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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About InnoSepra

- Started in 2007 by founders with 70+ years of industrial gas experience
- > 50 commercialized technologies in > 150 plants (20-2,000 tons per day) at BOC (>$10 B in sales in 2006)
  - **PSA and TSA Air purification, UHP N_2 production for electronics, Nitrogen PSA, Oxygen PSA and VSA, CO_2 production and purification, and NO_X control**
- >>$100 million in value creation at BOC
- 110 U.S. and over 500 international patents at BOC, and two major technology awards
  - **2001 Kirkpatrick Award for an ozone-based NO_X control process**
  - **1997 Kirkpatrick Award for olefin / paraffin separation**
- InnoSepra's current focus is on CO_2 capture, removal of pollutants from power plant flue gas, biogas purification and reduction in water usage for power production

Executive Summary

- Physical sorption based process
  - Treats flue gas after the FGD
  - Produces dry CO_2 at high purity (>98%) and high recovery (~90%)
- Significant CO_2 capture improvement over MEA
  - >50% reduction in capital
  - >40% reduction in parasitic power
- Current DOE Project Goals
  - Demonstrate process at one ton per day scale
  - Document performance on real flue gas
  - Address the process risks
  - Effect of contaminants
  - Confirm process economics

The Project Overview

Project Budget

Source	BP1 10/1/11- 12/31/12	BP2 1/1/13- 8/31/13	BP3 9/1/13- 3/31/14	Total
Dept of Energy	$850,187	$946,848	$732,850	$2,529,885
Cost Share	$212,547	$155,000	$287,808	$655,355
Total Project	$1,062,734	$1,101,848	$1,020,658	$3,185,240

Project Participants

DOE/NETL

- Elaine Everitt (Project Manager), Lynn Brickett, Shailesh Vora, James Black, Angela Harshman 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, plant testing, economic assessment and cost share

