Electrochemical Membrane for Carbon Dioxide Capture and Power Generation

FuelCell Energy

No. DE-FE0007634

Project Kick-off Meeting

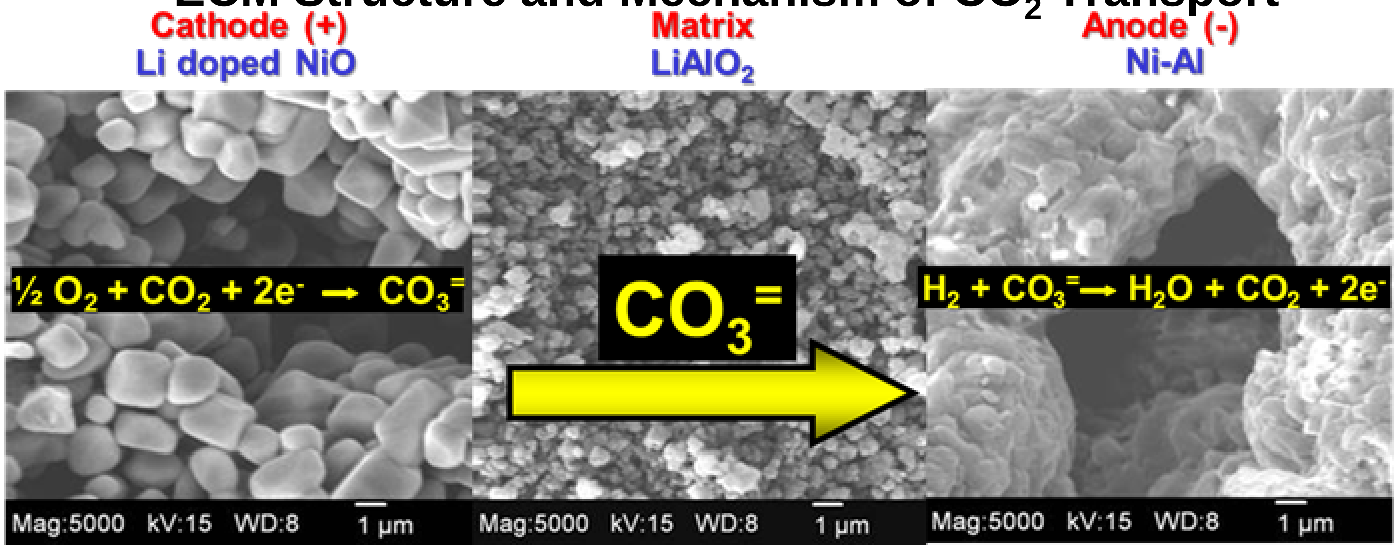
December 2, 2011

Presentation Outline

- **ECM Technology**
  - Background
  - Testing Results
- **Application to Pulverized Coal Plant**
- **Carbon Capture from Large Industries**
- **DE-FE0007634 Project Outline**
- **Summary**

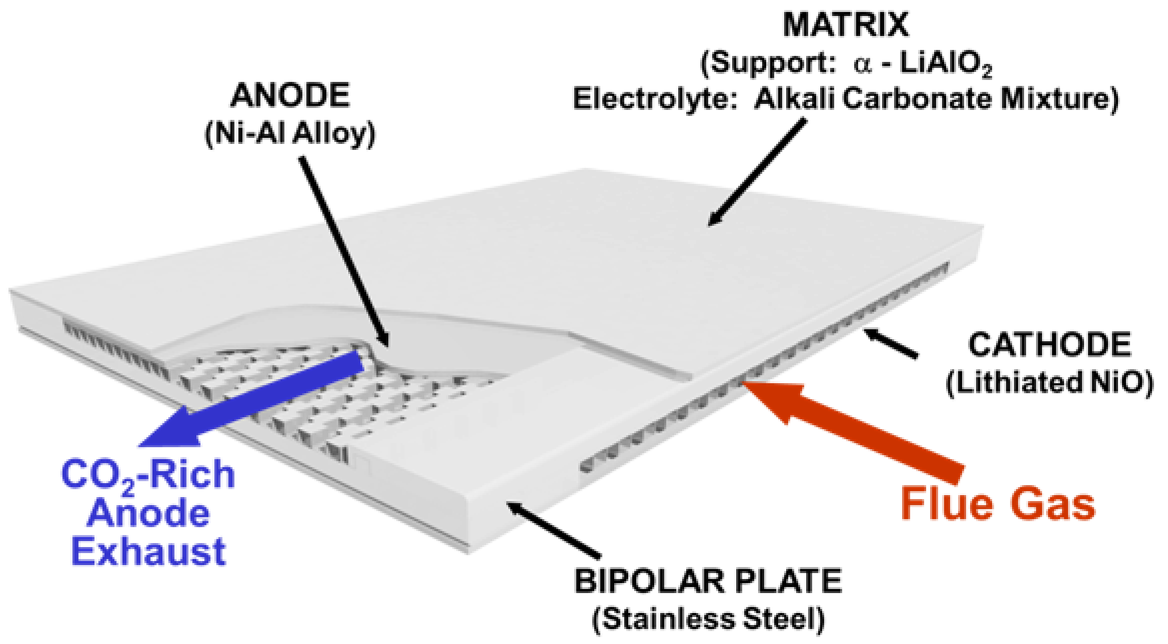
ECM Active Components

ECM Structure and Mechanism of CO_2 Transport



- ECM components are fabricated from inexpensive inorganic materials.
- Because of fast electrode kinetics at the operating temperatures of 550-650°C, ECM is suitable for CO_2 concentration of <15% normally found in the PC plant flue gas.
- 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).
- ECM is completely selective towards CO_2 as compared to N_2 (CO_2/N_2 selectivity = ∞).
- The driving force for the gas separation is electrical potential as opposed to the pressure differential. Flue gas does not need to be pressurized. ECM operates at atmospheric pressure without energy penalties normally associated with other membrane-based technologies.

ECM Cell Package



- **ECM cells are made using automated fabrication techniques such as tape casting (utilized in semiconductor industries).**
- **Repeat planar cell geometry has simple and inexpensive stacking characteristics.**

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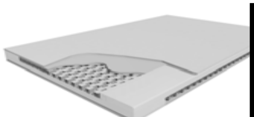
ECM Module Assembly

ECM is a modular technology:

- **Ease of scale up**
- **Suitable for incremental phased applications to almost any type of power plants**
- **Skid mounted modules easy to transport**



