InnoSepra

Bench-Scale Development & Testing of a Novel Adsorption Process for Post-Combustion CO_2 Capture

DOE Funding Award DE-FE-007948

NETL CO_2 Capture Meeting

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Executive Summary

- Physical sorption based process
  - Materials with low heat of sorption, **ΔH_{ads}<200 Kcal/kg**
  - Dry CO_2 at high purity (>98%) and high recovery (>90%)
  - Extensively tested in the lab and in the field (one ton per day scale) for period of over 6 years; little loss in performance over time
  - Product CO_2 with less than 1 pm SO_X and H_2O
- Significantly lower cost compared to MEA based on detailed internal and external evaluations
  - >45% reduction in capital
  - >40% reduction in parasitic power
  - Potential to provide CO_2 at a cost (~$40/ton) and quality (<1 ppm H_2O, 1 ppm SO_2, <10 ppm O_2) suitable for EOR applications

Executive Summary

- The DOE Project Goals
  - Demonstrate process at one ton per day scale with real flue gas
  - Address the process risks
  - Address the effect of contaminants
  - Confirm process economics
- The DOE project outcomes
  - Various process risks and scale up issues addressed through lab and field testing, process simulation, and detailed techno-economic evaluation
  - Successful field testing with real flue gas at one ton per day scale at NRG, Indian River
  - Field performance better than the lab performance
  - **CO_2 suitable for EOR (cost and quality) can be produced**

The DOE Project Overview

Project Budget

Source	BP1 10/1/11- 12/31/12	BP2 1/1/13- 10/31/13	BP3 11/1/13- 10/30/14	Total
Dept of Energy	$843,787	$937,110	$748,988	$2,529,885
Cost Share	$217,560	$226,985	$210,810	$655,355
Total Project	$1,061,347	$1,164,095	$959,798	$3,185,240

Project Participants

DOE/NETL

- Elaine Everitt (Project Manager), Lynn Brickett, Angela Harshman, Mike Matuszewski, Shailesh Vora, James Black, and David Lang

InnoSepra

- Technology development at lab and pilot scale leading to commercial adoption (more than 25 technologies in more than 100 plants)

EPRI

- Process modeling, economic assessment and cost share

NRG

- Field testing, commercial feedback and cost share

New Mexico State University

- Fundamental adsorption data

PNNL

- Environmental, Health & Safety (EH&S) assessment

Adsorptech

- Mechanical and controls system design, commissioning

DOE Project Objectives

Demonstrate the effectiveness of the InnoSepra sorbent-based post-combustion CO_2 capture technology in achieving at least 90% CO_2 removal with a potential for less than a 35% increase in cost of electricity ***(also <$40/ton in the CO_2 capture cost)***

as a retrofit to coal fired utility plants

- Based on lab testing and bench scale testing at NRG, Indian River plant at about one ton per day scale

and

- Scale up modeling, process and equipment design, engineering, and costing for a commercial 550 MW power plant to estimate LCOE (Levelized Cost of Electricity) and the CO_2 capture cost

