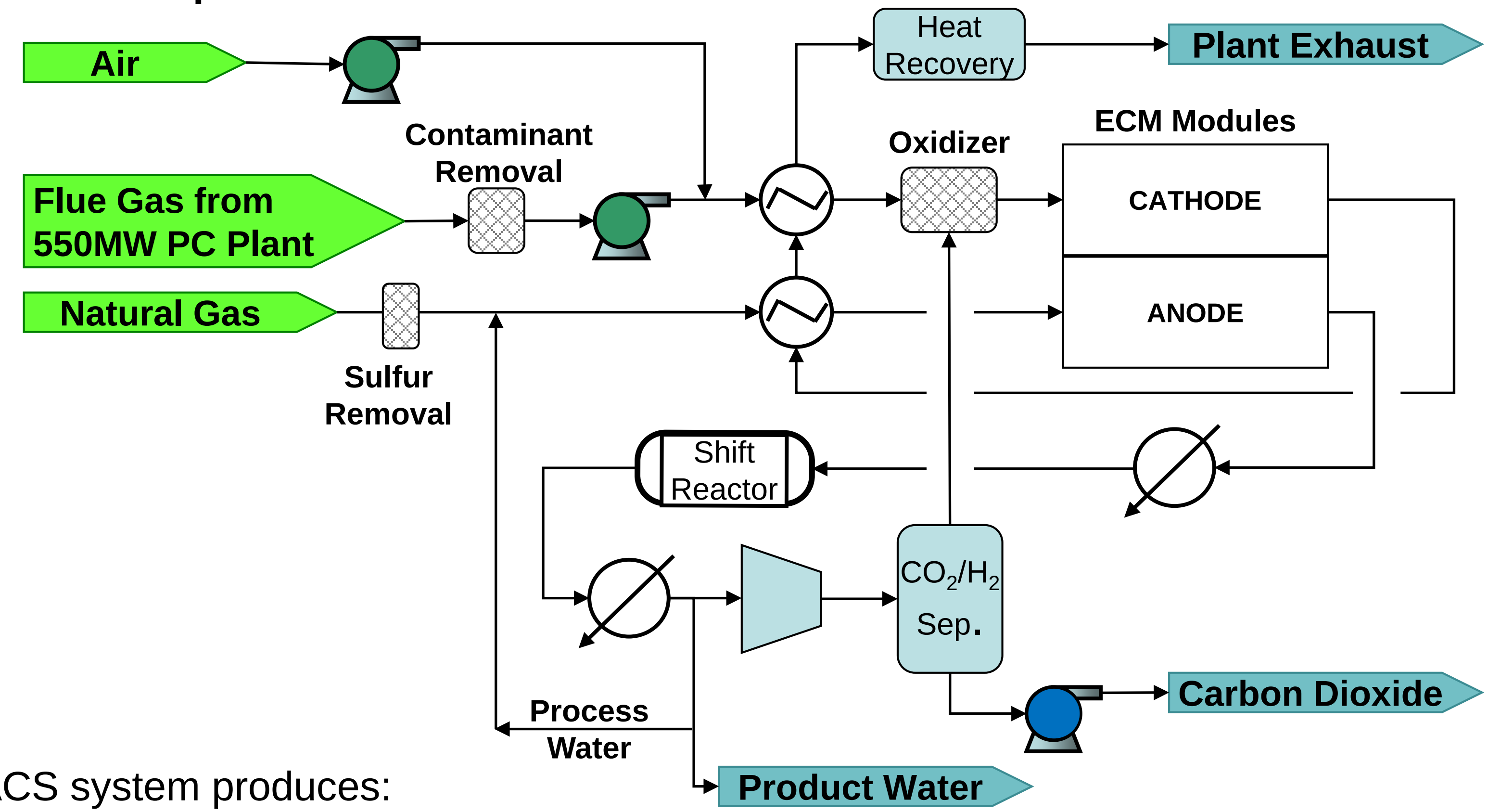
T&EFS Revision History

- BP1: Preliminary Technical & Economic Feasibility Study (PT&EFS) issued
- BP2 Updates:
  - Actual ECM performance from laboratory testing at CEPACS system operating conditions (vs. modeled performance in BP1)
  - Process design improvements
  - Improved plant layout to reduce hot ducting runs, and lower-cost module enclosures
  - Vendor quotations for key process equipment
- BP3 Updates:
  - Actual ECM performance from bench testing at CEPACS system operating conditions (vs. laboratory testing in BP2)
  - Continued process design improvements (heat integration)
  - Compact plant layout



Application of ECM for CO_2 Capture from Existing Power Plants

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

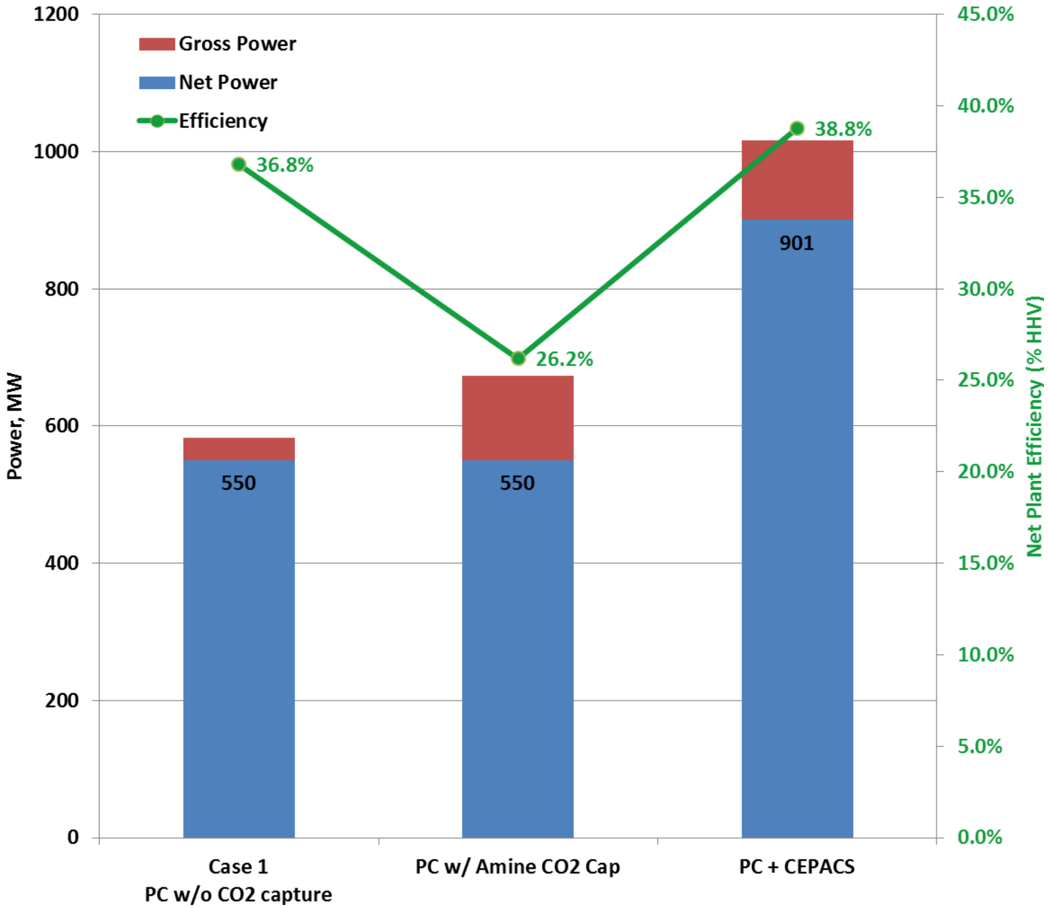


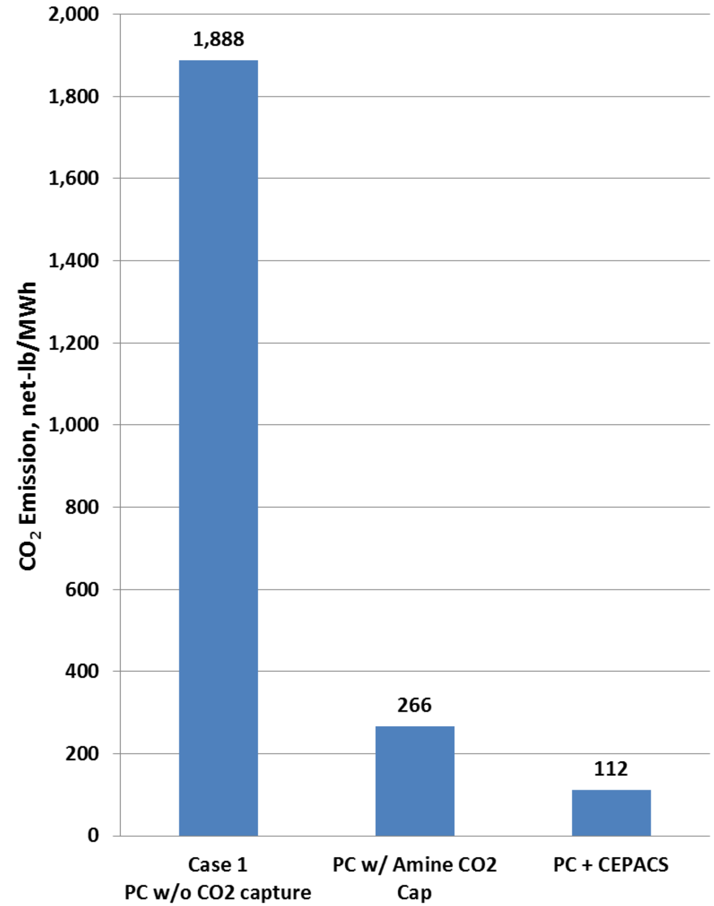
CEPACS system produces:

- Supercritical CO_2 (90% CO_2 capture from PC Plant)
- Excess Process Water
- Additional 351 MW of clean AC power @ 42.4% Efficiency (based on HHV 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.

Updated CEPACS System Performance

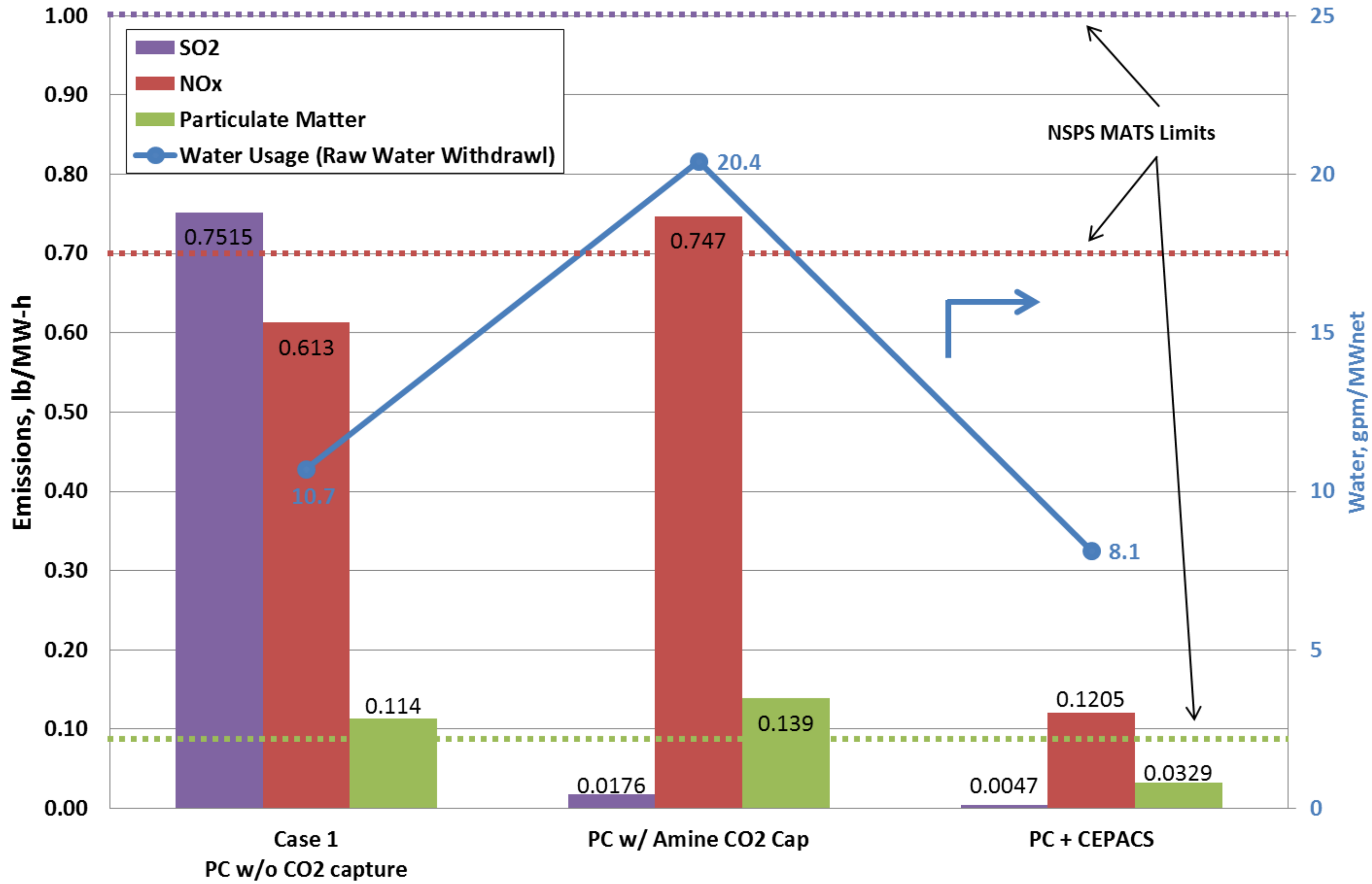




- CEPACS System increases power output of Baseline PC plant by 64%
- PC plant retrofitted with CEPACS system is 48% (12.6 percentage points) more efficient than amine scrubbing for carbon capture