NRG

- Field testing, commercial feedback and cost share

New Mexico State University

- Fundamental adsorption data

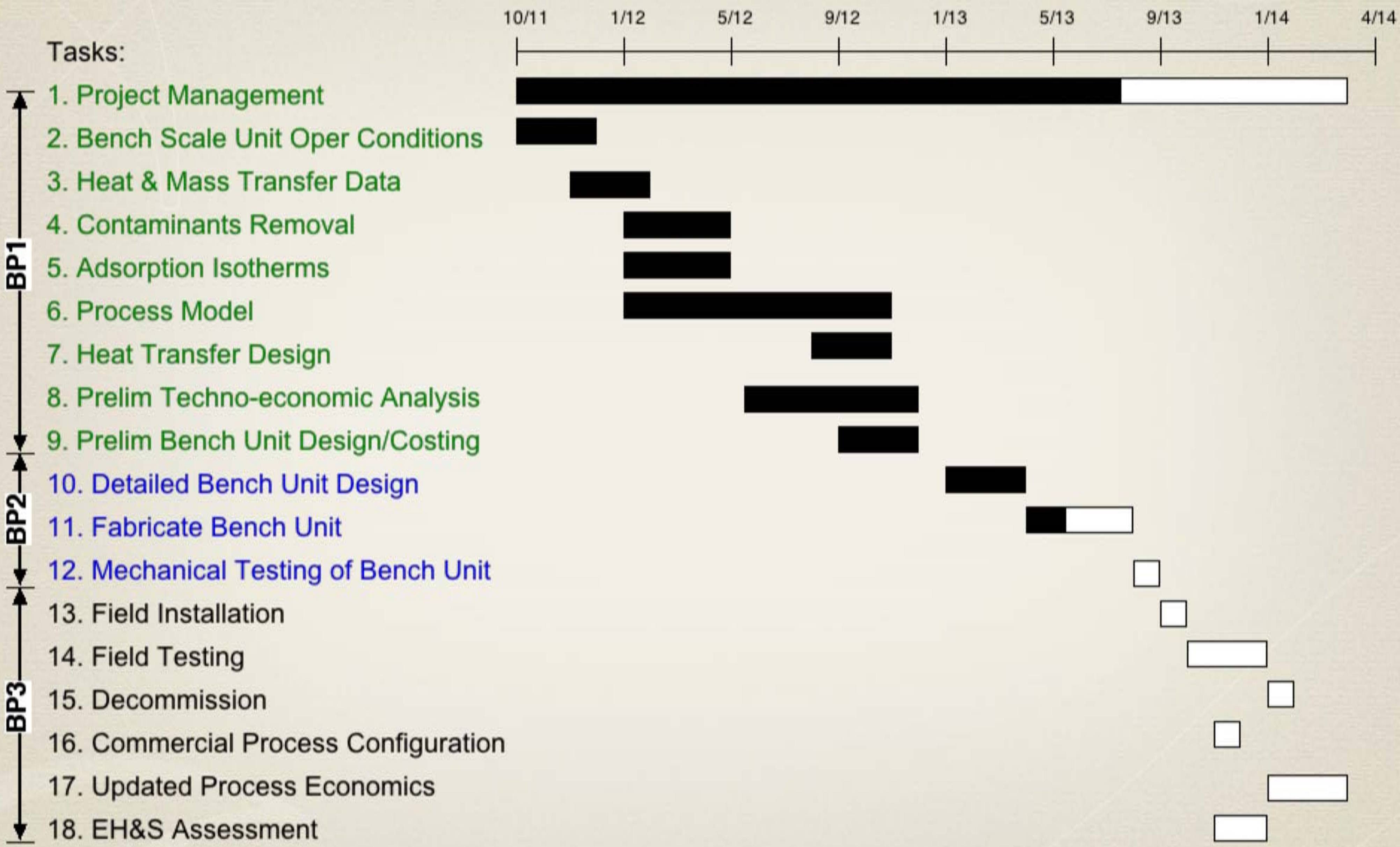
PNNL

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

Adsorptech

- Mechanical design, equipment costing and commissioning

Project Overview: Schedule



Project Objectives

The Overall Project Objective

- Demonstrate the effectiveness of the InnoSepra process in achieving at least 90% CO_2 removal with a potential pathway for no more than a 35% increase in LCOE

Specific Project Objectives

- Confirm the design basis for bench-scale testing based on lab scale results and process modeling
- Design, build and test the bench scale unit on actual coal-based flue gas (NRG, Indian River) at the one ton per day scale
- Perform process scale up and costing for installation of the technology at a commercial 550 MW power plant to estimate LCOE (Levelized Cost of Electricity) and CO_2 capture cost