ECM Assembly

ECM Stack

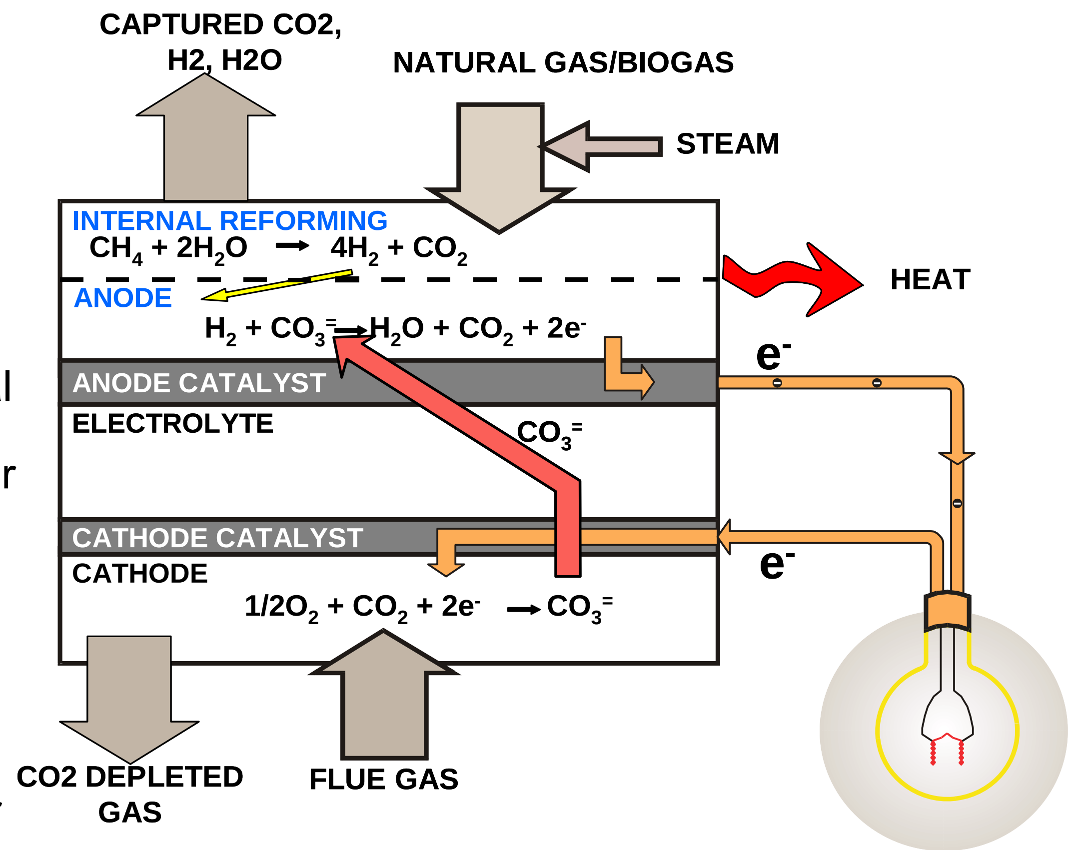
Four-Stack Module

Enclosed Module

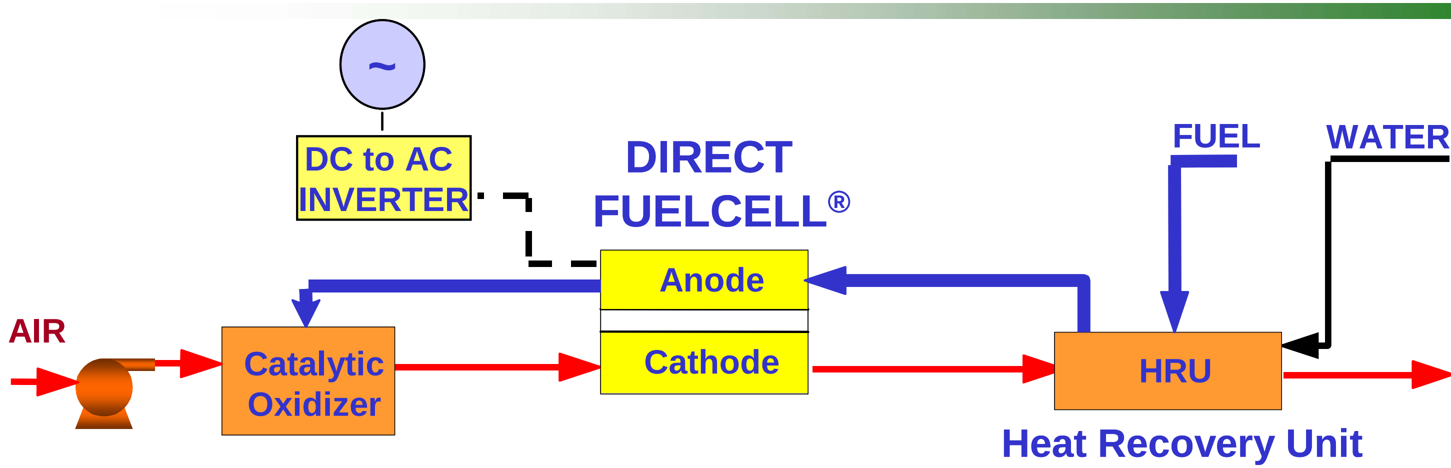
Planar Electrochemical Membrane Assemblies Are Stacked and Incorporated into MW-scale Modules.

Benefits of ECM for CO_2 Separation

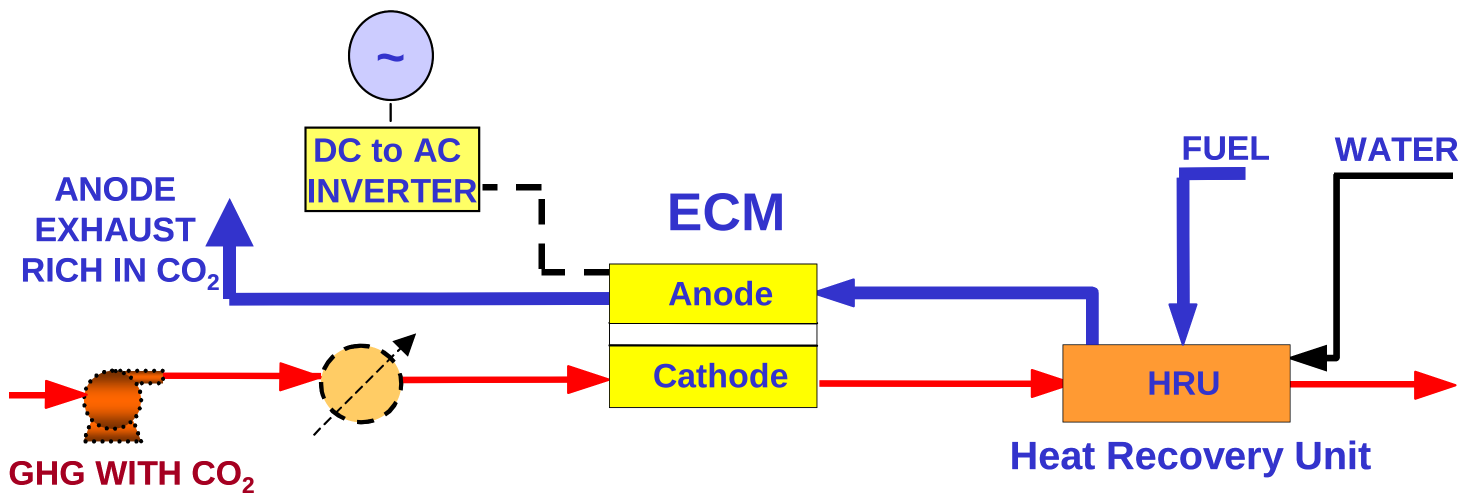
- ECM allows for separation of at least 90% of carbon dioxide from the greenhouse gases (GHG) generated by coal fired power plants and other industrial sites.
- Preliminary estimates show that DOE target of <35% increase in cost-of-electricity (COE) is achievable for commercial units.
- ECM internally converts fossil fuels (coal syngas, natural gas, renewables, etc.) into H_2 to produce electricity (no need for external conversion devices).
- Unlike other CO_2 capture technologies which reduce net electric power, ECM increases the power generated by the existing fossil fueled plants.
- ECM systems generate excess clean water, an important feature where water is scarce.
- Laboratory data has shown that ECM also significantly reduces NOx emissions produced by the older plants.



Basis for ECM Technology: Proven DFC Power Plants



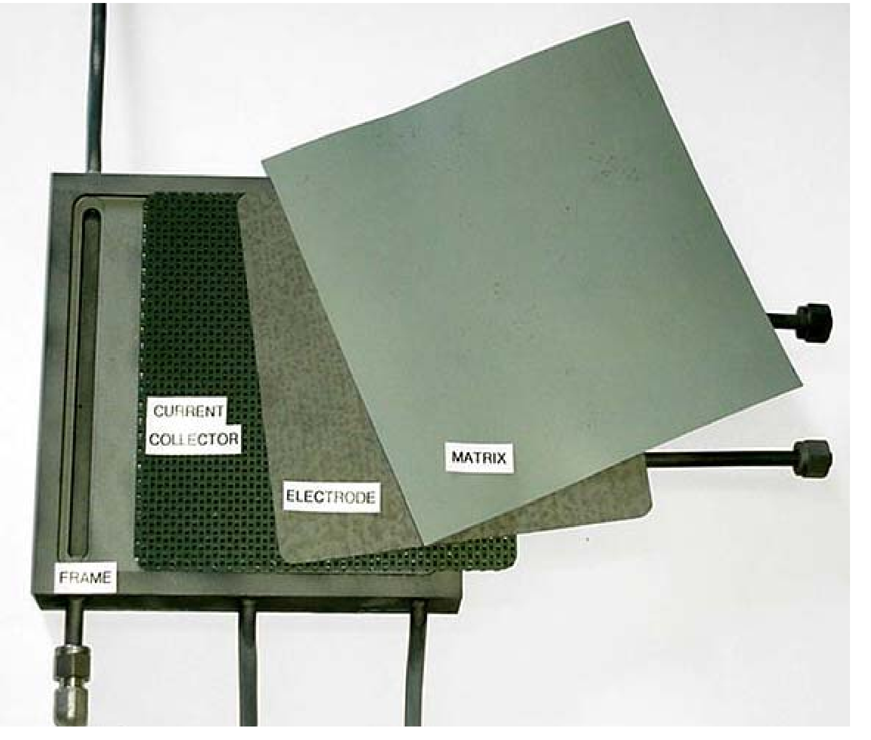
Commercially-proven Direct FuelCell (DFC) Power Plant