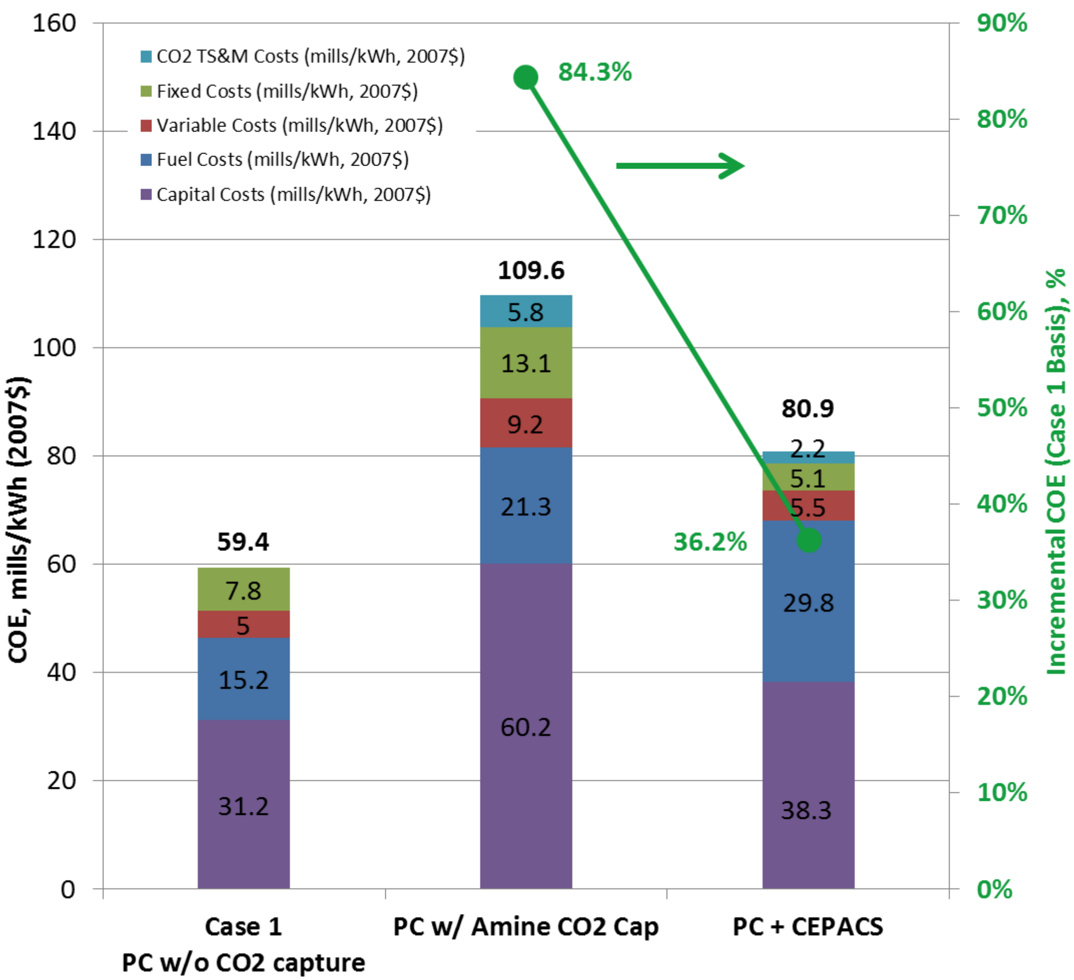
- PC + CEPACS System CO_2 Emissions are 60% lower than PC w/ Amine due to power generation (vs. consumption) @ 90% capture level

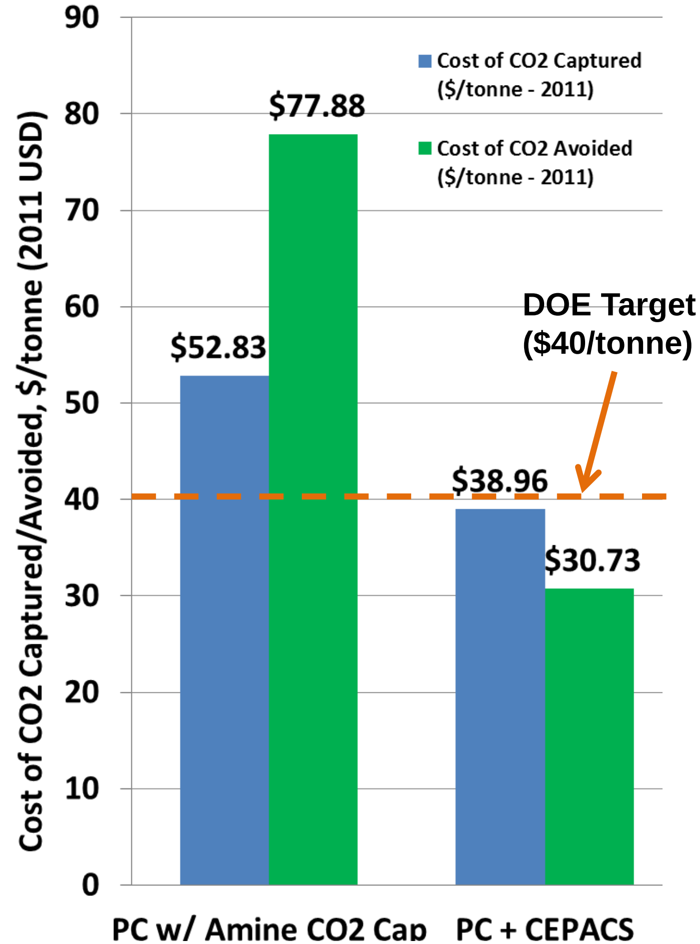
CEPACS System Performance: Emissions and Water Usage



- PC plant retrofitted with CEPACS system has lower emissions of NOx, SOx, and Hg than a PC plant retrofitted with Amine scrubber for CO_2 capture, below MATS limits
- CEPACS system produces excess process water, resulting in:
  - 60% less raw water withdrawal than with amine scrubbing
  - 24% less raw water withdrawal compared to baseline plant *without* CO_2 capture

CEPACS System Economics

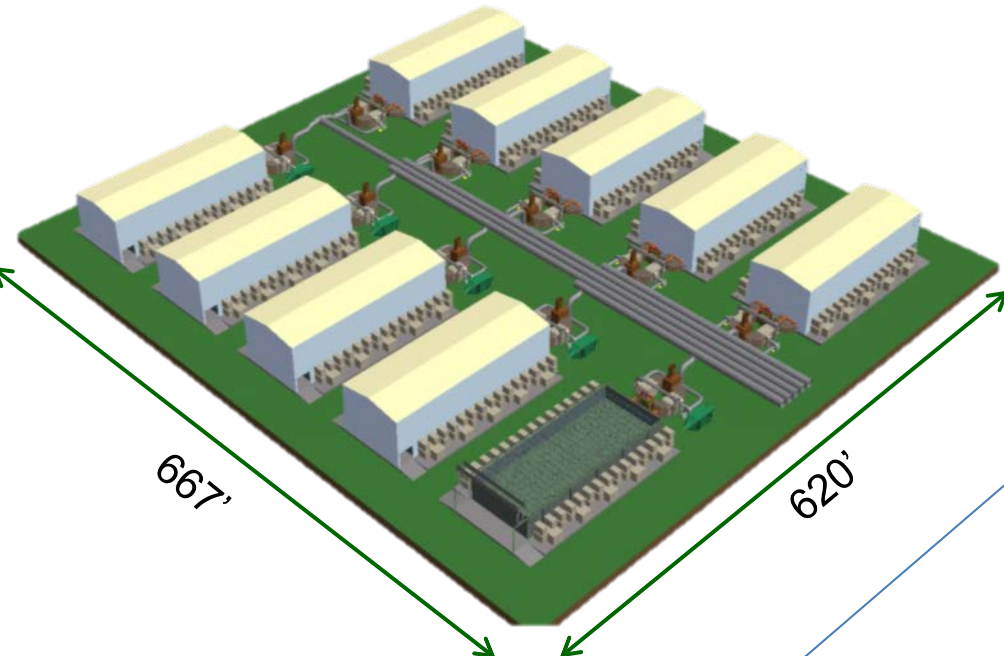




- PC plant retrofitted with CEPACS system has 26% lower COE than amine scrubbing
- ECM-Based CEPACS System can meet DOE Target of <$40/tonne CO_2 captured (2011 USD)

Plant Layout: Footprint Reduction

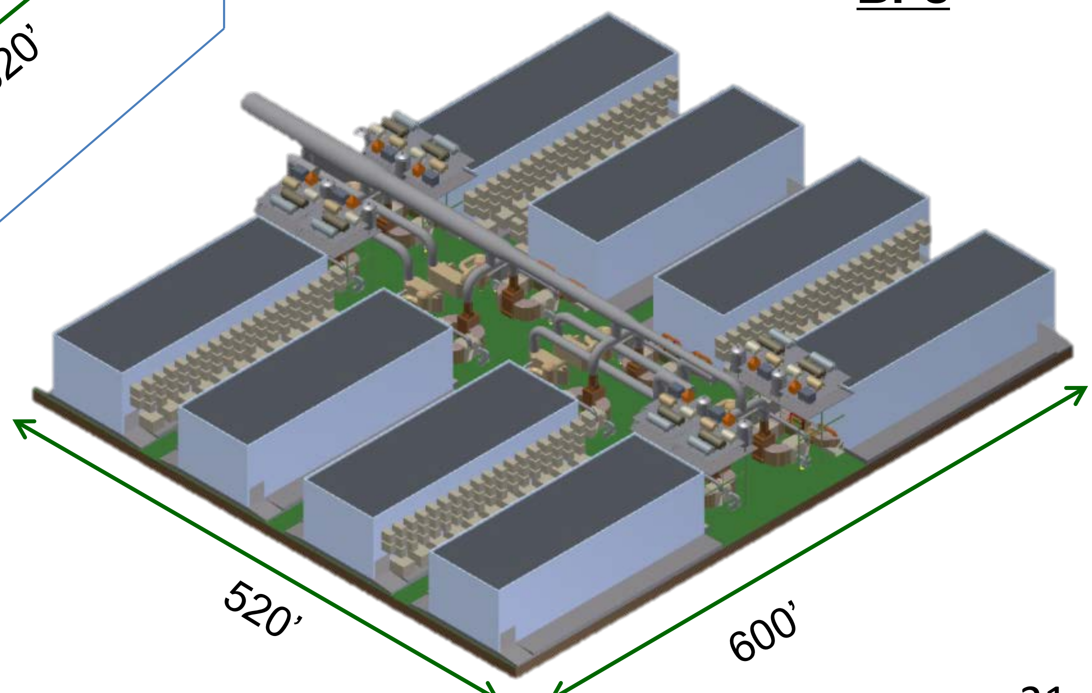
BP2



- 10 enclosures x 200 stacks ea. = 2,000 stacks
- 421 MWnet additional power
- 90% capture from 550 MW PC
- 10 acres

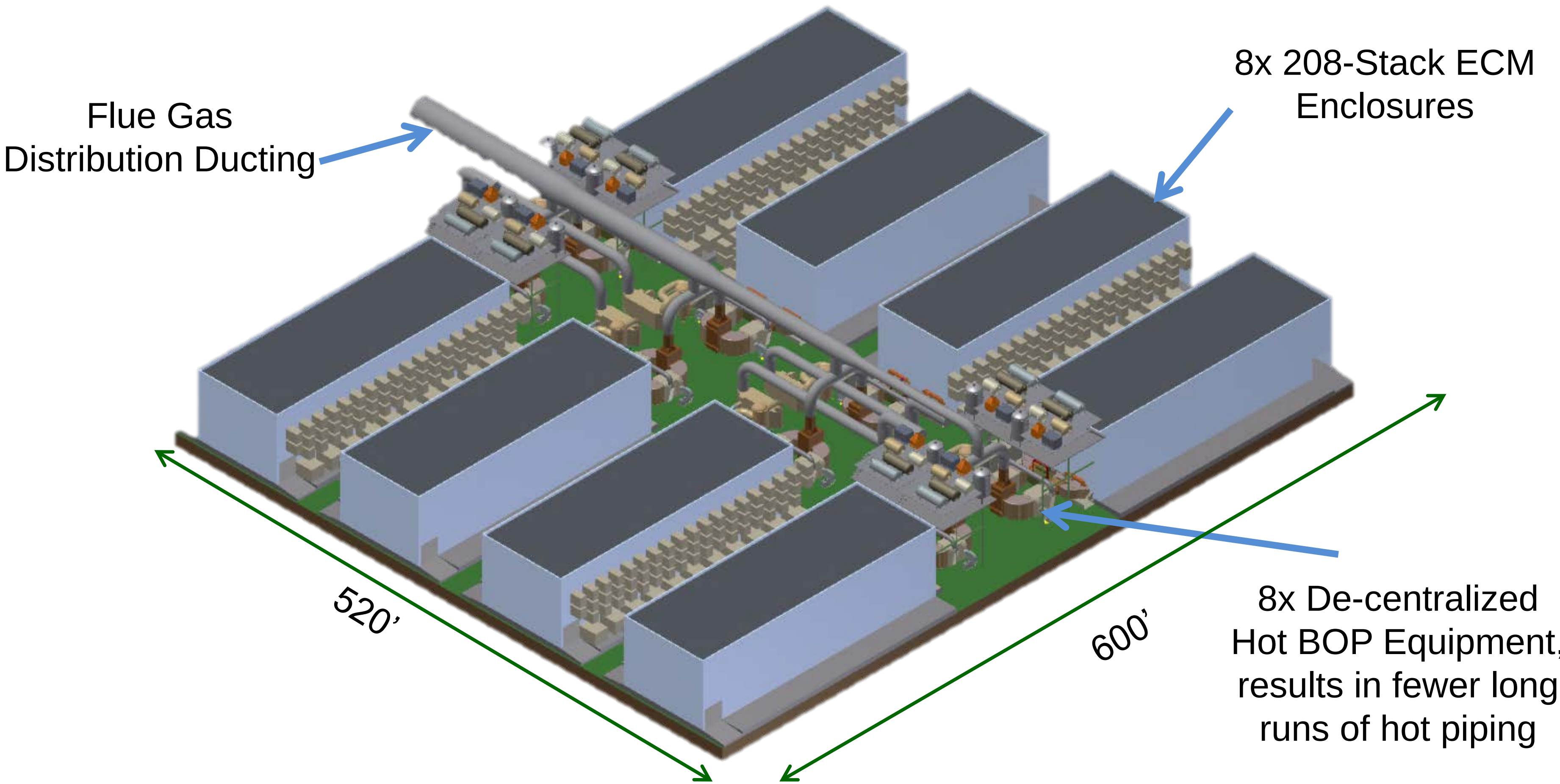
- 8 enclosures x 208 stacks ea. = 1,792 stacks
- 351 MWnet additional power
- 90% capture from 550 MW PC
- 7 acres