Background Information

Sorption-Based CO_2 Capture

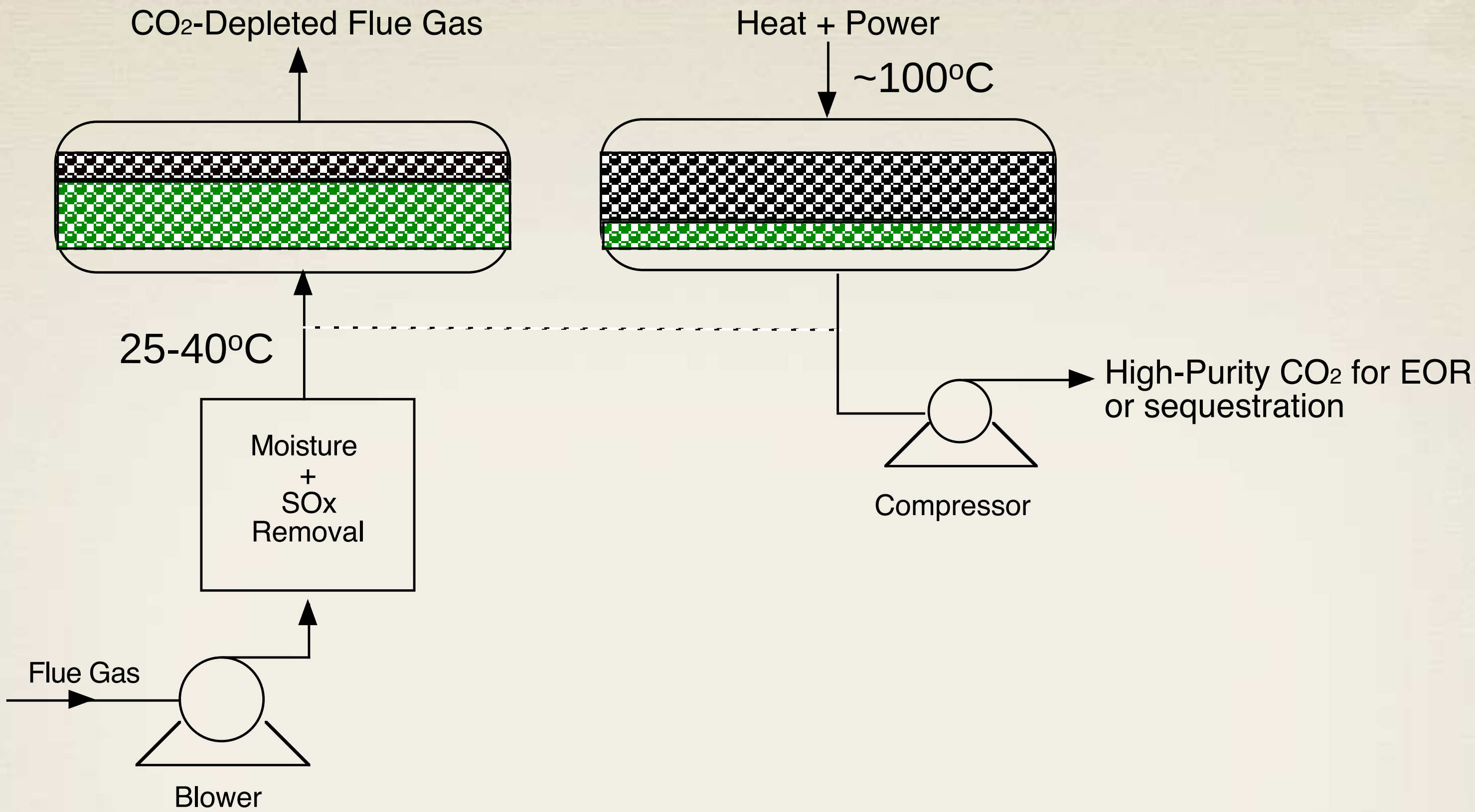
- *Capture CO_2 by physical sorption*
  - 140-240 kcal/kg (26-44 kJ/mol) heats of adsorption
    - Significantly lower than the total energy (heat of reaction + sensible heat + latent heat) for amine systems
- *Capture CO_2 by chemical reaction* with amine or carbonate based sorbents
  - 740-940 kcal/kg (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