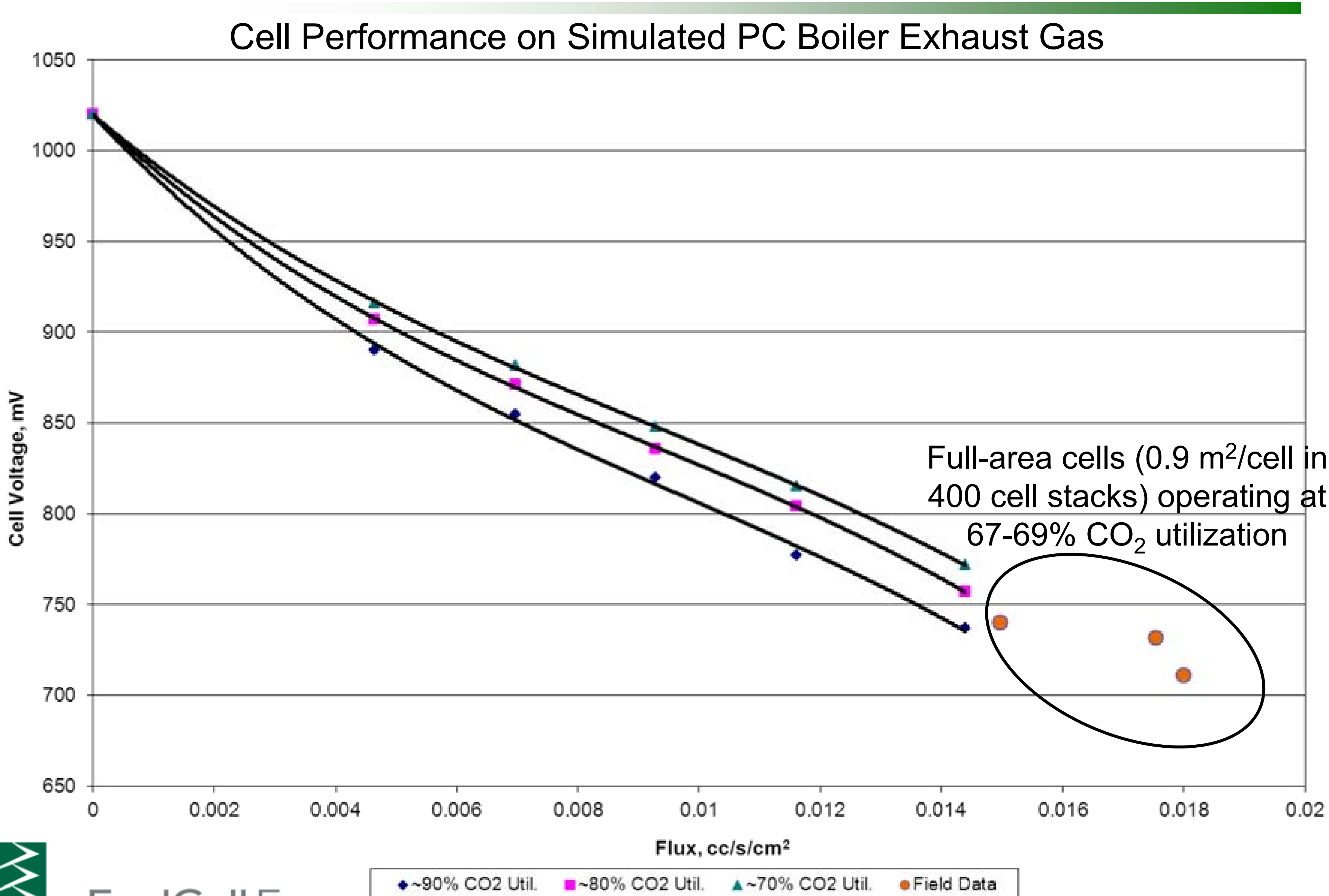
ECM system is an emerging application for proven DFC technology

ECM Lab-Scale Testing

- Laboratory Scale Proof-of-concept ECM tests were performed under a variety of R&D activities supported by FCE (IR&D), DOE (DE-FC26-04NT42206), and EPA (EP-D-11-042)



ECM Test Results
PC Boiler Case



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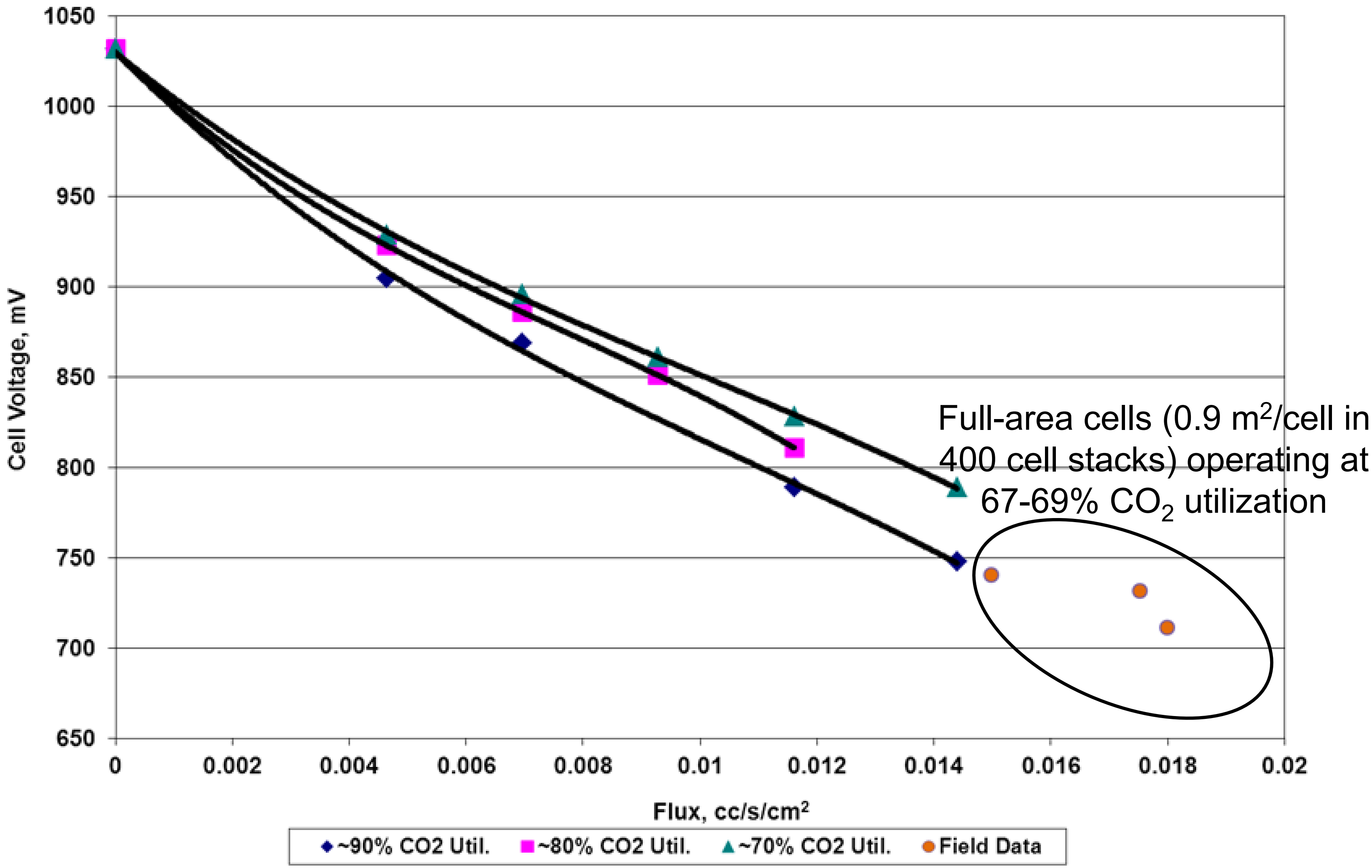
ECM Test Results
IGCC Case

Cell Performance on Simulated IGCC Exhaust Gas



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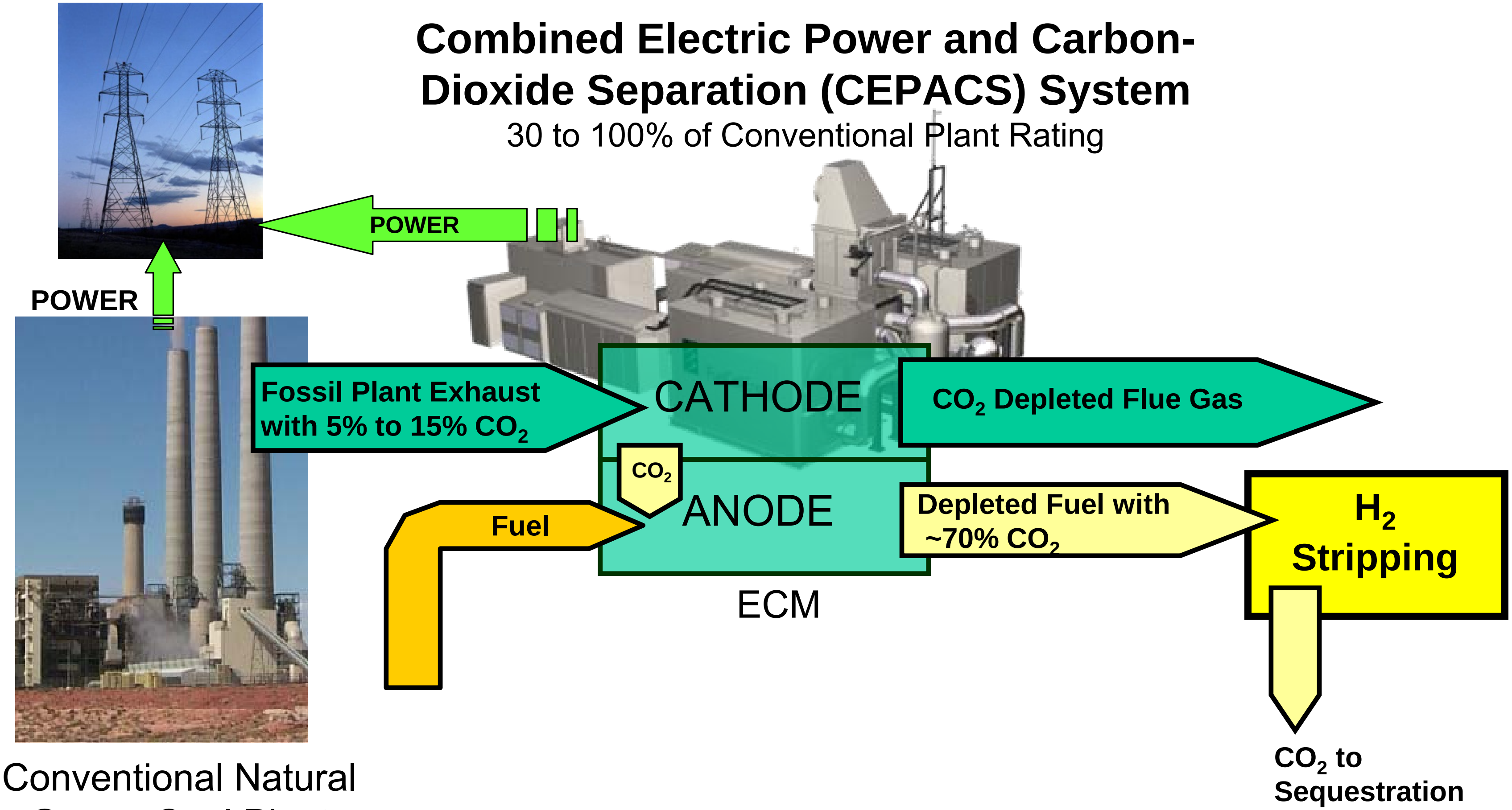
ECM Application for Carbon Separation from Fossil Plant Exhaust