BP3



Reduced-Footprint Plant Layout

351 MW CEPACS Plant for >90% Carbon Capture from 550MW Reference PC Plant requires ~ 7 Acres



CEPACS System modularity allows for isolation of a single enclosure, resulting in near-100% availability with >87% capacity factor

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Carbon Capture from Unit 8
W. A. Parish Using ECM

- Overlay of ECM Carbon Capture at Petra Nova site
- Capture ~40% Slip Stream of Unit 8: 5000 tonne/day CO_2
- Generate: 210 MW of Additional Electricity

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Balance-of-Plant

BoP Technology Gap Analysis

- Objective: Review CEPACS system BOP equipment to identify if any technology gaps exist between currently available process equipment and unique equipment that is required for CO_2 capture and compression.

- BOP equipment and designs evaluated included:
  - Flue Gas Polishing Cleanup System
  - CO_2 Compressors (for stream with H_2/CO_2)
  - Absorption chillers to liquefy CO_2 utilizing ECM waste heat
  - ECM Module interconnections (piping/ducting)
  - ECM plant layout

BOP Equipment Gap Analysis: Flue Gas Polishing System

Flue Gas Cleanup based on Commercially-Proven Large-Scale Technology

- Wet-FGD Polishing system performance analyzed by AECOM for multi-contaminant removal
- Wet-FGD system expected to exceed multi-contaminant removal efficiencies required by ECM
- Costs estimated based on AECOM database of installed cleanup systems
- Dry-sorbent flue gas polishing systems exist as alternative and/or addition to wet-FGD to achieve even higher removal efficiencies
  - Discussions with vendor, who has supplied operational systems up to 625 MW, indicated technical feasibility, however with ~$50MM cost penalty compared to wet-scrubbing

Membrane Testing

ECM Single-Cell Test Plan

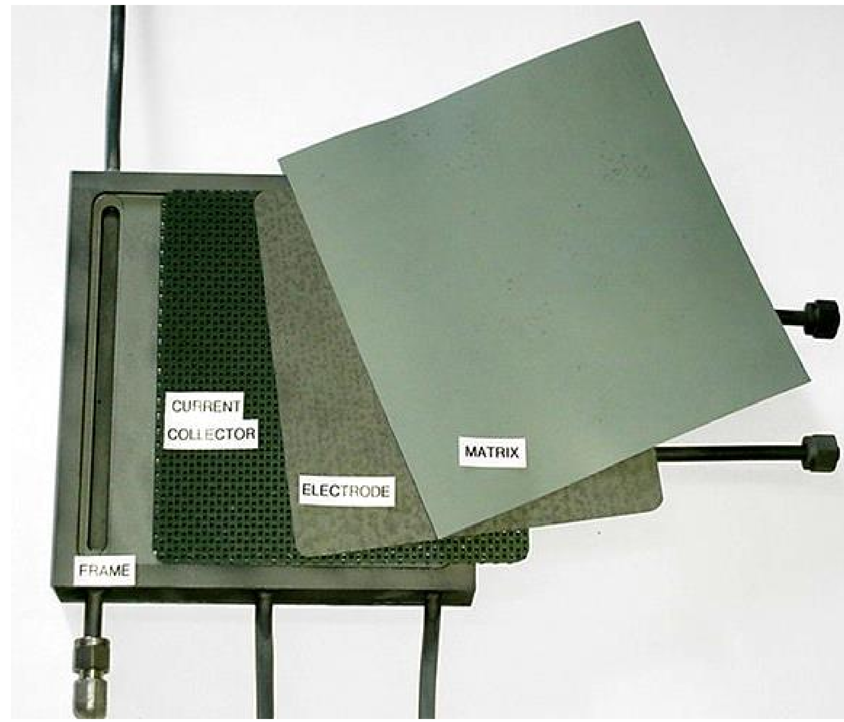
Test Objectives:

- Demonstrate ECM performance at baseline design conditions
- Parametric analysis to determine ECM performance as a function of:
  - CO_2 capture rate
  - Operating temperature
  - Flue gas (FG) composition
    - Supplemental air addition
    - Moisture content
    - NO_x concentration (ECM NO_x destruction capability)

Test Metrics:

- Demonstrate CO_2 flux ≥ 100 cc/m^2/s at baseline conditions
- Determine optimized operating conditions to maximize ECM power output through parametric analyses
- Demonstrate >50% NO_x destruction capability of ECM

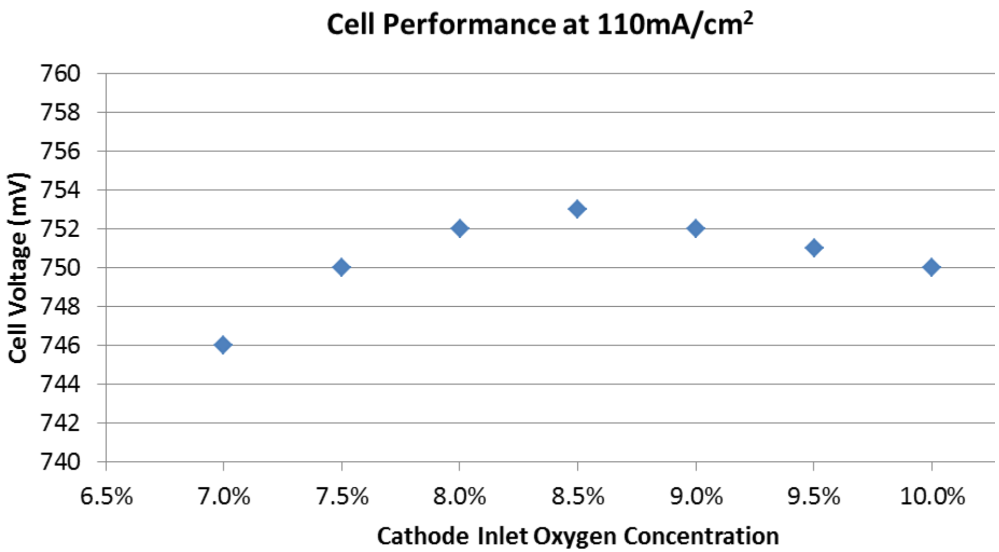
ECM Components and Single-Cell Testing Facilities



Laboratory facility for testing 250 cm^2 electrochemical membranes under a variety of system operating conditions.

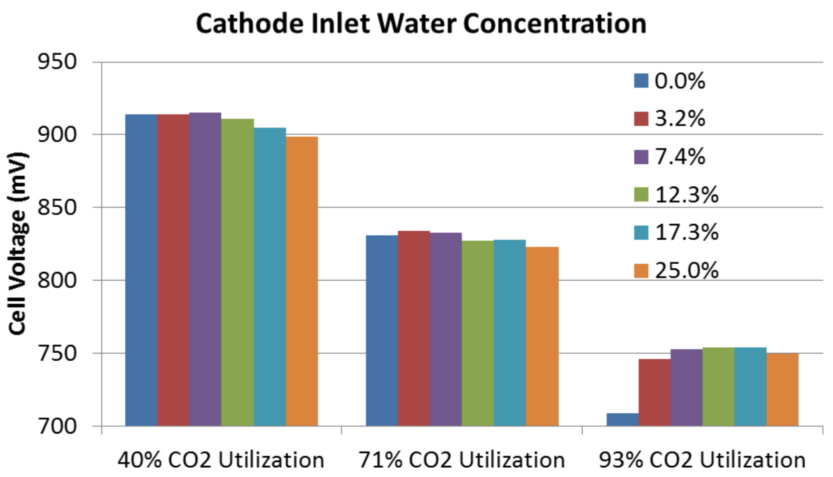
ECM Single-Cell Testing: Operating Conditions Optimization

Effect of Flue Gas O_2 Concentration:



- ECM performance is maximized at an oxygen concentration (wet) of 8-9%
- System design includes supplemental air addition to tune O_2 partial pressure

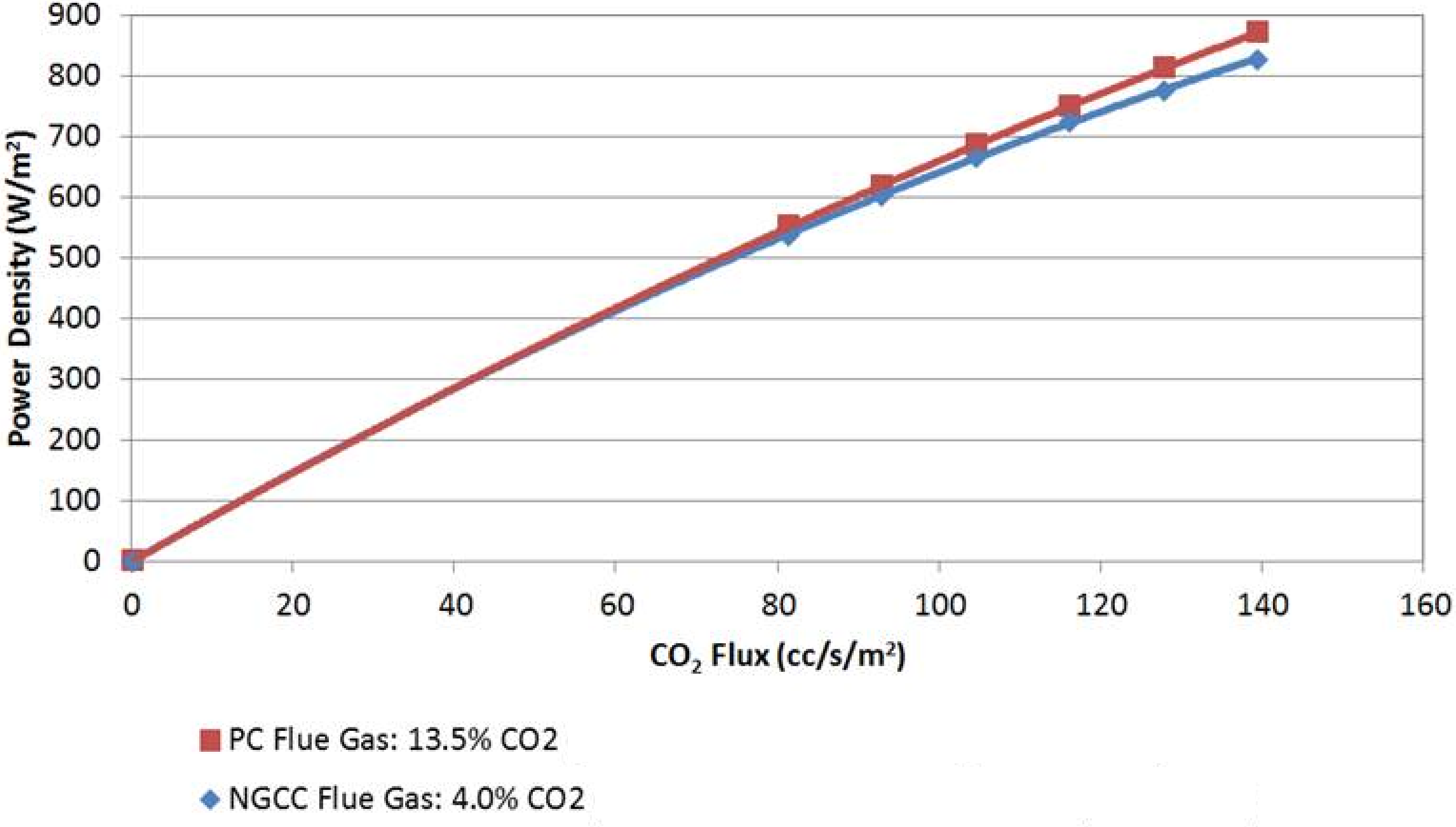
Effect of Flue Gas Humidity:



- ECM performs well in a wide range of moisture levels (3-25% H_2O)
- Baseline system design point (12.3% H_2O) provides optimum cell performance at high CO_2 utilization