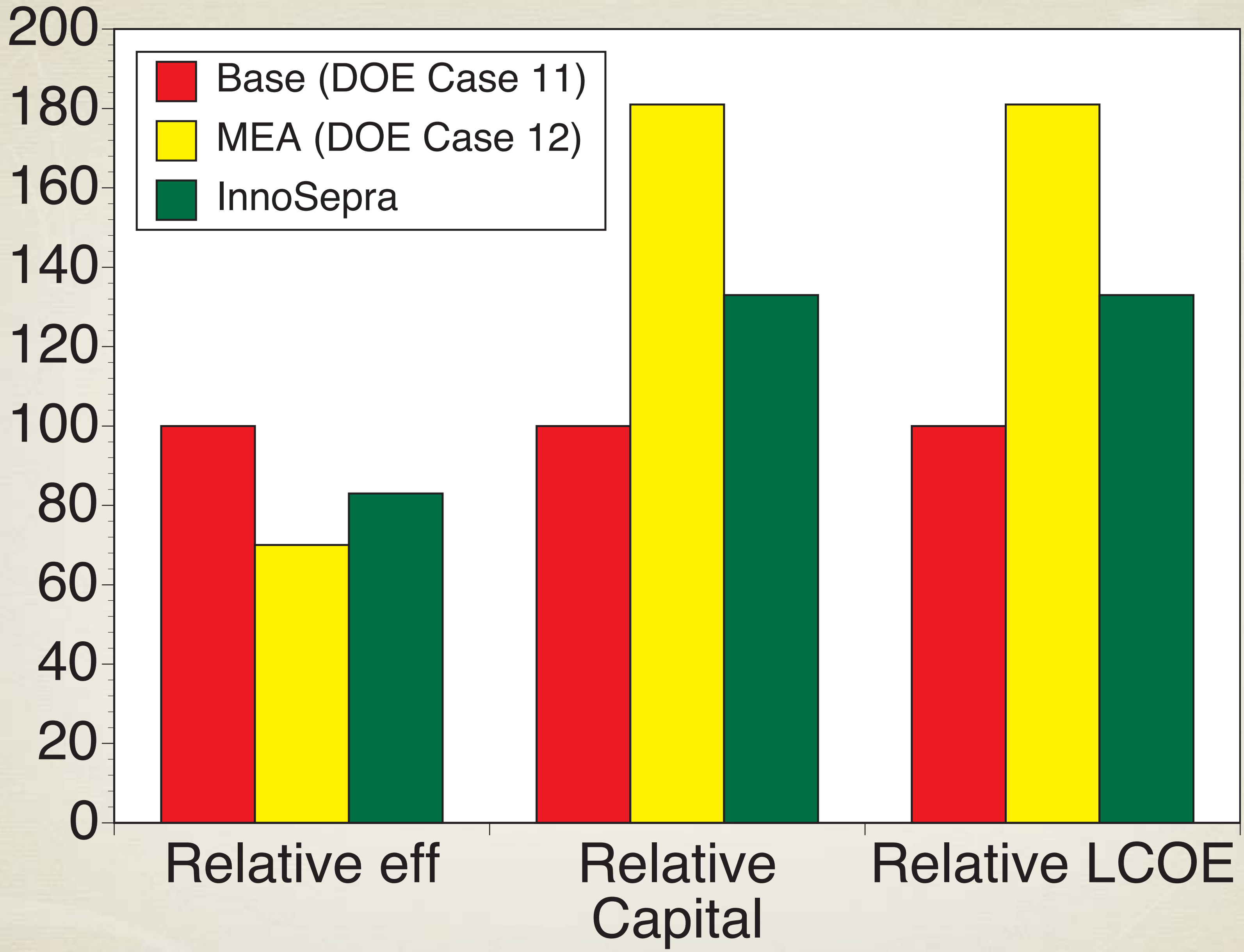
- **Both high net CO_2 capacity and low heat of adsorption are needed to minimize parasitic power**

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

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)

