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THE UNIVERSITY OF NORTH DAKOTA

# Evaluation of Carbon Dioxide Capture From Existing Coal Fired Plants by Hybrid Sorption Using Solid Sorbents


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# Presentation Overview

- Project team
- Background on the proposed technology and its scientific/technical merit
- Technical summary of budget period 1
- Project schedule and associated milestones
- Decision points and success criteria
- Budget
- Budget Period 2
- Technical approach and project scope
- Schedule and associated milestones
- Budget
- Decision points and success criteria

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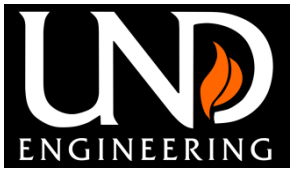
# Project Team

- US Department of Energy - NETL
- UND Institute for Energy Studies
- Envergex LLC
- Lignite Energy Council
- ALLETE Group
  - Minnesota Power
  - BNI Coal
- SaskPower
- Barr Engineering
- Solex Thermal





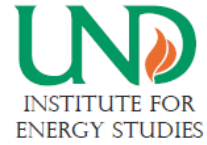












# Background on the Proposed Technology and its Scientific/Technical Merit

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# Background on the Proposed Technology and its Scientific/Technical Merit

- The hybrid sorption CACHYS process uses a regenerable alkali carbonate-based sorbent for $CO_2$ capture

- Initial testing of the concepts was conducted as part of a DOE STTR project conducted by Envergex and UND

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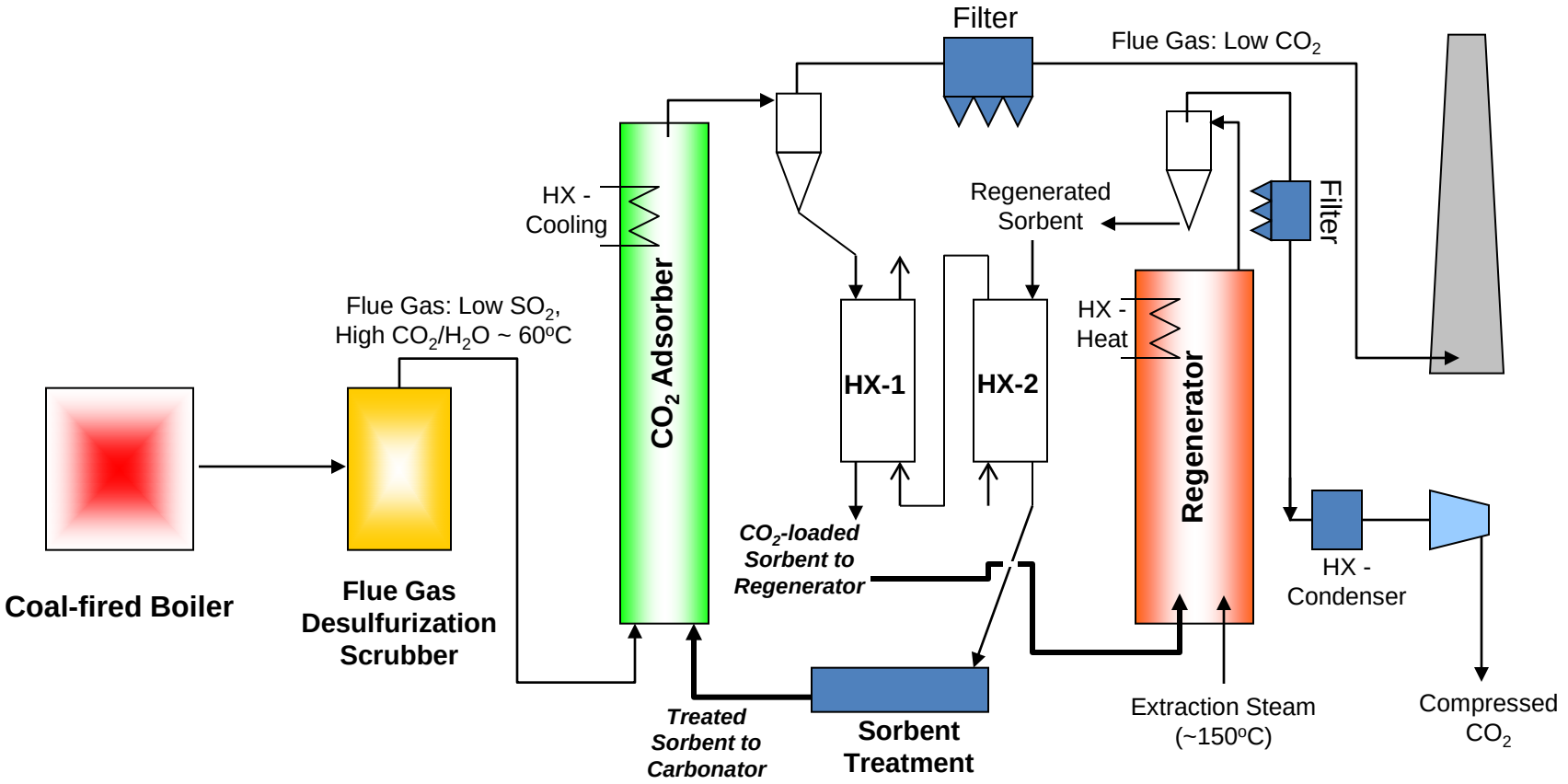
# CACHYS™ Hybrid Sorption Process




- Sorbents prepared from bulk commodity materials – low cost target
- Key component – metal carbonate salt
- Reacts with $CO_2$ to form adduct. Reversible with the addition of heat
- Enhanced adsorption kinetics and reduced regeneration energy

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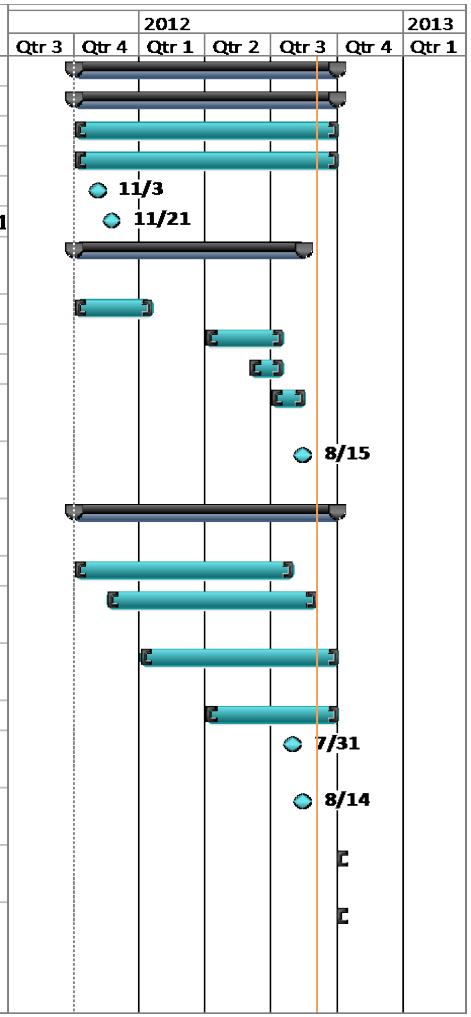
# Project Schedule – BP 1

| ID | Task Name | Duration | Start | Finish |
|---|---|---|---|---|
| 1 | **Budget Period 1** | **262 days** | **Sat 10/1/11** | **Sun 9/30/12** |
| 2 | **Task1 Project Management Plan** | **262 days** | **Sat 10/1/11** | **Sun 9/30/12** |
| 3 | 1.1 Project Management and Planning | 262 days | Sat 10/1/11 | Sun 9/30/12 |
| 4 | 1.2 Briefings and Reports | 262 days | Sat 10/1/11 | Sun 9/30/12 |
| 5 | Submit Project Mananagement Plan | 0 days | Thu 11/3/11 | Thu 11/3/11 |
| 6 | Conduct Kickoff Meeting | 0 days | Mon 11/21/11 | Mon 11/21/11 |
| 7 | **Task2 Initital Technology and Economic Feasiblity Study** | **229 days** | **Sat 10/1/11** | **Wed 8/15/12** |
| 8 | 2.1 Detailed Process Description | 77 days | Sat 10/1/11 | Sun 1/15/12 |
| 9 | 2.2 Process Modeling and Equipment De | 77 days | Sun 4/1/12 | Sun 7/15/12 |
| 10 | 2.3 Equipment Design | 32 days | Fri 6/1/12 | Sun 7/15/12 |
| 11 | 2.4 Preliminary Technical and Economic Analysis | 34 days | Sun 7/1/12 | Wed 8/15/12 |
| 12 | Complete Preliminary Technical and Economic Feasiblity Study | 0 days | Wed 8/15/12 | Wed 8/15/12 |
| 13 | **Task3 Determinination of Hybrid Sorbent Performance Metrics** | **262 days** | **Sat 10/1/11** | **Sun 9/30/12** |
| 14 | 3.1 Sorbent Formulation and Selection | 218 days | Sat 10/1/11 | Tue 7/31/12 |
| 15 | 3.2 Bench-scale Testing of Sorbents Using Pressurized TGA/DSC | 209 days | Tue 11/15/11 | Fri 8/31/12 |
| 16 | 3.3 Determination of Sorbent Physical Properties | 197 days | Sun 1/1/12 | Sun 9/30/12 |
| 17 | 3.4 Fixed-Bed Reactor Testing | 132 days | Sun 4/1/12 | Sun 9/30/12 |
| 18 | Complete pressurized TGA/DSC testing of 5 sorbent formulations | 0 days | Tue 7/31/12 | Tue 7/31/12 |
| 19 | Down-selected to two optimal sorbent formulations for fixed-bed testing | 0 days | Tue 8/14/12 | Tue 8/14/12 |
| 20 | Complete fixed-bed testing of the CACHYS™ process with two optimal | | Sun 9/30/12 | |
| 21 | Determine the optimal process operating conditions, including temp/pressure of the adsorber and regenerator units, for low energy operation | | Sun 9/30/12 | |

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# TECHNICAL SUMMARY FOR BUDGET PERIOD 1

# Task 1 - Project Management and Planning

Subtask 1.1 – Project Management and Planning

- The Project Management Plan submitted at the initiation of the project and was revised to include Barr Engineering
- Project meetings and conference calls including UND and selected subcontractors held weekly to biweekly.