ECM Single-Cell Testing: Effect of Flue Gas Composition

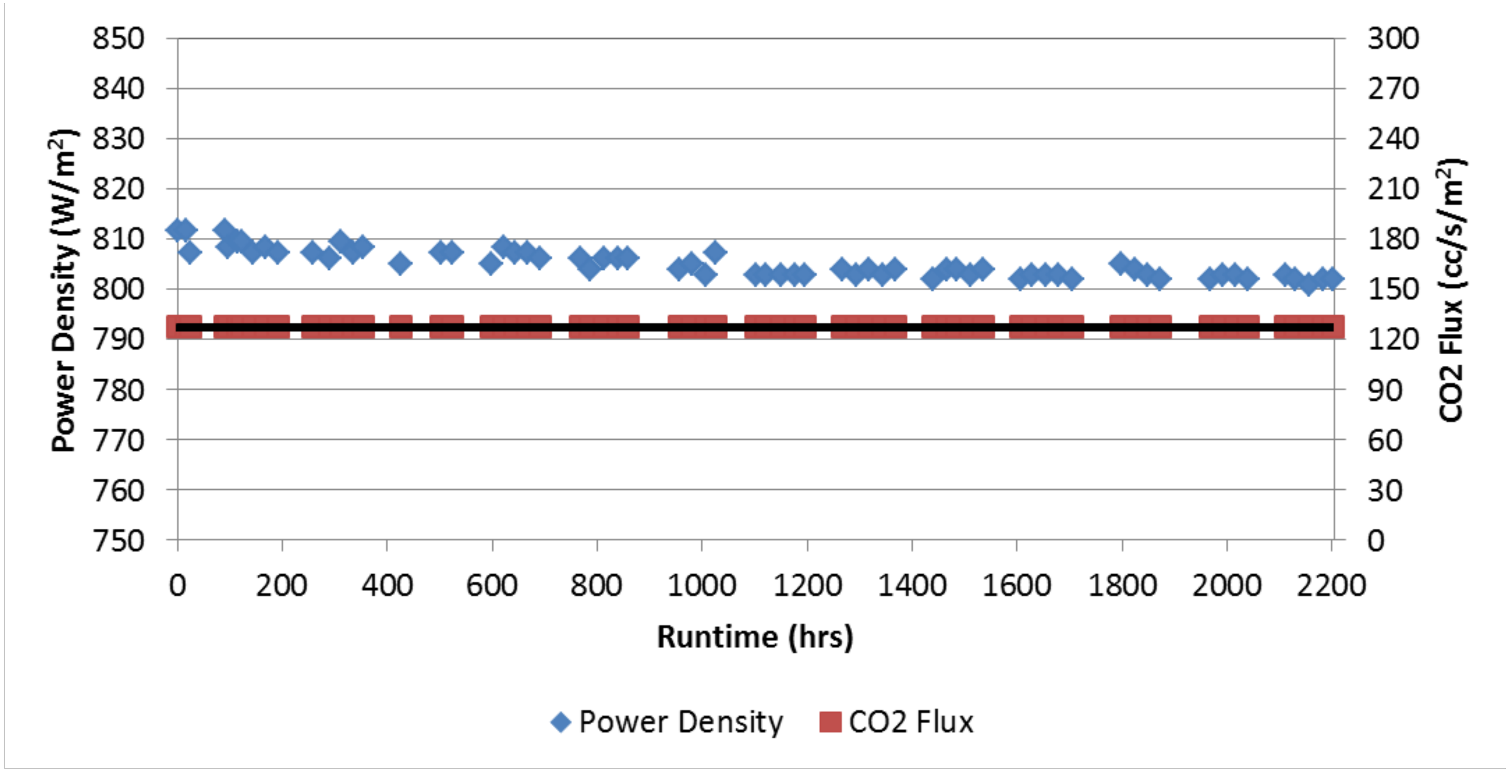
ECM cell performance data for NGCC and PC plant flue gases at 93% carbon capture:



- ECM is capable of operating on flue gases with a wide range of CO_2 partial pressure
- System features (e.g. supplemental air addition, product recycle) allow tuning of cathode-side composition to optimize ECM performance

ECM Endurance Testing Results

- ECM cell stability testing at steady state baseline system conditions (75% Uf, 93% Uco_2, 110mA/cm^2) for over 2200 hours of operation:



- The CO_2 flux remained constant through over 2200 hours of testing, indicating constant 90+% CO_2 capture
- The power production remained stable during test duration

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Contaminant Evaluation

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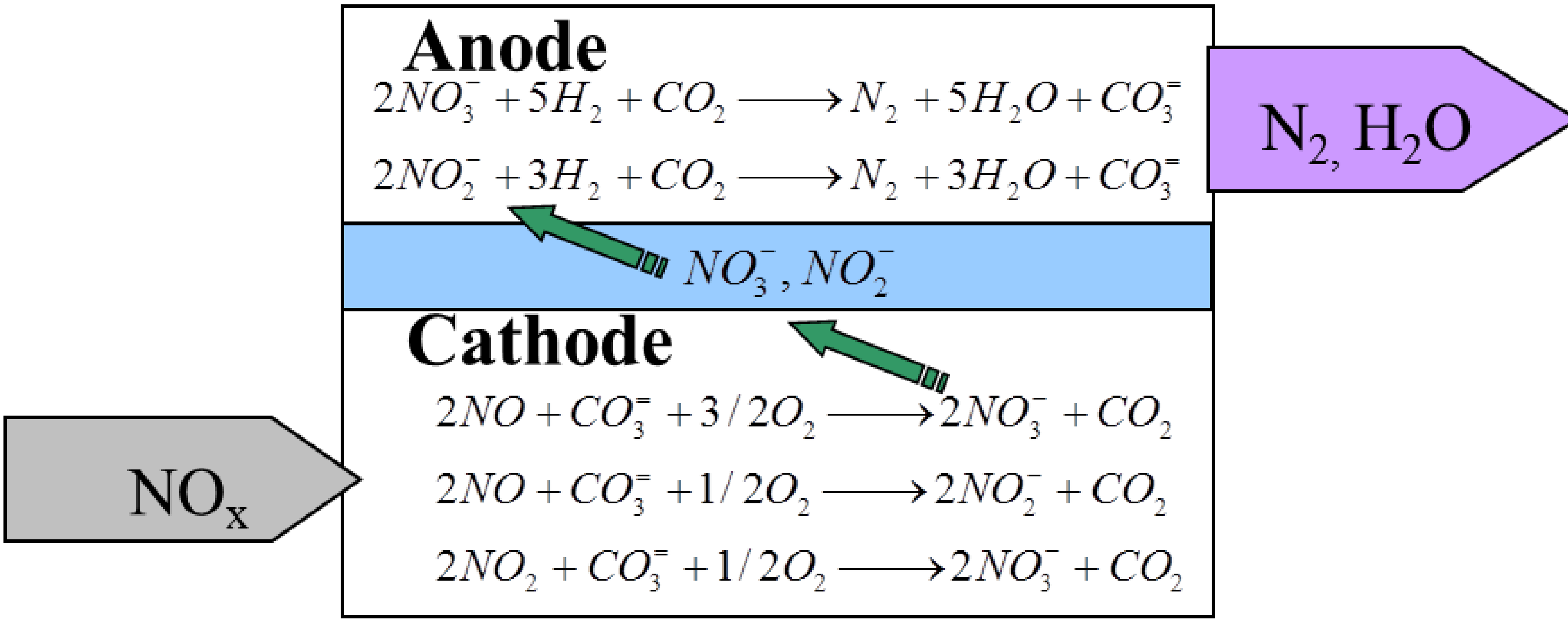
ECM NO_x Removal Mechanism

- 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

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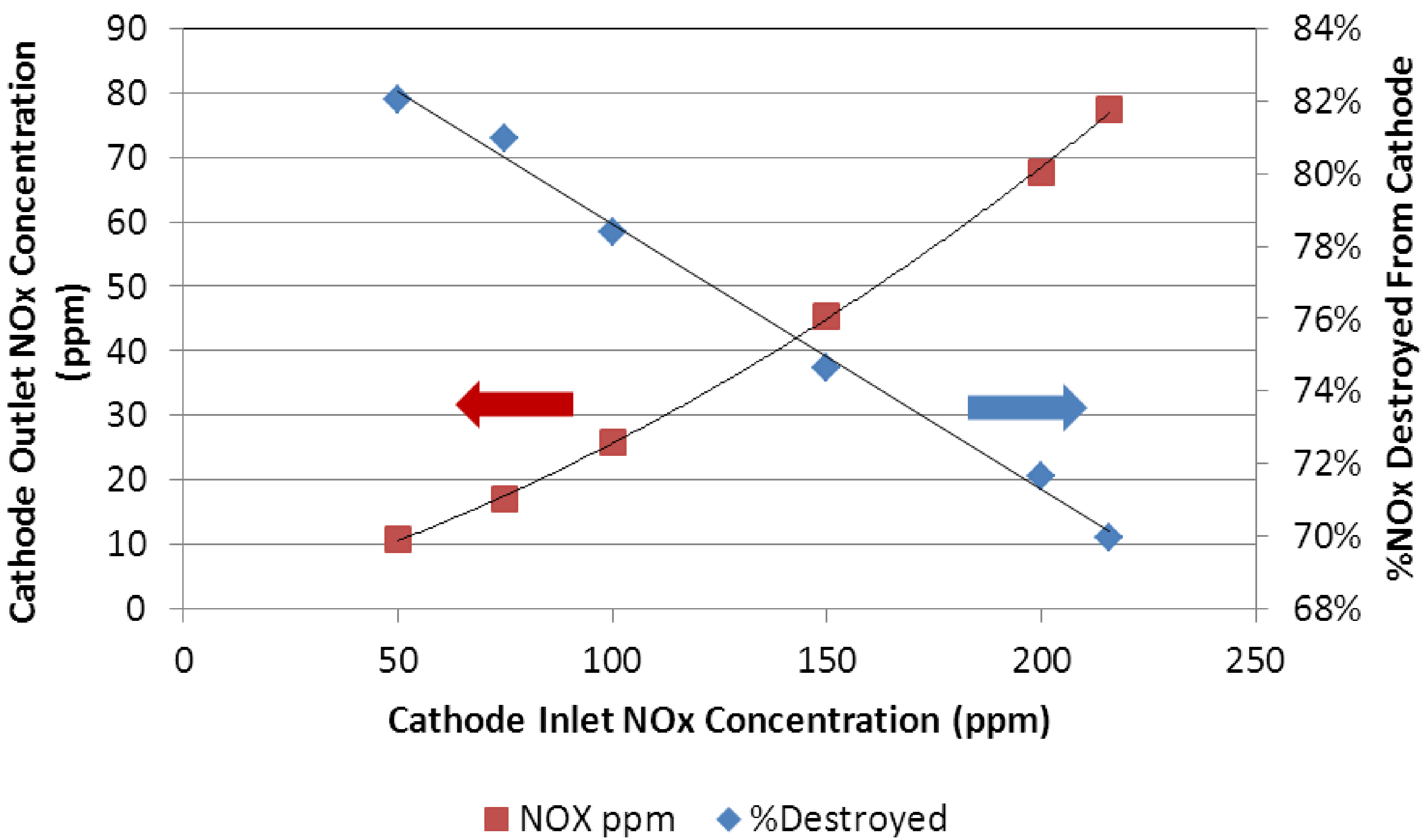
ECM NO_x Removal Test Results



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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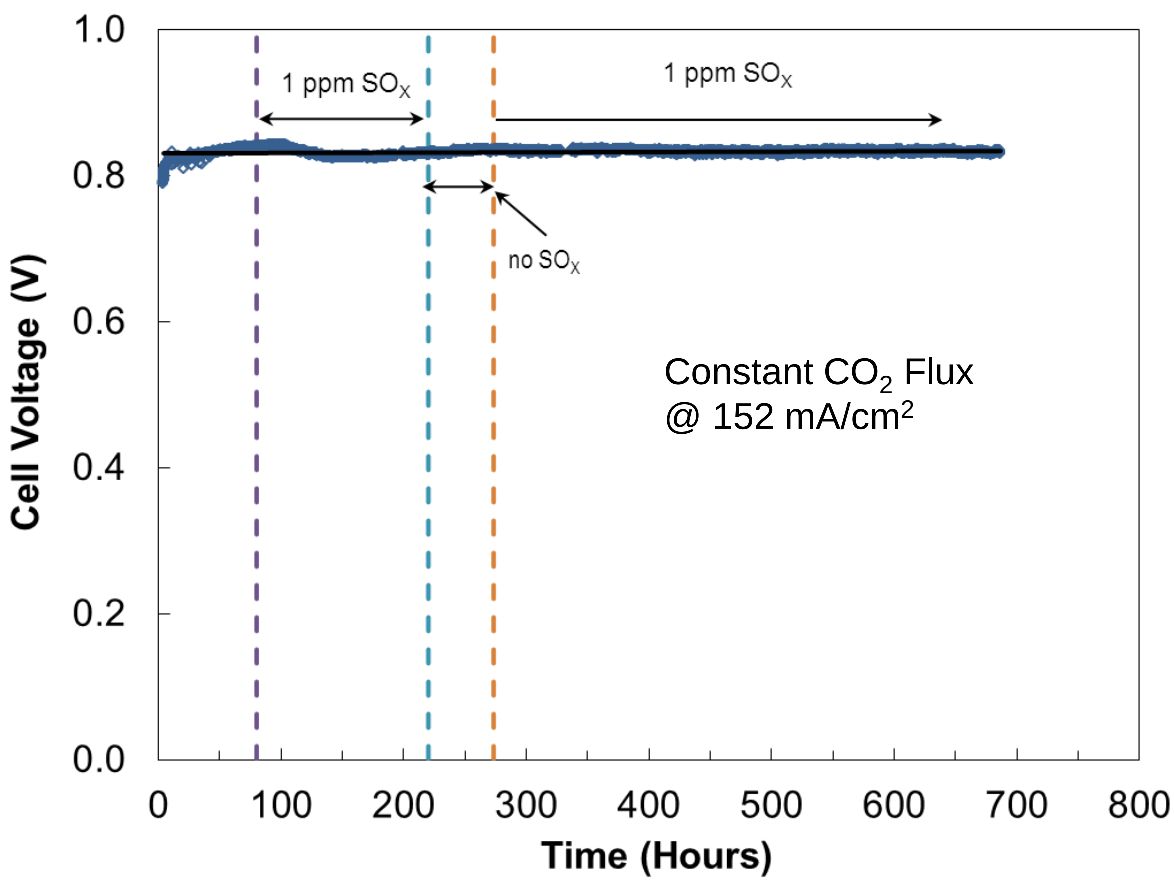
Overview of ECM Contaminant Tolerance Testing