Current 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

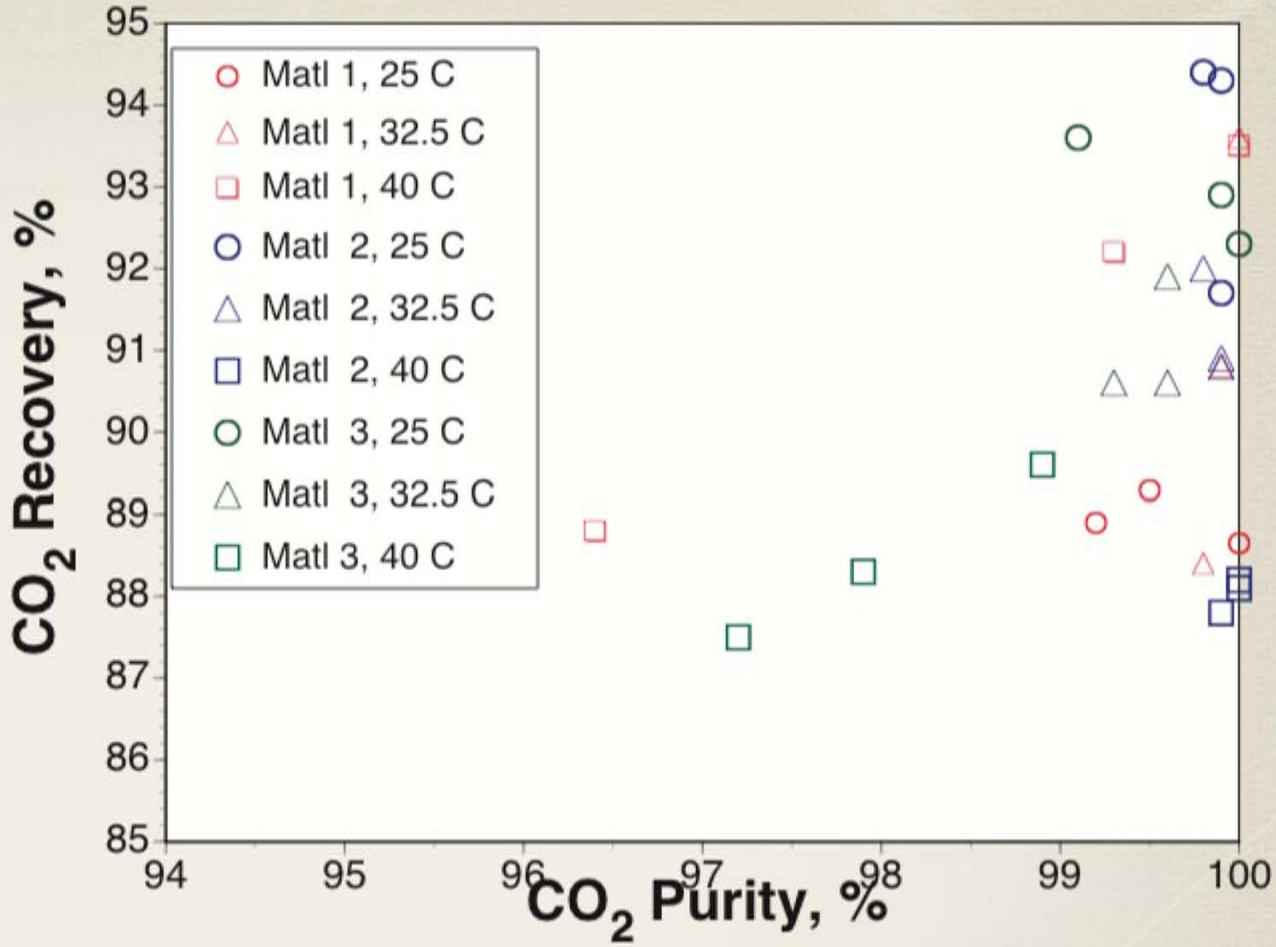
Budget Period III – Installation, Testing and Evaluation

- 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 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