Subtask 1.2 – Briefings and Reports

- A project kick-off meeting at NETL in Pittsburgh was held on November 21, 2011.
- Presentation describing the project and results of the project at the recent $CO_2$ Capture Technology conference held in Pittsburgh during the week of July 9-12, 2012.

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# Task 2 - Initial Technology and Economic Feasibility Study

- Subtask 2.1 – Detailed Process Description
- Subtask 2.2 - Process Modeling and Equipment Design
- Subtask 2.3 - Equipment Design
- Subtask 2.4 – Preliminary Technical and Economic Analysis

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# Subtask 2.1 – Detailed Process Description

- Main Elements of the CACHYS™ Process
  - Adsorber: operating conditions for enhanced reaction kinetics and low heats of adsorption
  - Sorbent: high $CO_2$ capacity, physically compatible with reactor operation, composition for enhanced kinetics and low heat of adsorption
  - Regenerator: reactor modules operated under conditions to minimize heat of regeneration
  - Regenerated gas condenser and $CO_2$ separation
  - $CO_2$ compression

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# Subtask 2.2 - Process Modeling and Equipment Design

- Used ASPEN Plus software for CACHYS process model

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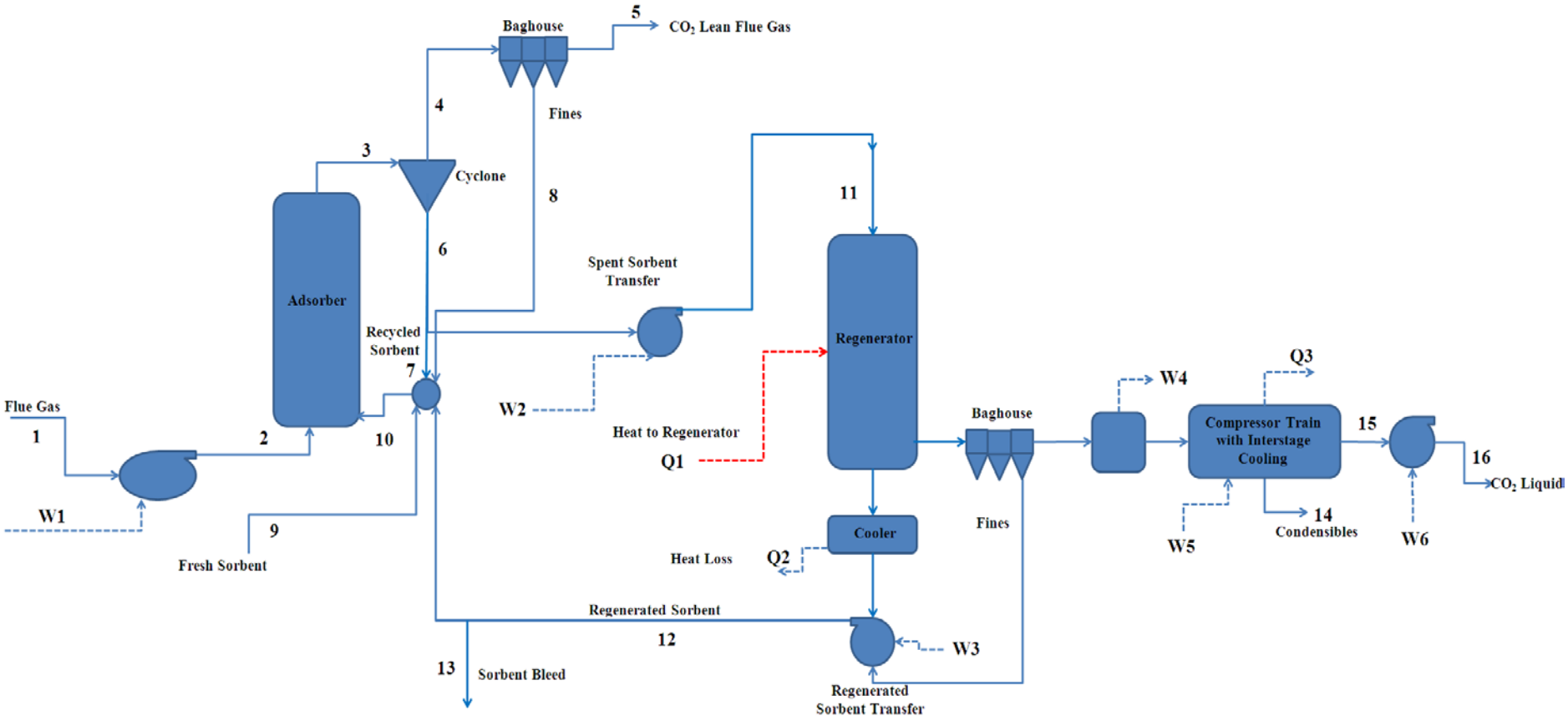
# Block Flow Diagram

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# Selected Stream Table Data

| Stream Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Identity | Flue Gas | Pressurized Flue Gas | Spent Sorbent and $CO_2$ lean Flue Gas | $CO_2$ Lean Flue Gas | $CO_2$ Lean Flue Gas to Stack | Separated Spent Sorbent | Recycled Sorbent | Sorbent Fines Balance to Regenerator |
| Flow [lbm/hr | 6517745 | 6517745 | 20079737 | 5817935 | 5441142 | 14694916 | 1469492 | 376793 |
| Temp [°F] | 136 | 159 | 186 | 185 | 185 | 185 | 185 | 185 |
| Pressure [psia] | 14.7 | 16.9 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 |

| Stream Number | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|
| Identity | Fresh Sorbent | Total Sorbent to Adsorber | Spent Sorbent to Regenerator | Regenerated Sorbent | Sorbent Bleed | Total Flashed liquids after Stage 4 Compression | Compressed Liquid $CO_2$ Stream | Pumped $CO_2$ Stream |
| Flow [lbm/hr | 20000 | 13995105 | 13225424 | 11978715 | 20000 | 30803 | 1204047 | 1204047 |
| Temp [°F] | 136 | 138 | 185 | 136 | 136 | 86 | 86 | 87 |
| Pressure [psia] | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 103 | 1124 | 2214 |

| Q1 | Q2 | Q3 | | | W1 | W2 | W3 | |
|---|---|---|---|---|---|---|---|---|
| -897.7 | 100.59 | 169.67 | | | -15094 | -1837 | -1837 | |
| MMBTU/hr | MMBTU/hr | MMBTU/hr | | | hp | hp | hp | |
| | | | | | | | | |
| W4 | W5 | W6 | Heat Recovery From Regenerator in Form of Power | Heat Duty for Regeneration | $CO_2$ Captured and Compressed | | Heat Duty for Regeneration | |
| 19392 | -51493 | -2891 | 14460.6 | 897.7 | 27358.5 | 12420753.0 | 76.20 | |
| hp | hp | hp | kW | MMBTU/hr | lbmol $CO_2$/hr | mol $CO_2$/hr | kJ/mol $CO_2$ | |

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# Subtask 2.3 - Equipment Design

1. Flue Gas Cleanup
2. Sorbent Regeneration
3. Gas Preconditioning and Compression Train
4. Sorbent Handling
5. Waste Sorbent Recovery and Handling
6. Balance of Plant Equipment
7. Electrical
8. Instrumentation and Controls

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# Subtask 2.4 – Preliminary Technical and Economic Analysis

- Econoamine$^{TM}$-based system for carbon capture used for baseline comparison (DOE Report)
- Case 12 supercritical pulverized coal fired boiler with net output of 550MW$_e$

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# CACHYS™ Process Plant Performance Summary

| | Case 12 | CACHYS™ |
|---|---|---|
| Steam Turbine Power (kW) | 662,880 | 773,200 |
| | Auxiliary Load Summary (kW) | |
| Total Power Block (kW) | 47,340 | 47,800 |
| | | |
| $CO_2$ System | 65,490 | 55,000 |
| | | |
| Total Auxiliary Use (kW) | 112,830 | 102,800 |
| | | |
| Net Power (kW) | 549,970 | 670,400 |
| | | |
| Net Plant Efficiency | 28.4% | 34.6% |
| | | |
| Net Plant Heat Rate (HHV) (BTU/kWh) | 12,002 | 9,859 |

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# CACHYS™ Heat Duty Summary

| PFD Identifier | Pressure (psia) | Temperature (°F) | Heat Duty (MMBtu/hr) |
|---|---|---|---|
| Q1 | 134.9 | 687.5 | 897.6 |
| Case 12- Econoamine Process | 75.0 | 556.3 | 2335.0 |