- Minor amounts of sulfur, chlorine, mercury, and selenium remain in flue gases after clean-up
- Testing Goals:
  - Assess physical & chemical interactions of main flue gas pollutants with the ECM
  - Determine ECM performance effects with S, Cl, Hg, and Se in flue gases
  - Enable selection of clean-up technology for CEPACS System
- PNNL Capabilities include:
  - Facilities for testing of button cells and membrane coupons with multiple impurity concentrations, temperature, reaction time, extent of reactions, and CO_2 flux
  - In-situ electrochemical measurements
  - Post-test analyses by SEM/EDS, TEM, FIB-SEM, AES, XPS, etc.
  - Analytical & modeling capabilities to study degradation mechanisms caused by contaminants

Walk-in ventilated lab space and multiple work stations are used for this work

Multiple button cells per furnace with individual gas flow and electrical controls

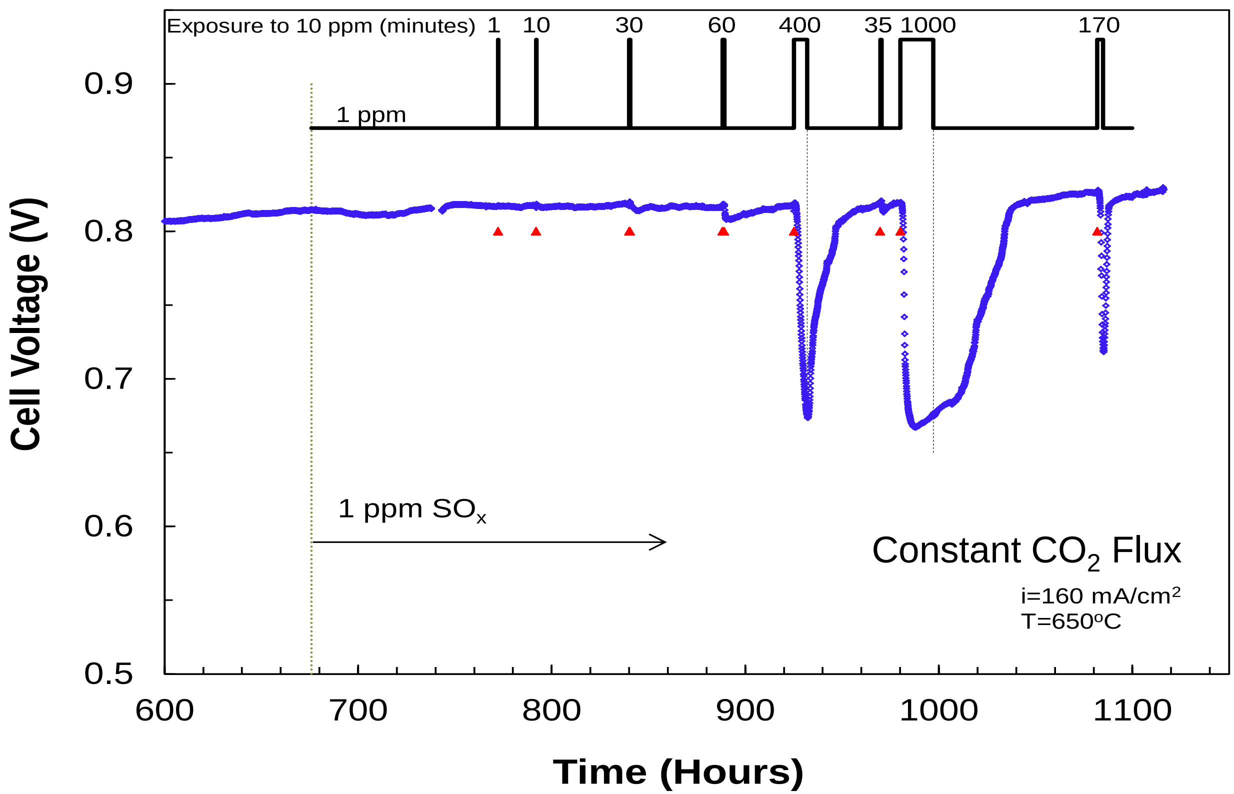
ECM Flue Gas Contaminant Tolerance: SO_2



- Polishing equipment upstream of ECM reduces SO_2 concentration in the flue gas (cathode gas) to <1 ppm
- ECM stable operation has been verified with 0.4 - 1 ppm SO_2 in the cathode without significant performance loss in two 600+ hour tests

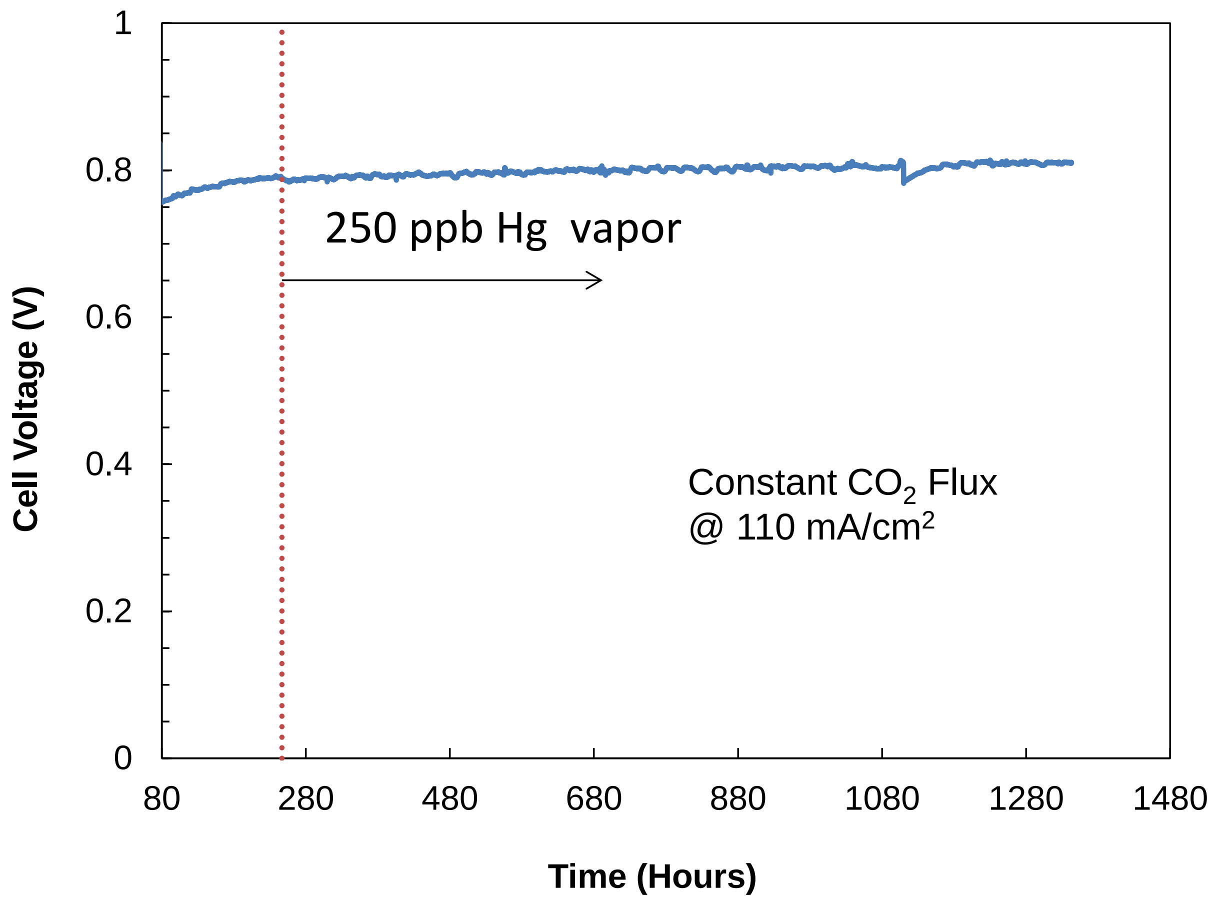
ECM Flue Gas Contaminant Tolerance: SO_2

To simulate flue gas cleanup system upsets, ECM response to high SO_2 concentrations was tested:



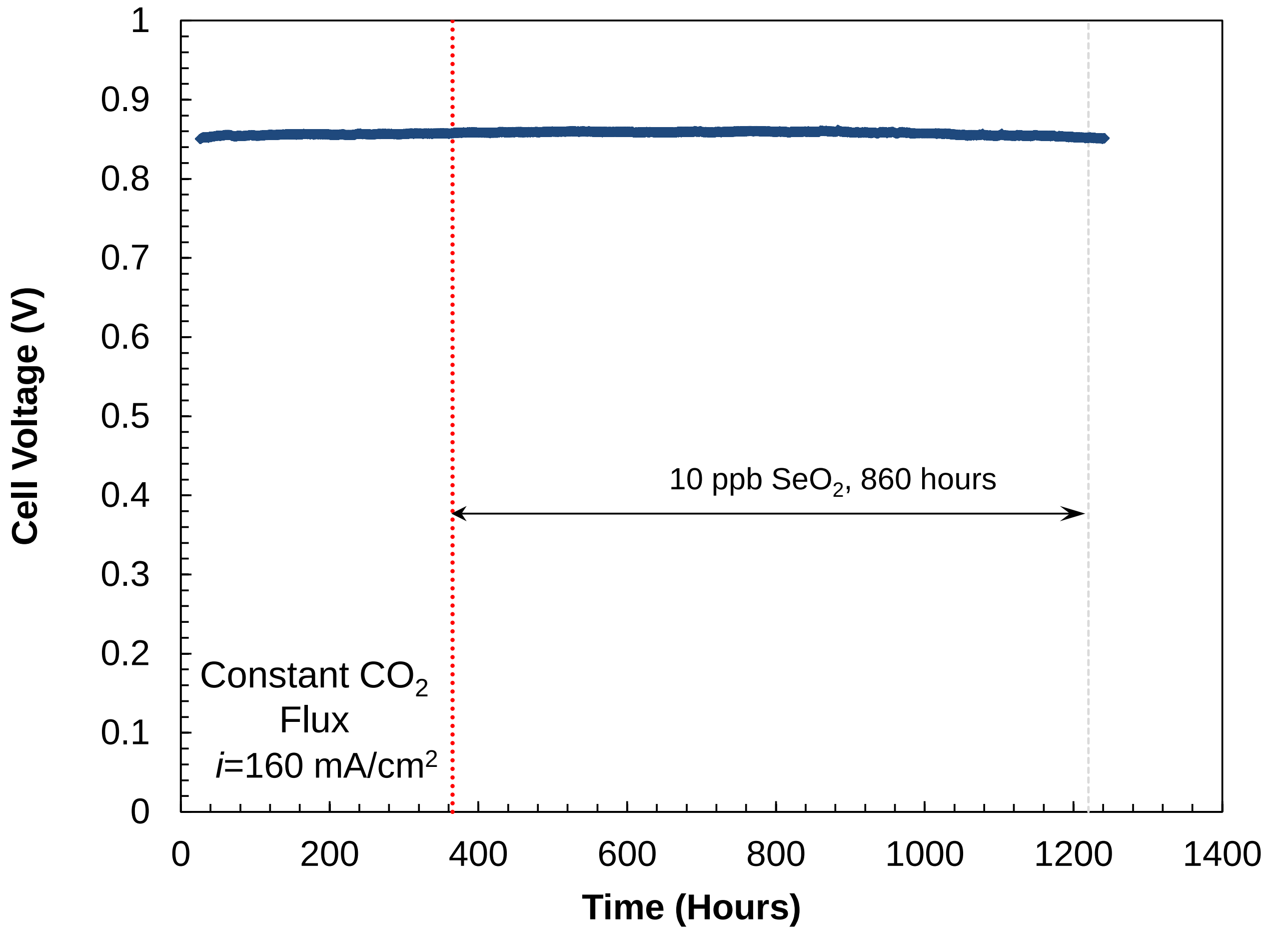
- Continuation of sulfur testing involved exposing cathode to baseline 1 ppm SOx with 10 ppm transients of varying lengths.
- Performance loss was fully recoverable, with recovery time proportional to length of transient.