Combined Electric Power and Carbon-Dioxide Separation (CEPACS) System

30 to 100% of Conventional Plant Rating

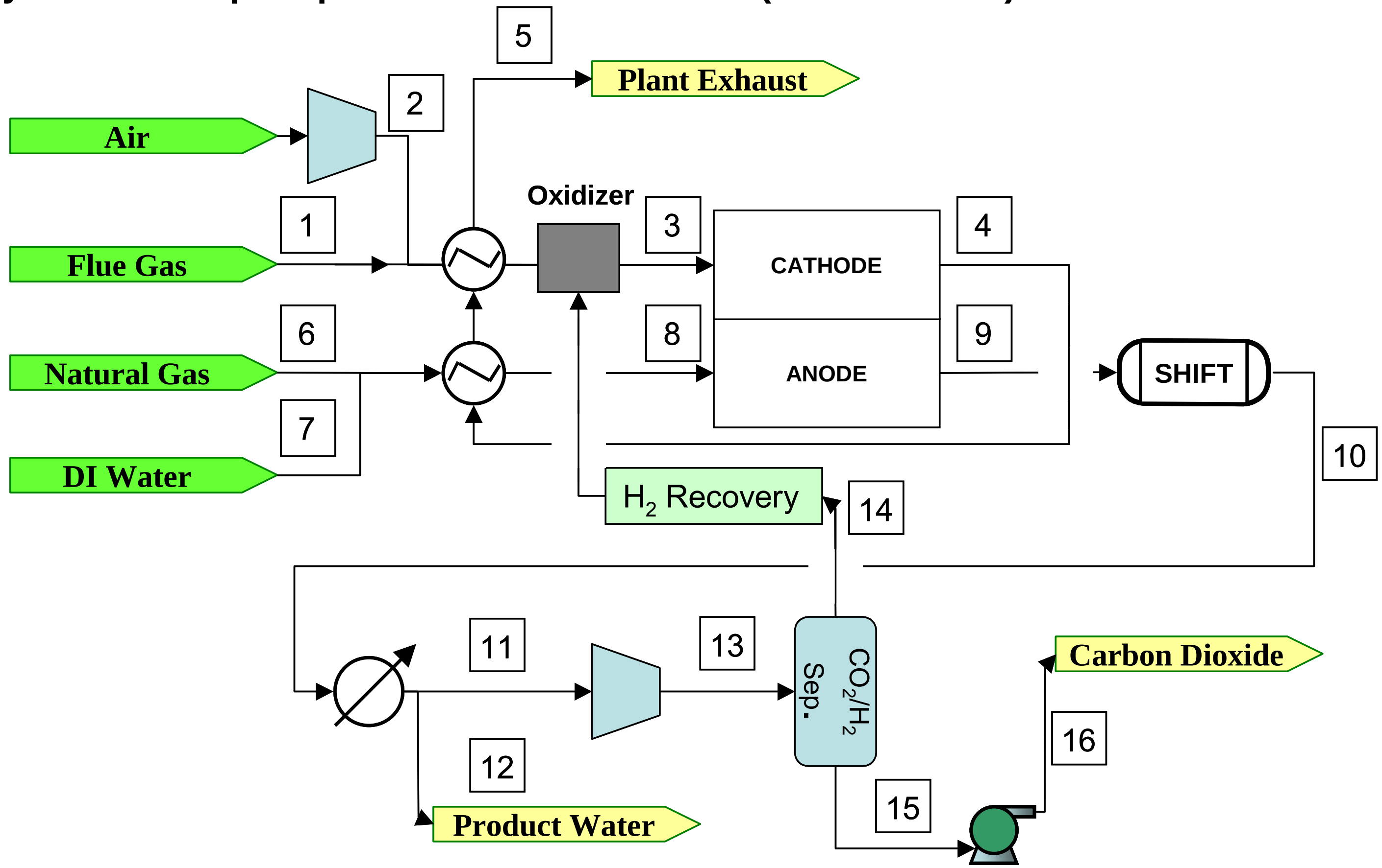


Conventional Natural Gas or Coal Plant

- Carbonate electrochemical process transfers CO_2 from Air Electrode (Cathode) to Fuel Electrode (Anode)
- CO_2 is easily separated from Fuel Electrode exhaust gas because it is no longer diluted with air

CEPACS System Block Flow Diagram

CEPACS System Concept Implementation for 433 MW (Conesville #5) PC Plant Located in Ohio



CEPACS system design produces liquid CO_2. The low permeate-gas outlet pressure is not a significant factor relative to the required CO_2 delivery pressure, as the liquid CO_2 is pumped to the pipeline pressure (~152 bars) without significant energy penalty.

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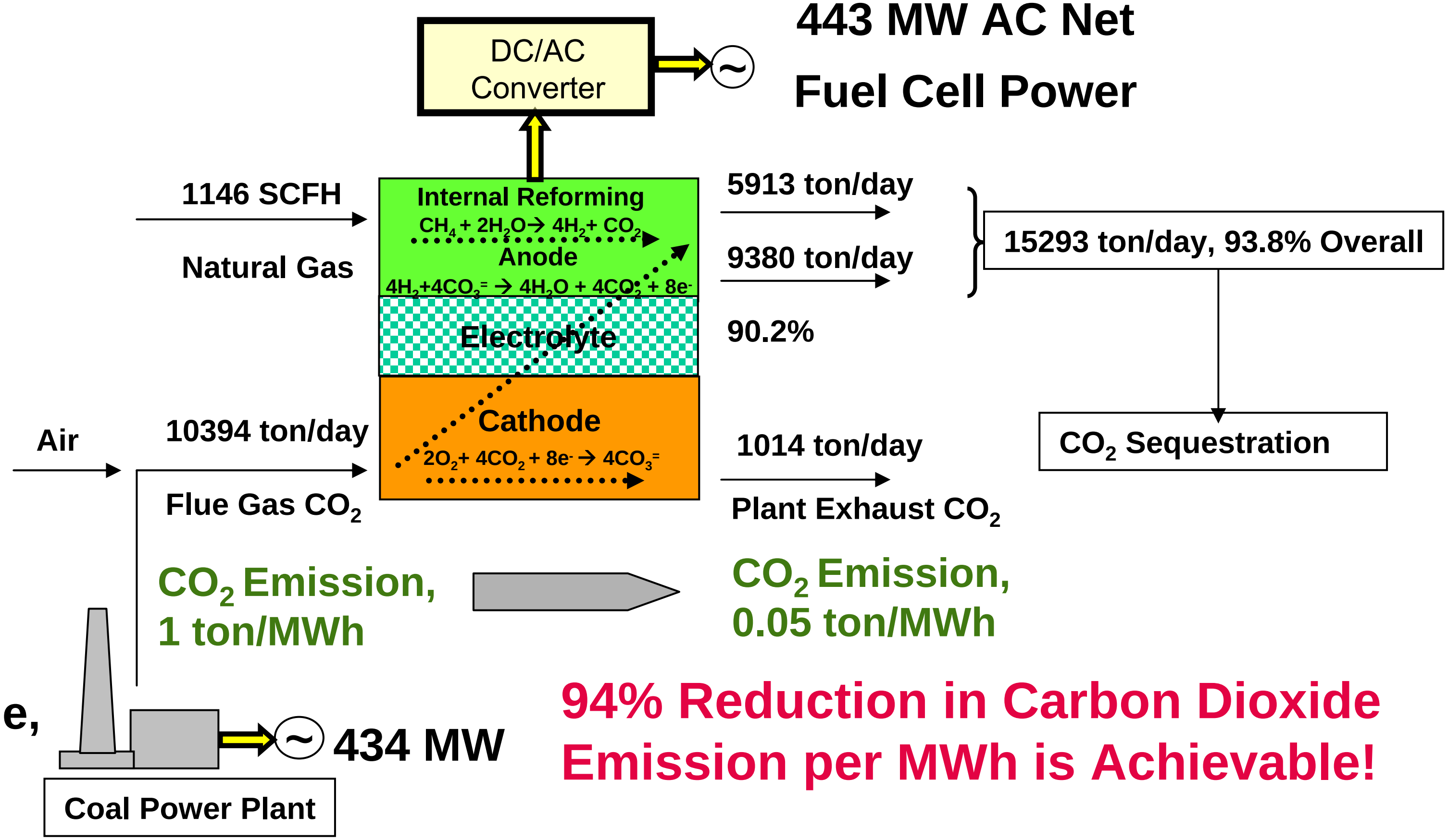
Case Study:
Carbon Capture from Conesville Plant



AEP,
Unit # 5
Conesville,
OH

94% Reduction in Carbon Dioxide Emission per MWh is Achievable!