Laboratory Testing of Preferred Sorbents

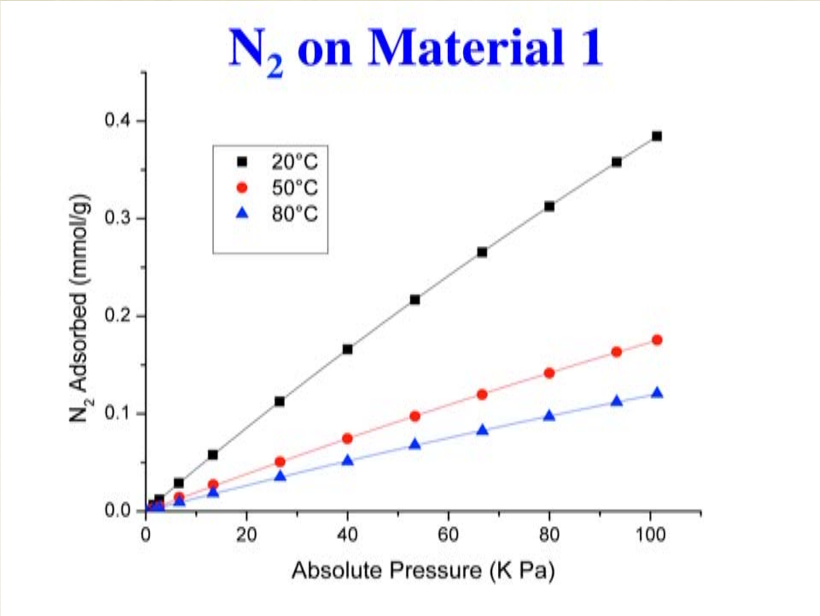


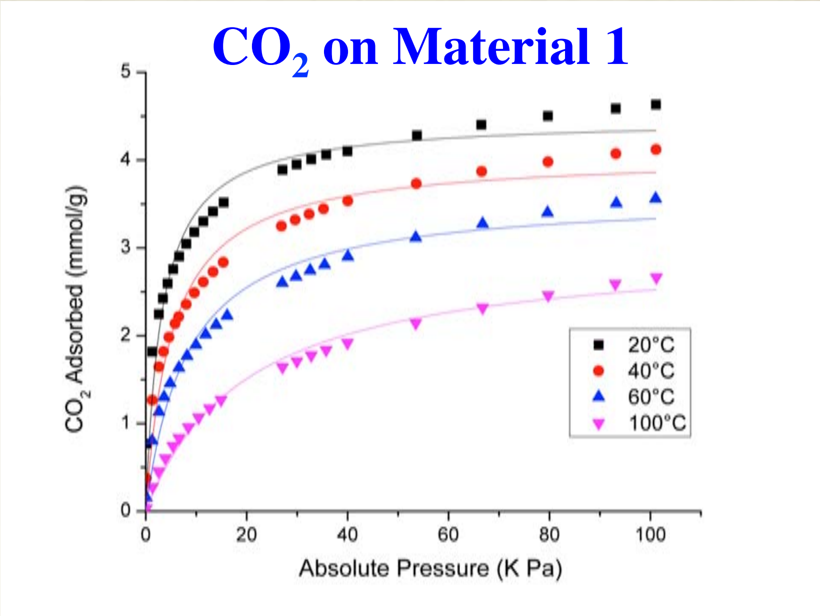
- For a CO_2 purity of >99% and a CO_2 recovery of >90%, net CO_2 capacities of over 6 wt% have been obtained for flue gas temperatures of 25-30^{o}C and a feed CO_2 concentration of 15%
- Same or higher CO_2 purity, recovery and net loading compared to reactive adsorbents using materials with much weaker affinity for CO_2. Cycle modifications allow production of CO_2 with 10-30 ppm O_2.

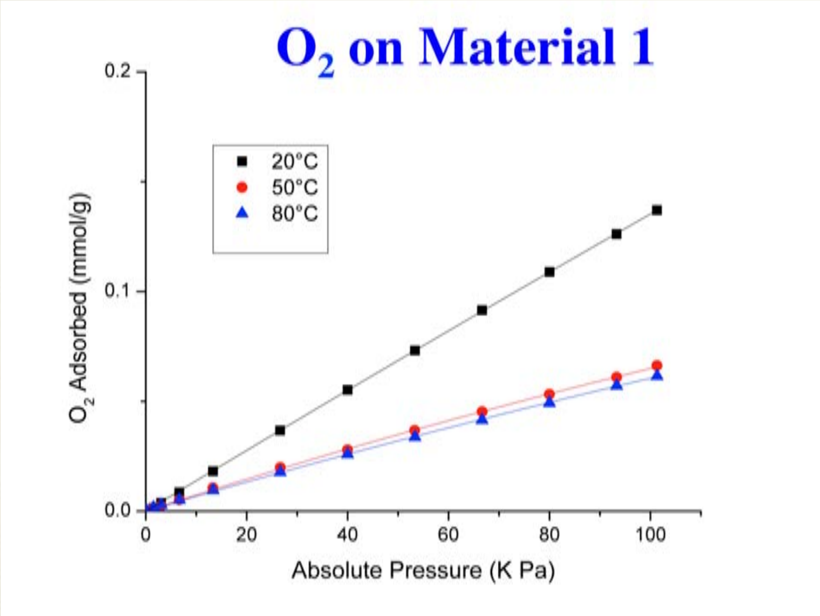
Heat and Mass Transfer Data, Contaminants Removal