ECM Flue Gas Contaminant Tolerance: Hg



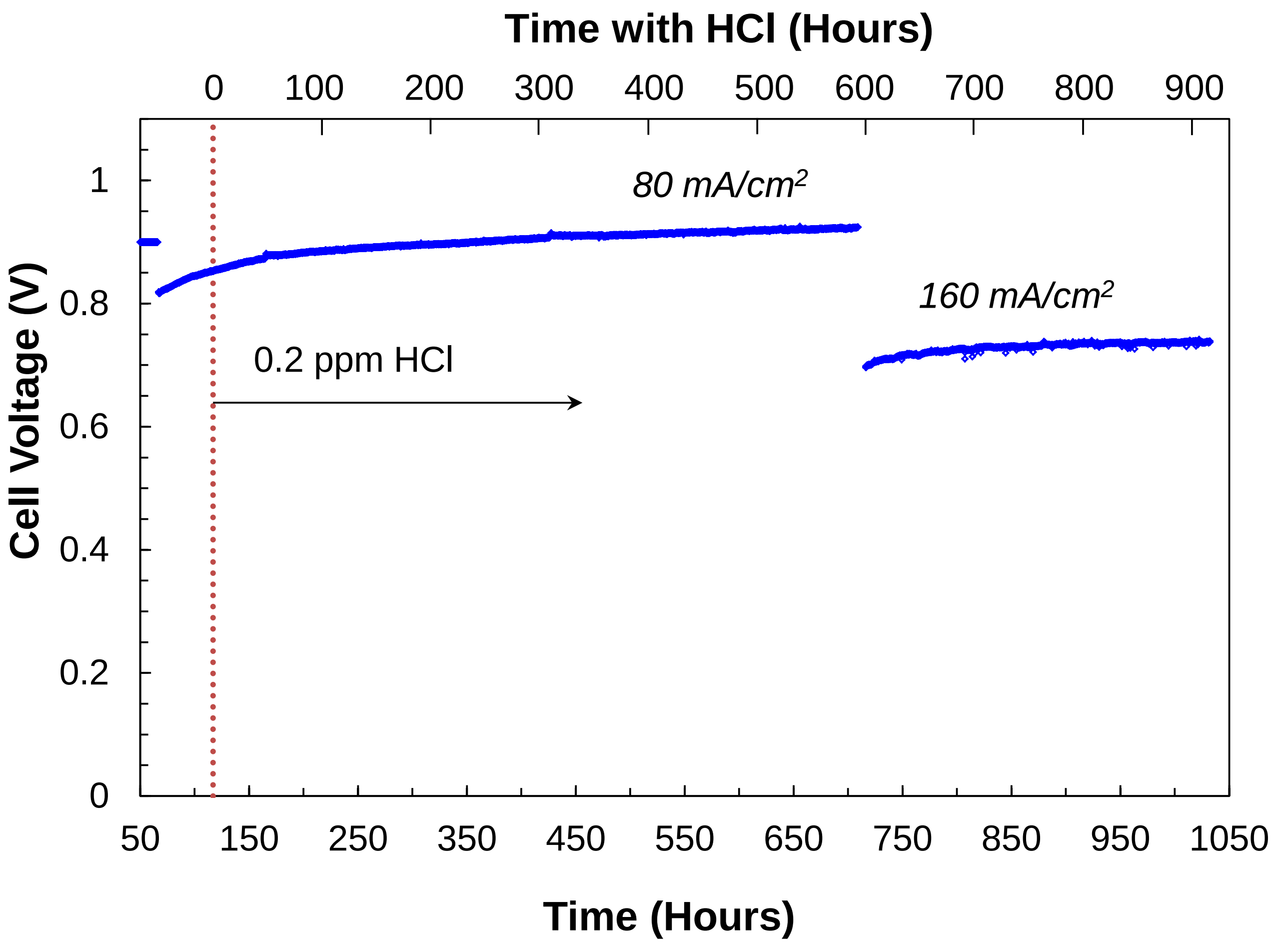
- Stable operation was observed with 250 ppb Hg in ECM cathode gas (500 times higher than typically present in coal plant flue gas)
- Test data analysis confirmed no accumulation of Hg in ECM components

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

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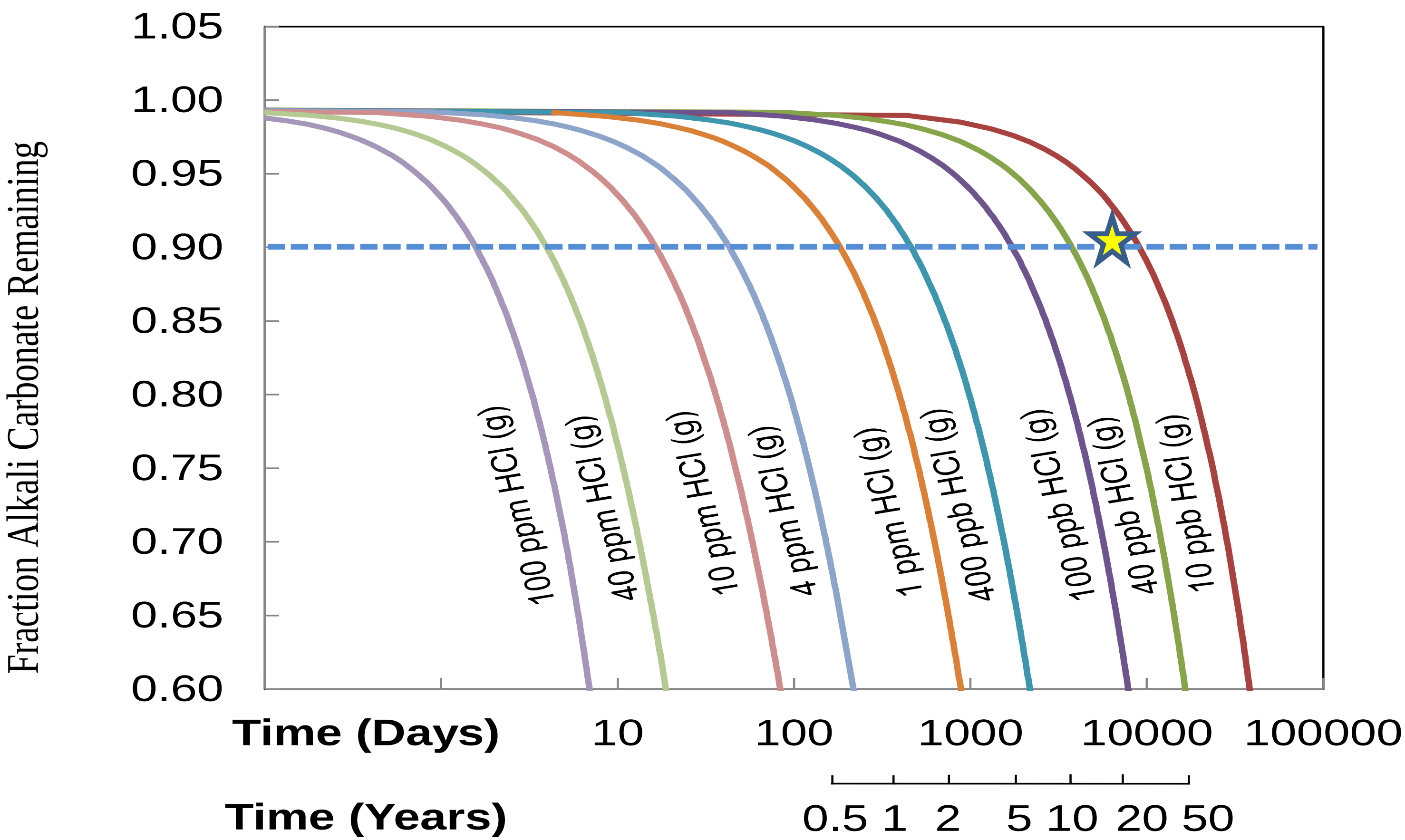
ECM Flue Gas Contaminant Tolerance: Chlorine

Thermodynamic Modeling Results:



- At expected flue gas Cl concentration of 10-20ppb, significant electrolyte loss (>10%) is not predicted before ~20 years of operation (2x ECM design life)

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ECM Flue Gas Contaminants Tolerance: Summary

Flue Gas Contaminant	Highest Concentration Tested by PNNL, with low/no power degradation		Concentration in Cathode Inlet Gas After Polishing FGD, Estimated by URS		Notes
SO_2	1	ppmv	0.18	ppmv	Performance losses due to short-term SO_2 exposure up to 40ppm were fully reversible
Se	10	ppbv	0.30	ppbv	No apparent degradation over 860 hours.
Hg	250	ppbv	0.08	ppbv	Expected form is predominantly elemental Hg. No apparent degradation over 1100 hours.
HCl	200	ppbv	12.7	ppbv	No apparent degradation over 900 hours.

- Based on PNNL testing and URS performance estimates, a polishing wet-FGD scrubber is expected to sufficiently clean flue gas for ECM operation

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  - Task 1. Project Management & Planning
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Task 4. Environmental, Health, and Safety (EH&S) Review

Objectives:

- Perform a technical EH&S review to assess the environmental friendliness and safety of future deployment of the ECM system:
  - Evaluate waste stream types (gas, liquid, solid), levels, and properties (hazardous, toxicity, flammability, etc.)
  - Regulatory compliance and implications
  - Safe handling and storage procedures for raw materials, intermediates, products, and by-products.
- Complete Technical EH&S Review Report

Success Criterion: Illustrate that there are no environmental or safety concerns which would prohibit commercialization efforts for the ECM system.

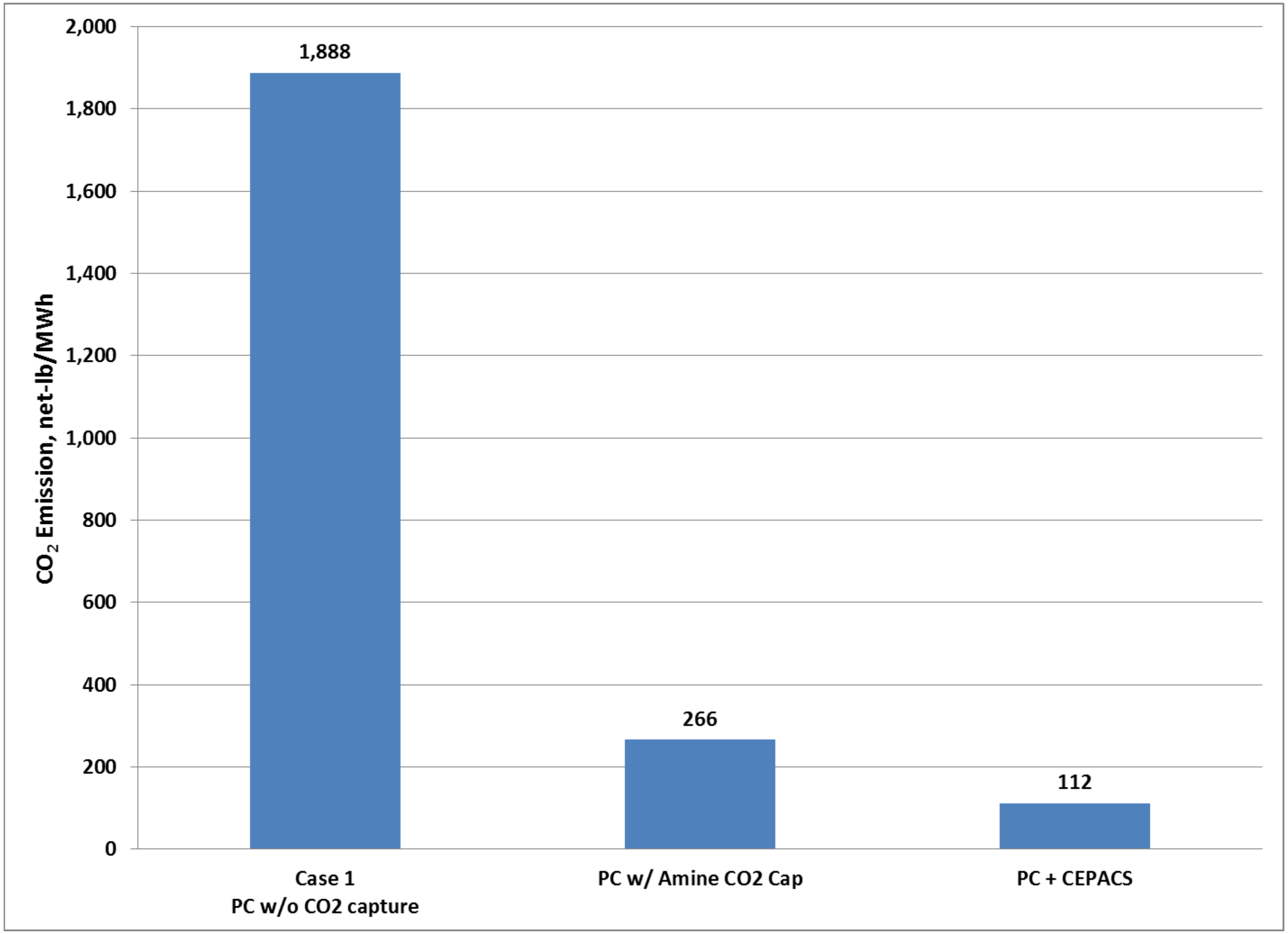
Gaseous Emissions

Summary of CEPACS Estimated Gaseous Emission

	kg/GJ (lb/MMBtu)		Tonne/year (ton/year) 85% CF		kg/MWh (lb/MWh)	
SO_2	0.0003	(0.0006)	16	(18)	0.002	(0.005)
NO_x	0.007	(0.015)	414	(456)	0.055	(0.121)
Particulates	0.002	(0.004)	113	(124)	0.015	(0.033)
Hg	0.0000	(0.00)	0.020	(0.022)	2.60E-06	(5.74E-06)
CO_2	5.4	(12.6)	337,109	(371,595)	45	(98)