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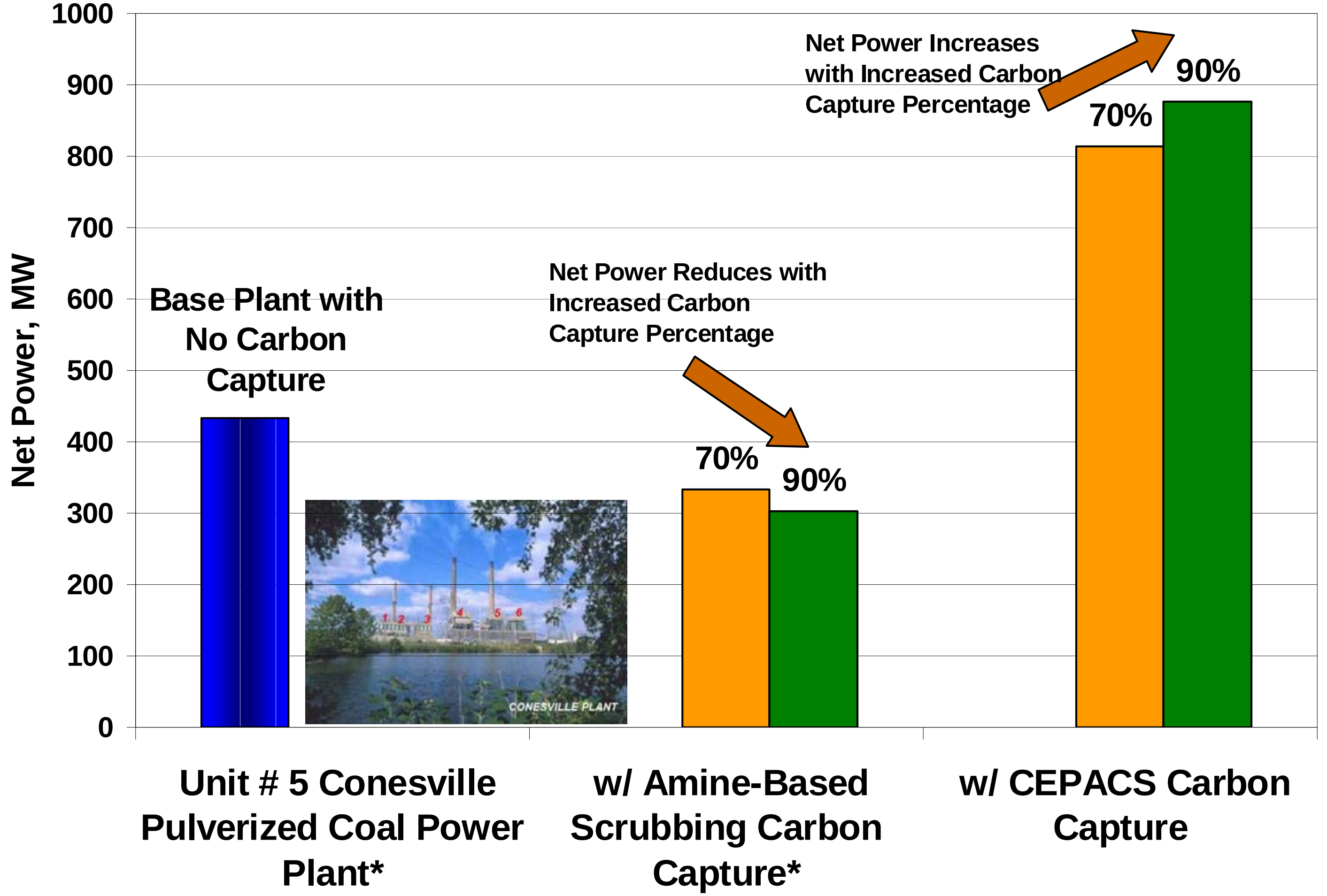
Case Study: Advantage of CEPACS System

ECM Based System Compared to State-of-the-Art Amine Scrubbing Technology

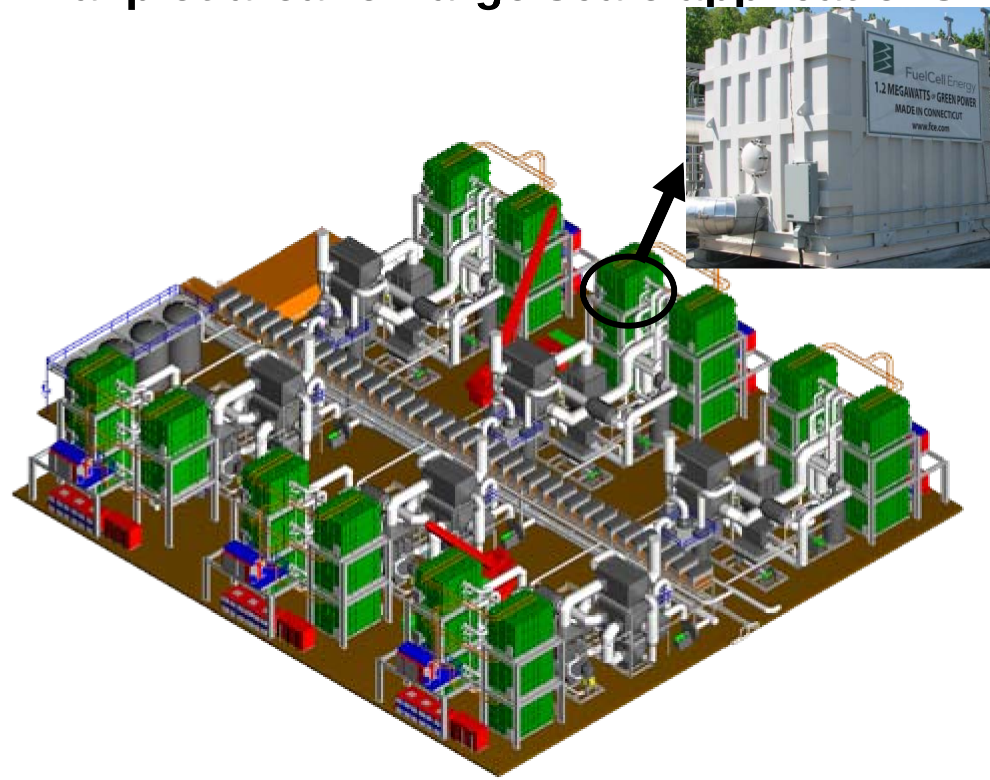


* Reference: Carbon Dioxide Capture from Existing Coal-Fired Power Plants, DOE/NETL-401/110907, November 2007

CEPACS vs. Amine Scrubbing

CEPACS is designed using minimal plot area for large scale applications.

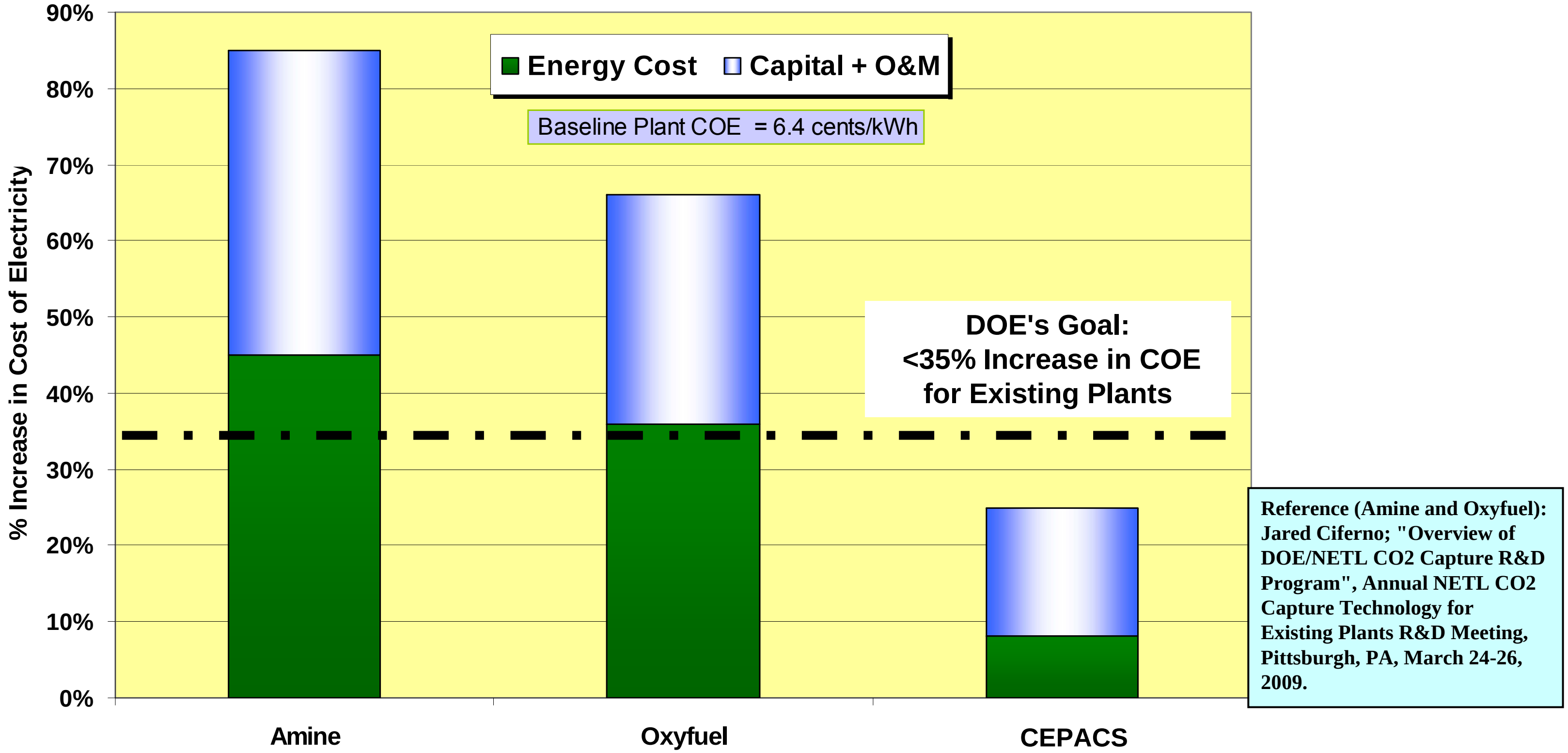
Amine Scrubbing Technology
330 ton CO_2/day
Steam Consumption:
~1.3 ton Steam/ton CO_2 (~650 kWh/ton CO_2)
Ref: Mitsubishi Heavy Industry, Ltd, M. Lijima
Footprint for Conesville Retrofit: 4 Acres



32 MW CEPACS Using ECM
930 ton CO_2/day
Power Generation:
~1150 kWh/ton CO_2
Footprint for Conesville Retrofit: 10-12 Acres

Percent Increase in Cost-of-Electricity: Comparison with Competing Technologies

- Percent increase in cost-of-electricity for a PC plant producing power at 6.4¢/kWh



Less than 35% increase in COE is achievable by using the electrochemical separation technology.