Background Information

Sorption-Based CO_2 Capture

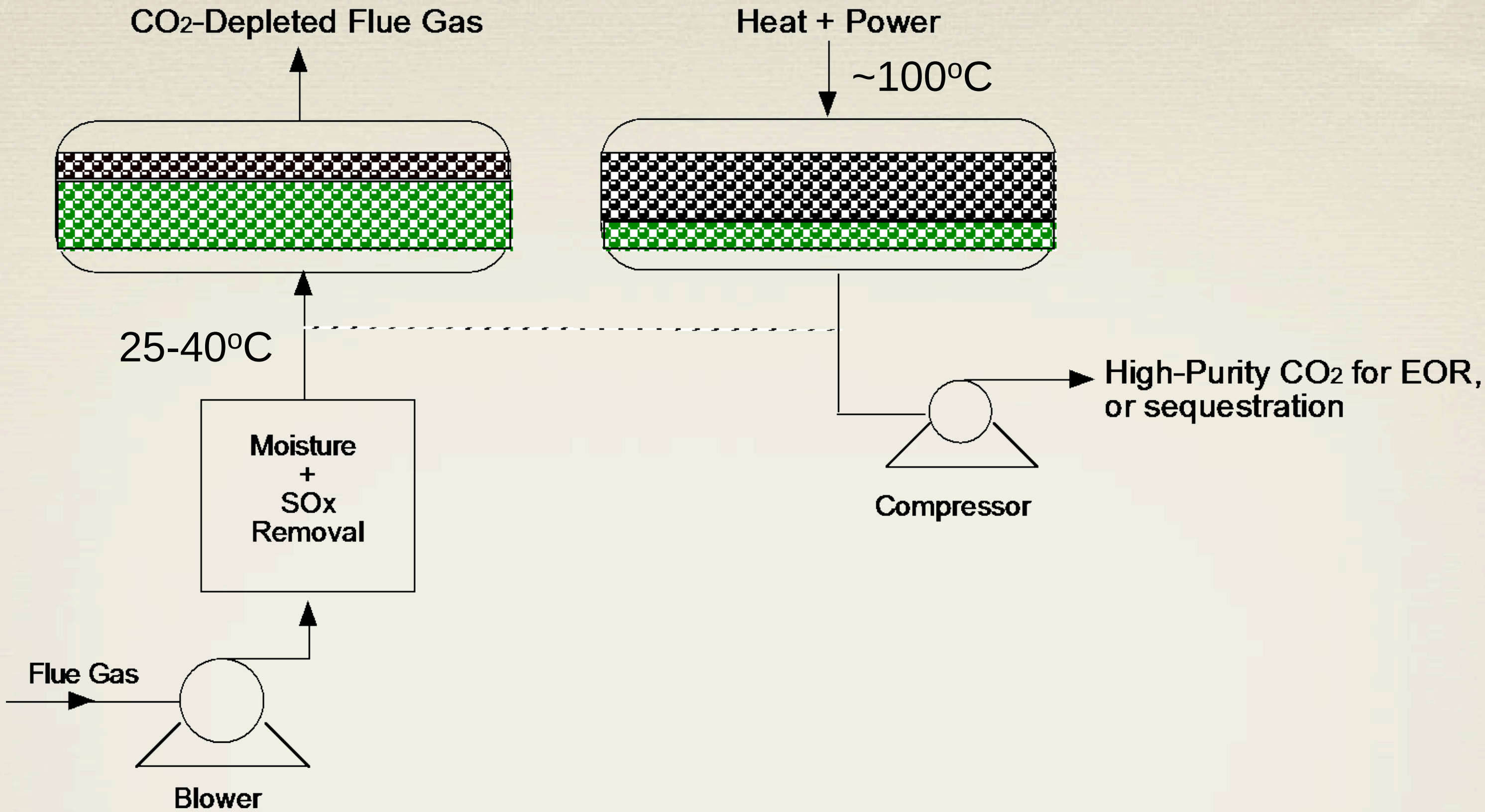
- ***Capture CO_2 by physical sorption***
  - 140-240 kcal/kg (26-44 kJ/mol) heats of adsorption
    - Significantly lower than the total energy (heat of reaction + sensible heat + latent heat) for amine systems
- ***Capture CO_2 by chemical reaction*** with amine or carbonate based sorbents
  - 740-940 kcal/kg (136-174 kJ/mol) heats of reaction
    - Similar to the aqueous amine-based absorption systems
  - Ex. $Na_2CO_3 + CO_2 + H_2O$ -------> 2 $NaHCO_3$
    ΔH_{rxn} = -740 Kcal/kg (-136 kJ/mol) of CO_2
  - Possible degradation due to SO_X, NO_X, and O_2
  - May not result in energy savings compared to MEA

Effect of Adsorption Capacity on Regeneration Energy

	Carbonaceous adsorbent	Sodium carbonate adsorbent	Hypothetical Physical adsorbent
Net CO_2 Capacity, wt%	1.5	2.5	7.0
Adsorbent Density, lbs/ft^3	30	50	40
Heat of Adsorption, kcal/kg CO_2	160	740	200
Adsorbent Sensible Heat, kcal/kg CO_2	700	420	150
Total Heat Required Excluding Vessel Heating, kcal/kg CO_2	860	1160	350

- **Both high net CO_2 capacity and low heat of adsorption are needed to minimize the parasitic power**

InnoSepra CO_2 Capture Process



- Flue gas pretreatment to remove moisture and SO_X to <1 ppm each, adsorption at 25-40ºC and regeneration at about 100ºC
- High purity CO_2 (>98% CO_2, <30 ppm O_2) at >90% recovery
- Key innovation is ***the combination*** of process and materials (physical sorbents) that provides performance similar to or better than reactive systems and a total regeneration energy requirement of less than 450 Kcal/Kg of CO_2
- The key scale up challenges are likely to be engineering based

The DOE Project Status

Project Scope

Budget Period I – Lab Testing & Design

- Lab scale process data, adsorption/desorption isotherms and heat and mass transfer rate measurements
- Identification of the adsorbents for the removal of contaminants
- Development of a rigorous process model
- Preliminary technical and economic feasibility study
- Preliminary design & costing of the bench scale unit

Go/No-Go Decision point

Budget Period II – Procurement and Construction

- Bench unit process and mechanical design and construction (~one tpd CO_2)
- Mechanical testing of the bench scale unit