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# Total Plant Cost Summary for the CACHYS™ System

| Acct No. | Item/Description | Equipment Cost | Material Cost | Labor | | Sales Tax | Bare Erected Cost | Engineering, Const Mgt, & Contractor's Fee | Contingencies | | Total Plant Cost | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Direct | Indirect | | | | Process | Project | $ | $/KW |
| 1 | SITEWORK | $0 | $661,300 | $391,333 | $119,386 | $0 | $1,172,018 | $538,116 | $0 | $513,040 | $2,223,175 | $3 |
| 2 | FOUNDATIONS AND CONCRETE | $0 | $2,967,390 | $4,295,548 | $1,310,462 | $0 | $8,573,401 | $3,936,360 | $0 | $3,752,928 | $16,262,688 | $24 |
| 3 | STRUCTURAL | $0 | $8,440,000 | $3,043,366 | $928,454 | $0 | $12,411,819 | $5,698,717 | $0 | $5,433,161 | $23,543,698 | $35 |
| 4 | PIPING, VALVES & SUPPORTS | $0 | $5,596,000 | $8,555,449 | $2,610,050 | $0 | $16,761,500 | $7,695,813 | $12,228,656 | $11,005,791 | $47,691,760 | $71 |
| 5 | FLUE GAS CLEANUP | $43,800,000 | $0 | $16,927,557 | $5,164,168 | $0 | $65,891,725 | $30,253,285 | $16,961,775 | $33,938,035 | $147,064,820 | $219 |
| 6 | SORBENT REGENERATION | $61,630,000 | $0 | $8,131,323 | $2,480,660 | $0 | $72,241,983 | $33,168,919 | $52,705,451 | $47,434,906 | $205,551,260 | $307 |
| 7 | PRECONDITIONING & CO2 COMPRESSION TRAIN | $43,045,000 | $0 | $1,703,829 | $519,795 | $0 | $45,268,623 | $20,784,470 | $16,513,273 | $24,769,910 | $107,336,276 | $160 |
| 8 | SORBENT HANDLING | $3,570,000 | $0 | $2,135,662 | $651,536 | $0 | $6,357,198 | $2,918,821 | $2,985,947 | $3,678,590 | $15,940,556 | $24 |
| 9 | WASTE SORBENT RECOVERY & HANDLING | $16,270,000 | $0 | $4,889,120 | $1,491,546 | $0 | $22,650,667 | $10,399,744 | $8,929,545 | $12,593,967 | $54,573,943 | $81 |
| 10 | BOP EQUIPMENT | $1,230,000 | $0 | $226,789 | $69,188 | $0 | $1,525,977 | $700,632 | $556,652 | $834,978 | $3,618,239 | $5 |
| 11 | ELECTRICAL | $5,361,200 | $2,171,120 | $5,248,210 | $1,601,096 | $0 | $14,381,626 | $6,603,127 | $5,171,901 | $7,869,282 | $34,100,224 | $51 |
| 12 | INSTRUMENTATIONS AND CONTROLS | $4,000,000 | $650,000 | $1,245,614 | $380,005 | $0 | $6,275,619 | $2,881,365 | $2,289,246 | $3,433,869 | $14,880,098 | $22 |
| | **TOTAL PLANT COST** | **$178,906,200** | **$20,485,810** | **$56,793,801** | **$17,326,345** | **$0** | **$273,512,157** | **$125,579,368** | **$118,362,448** | **$155,258,478** | **$672,786,738** | $1,004 |

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# Annual Operating and Maintenance Costs for the CACHYS™ Process

| Category | Cost per year |
|---|---|
| Personnel | $2,723,000 |
| Maintenance Materials | $1,380,000 |
| Sorbent | $29,784,000 |
| Assumption -<br>No revenue from sale of used sorbent | |
| Total | $33,887,000 |

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# Summary of the Levelized Cost of Steam and Electricity

| | Base Case FOA Appendix 3 | Case 11 DOE Report | Case 12 FOA Appendix 3 | CACHYS™ FOA Appendix 3 | % Increase Over Base Case FOA Appendix 3 |
|---|---|---|---|---|---|
| Electricity (mills/kWh) | 64.0 | 74.7 | 132.3 | 95.1 | 48.6 |
| Steam ($/1,000 lbs) | 5.8 | NA | 12.1 | 8.7 | 48.5 |

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# Cost of $CO_2$ Capture Summary Base Case - 773 $MW_e$ Gross (with Zero Value Spent Sorbent)

| | CACHYS™ Base Case (Value For Spent Sorbent) Cost Per Year | CACHYS™ Base Case (Zero Value For Spent Sorbent)Cost Per Year |
|---|---|---|
| Total O&M | $18,995,000 | $33,887,000 |
| Capital Charge | $117,740,000 | $117,740,000 |
| Total Cost | $136,735,000 | $151,627,000 |
| | Tons Per Year | Tons Per Year |
| $CO_2$ Captured | 4,405,200 | 4,405,200 |
| | Cost Per Ton | Cost Per Ton |
| Cost of $CO_2$ Capture | $31.04 | $34.42 |

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# Cost of CO2 Capture Summary 550 $MW_e$ Net (with Zero Value Spent Sorbent)

| | 550 MW Sensitivity Case – Value for Spent Sorbent | Zero Value for Spent Sorbent Cost Per Year |
|---|---|---|
| Total O&M | $16,072,000 | $28,290,000 |
| Capital Charge | $102,504,000 | $102,504,000 |
| Total Cost | $118,577,000 | $130,794,000 |
| | Tons Per Year | Tons Per Year |
| $CO_2$ Captured | 3,614,000 | 3,614,000 |
| | Cost Per Ton | Cost Per Ton |
| Cost of $CO_2$ Capture | $32.81 | $36.19 |

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# Task 3 - Determination of Hybrid Sorbent Performance Metrics

- Subtask 3.1- Sorbent Formulation and Selection
- Subtask 3.2 - Bench-scale testing of sorbents using TGA/DSC
- Subtask 3.3 – Determination of Sorbent Physical Properties
- Subtask 3.4. Fixed-Bed Reactor Testing

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# Linseis TGA-DSC Instrument

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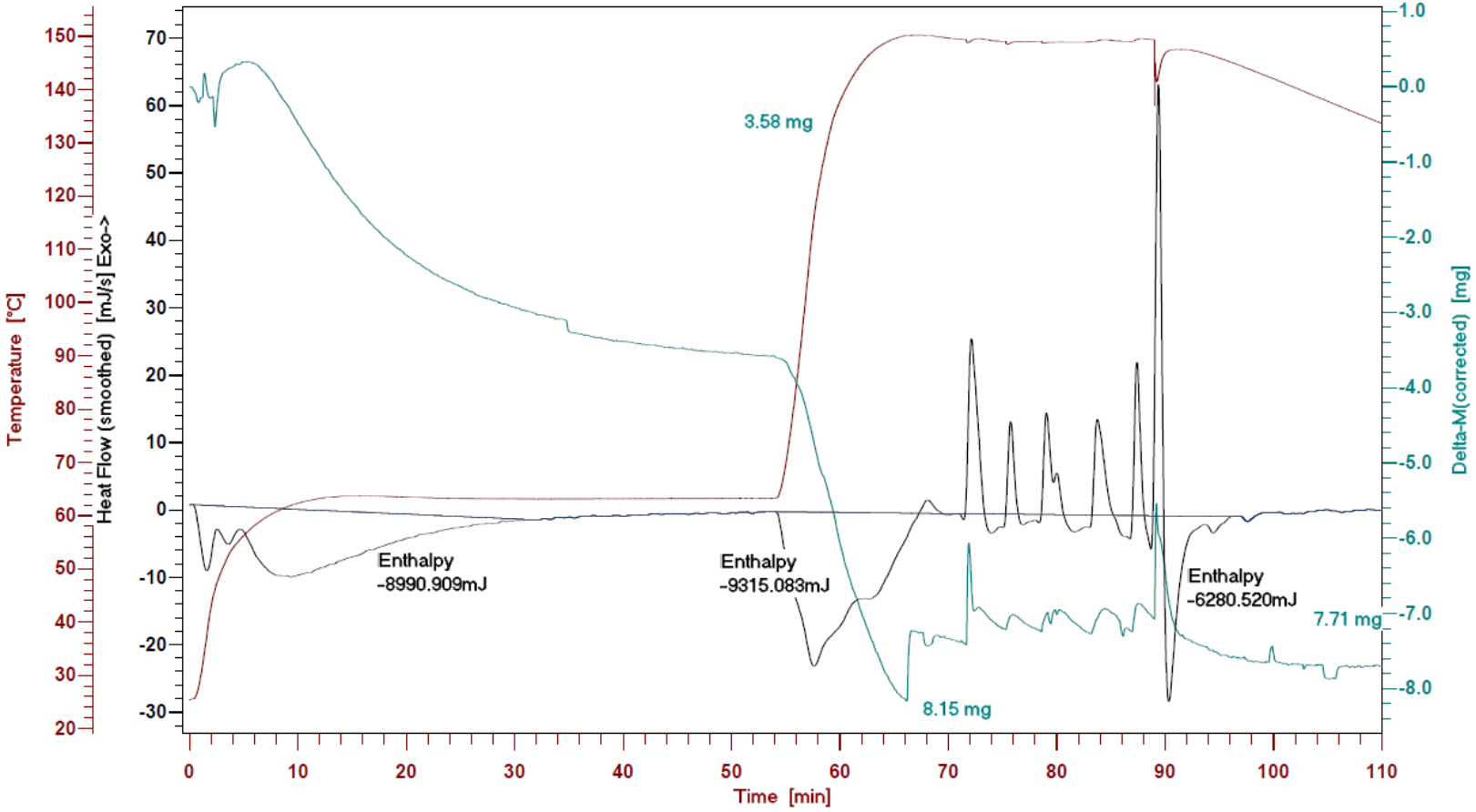
# Adsorption-Desorption: Linseis TGA/DSC Run