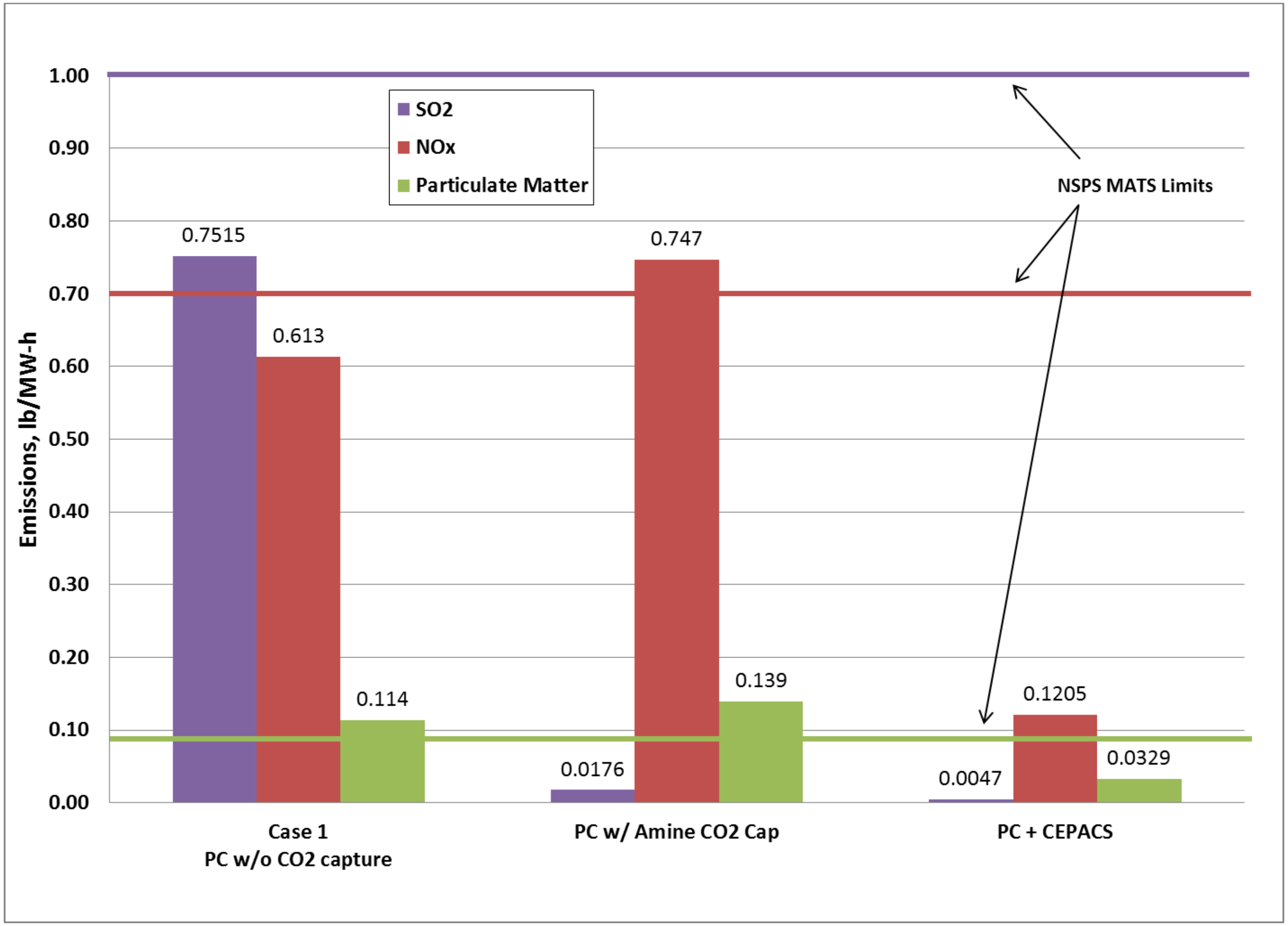
- The CEPACS system generates additional power, the CO_2 emissions (normalized by total plant output) are 57.9% lower than typical Amine scrubbers.
- SO_2 emissions are very low for the CEPACS system due to the Polishing FGD scrubber
- ECM process reduces >70% of the flue gas NO_x content. The NO_x emission rate of 0.055 kg/MWh is a fraction of the MATS emission limit of 0.339 kg/MWh.
- Particulate Matters, not removed by the PC plant baghouse and two Wet Lime scrubbers in series, will exit in the CEPACS plant exhaust stream at a level of <37% of the MATS limit of 0.041 kg/MWh.

Comparative CO_2 Emissions



Note: Based on plant's net power generated

Comparative SO_2, NO_x & PM Emissions



- The CEPACS system significantly reduces emissions of SO_2, NO_x, and PM to below the requirements by NSPS MATS rules

Liquid Emissions

1. **Cooling Tower Discharge**
   - The Cooling Tower system must also use a blowdown procedure to remove corrosion products and the buildup of other contaminants within the cooling system.
     – The blowdown is sent to the facility's waste water treatment system for further processing before disposal. A portion of blowdown water may be utilized as feed water to the Polishing FGD scrubber.
     – The most likely chemicals discharged through the cooling tower are chlorine (chloride salts) and bromine (bromide salts), especially if the pH is low.
2. **Water from FGD Polishing**
   - The effluent water from the polishing scrubber is a small fraction (2%) of the effluent water from the primary scrubber. It will be either recycled (ZLD, Zero Liquid Discharge) or discharged through PC plant waste water treatment outfall.
3. **Process Water**
   - The CEPACS system is a net producer of clean process water which is sent to the PC plant.
4. **Boiler Water Blow-Down**
   - The boiler system is closed loop and under normal operation, blowdown is the only discharge of boiler water. During blowdown, solids and other contaminants that have built up inside of the system are removed.
     – The blowdown water is sent to the site's waste water treatment system for further treatment before disposal.
     – The site's final treatment generally includes pH neutralization, biological oxygen demand control and removal of suspended solids.

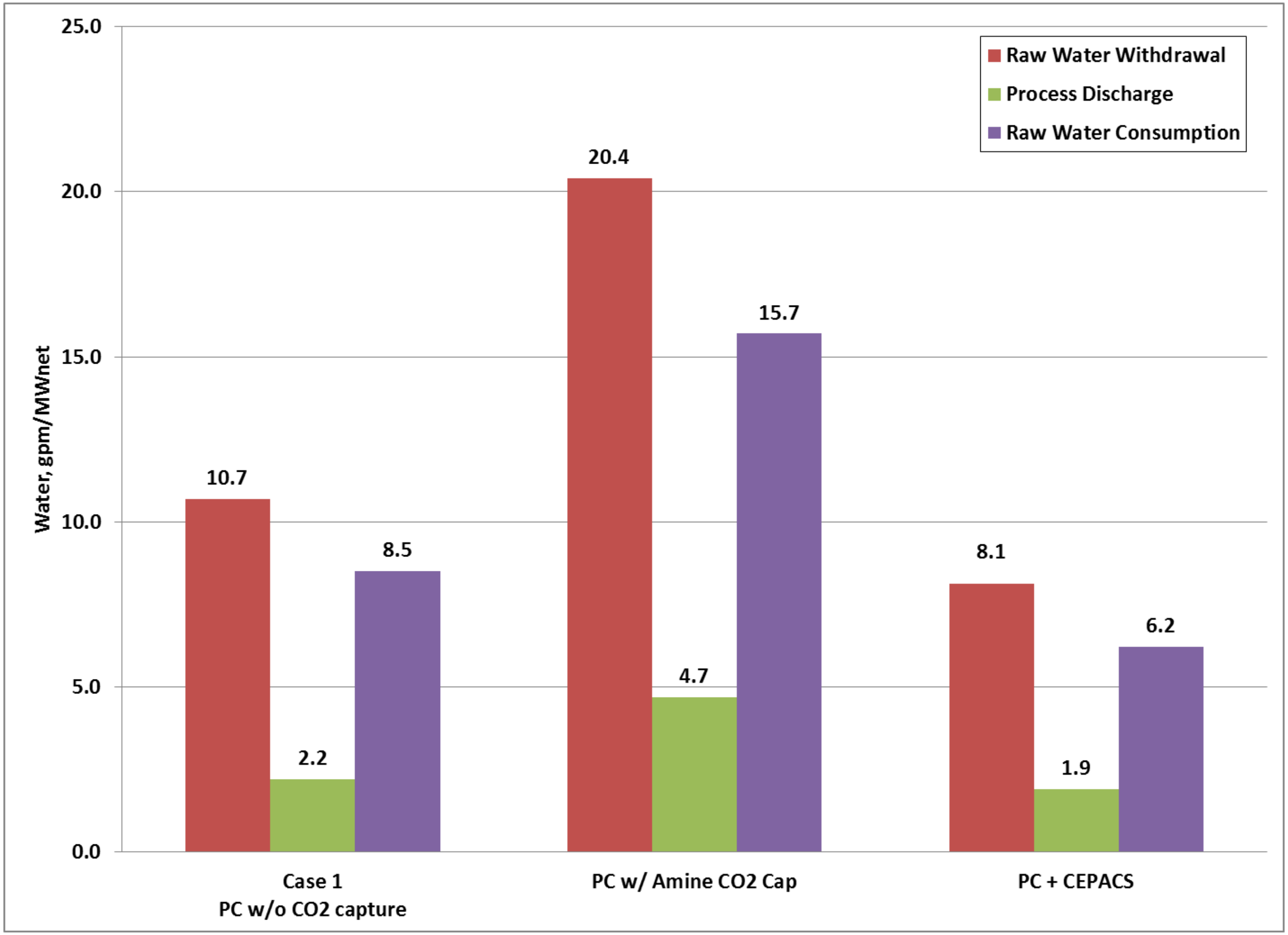
PC+CEPACS Water Balance

CEPACS Water Usage by Group	Raw Water Withdrawal, m3/min (gpm)	Process Water Discharge, m3 /min (gpm)	Raw Water Consumption, m3/min (gpm)
BFW Makeup	0.0 (0)	0.0 (0)	0.0 (0)
CEPACS Process	-1.5 (-386)	0.0 (0)	-1.5 (-386)
Cooling Tower & Polishing FGD	6.8 (1,806)	1.9 (500)	4.9 (1,306)
Totals	5.4 (1,421)	1.9 (500)	3.5 (921)

Case 9 PC Plant Water Usage by Group	Raw Water Withdrawal, m3/min (gpm)	Process Water Discharge, m3 /min (gpm)	Raw Water Consumption, m3/min (gpm)
Primary FGD Makeup	3.9 (1,017)	0.0 (0)	3.9 (1,017)
BFW Makeup	0.3 (74)	0.0 (0)	0.3 (74)
Cooling Tower	18.2 (4,804)	4.6 (1,215)	13.6 (3,589)
Totals	22.3 (5,895)	4.9 (1,215)	17.7 (4,680)

PC Plant + CEPACS Water Usage by Group	Raw Water Withdrawal, m3/min (gpm)	Process Water Discharge, m3/min (gpm)	Raw Water Consumption, m3/min (gpm)
Primary FGD Makeup	3.9 (1,017)	0.0 (0)	3.9 (1,017)
BFW Makeup	0.3 (74)	0.0 (0)	0.3 (74)
CEPACS Process	-1.5 (-386)	0.0 (0)	-1.5 (-386)
Cooling Tower & Polishing FGD	25.0 (6,610)	6.5 (1,715)	18.5 (4,895)
Totals	27.7 (7,317)	6.5 (1,715)	21.2 (5,602)

System Water Use Comparison



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Ancillary Emissions and Solid Wastes

- Carbon-based adsorption media used for the desulfurization of the NG is estimated at ~33 tons twice annually. Disposal is covered by OSHA hazcom and other General Industry Standards including EPA Tier II reporting, RCRA (Resource Conservation Recovery Act) waste management rules and DOT Hazardous Material Rule (HMR) requirements.

- Water treatment wastes:
  - The waste stream from the regeneration of the water softener media process is sent to the PC plant waste water treatment system.
  - Minimal generation of waste carbon and filter media is expected due to backwashing to regenerate the beds rather than replace them.
  - Filter cartridges need to be replaced every 3-4 months depending on the level of particles in the water and the water demand.

- Heavy metals are primarily removed with the fly ash via PM control in the PC plant.
  - CEPACS system will not add to the existing heavy metal emissions from the host PC plant.
  - If heavy metals are found in the scrubber gypsum product, the product may need to be landfilled.