Go/No-Go Decision point

Budget Period III – Installation, Testing and Evaluation

- Installation and testing at the NRG, Indian River coal fired power plant
- Final techno-economic assessment
- Preliminary technology EH&S risk assessment

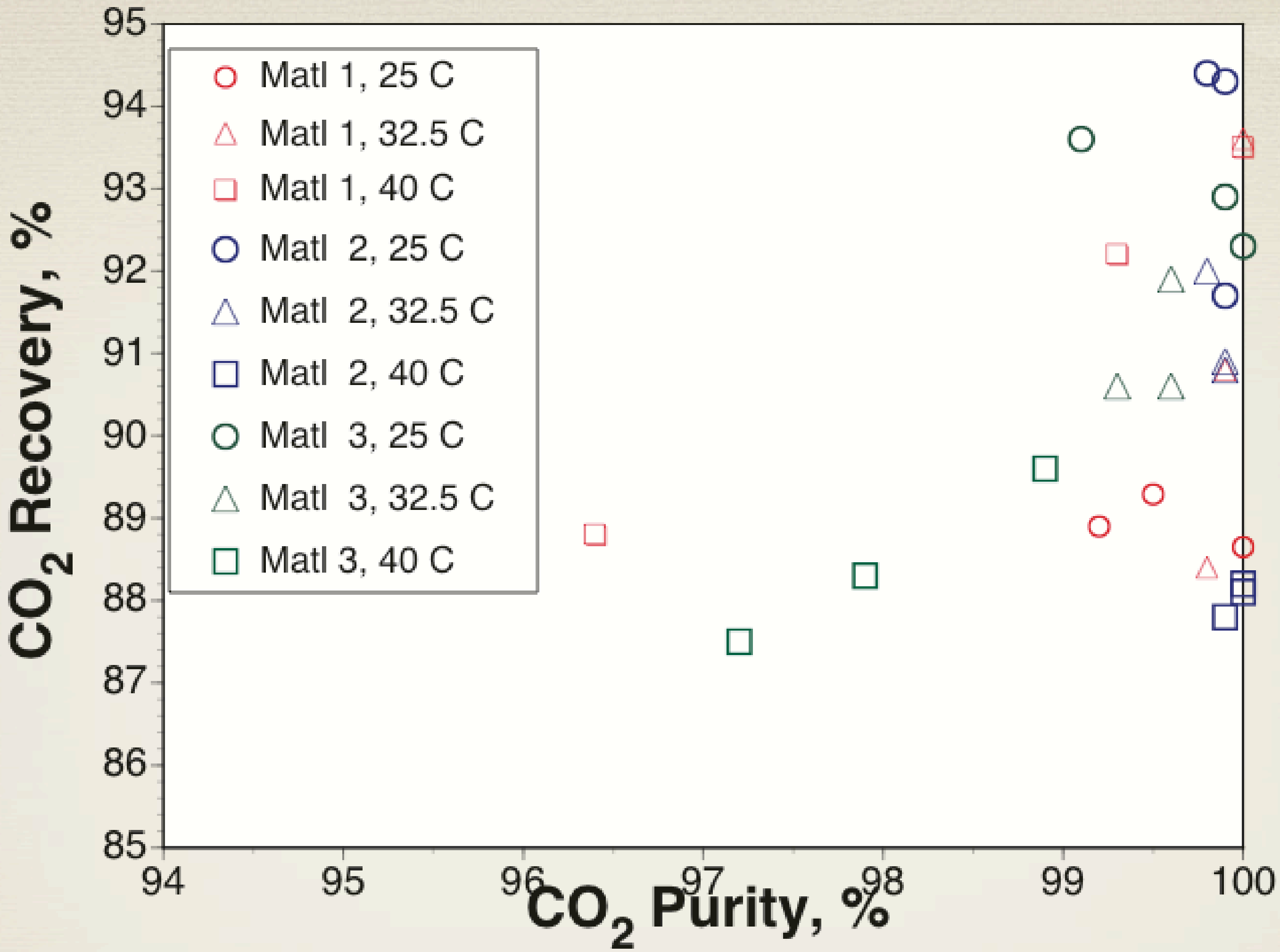
Project Overview: Key Milestones

1. Identify two adsorbent materials based on CO_2 recovery and capacity ☑
2. Obtain heat and mass transfer data ☑
3. Obtain estimate of adsorbents for moisture and contaminants ☑
4. Obtain adsorption and desorption isotherms for the preferred adsorbents ☑
5. Develop a rigorous process model ☑
6. Preliminary Technical and Economic Feasibility Study ☑
7. Detailed engineering and mechanical design of the bench scale process unit ☑
8. Fabricate the bench scale test unit ☑
9. Commission the bench-scale unit ☑
10. Bench-scale testing with flue gas from NRG's Indian River Plant
11. Final Technical and Economic Feasibility study