- Heat and mass transfer data were obtained for various process configurations and during 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
- The equipment size for moisture and SO_2 removal is much smaller than the equipment for CO_2 adsorption
- The impact of SO_2 and moisture removal on LCOE and the CO_2 capture cost is small

Representative Adsorption Isotherms







- High isotherm CO_2 capacities (>14 wt%) at the feed conditions (P_{CO2} ~ 15 kPa, 30^{o}C)
- Fairly high separation factors between CO_2 & N_2, and CO_2 & O_2 at the flue gas conditions
- Low heat of adsorption, 190 kcal/kg

Process Simulation Models

- Rigorous solution of coupled heat and mass transfer partial differential equations with both the in-house simulator and ASPEN Adsorption. EPRI is involved in modeling as well as in integration with the power plant.
  - The models have been modified to include the heat transfer equipment
- 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
  - Overall mass transfer coefficient obtained by fitting the experimental data to the simulation
- 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 will be updated with data from larger test units to improve the predictions
  - The model is expected to be very useful for modeling heat transfer in full scale plants and for providing estimates of the thermal and electrical energy needed

Techno-economic Analysis

The Parasitic Power

- Electric power for the blower, various pumps and the CO_2 compressor
- Heat energy required for the removal of moisture & impurities and for CO_2 desorption
- Heat energy required for adsorbent and vessel heating

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 compressors and interstage coolers

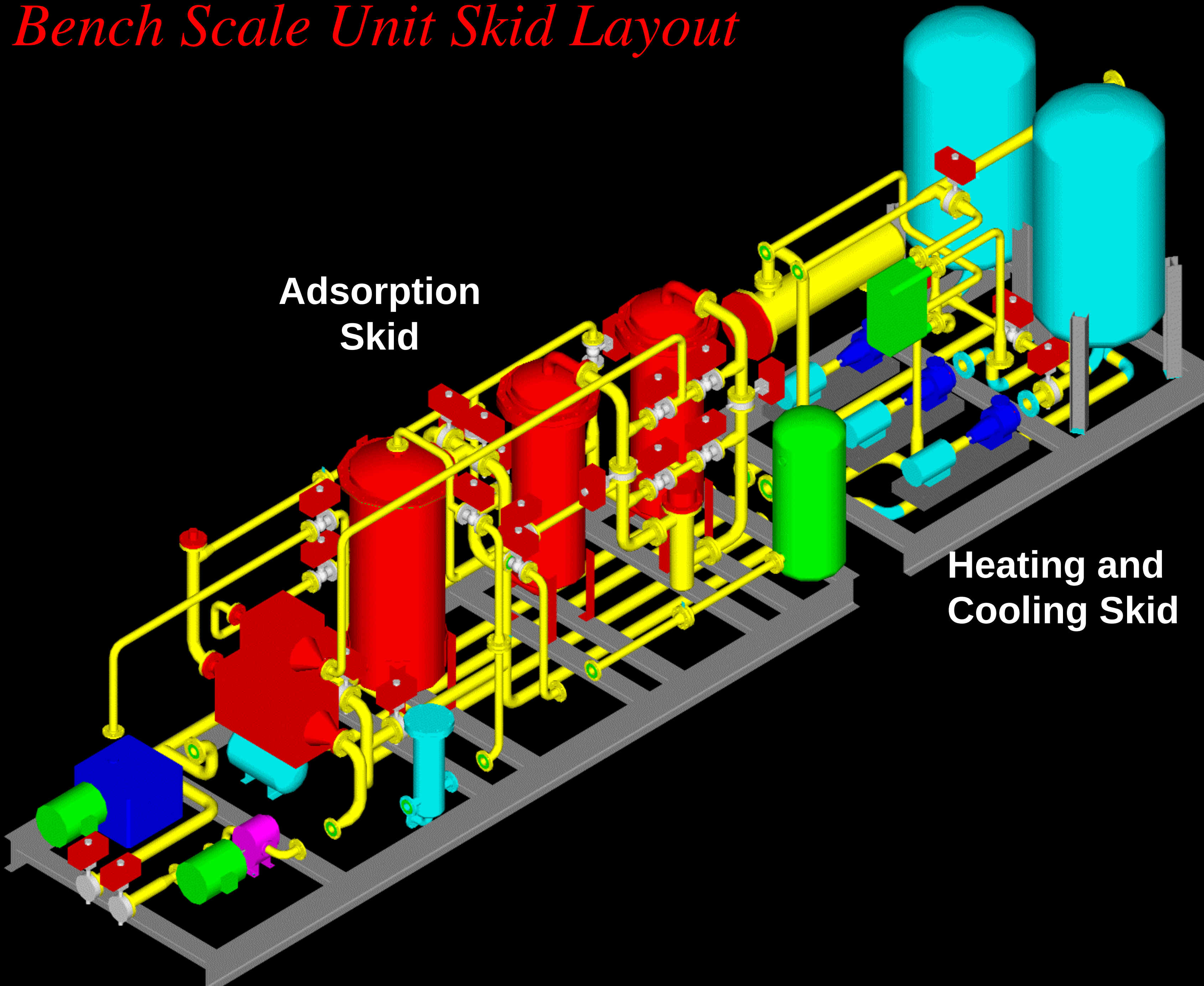
Techno-economic Analysis for a 550 MW Supercritical PC Power Plant