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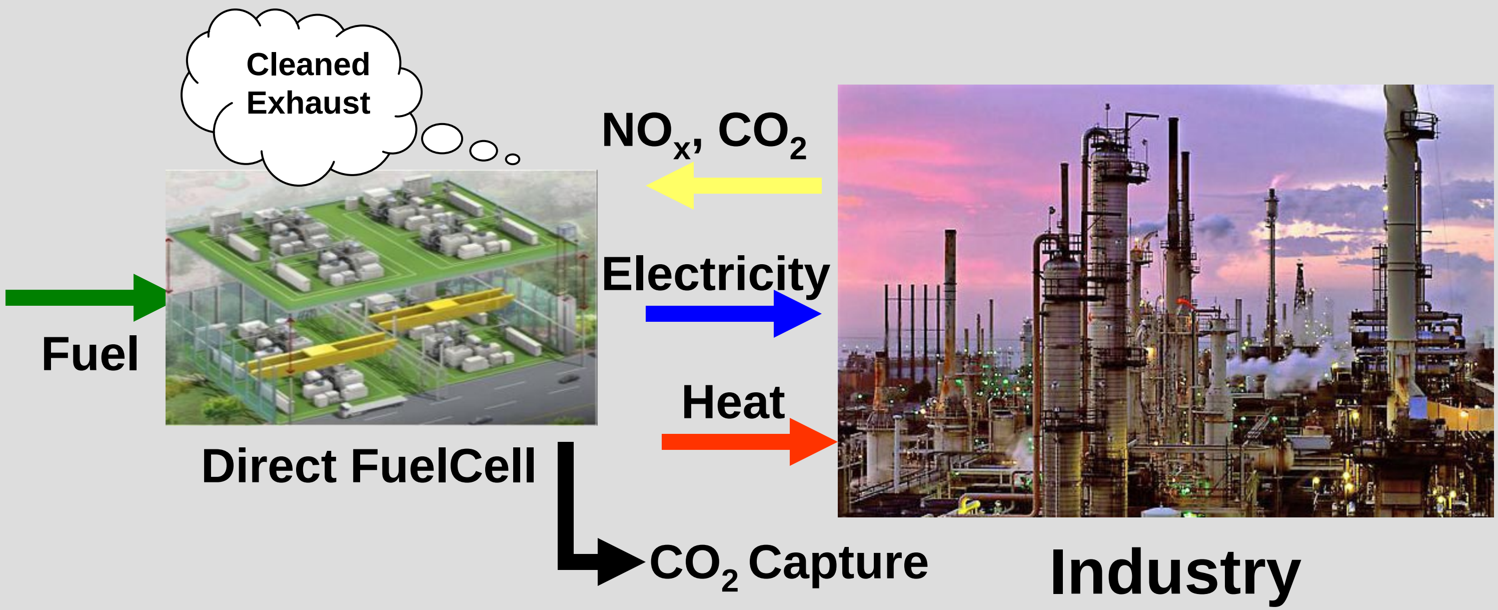
Application of ECM to Large Industry

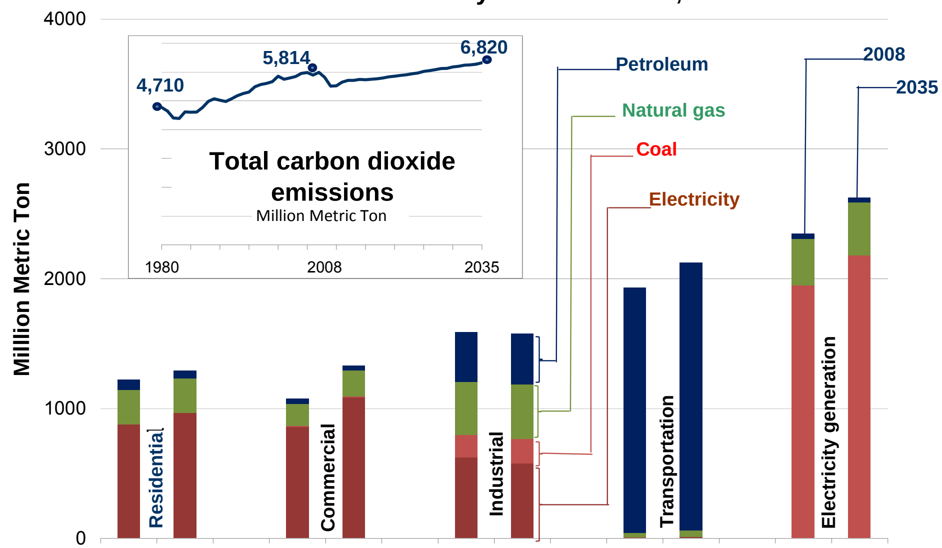
ECM can provide efficient onsite electric power and heat while simultaneously removing NO_x and CO_2 pollutants.



Industrial Sources

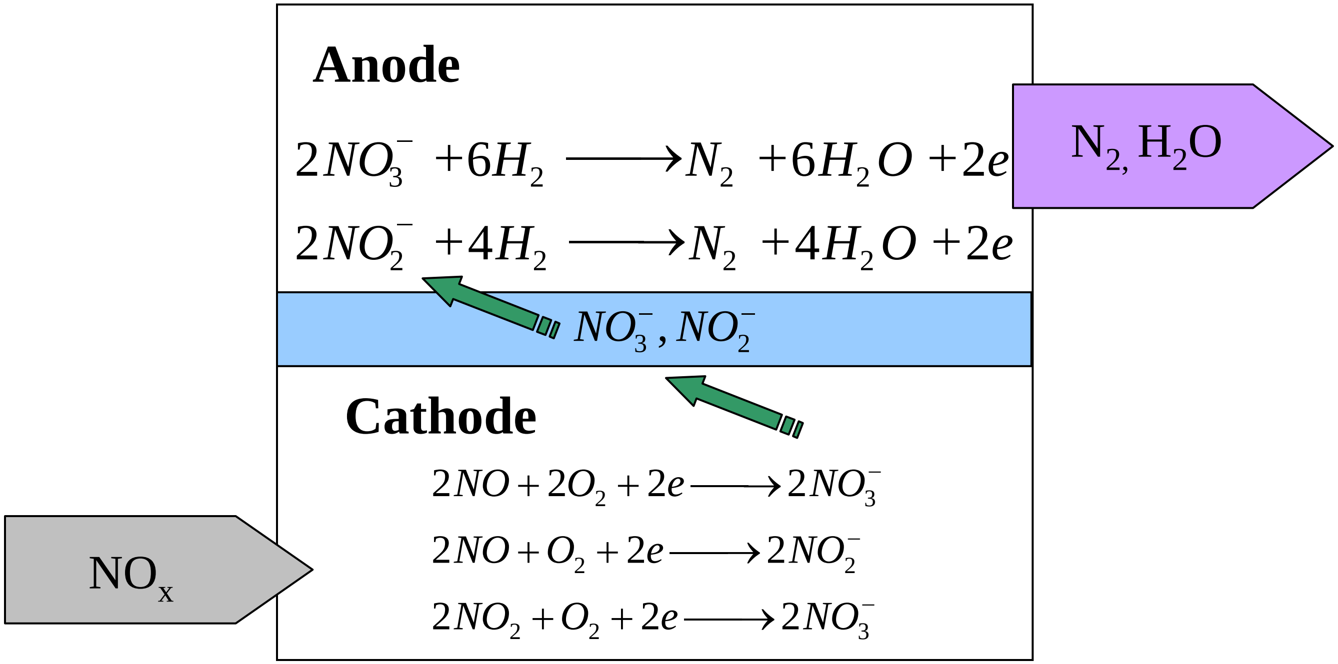
- CO_2 separation from industrial flue gases represents a promising mid-term market entry opportunity for CEPACS system.
- Large <u>industrial sites</u> produce significant amount of carbon dioxide resulting from combustion of fossil fuels in providing heat for various processes:
  - > Refinery
  - > Cement
  - > Pulp and paper
  - > Steel
- These industries also consume substantial amount of electricity and heat.