CO_2 Capture Testing Summary (Lab)

- More than 10 commercial and laboratory materials tested for over 5 years, >10,000 complete cycles
- Isotherm CO_2 capacities of 18-20 wt% for the flue gas from a PC plant, and a cyclic CO_2 capacities of 7-9 wt% for the preferred materials
- Regeneration temperatures of about 100^oC are sufficient
- 90% CO_2 recovery and over 99% purity under optimized conditions for multi-bed experiments simulating a coal-fired power plant (13-15% CO_2)
- Less than 1 ppm each of H_2O, NO and SO_X and 10-30 ppm oxygen in the CO_2 product

Summary of Adsorbent Tests (Lab)



- For a CO_2 purity of >99% and a CO_2 recovery of >90%, net CO_2 capacities of 7-9 wt% have been obtained (~15% feed CO_2)
- Same or higher CO_2 purity, recovery and loading compared to reactive absorbents / adsorbents using materials with much weaker affinity for CO_2. Cycle modifications allow production of CO_2 with 10-30 ppm O_2.

Heat and Mass Transfer Data, Contaminants Removal

- Heat and mass transfer data obtained for various process configurations and for various process steps
- The heat transfer rates during the adsorption and regeneration steps are adequate for our process conditions and cycle times
- Moisture and SO_X removed to a level of <1 ppm each for feeds containing 50-1,000 ppm SO_X
  - Possible to handle flue gas from a non-FGD plant
- The equipment size and energy required for moisture and SO_2 removal is much smaller than that for CO_2 adsorption
  - Small impact of SO_2 and moisture removal on LCOE and the CO_2 capture cost