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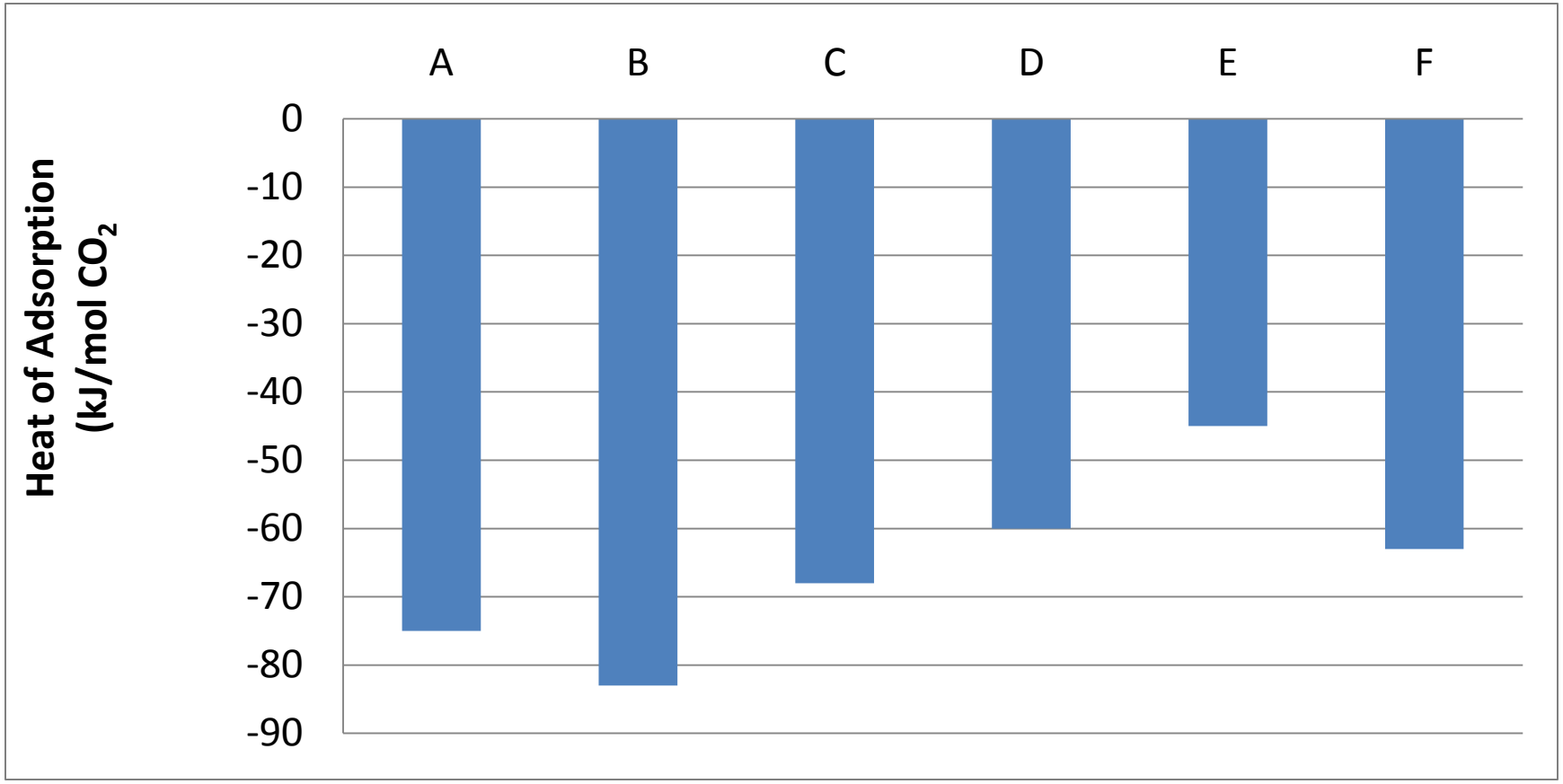
# HCK2 TGA/DSC adsorption energy data (A-F represent different cycles)

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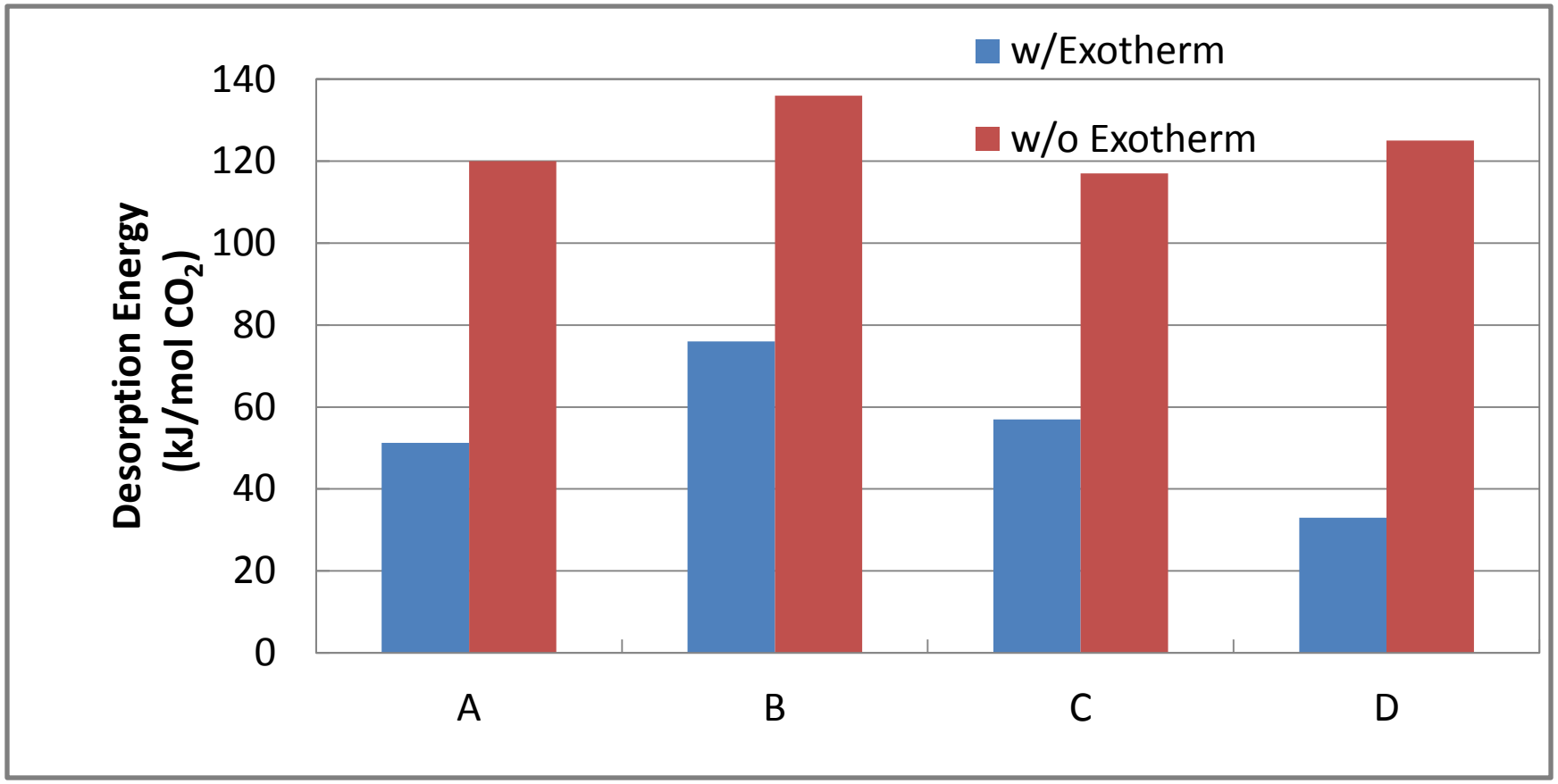
# HCK2 TGA/DSC desorption energy data (A-D represent different cycles)

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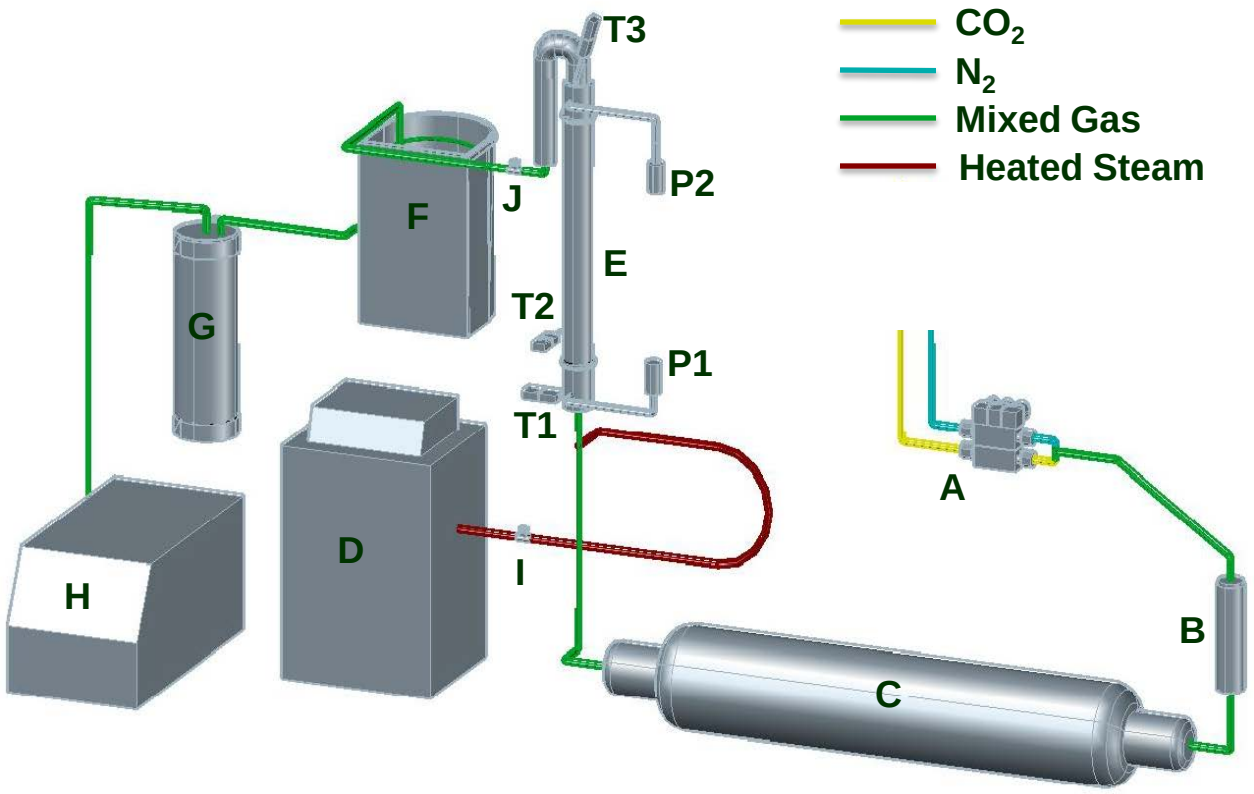
# Subtask 3.4. Fixed-Bed Reactor Testing




| | Components |
|---|---|
| A | Mass Flow Controllers |
| B | Bubbler |
| C | Air Preheater |
| D | Steam Generator |
| E | Reactor |
| F | Condenser |
| G | Water Knockout Drum |
| H | 5 Gas Analyzer |
| I | Manual Steam Control #1 |
| J | Manual Steam Control #2 |
| T1 | Thermocouple – Air In |
| T2 | Thermocouple – Reactor Wall |
| T3 | Thermocouple – Air Out |
| P1 | Pressure Transducer (Bottom) |
| P2 | Pressure Transducer (Top) |