Carbon dioxide emissions by sector and fuel, 2008 and 2035



Amount of CO_2 generated in US annually from 2008 and projected to 2035, broken down by various sources of emissions including industrial, commercial, and residential and transportation sectors.

ECM's NOx Destruction Mechanism



ECM

- NOx is converted to Nitrate and Nitrite ions in the cathode.
- Nitrite and Nitrate ions migrate to the anode where they are reduced by hydrogen to nitrogen and water

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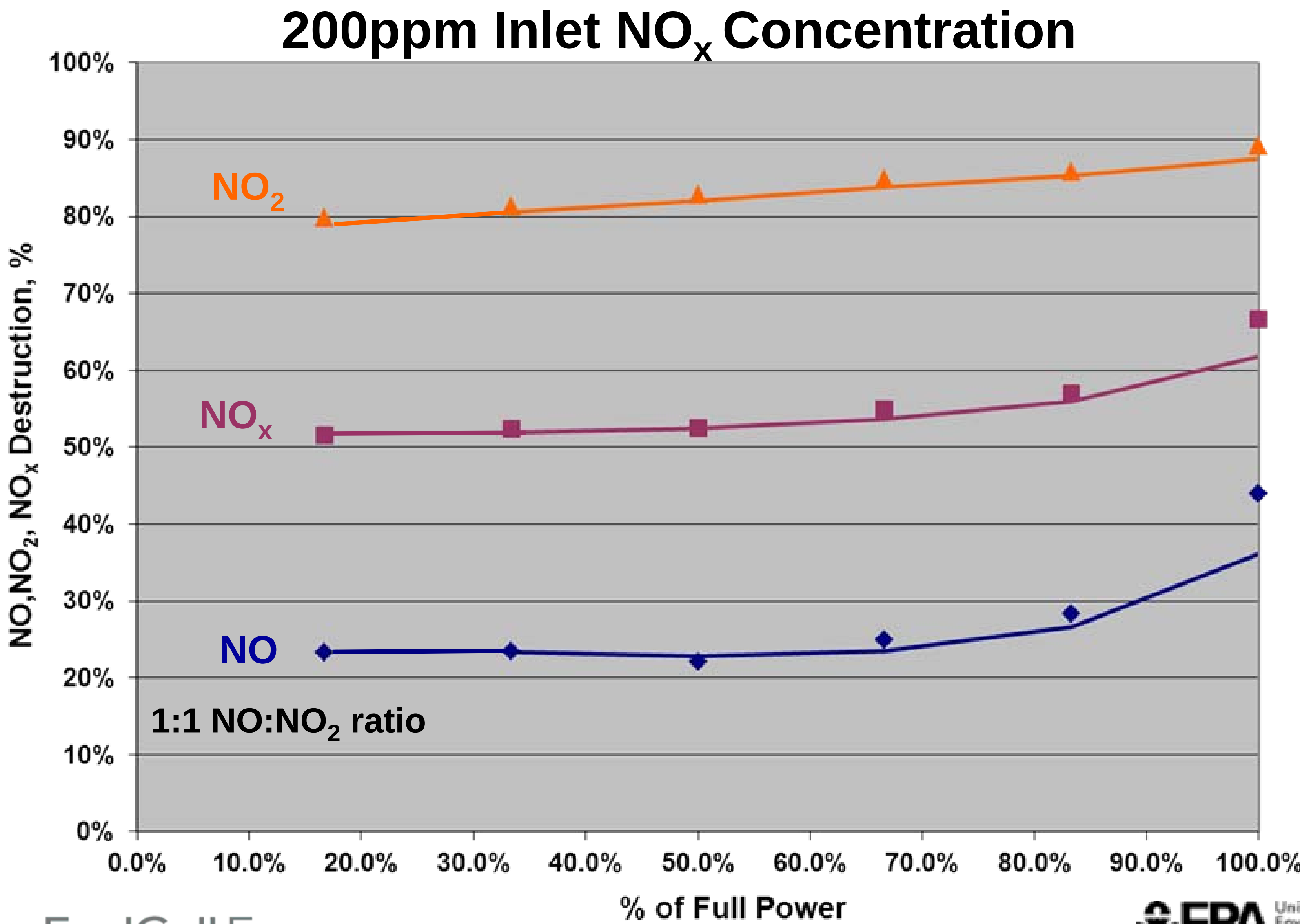
NO_x Destruction with Power Production



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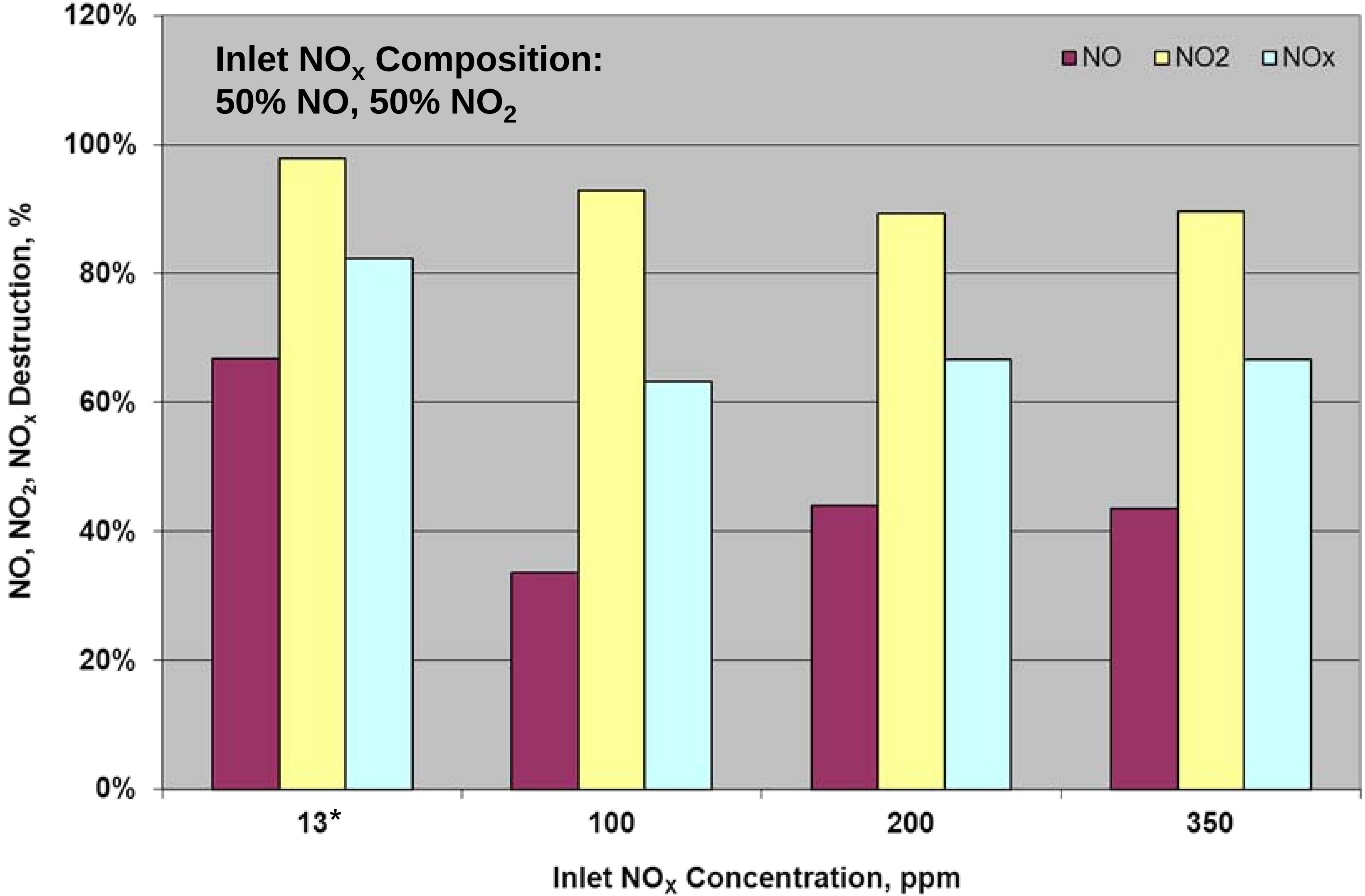
EPA United States Environmental Protection Agency

NO_x Destruction as a Function of Inlet NO_x Concentration



* 13ppm data at open circuit conditions (no power generation)

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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

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

Pacific Northwest National Laboratory (PNNL), Richland, WA

- **Key Experience:** Extensive research expertise in high-temperature fuel cell fabrication, development and characterization
- **Project Role:** Testing effects of flue gas contaminants on ECM

URS Corporation (URS), Austin, TX

- **Key Experience:** Leading global EPC & technology development firm
- **Project Role:** Review ECM system design, Equipment and plant costing, Flue gas clean-up system design

URS: Leading Global EPC and 1st Tier Federal Contractor

- 48,000 employees in >40 countries
- $10 Billion in revenue annually
- ENR's List of Top Firms: #2 for Design, Green Design and Environmental Design among other honors

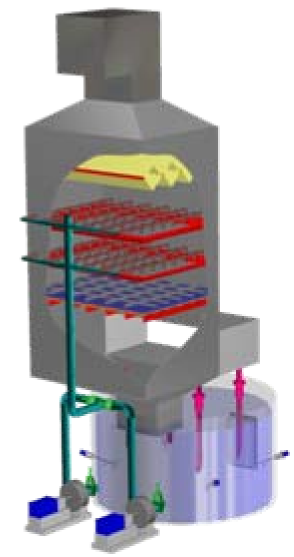
- Current DOE NETL CO_2 Capture Projects
  - Dry Sorbent Technology for Pre-combustion CO_2 Capture (prime)
  - Evaluation of Concentrated PZ from Coal Fired Flue Gas (prime)
  - Waste Heat Integration for CO_2 Capture from Coal-Fired Flue Gas (subcontractor)