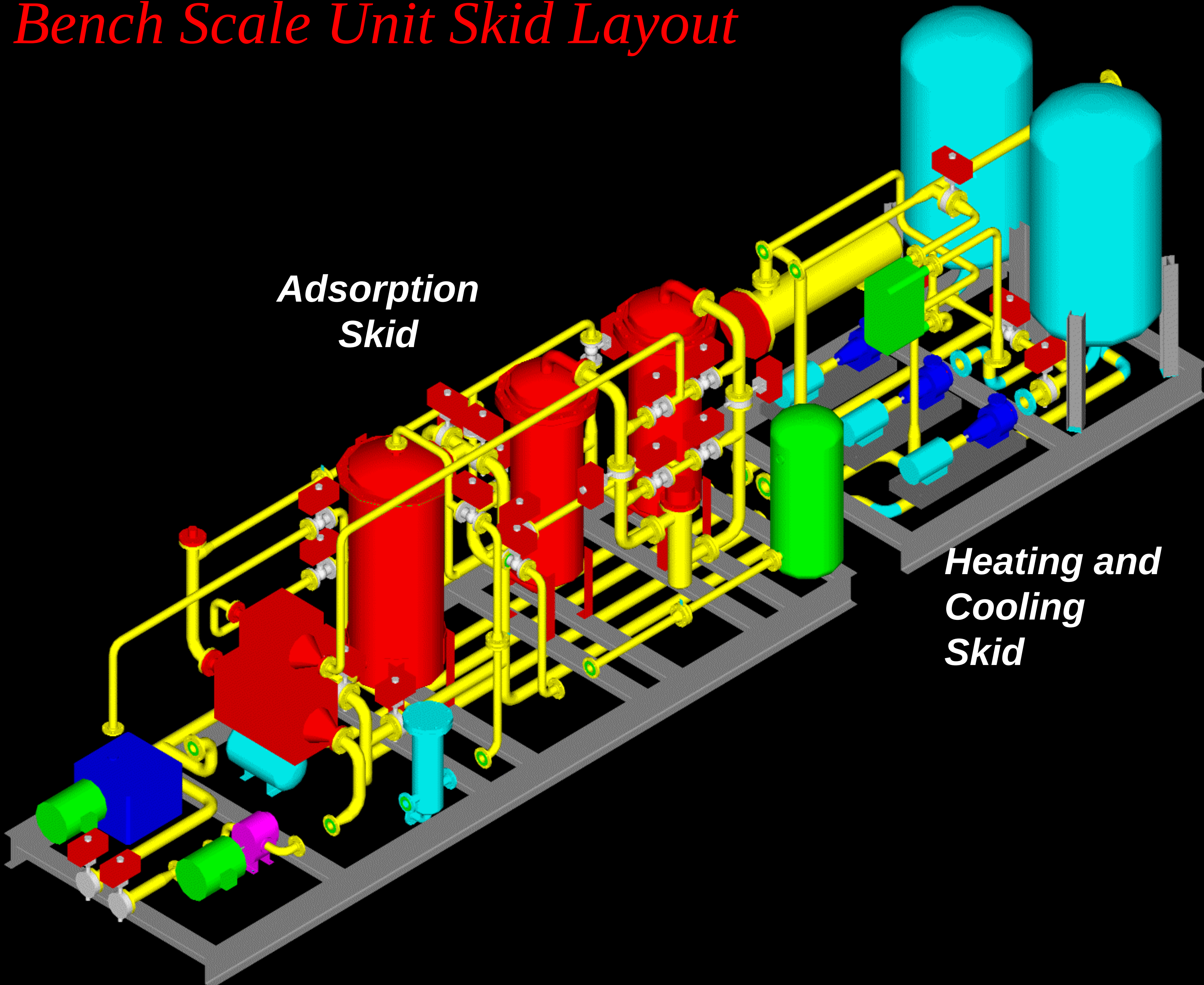
Process Simulation Models

- Rigorous solution of coupled heat and mass transfer partial differential equations with both the in-house simulator and ASPEN Adsorption **(InnoSepra)**. InnoSepra adsorption unit integration with the power plant **(EPRI)**.
- Single component adsorption isotherms and diffusivities from New Mexico State Data
  - Langmuir mixing rules to obtain the multicomponent isotherms from single component isotherms
- Lumped parameter model for mass transfer
  - Micropore, macropore and film diffusion resistances are combined
- The simulation is continued until a cyclic steady state is obtained
  - The simulation is computationally intensive, typically requiring more than three days for attainment of cyclic steady state
- The model has been validated with laboratory data and is being updated with data from the bench tests to improve the predictions
- EPRI modeling has provided optimum integration points for integrating the adsorption unit with the power plant

Field Demonstration of the Bench Unit

- The bench unit testing at NRG's Indian River, DE plant
  - Flue gas from unit 4 at Indian River
  - Nominal 500 MW capacity
  - SCR for NO_X control, dry FGD with recycle for SO_X control
- The bench unit takes flue gas after the dry FGD
  - The feed to bench unit is saturated at 60^oC
  - About 50 ppm SO_2, 10-12% CO_2
- The bench unit was installed and commissioned with significant help from NRG
- Testing started in May