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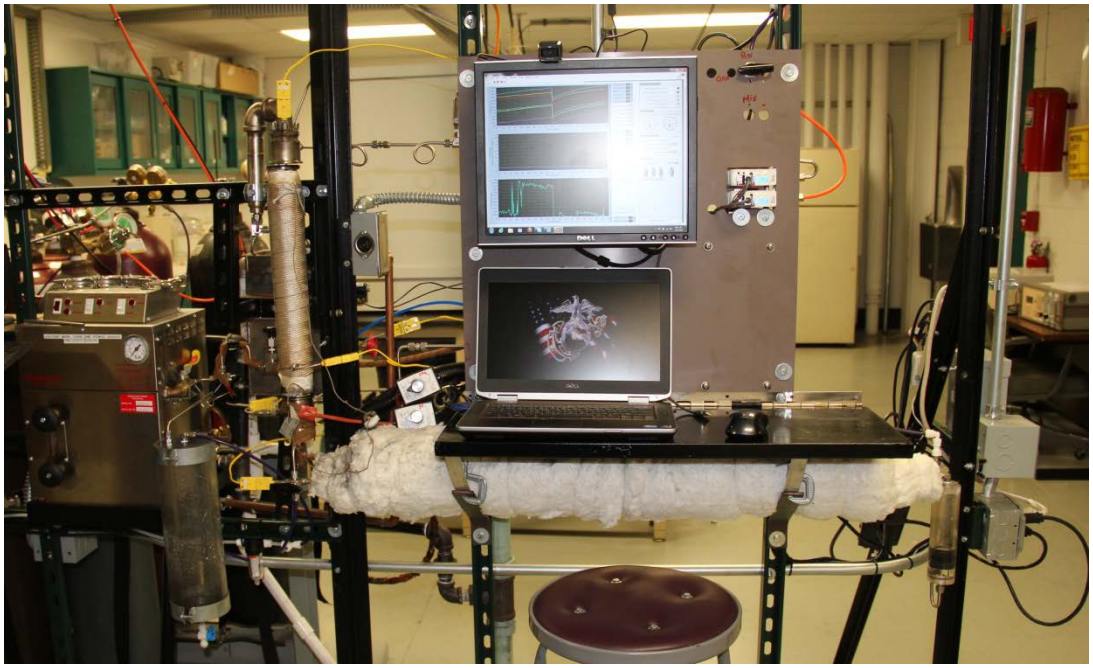
# Fixed Bed Reactor



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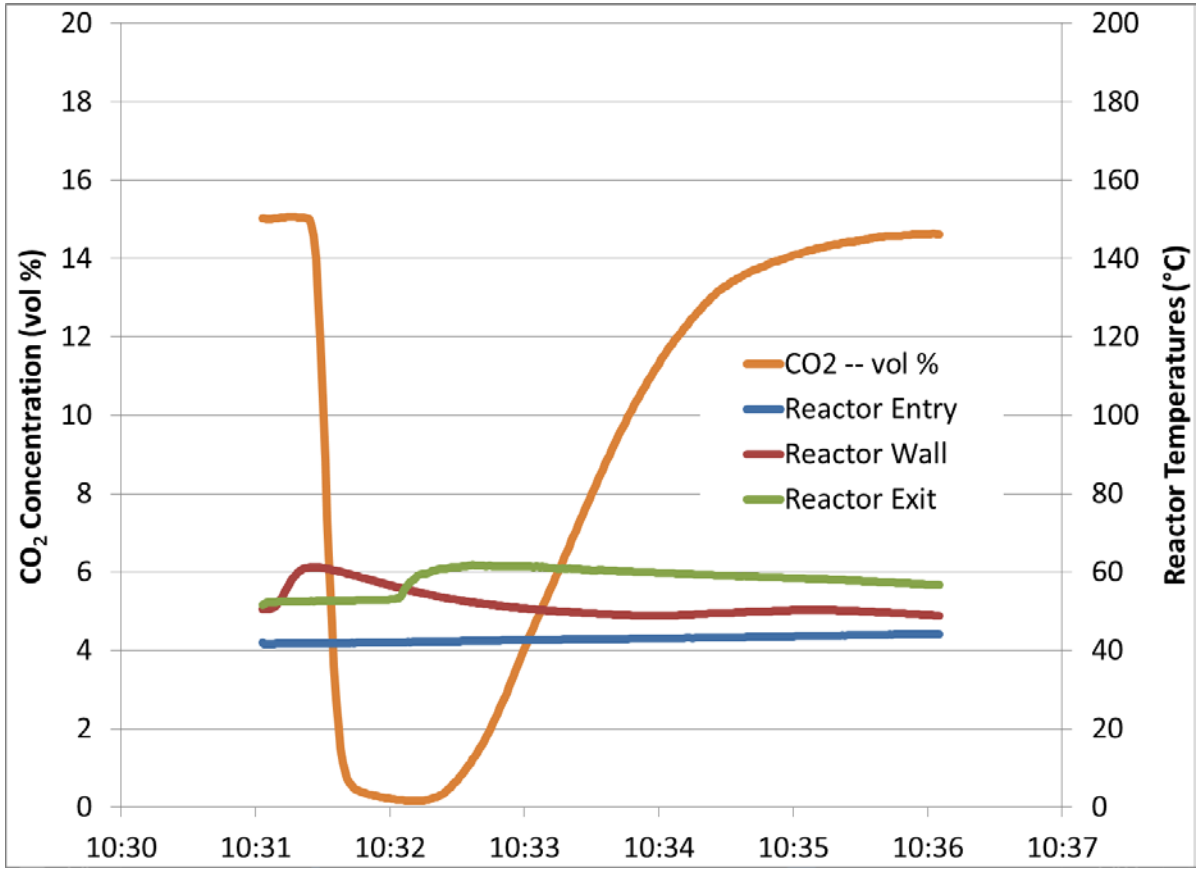
# Typical adsorption cycle (fixed/bubbling bed testing)

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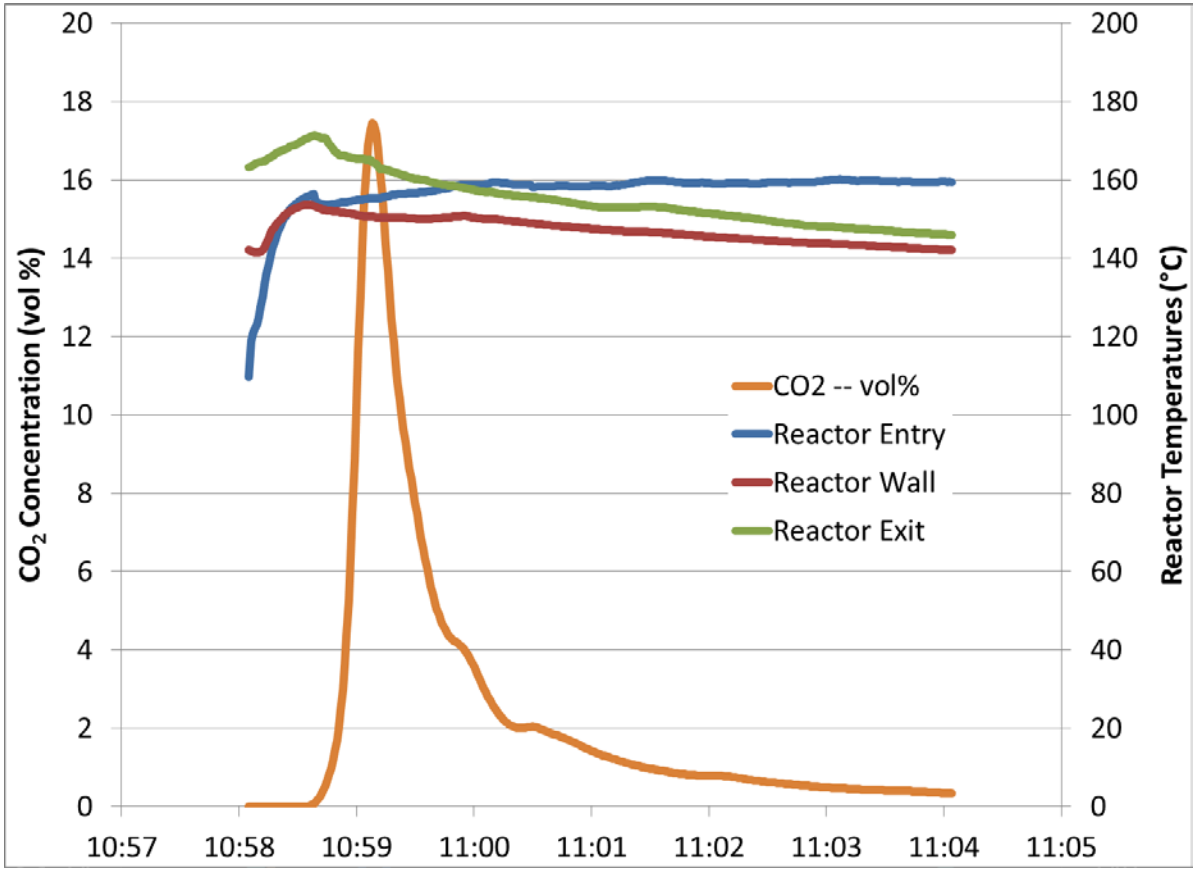
# Typical desorption cycle (fixed/bubbling bed testing)

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# Adsorption loadings for sorbents tested

| Test Number | Sorbent | Total Cycles | Average Adsorption (g $CO_2$)* | Normalized Average Adsorption** (g $CO_2$ / 100 g pure sorbent) |
|---|---|---|---|---|
| 1 | HCK-1 | 4 | 5.5 | 7.1 |
| 2 | HCK-2 | 5 | 6.5 | 7.1 |
| 3 | Used HCK-1 | 5 | 8.0 | 9.0 |
| 4 | HCK-4 | 5 | 6.7 | 7.1 |
| 5 | HCK-5 | 6 | 7.6 | 9.2 |
| 6 | HCK-6 | 6 | 7.3 | 8.4 |
| 7 | HCK-7 | 6 | 6.6 | 8.3 |
| 8 | HCK-7 | 7 | 7.7 | 9.1 |