- Multiple private industry CO_2 capture and sequestration clients

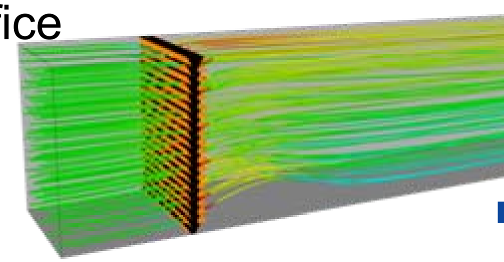
- DOE CO_2 projects being conducted out of Austin, TX Process Technologies Office (PTO)

URS Process Technologies Office: Air Pollution Control Expertise and Experience

- PTO rooted in R&D
- Air pollution abatement systems
  - SO_2
  - SO_3
  - NO_x
  - Hg & other toxics (*e.g.*, Se, As)
  - VOC and Cl
  - Particulate Matter
  - CO_2



- Coal-fired flue gas clean-up
  - Wet FGD, SBS (SO_3)
  - Control technology evaluations (e.g., Hg, MACT pollutants)
- Capabilities and Resources
  - >25 licensed engineers in 125 person office
  - CFD, Aspen, FGDPRISM, AutoCAD, etc



PNNL Relevant Experience and Fuel Cell Test Facilities

- Significant base of knowledge, equipment, expertise, and experiences related to SOFCs, PEMs, micro-channel reformers, carbon capture, catalysis, high temperature electrochemistry, gas and water cleanup has been developed
- 25 year experience in SOFC technology is well documented in numerous technical papers and patents
- SECA-related activities include extensive experimental work on fuel cell degradation in the presence of coal gas impurities (S, Se, P, As, Cl, etc), in addition, supported by thermochemical and computational modeling


Walk-in ventilated lab space

Multiple test rigs in the ventilated lab space

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 Technical Review
    - Task 2.2 Economic Feasibility Study
    - URS 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.**

Task 2 – Technical & Economic Feasibility Study

Task 2 Objective: Complete a Preliminary Technical and Economic Feasibility Study on FCE's ECM technology scaled up to a carbon capture system applied to a 550MW PC power plant

Success criterion: Show that the ECM technology has an economic advantage over the Econamine system (Case 10 in DOE report: *Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, rev 2010*), and that a path forward to reducing the incremental COE resulting from carbon capture has been identified and correlates with DOE's cost target.

- Perform detailed system analysis utilizing Chemcad simulation software
  - > System performance, including parasitic power losses
  - > Mass and Energy Balances
  - > Carbon and Water Balances
  - > Process specifications for major equipment
- Develop preliminary cost estimate of the ECM system according to DOE guidelines
  - > Capital cost of ECM system (Bare Erected Cost → Total As-Spent Capital)
  - > Incremental cost of electricity

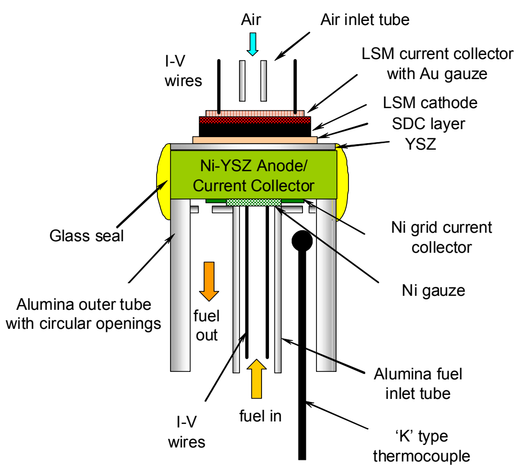
Task 2 – URS Scope of Work

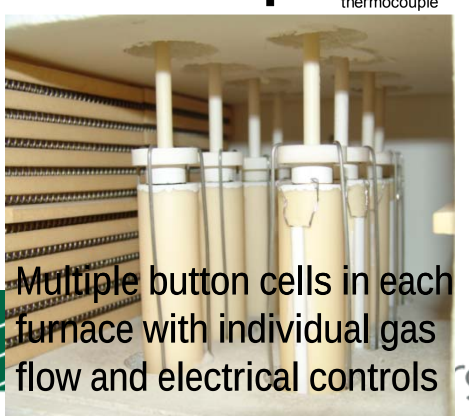
- Engineering review and assessment of:
  - > FCE PFD
  - > Heat and material balances
  - > Equipment specifications
- Optimize system heat recovery and integration
- Flue gas clean-up
  - > Existing state-of-the-art
  - > Additional cleanup technologies required
- Cost estimating and economic analysis
  - > Software packages
    - » Aspen Icarus
    - » RS Means and Richardson Cost Database (commodities)
  - > Construction estimates based on ‘pieces, parts, and components’
    - » Vendor quotes for large, specialty equipment
    - » Labor estimated based on:
      - – Factored estimate
      - – Labor survey (contact unions or contractor hot-sheets and industry sources for regional labor rates)

Task 3.1 – Contaminant Analysis

Task Objective: Establish maximum permissible concentrations of impurities in flue gas without causing unacceptable ECM degradation

- Assess interactions of main pollutants (S, Se, HCl, Hg) with the ECM cathode
- Perform button cell tests using synthetic flue gas with individual contaminants present at realistic concentrations




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

> Monitor changes in the electrochemical performance due to impurity interactions and compare to control cells

> Evaluate cell degradation as a function of impurity concentration, temperature, current density, and the exposure time

» Perform post-test analysis to determine nature of impurity/ cathode interactions, whether alteration phases are formed from any reactions or the effects are due to surface adsorption

» Recommend specific cleanup levels to avoid negative impact on the membrane life and performance

Task 3.2 & 3.3 – Membrane Testing & BOP

Task 3.2 –Membrane Testing

- Test Objective: Document the performance, operating limits, and reliability of the membrane under varying conditions that would be expected in a PC power plant.
- Vary flue-gas composition and operating parameters to identify the ECM's versatility to successfully remove CO_2
- Small area membrane tests may also include tests with contaminants identified in subtask 3.1.

Task 3.3 – BOP Equipment

- Objective: Identify BOP equipment that could have a technology gap between currently available process equipment and unique equipment that is required for CO_2 capture and compression.
- BOP equipment that will be evaluated includes:
  - Hydrogen (H_2) recovery systems, specialty blowers, heat exchangers, and other unique components.
- Equipment that could impact development and deployment of the ECM system will be highlighted in the BP2 Technology Gap Analysis Topical Report.

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Task 4 – EH&S Review

Task Objective: Perform a technical EH&S review to assess the environmental friendliness and safety of future deployment of the ECM system

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

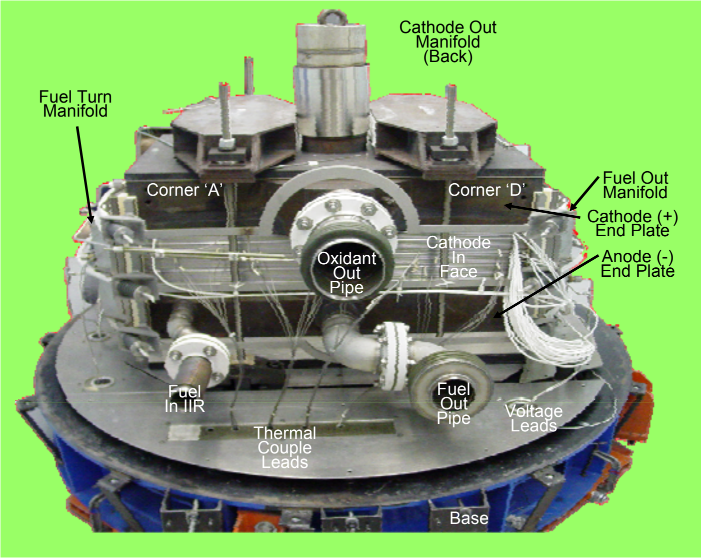
- Evaluate emissions types (gas, liquid, solid), emission levels, emission properties (hazardous, toxicity, flammability, etc.), regulatory compliance and implications, and safe handling and storage procedures for raw materials, intermediates, products, and by-products.
- Complete BP3 Technical EH&S Review Report

Task 5 – Bench Scale Testing

Task Objective: Validate ECM performance in large-area membrane module under simulated flue gas operating conditions

- Modify test facility to include additional ECM system components
- Fabricate 11.7m^2 membrane module (15 cells w/ 7800cm^2 active area each), which will produce ~10kW
- Perform testing for 13 months: 9 months steady-state, followed by 4 months of transient and parametric studies
- Perform post-test analysis

10 kW DFC Stack Installed in Module Base



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- ECM technology offers a unique and attractive alternative for CO_2 capture.
- Preliminary tests have indicated the potential of ECM technology for achieving >90% carbon dioxide separation.
- Conceptual designs of ECM-based systems, focusing on GHG mitigation from coal fired plants, were developed.
- Preliminary economic analysis has indicated that ECM-based systems offer cost-effective solutions for combined power generation and CO_2 capture.
- Incremental cost of electricity is anticipated to be less than 35% due to the on-going commercialization of the technology and high volume manufacturing.
- ECM is based on commercially proven Direct FuelCell® technology.

Thank You!

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