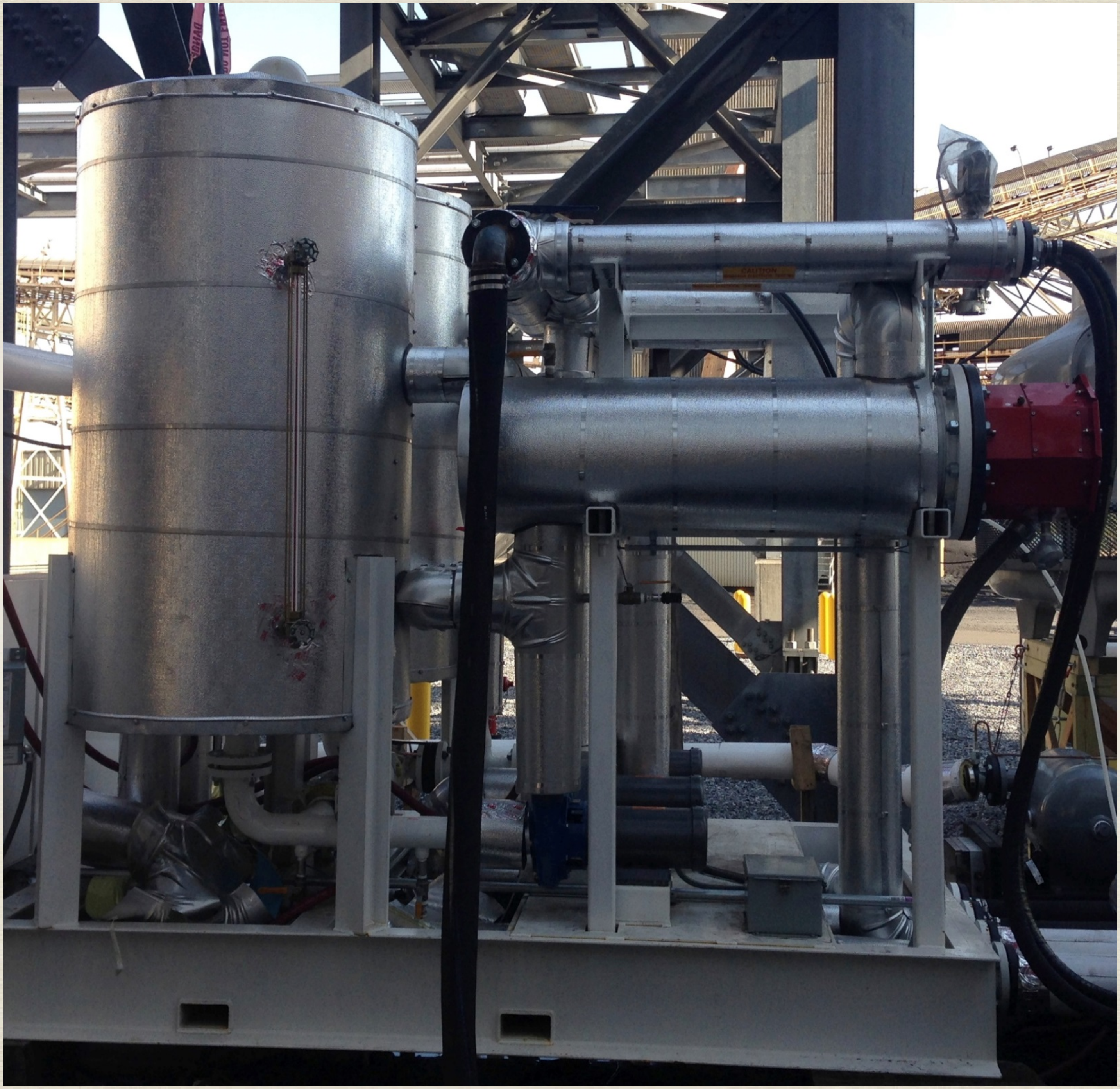
Bench Scale Unit Skid Layout



Adsorption Skid

Cooling Tower

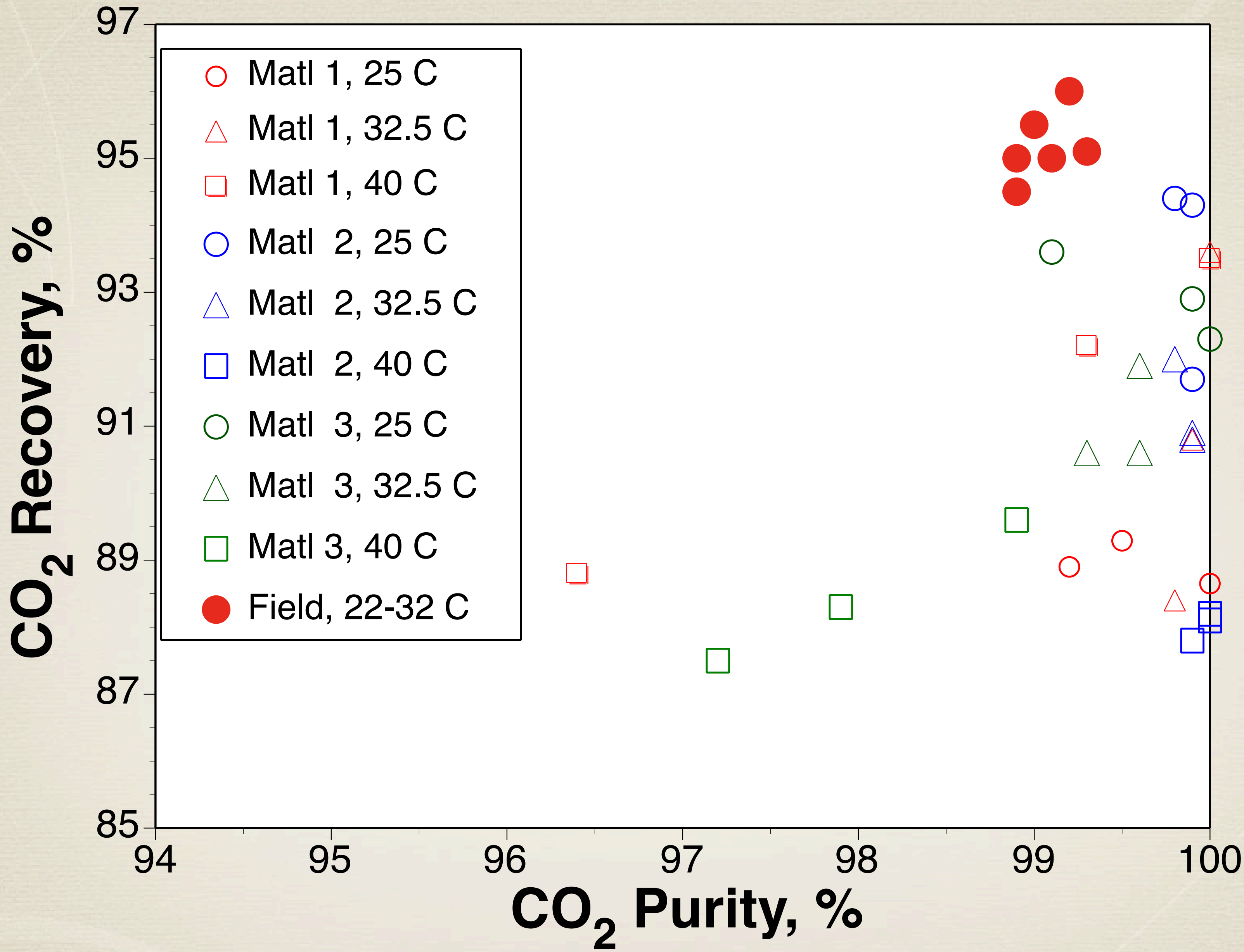
Heating and Cooling Skid



Field Demonstration of the Bench Unit

- Process conditions for testing
  - Two different flue gas flow rates (80 & 100 scfm)
  - 22-32°C feed temperature
  - Three different cycles for each flow rate and temperature
- About six weeks of testing has been done so far
  - Significant interruptions due to the NRG plant
- Field performance is better than the performance in the lab
  - 8-10.5 wt% net CO_2 capacity in the field
  - CO_2 recovery over 94% for product CO_2 purities between 98.5 and 99.5%
- Testing to be completed in August

Summary of Adsorbent Tests (Lab & Field)



- Significantly higher CO_2 recovery in the field compared to lab experiments

Techno-economic Analysis

The Parasitic Power

- Heat and electrical energy for the adsorption system
- Electric power for the blower, various pumps and the CO_2 compressor