* Does not include the first cycle
** Calculated using TGA/DSC analyses

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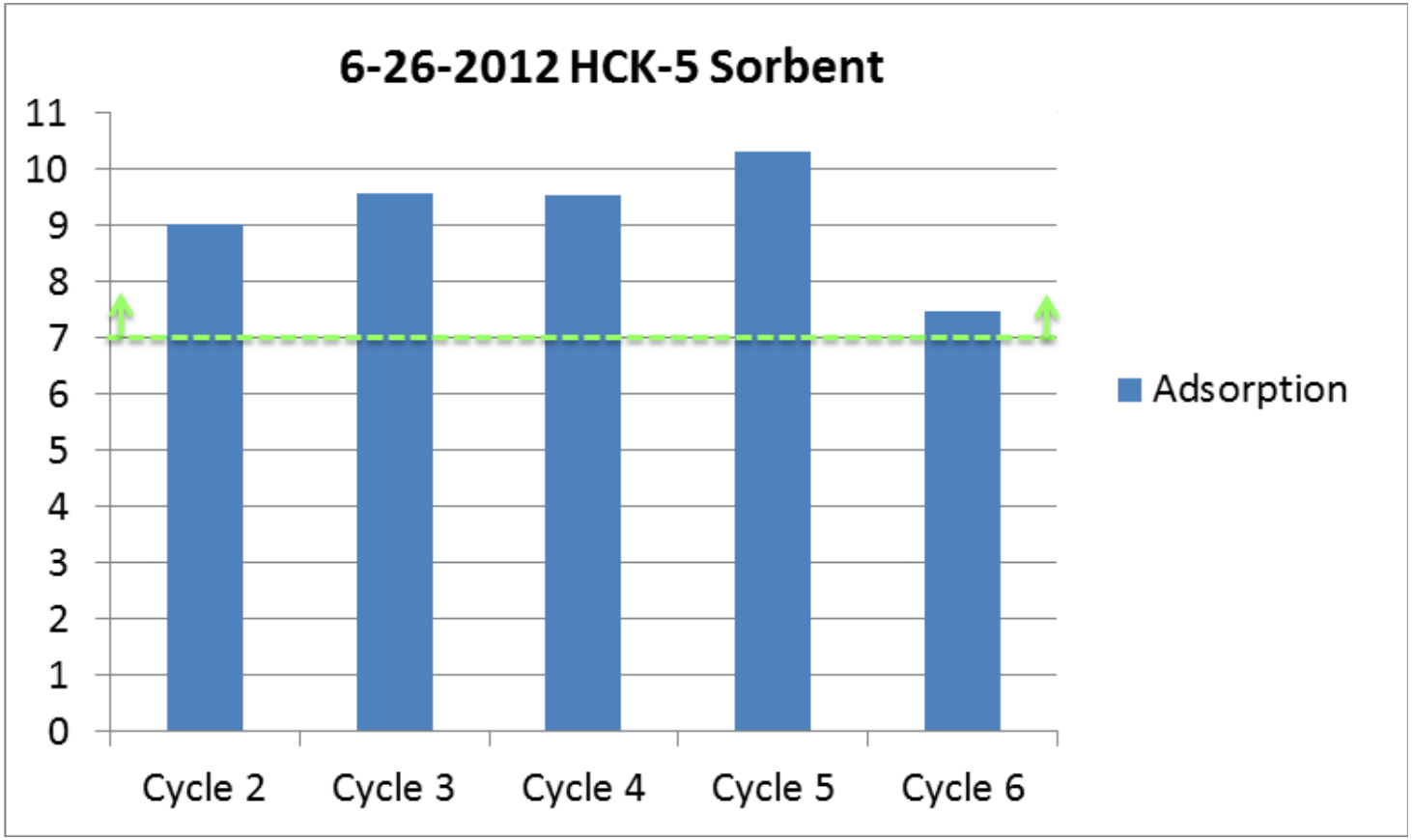
# $CO_2$ adsorption amounts for multiple cycles with HCK-5 sorbent

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# Sorbent Selection For Continued Evaluation

- HCK-4 sorbent averaged 7.1 g $CO_2$ and was consistently in the range of 6.8 – 7.4 g $CO_2$ per 100 grams of sorbent.
- HCK-7 sorbent averaged 9.1 g $CO_2$ (capacities as high as 10.0 g $CO_2$) per 100 grams of sorbent.

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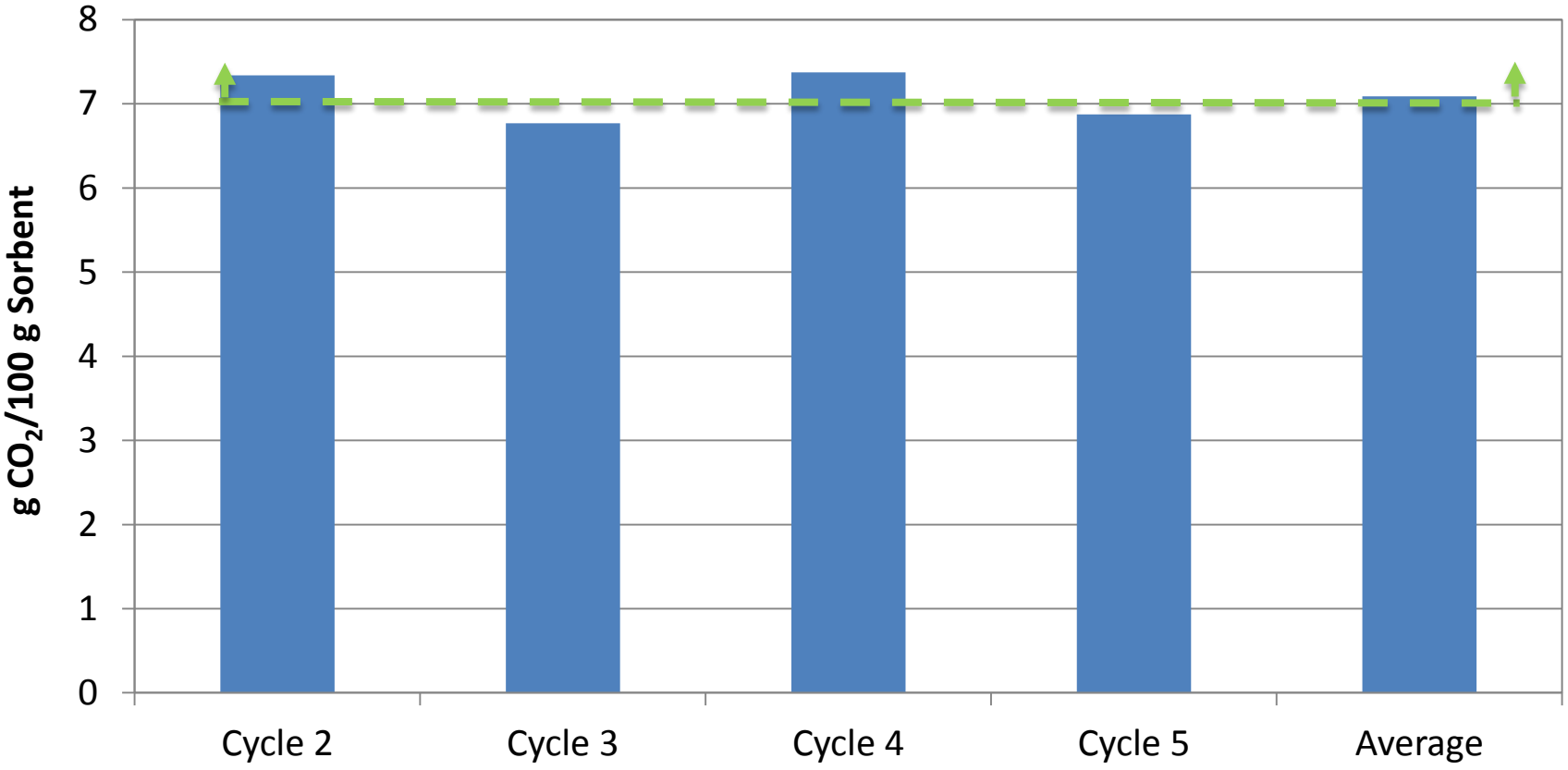
# Adsorption loadings for multiple cycles of HCK-4 sorbent