Estimated Capital Cost	$246 MM
Power consumption including compression	94 MW
Steam cost per 1,000 lb for the base plant	$5.83
Increase in steam cost with capture*	45%
Electricity cost for the base plant	$0.064/kWh
Increase in electricity cost with capture*	45%
CO_2 production rate, million tons/yr	3.5
CO_2 Recovery Cost**	$40.7/ton

*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.

Bench Scale Unit Skid Layout



Future Plans

Current DOE Project

- Fabricate the Bench Scale Unit
- Install and commission at NRG's Indian River plant
- Test with actual flue gas for 8-12 weeks
  - Vary feed flow, feed temperature and cycle time
  - EPRI sampling and evaluation of used adsorbents
- Set commercial unit process configuration
- Independent techno-economic analysis (EPRI)
- Prepare EH&S risk assessment (PNNL)

Next Scale Up Phase

- Testing at 0.5-2.0 MW scale and also address engineering challenges related to scale up
- Can be used to design up to 500 tpd CO_2 capture systems
- Pursuing other applications that can provide technology validation in commercial applications

Overall Accomplishments

- The InnoSepra CO_2 capture process combines several innovative features to reduce the capital and power cost of 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 (10-30 ppm O_2)
  - **ΔH_{ads}<200 Kcal/Kg, parasitic power <450 Kcal/kg**
  - 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)
  - Field testing at the one ton per day scale will further validate the technology

Summary

- Physical sorption to produce dry CO_2 at high purity and high recovery from the flue gas after the FGD
- Capital and the parasitic power estimates based on an externally funded technology study and internal estimates indicate the potential for more than 50% reduction in capital and more than 40% reduction in parasitic power
- Significant progress has been made since the start of the DOE project validating some of the process data and the bench scale unit construction is underway
- Potential approaches to further decrease the cost of CO_2 capture have been identified
- **The InnoSepra process can provide CO_2 at a cost and quality suitable for enhanced oil recovery (EOR) which can make CO_2 capture profitable even in the absence of climate legislation**

Acknowledge and Disclaimer

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