The Capital Cost

- Heating and cooling system cost including direct contact cooler, pumps, blowers, and heat exchangers
- Adsorption system cost including adsorption vessels, switching valves, pumps and heat exchangers, electrical, controls, adsorbents, piping skids, shipping, engineering and installation
- CO_2 compression system cost including CO_2 compressor and interstage coolers

Energy Requirements for the Adsorption System

- Consists of
  - **Pressure drop through the system**
  - **Heat of desorption for CO_2**
  - **Vessel and sieve heating**
  - **Sensible heat for heating CO_2 to the regeneration temperature**
  - **Energy required for flue gas and/or CO_2 product dehydration**
  - **Mechanical energy for CO_2 from the sorption system**
- The total energy requirement for the InnoSepra process, excluding compression, is <450 Kcal/Kg of CO_2

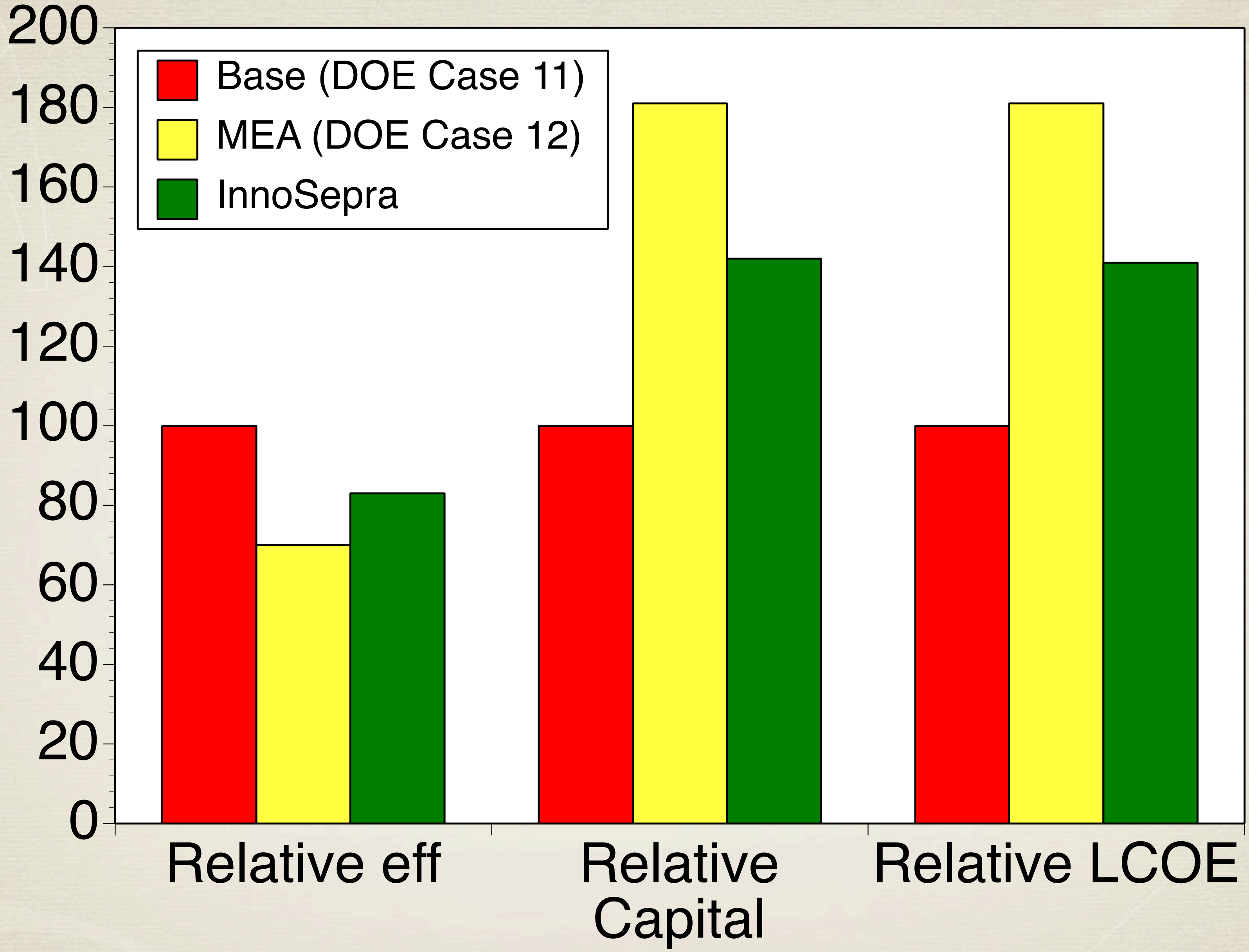
Updated Techno-economic Analysis for a 550 MW Supercritical PC Power Plant