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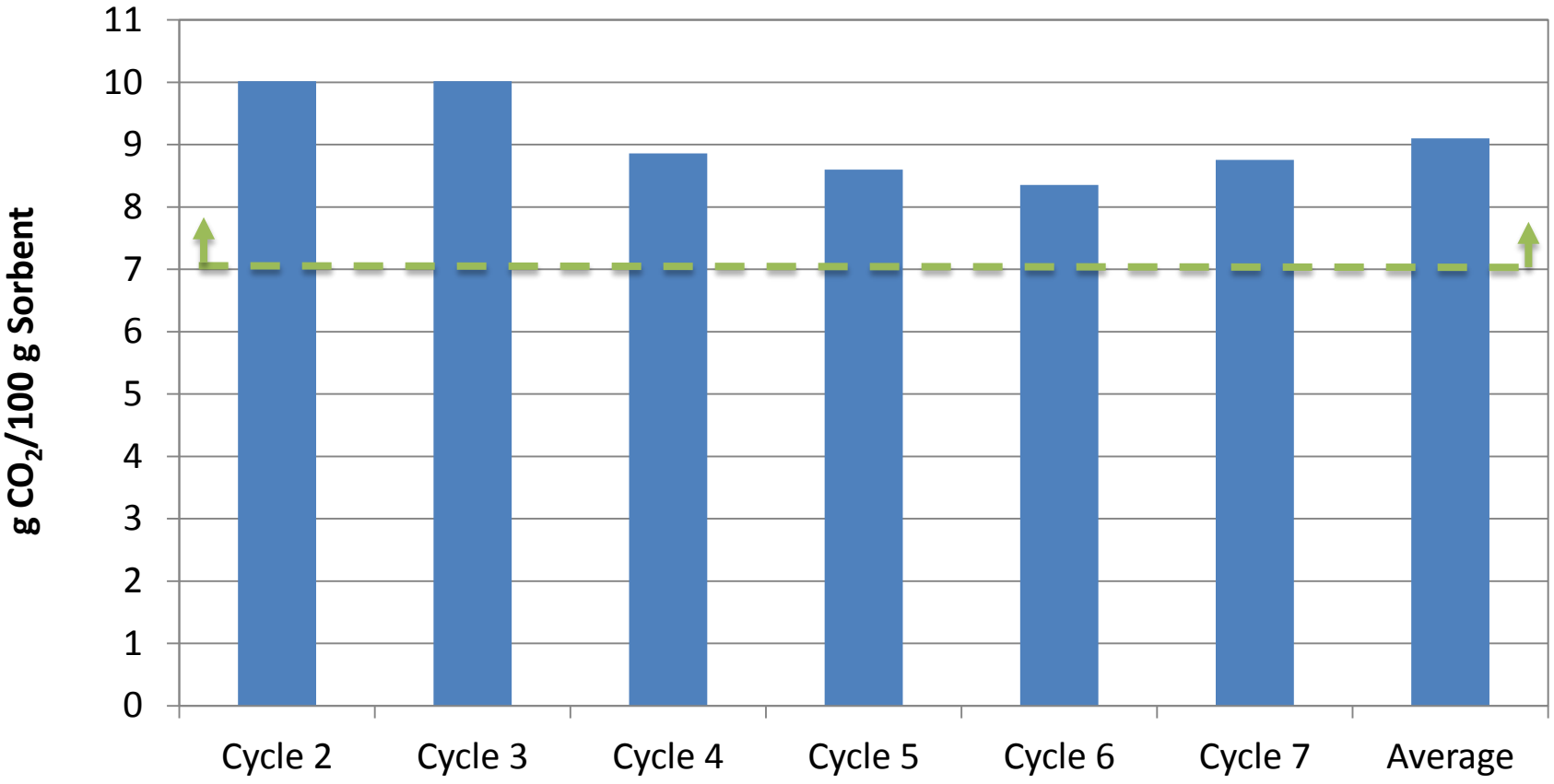
# Adsorption loadings for multiple cycles of HCK-7 sorbent

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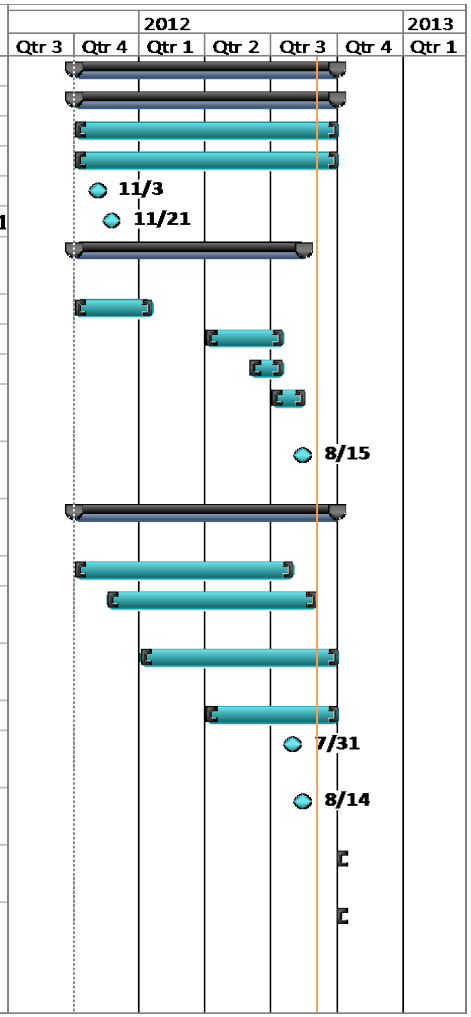
# Project Schedule – BP 1

| ID | Task Name | Duration | Start | Finish |
|---|---|---|---|---|
| 1 | **Budget Period 1** | **262 days** | **Sat 10/1/11** | **Sun 9/30/12** |
| 2 | **Task1 Project Management Plan** | **262 days** | **Sat 10/1/11** | **Sun 9/30/12** |
| 3 | 1.1 Project Management and Planning | 262 days | Sat 10/1/11 | Sun 9/30/12 |
| 4 | 1.2 Briefings and Reports | 262 days | Sat 10/1/11 | Sun 9/30/12 |
| 5 | Submit Project Mananagement Plan | 0 days | Thu 11/3/11 | Thu 11/3/11 |
| 6 | Conduct Kickoff Meeting | 0 days | Mon 11/21/11 | Mon 11/21/11 |
| 7 | **Task2 Initital Technology and Economic Feasiblity Study** | **229 days** | **Sat 10/1/11** | **Wed 8/15/12** |
| 8 | 2.1 Detailed Process Description | 77 days | Sat 10/1/11 | Sun 1/15/12 |
| 9 | 2.2 Process Modeling and Equipment De | 77 days | Sun 4/1/12 | Sun 7/15/12 |
| 10 | 2.3 Equipment Design | 32 days | Fri 6/1/12 | Sun 7/15/12 |
| 11 | 2.4 Preliminary Technical and Economic Analysis | 34 days | Sun 7/1/12 | Wed 8/15/12 |
| 12 | Complete Preliminary Technical and Economic Feasiblity Study | 0 days | Wed 8/15/12 | Wed 8/15/12 |
| 13 | **Task3 Determinination of Hybrid Sorbent Performance Metrics** | **262 days** | **Sat 10/1/11** | **Sun 9/30/12** |
| 14 | 3.1 Sorbent Formulation and Selection | 218 days | Sat 10/1/11 | Tue 7/31/12 |
| 15 | 3.2 Bench-scale Testing of Sorbents Using Pressurized TGA/DSC | 209 days | Tue 11/15/11 | Fri 8/31/12 |
| 16 | 3.3 Determination of Sorbent Physical Properties | 197 days | Sun 1/1/12 | Sun 9/30/12 |
| 17 | 3.4 Fixed-Bed Reactor Testing | 132 days | Sun 4/1/12 | Sun 9/30/12 |
| 18 | Complete pressurized TGA/DSC testing of 5 sorbent formulations | 0 days | Tue 7/31/12 | Tue 7/31/12 |
| 19 | Down-selected to two optimal sorbent formulations for fixed-bed testing | 0 days | Tue 8/14/12 | Tue 8/14/12 |
| 20 | Complete fixed-bed testing of the CACHYS™ process with two optimal | | Sun 9/30/12 | |
| 21 | Determine the optimal process operating conditions, including temp/pressure of the adsorber and regenerator units, for low energy operation | | Sun 9/30/12 | |

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# Milestone Log for Budget Period 1

| ID | Task | Title/Description | Planned Completion Date | Actual Completion Date | Verification Method |
|---|---|---|---|---|---|
| a | 1 | Submit Project Management Plan | 10/31/2011 | 10/28/2011 | Project Management Plan file |
| b | 1 | Complete Kick-off Meeting | 11/21/2011 | 11/21/2011 | Briefing Document & Meeting Results |
| c | 2 | Complete Preliminary Technical and Economic Feasibility Study | 8/15/2012 | 8/15/2012 | Topical Report file |
| d | 3 | Complete pressurized thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) testing of 5 sorbent formulations | 7/31/2012 | 7/31/2012 | Results reported in the quarterly report |
| e | 3 | Down-select to two optimal sorbent formulations for fixed-bed testing | 8/15/2012 | 8/15/2012 | Results reported in the quarterly report |
| f | 3 | Complete fixed-bed testing of the CACHYS™ process with two optimal sorbent formulations | 9/30/2012 | | Results reported in the quarterly report |
| g | 3 | Determine the optimal process operating conditions, including temperature and pressure of the adsorber and regenerator units, for low energy operation | 9/30/2012 | | Results reported in the quarterly report |

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# Decision Points and Success Criteria

| Decision Point | Basis for Decision/Success Criteria |
|---|---|
| Completion of Budget Period 1 Year 1 | 1. Successful completion of all work proposed in Budget Period 1 |
| | 2. Demonstrate sorbent $CO_2$ equilibrium capacity of greater than 70 g of $CO_2$/kg of sorbent - **CACHYS™ sorbents have capacities that range from 70 to 100 g $CO_2$/kg sorbent.** |
| | 3. Demonstrate a heat of sorption of 80 kJ/mole of $CO_2$ or less - **desorption energies ranged from 30 to 80 kJ/mole of $CO_2$** |
| | 4. Submission of a Topical Report – Preliminary Technical and Economic Feasibility Study - **Draft submitted and updated** |
| | 5. Submission/approval of a Continuation Application to DOE – **Draft submitted, and updated** |

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# Budget Summary BP - 1

| | Federal | | | | | Cost Share | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Budget | exp to date | 09/04/2012 | expense | balance 9/30 | Budget | exp to date | 09/04/2012 | expense | balance 9/30 |
| Personnel | $296,588 | $173,361 | $123,227 | $83,800 | $39,427 | $46,396 | $31,143 | $15,253 | $10,264 | $4,989 |
| Fringe Benefits | $93,088 | $52,164 | $40,924 | $29,330 | $11,594 | $17,024 | $8,113 | $8,911 | $2,052 | $6,859 |
| Travel | $8,340 | $317 | $8,023 | $0 | $8,023 | $11,613 | $4,633 | $6,980 | $6,980 | $0 |
| Equipment | $52,247 | $51,907 | $340 | $0 | $340 | $157,753 | $141,493 | $16,260 | $0 | $16,260 |
| Supplies | $3,593 | $3,593 | $0 | | $0 | $10,750 | $1,740 | $9,010 | $5,000 | $4,010 |
| Contractual | $461,755 | $74,157 | $387,598 | $277,598 | $110,000 | $0 | | $0 | | $0 |
| Construction/UND CS | $0 | | $0 | | $0 | $0 | | $0 | | $0 |
| Other | $31,031 | $18,476 | $12,555 | $0 | $12,555 | $15,283 | $0 | $15,283 | $5,000 | $10,283 |
| Total Direct Charges | $946,642 | $373,975 | $572,667 | $390,728 | $181,939 | $258,819 | $187,123 | $71,696 | $29,296 | $42,400 |
| Indirect Charges | $182,263 | $103,706 | $78,557 | $51,349 | $27,208 | $38,406 | $17,340 | $21,066 | $11,132 | $16,112 |
| Totals | $1,128,905 | $477,681 | $651,224 | $442,077 | $209,147 | $297,225 | $204,462 | $92,763 | $40,428 | $58,512 |