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Bench-Scale CEPACS Demonstration System

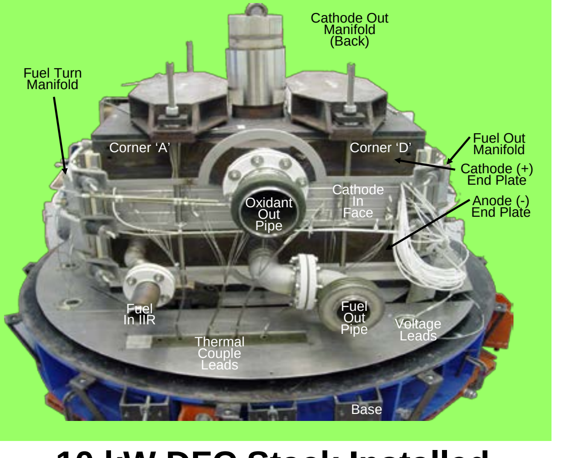
Task Objective: Validate ECM performance in large-area membrane module under simulated clean flue gas operating conditions and demonstrate CEPACS system operation to produce high-purity liquid CO_2 product

BP2 Scope

- Design and initiate fabrication of bench-scale CEPACS System process skid as add-on to FCE's "10kW Test Facility"
- Fabricate $11.7m^2$ ECM module (14 cells w/ $8387cm^2$ area each)

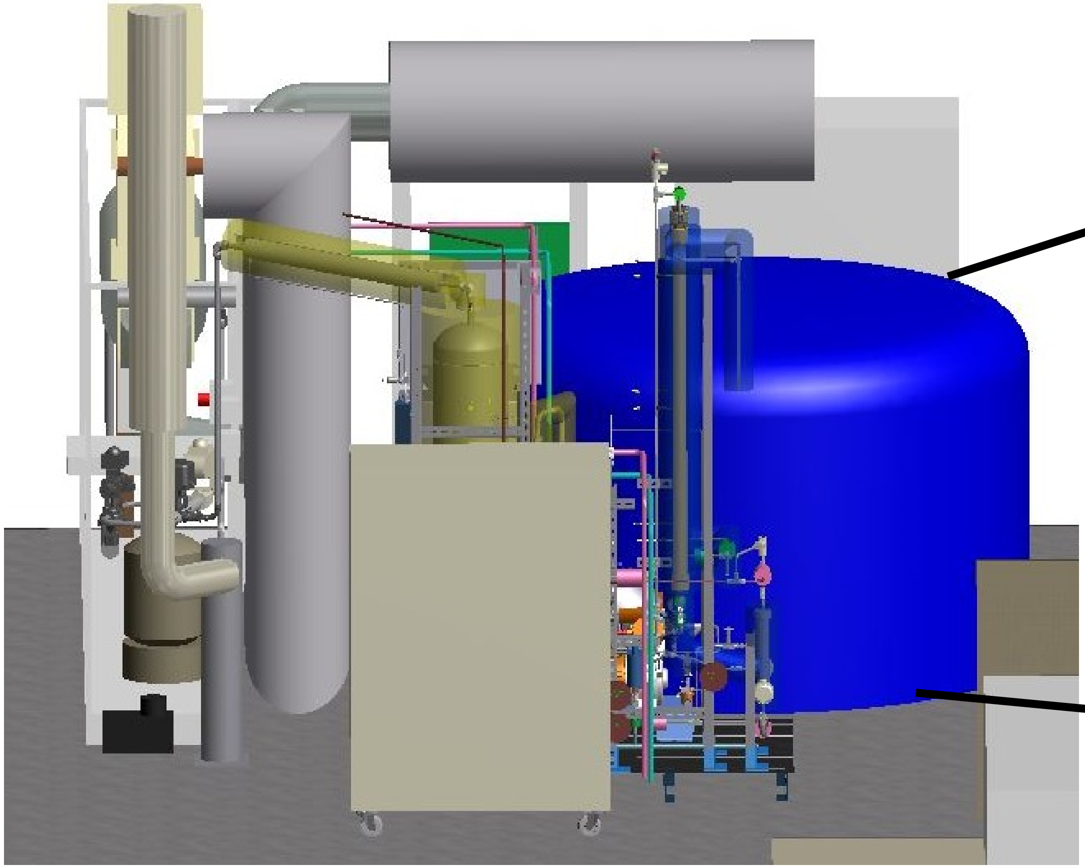
BP3 Scope

- Perform testing for 13 months: 9 months steady-state, followed by 4 months of transient and parametric studies



10 kW DFC Stack Installed in Module Base

Bench-Scale Demonstration System



ECM Membranes (qty. 14)

CEPACS Demonstration system capabilities: 100 tons/year liquid CO_2 production and 10 kW gross DC Power

10kW ECM Demonstration System Build Progress

Low Temperature Shift Converter (LTSC)

Chiller (-76°F)

CO_2 Condensers (x2)

CO_2 Compressor

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ECM Stack/Module Fabrication

- 14-cell ECM Stack
  - ECM cell-packages manufactured in FCE's commercial production facility (Torrington, CT)

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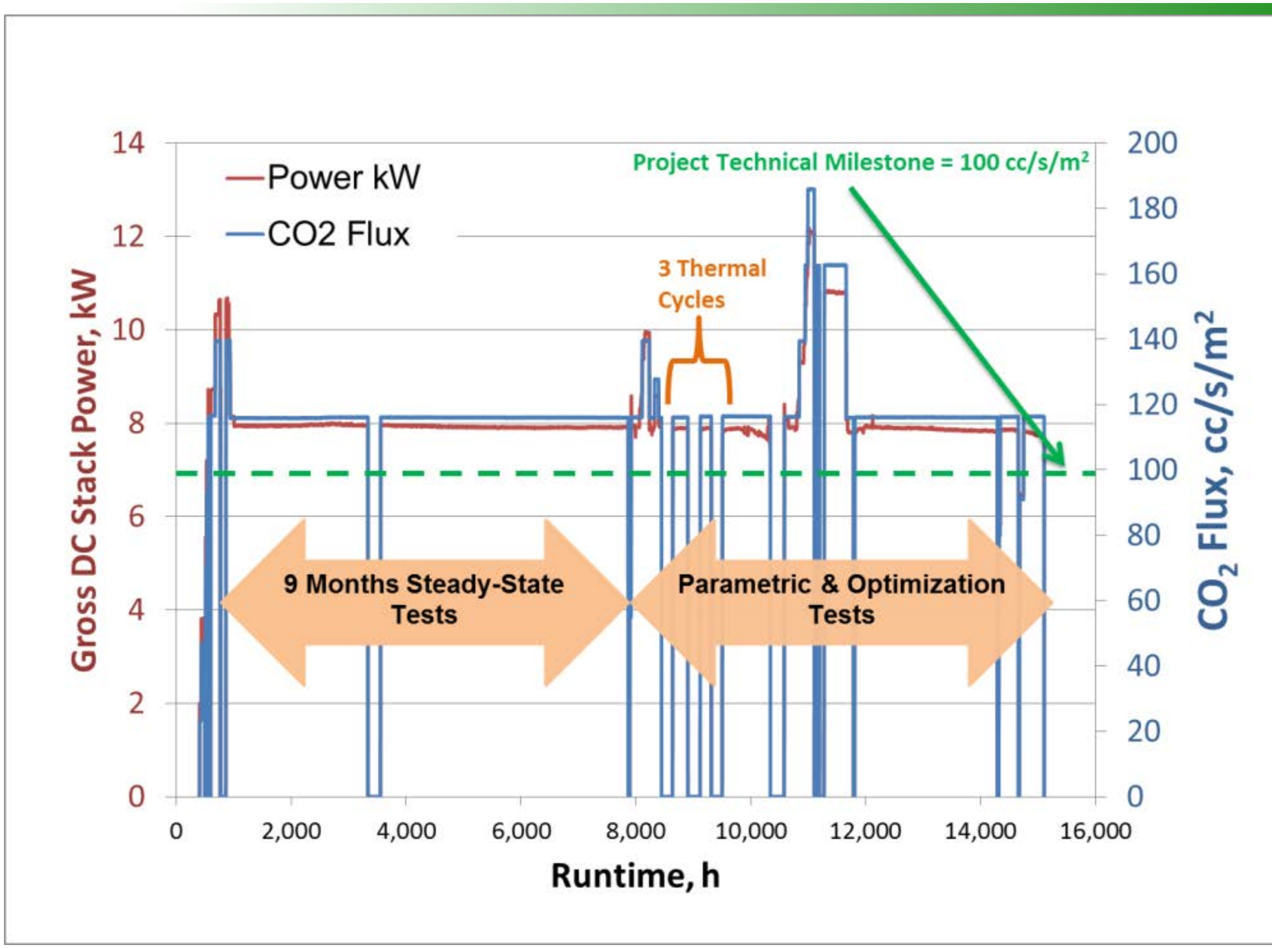
Bench-Scale Demonstration



Completed testing of CEPACS demonstration system using simulated PC flue gas:

- >100 tons/year CO_2 capture capability
- >10 kW peak power production
- 15,715 hours total runtime

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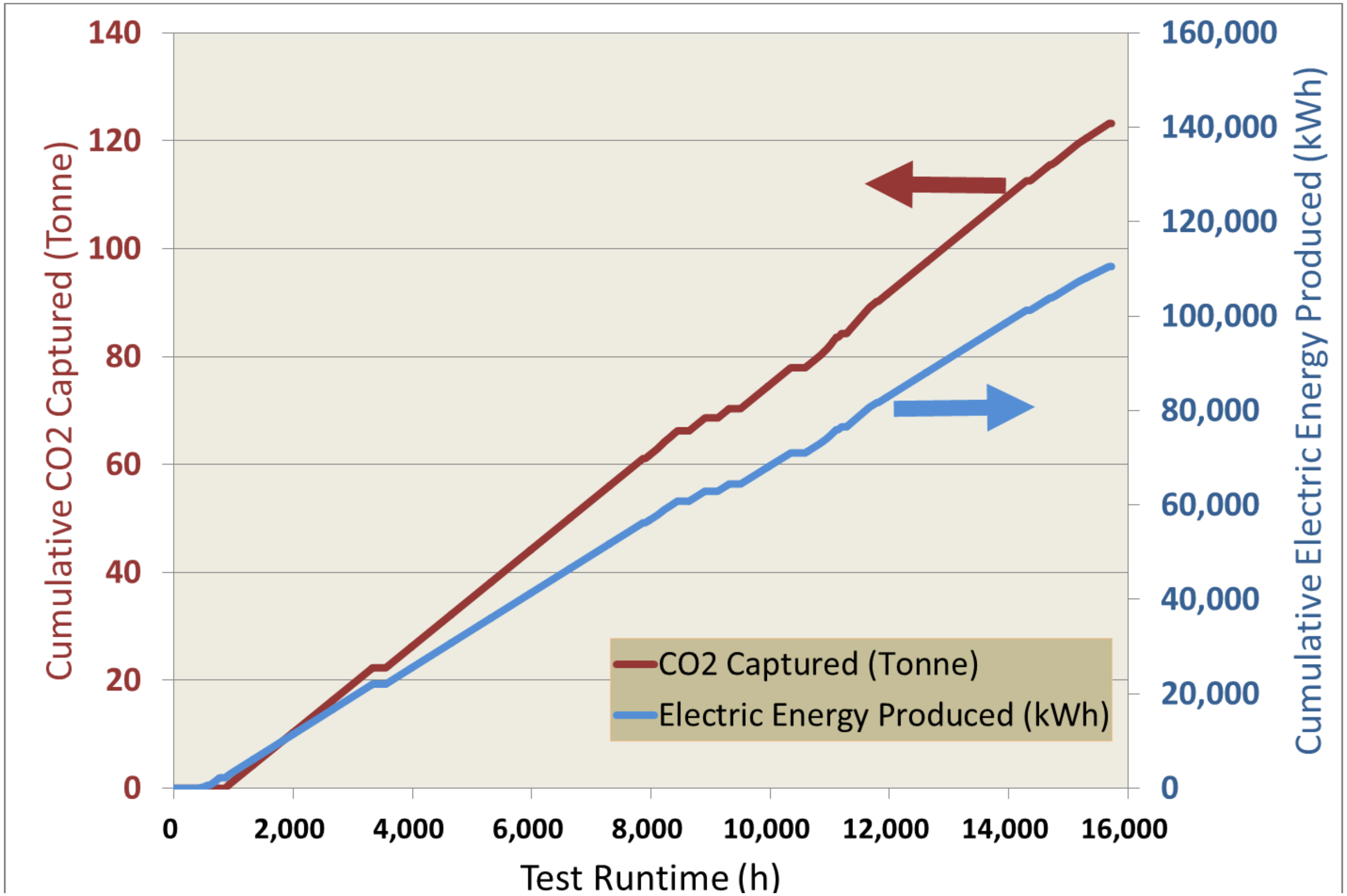
Bench-Scale ECM Test Summary



Net CO_2 captured >120 Tonne and net DC electric power generated >110MWh

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ECM Demonstration Project Accomplishments and Summary

- All BP1 and BP2 project Milestones have been met
- A Technical and Economic Feasibility Study (T&EFS) was completed for a CEPACS system to separate 90% of CO_2 from the flue gas of a Reference Plant (550 MW PC)
  - A PC plant equipped with CEPACS has the potential for achieving the DOE incremental cost of electricity (COE) target of 35% while capturing 90% of CO_2.
  - The CEPACS-equipped PC plant has the lowest Total Overnight Cost of $2,297 /kW and the highest overall efficiency (38.8% Higher Heating Value) among the alternative systems studied.
  - The CEPACS system generates excess process water, thereby reducing the water consumption compared to a Reference PC plant without carbon capture.
  - The Reference Plant equipped with CEPACS has a cost of CO_2 captured of about $39/tonne CO_2 (2011 USD), which meets the DOE target of <$40/tonne.
- Tests of a 250 cm^2 ECM have verified that:
  - ECM can achieve a CO_2 flux of >100 $cc/m^2/s$ while separating >90% of CO_2 at very low partial pressures representative of PC or NGCC plant flue gas
  - ECM destroys 70-80% of NO_x from flue gases
  - ECM CO_2 flux remains constant as the membrane ages
- Button-cell testing indicated that ECM performance is stable in the presence of S, Se, Cl, and Hg levels expected downstream of a conventional wet-FGD polisher
- CEPACS system utilizes commercially-available process equipment and poses no unusual EH&S risks
- Bench-scale CEPACS demonstration testing proved feasibility by achieving milestones related to CO_2 flux and thermal cycle tolerance

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ECM
Commercialization Prospects

- ECM, utilizing commercially proven Direct FuelCell® technology, is a compelling alternative for CO_2 capture that is efficient and cost effective for central generation and industrial applications
- ECM commercialization potential is benefiting from higher production volumes of Direct FuelCells
- Utilization of ECM technology in large scale fuel cell systems demonstrates the viability of carbon capture for centralized PC and NGCC plants
- Near term application: Enhanced oil recovery, SAGD Tar Sands – Alberta, CA, capture from natural gas power plants

Fuel Cell Manufacturing Facility, Torrington, CT

Hwaseong, South Korea 59MW Fuel Cell System

Acknowledgements

Guidance from the NETL Management team: José Figueroa and Lynn Brickett