Estimated Capital Cost	$260 MM
Power consumption including compression (PP)	92 MW
Steam cost per 1,000 lb for the base plant	$5.83
Steam cost with capture* = 0.028* PP (MWe) + 5.83	$8.41 **(+44%)**
Electricity cost for the base plant	$0.064/kWh
Electricity cost with capture* = 0.3073* PP (MWe) + 64	$0.092/kWh **(+44%)**
CO_2 production rate, million tons/yr	3.5
CO_2 Recovery Cost**	**$40.5/ton**

*Based on the DE-FOA-0000403 guidelines. No explicit dependence of steam cost and LCOE on capital.

**85% plant utilization factor. Includes capital charge, maintenance, CO_2 transportation cost, and parasitic power. No increase in LCOE if CO_2 can be sold for this price.

Comparison with MEA for DOE Baseline Study



"Cost and Performance Baseline for Fossil Energy Plants", DOE/ NETL-2007/1281, Aug 2007. (http://www.netl.doe.gov/energyanalyses/pubs/Bituminous%20Baseline_Final%20Report.pdf)

Overall Accomplishments

- The InnoSepra CO_2 capture process combines several innovative features to reduce the capital cost and parasitic power for CO_2 capture

- It is possible to obtain very high recovery (>90%), and high purity (>99%) CO_2 with physical sorbents while meeting the EOR/sequestration oxygen specification

  - □ **ΔH_{ads}<200 Kcal/kg, parasitic power <450 Kcal/kg**

  - **High net CO_2 capacity (>8 wt%)**

- The capital cost and parasitic power estimates based on a detailed component level analysis indicate that we are close to DOE's LCOE target (<35% increase) and the CO_2 cost target (<$40/ton)

- Successful field testing at the one ton per day scale has further validated the technology

Future Plans

Current DOE Project

- Finish testing at NRG's Indian River plant
- Set commercial unit process configuration
- Independent techno-economic analysis (EPRI)
- Prepare EH&S risk assessment (PNNL)

Next Scale Up Phase

- Testing at 1.0-2.0 MW scale, also address engineering challenges related to scale up
- Results from this scale up testing can be used to design CO_2 capture systems of up to 2,000 tpd size
- Pursuing other applications that can provide technology validation in commercial applications

Summary

The major milestones for the DOE project include:

- Preferred physical sorbents for CO_2 capture identified
- Adsorption and regeneration heat transfer data obtained
- Removal of moisture and SO_2 to below 1 ppm has been experimentally verified
- Adsorption isotherms for two preferred adsorbents obtained
- The process modeled with the Process Simulator
- The bench scale unit constructed, commissioned, and tested at the one ton per day scale
- A techno-economic analysis based on the lab and field data, process simulation and detailed engineering design indicates the potential for a CO_2 capture cost below $40/ton
  - Very attractive for EOR applications even in the absence of climate legislation
- The potential approaches to further decrease the CO_2 capture cost identified

Acknowledge and Disclaimer

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