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# BUDGET PERIOD 2

# Technical Approach and Project Scope

## Budget Period 2 (10/1/12 – 9/30/13) – I

### Added Work – funds from BP-1

- Task 4. Bench-Scale Process Design
  - Subtask 4.1 – Bench-Scale Adsorber Design
  - Subtask 4.2 – Bench-Scale Regenerator Design
  - Subtask 4.3 – Cycling and Sorbent Transport Testing
  - Subtask 4.4 – Recycle Sorbent Feed System Design
- Task 5. Bench-Scale Process Procurement and Construction
  - Subtask 5.1 - Bench-Scale Process Procurement
  - Subtask 5.2 – Bench-Scale Adsorber Construction
  - Subtask 5.3 – Bench-Scale Regenerator Construction (includes recycle system)

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# Technical Approach and Project Scope
## Budget Period 2 (10/1/12 – 9/30/13) - II

- Task 6. Initial Operation of the Bench-Scale Unit
  - Subtask 6.1 Bench-Scale Shakedown Testing
  - Subtask 6.2 Bench-Scale Process Optimization

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# Technical Approach and Project Scope

## Budget Period 2 (10/1/12 – 9/30/13) - III

- Purpose of Tasks 4-6: Process design of bench scale system as well as construction and shakedown testing of adsorption and desorption system
  - Process design of bench-scale adsorption and regenerator systems
  - Construction and installation of flue gas handling, adsorber and regenerator systems
  - Shakedown testing as well as optimization of flue gas handling, adsorber and regenerator systems
- This work will be conducted by UND, Solex Thermal and Envergex LLC, Barr Engineering

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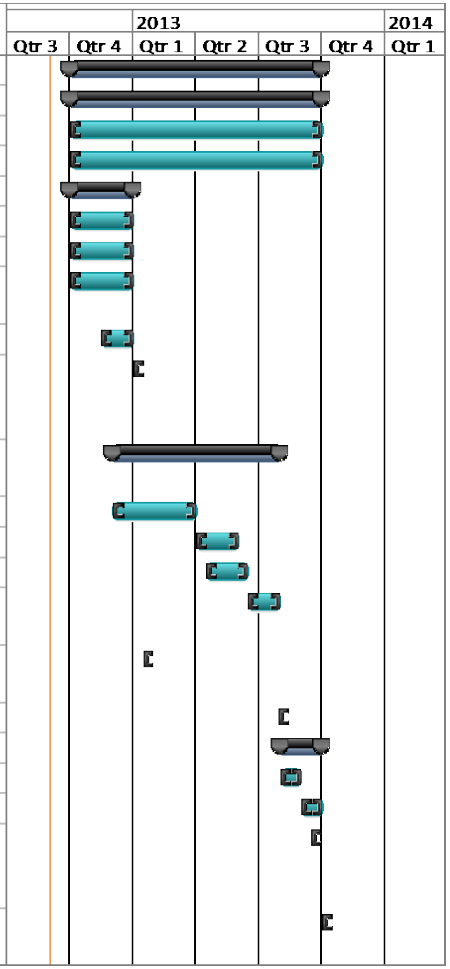
# Schedule – Budget Period 2

| ID | Task Name | Duration | Start |
|---|---|---|---|
| 22 | **Buget Period 2** | **261 days** | **Mon 10/1/12** |
| 23 | **Task 1 Project Management Plan** | **261 days** | **Mon 10/1/12** |
| 24 | 1.1 Project Management and Planning | 261 days | Mon 10/1/12 |
| 25 | 1.2 Briefings and Reports | 261 days | Mon 10/1/12 |
| 26 | **Task 4 Bench-Scale Process Design** | **66 days** | **Mon 10/1/12** |
| 27 | 4.1 Bench-Scale Adsorber Design | 66 days | Mon 10/1/12 |
| 28 | 4.2 Bench-Scale Regenerator Design | 66 days | Mon 10/1/12 |
| 29 | 4.3 Additional Cycling and Sorbent Transport Testing | 66 days | Mon 10/1/12 |
| 30 | 4.4 Recycle Sorbent Feed System Design | 33 days | Thu 11/15/12 |
| 31 | Complete bench-scale unit column design utilizing a refined mass and energy balance of the CACHYS™ process | | Mon 12/31/12 |
| 32 | **Task 5 Bench-Scale Process Procurement and Construction** | **174 days** | **Sat 12/1/12** |
| 33 | 5.1 Bench-Scale Process Procurement | 87 days | Sat 12/1/12 |
| 34 | 5.2 Bench-Scale Adsorber Construction | 46 days | Mon 4/1/13 |
| 35 | 5.3 Bench-Scale Regenerator Construction | 46 days | Mon 4/15/13 |
| 36 | 5.4 Bench-Scale Process Installation and Integration | 34 days | Sat 6/15/13 |
| 37 | Bench-scale unit engineering design package released for bid | | Tue 1/15/13 |
| 38 | Complete bench-scale unit construction | | Tue 7/30/13 |
| 39 | **Task 6 Initital Operation of the Bench-Scale Unit** | **43 days** | **Thu 8/1/13** |
| 40 | 6.1 Bench-Scale Shakedown Procurement | 23 days | Thu 8/1/13 |
| 41 | 6.2 Bench-Scale Process Optimizatoin | 22 days | Sun 9/1/13 |
| 42 | Complete shakedown testing of the flue gas sampling and conditioning system, as well as the adsorber and regenerator | | Sun 9/15/13 |
| 43 | Submit a test matrix for the bench-scale parametric test campaign | | Mon 9/30/13 |

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# Budget – BP-2

Budget Period 2 Costs

| Category | Task No. 1.0 | Task No. 2.0 | Task No. 3.0 | Task No. 4.0 | Task No. 5.0 | Task No. 6.0 | Task No. 7.0 | Task 8.0 | Total |
|---|---|---|---|---|---|---|---|---|---|
| Personnel | 59,926 | | | 98,627 | 112,418 | 97,296 | | | 368,267 |
| Fringe Benefits | 19,755 | | | 29,571 | 36,098 | 28,496 | | | 113,920 |
| Travel | 18,842 | | | | | 693 | | | 19,535 |
| Equipment | | | | | 213,011 | | | | 213,011 |
| Supplies | 1,848 | | | | | 1,224 | | | 3,072 |
| Construction | | | | | | | | | 0 |
| Other Direct Costs | 18,000 | | | | | 4,400 | | | 22,400 |
| ENVERGEX | 69,837 | | | 95,832 | 80,447 | 41,407 | | | 287,523 |
| BARR ENGINEERING | | | | 20,000 | | | | | 20,000 |
| SOLEX THERMAL | | | | 34,000 | 178,240 | 28,760 | | | 241,000 |
| Total Subcontractors | 69,837 | | | 149,832 | 258,687 | 70,167 | | | 548,523 |
| Total Direct Charges | 188,208 | | | 278,030 | 620,214 | 202,276 | | | 1,288,728 |
| Indirect Charges | 38,141 | | | 58,215 | 56,436 | 39,273 | | | 192,065 |
| TOTAL AWARD BUDGET | 226,349 | | | 336,245 | 676,650 | 241,549 | | | 1,480,793 |

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# Schedule and Milestones Budget Period 2

| ID | Task | Title/Description | Planned Completion Date | Actual Completion Date | Verification Method |
|---|---|---|---|---|---|
| h | 4 | Complete bench-scale unit column design utilizing a refined mass and energy balance of the CACHYS™ process | 12/31/2012 | | Results reported in the quarterly report |
| i | 5 | Bench-scale unit engineering design package released for bid | 1/15/2013 | | Bid package is submitted to system integrator/fabricator and submitted to NETL for record |
| j | 5 | Complete bench-scale unit construction | 7/30/2013 | | Results reported in the quarterly report |
| k | 6 | Complete shakedown testing of the flue gas sampling and conditioning system, as well as the adsorber and regenerator | 9/15/2013 | | Results reported in the quarterly report |
| l | 6 | Submit a test matrix for the bench-scale parametric test campaign | 9/30/2013 | | Results reported in the quarterly report |
| | | | | | |

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# Decision Points and Success Criteria

| Decision Point | Basis for Decision/Success Criteria |
|---|---|
| Completion of Budget Period 1 Year 1 | 1. Successful completion of all work proposed in Budget Period 1. |
| | 2. Demonstrate sorbent $CO_2$ equilibrium capacity of greater than 70 gm of $CO_2$/kg of sorbent |
| | 3. Demonstrate a heat of sorption of 80 kJ/mole of $CO_2$ or less |
| | 4. Submission of a Topical Report – Preliminary Technical and Economic Feasibility Study |
| | 5. Submission/approval of a Continuation Application to DOE |
| **Completion of Budget Period 2 Year 2** | 1. Successful completion of all work proposed in Budget Period 2. |
| | 2. Submission of a bench-scale engineering design package |
| | 3. Complete construction of a bench-scale CACHYS™ system |
| | 4. Submission of a test matrix for the bench-scale testing campaign |
| | 5. Submission/approval of a Continuation Application to DOE |
| End of Project Year 3 | 1. Successful completion of all work proposed. |
| | 2. Complete continuous testing of integrated bench-scale CACHYS™ process for 1 month |
| | 3. Submission of a Topical Report - Final Technical and Economic Feasibility Study |
| | 4. Submission of a Topical Report – Preliminary EH&S Assessment |
| | 5. Submission of a Final Report |

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