Bench-Scale Development of a Hybrid Membrane-Absorption CO_2 Capture Process (DE-FE0013118)

MTR Team: Brice Freeman, Richard Baker, Jay Kniep, Pingjiao Hao, and Saurabh Pande

UT Austin Team: Gary Rochelle, Eric Chen, and Frank Siebert

Project Kickoff Meeting
Pittsburgh, PA
December 20, 2013

Outline

- Project Overview & Objectives
- Background & Technical Approach
- Project Organization Structure
- Project Schedule & Tasks
- Project Budget
- Project Management Plan
- Questions and Answers

Project Overview

- **Award name:** Bench-Scale Development of a Hybrid Membrane-Absorption CO_2 Capture Process (DE-FE0013118)
- **Project period:** 10/1/13 to 9/30/16
- **Funding:** $3.0 million DOE + $1.5 million MTR cost share
- **DOE-NETL Project Manager:** Mike Mosser
- **Participants:** MTR, University of Texas at Austin
- **Overall goal:** Evaluate a hybrid post-combustion CO_2 capture process for coal-fired power plants that combines membrane and amine absorption/stripping technology.
- **Project plan:** The key project work organized by budget period is as follows:
  - **BP1**: Develop process simulation and initial techno-economic analysis (TEA) for the hybrid process, and fabricate a 200-300 m^2 membrane test unit at MTR.
  - **BP2**: Conduct comprehensive parametric tests of technologies separately at MTR and UT Austin, covering full range of operating conditions expected for serial and parallel hybrid designs. Refine simulations and prepare for operation of the integrated membrane–absorption system. Upgrade SRP.
  - **BP3**: Run full parametric test program on integrated hybrid unit at UT-Austin. Use test data to refine simulations and prepare final TEA.

Program Goal and Objectives

Overall Goal

Evaluate a hybrid post-combustion CO_2 capture process for coal-fired power plant applications that combines the latest development in membrane and amine absorption/stripping technology developed by MTR and UT Austin.

MTR Objectives (BP1 + 2)	UT-Austin Objectives (BP1 + 2)
Demonstrate reliability and efficiency of large-area plate-and-frame modules in a field environment.	Demonstrate CAPEX and OPEX benefits of 5 molal piperazine with advanced flash process scheme.
BP3 Objective Determine synergies of membrane contactor/ advanced amine hybrid processes in parallel and series configurations	

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Project Team

- **DOE-NETL:**
  - Mike Mosser (Federal Project Manager)
- **MTR:**
  - Brice Freeman (PI)
  - Richard Baker (Technical Advisor)
  - Jay Kniep (Research Manager)
  - Saurabh Pande (Sr. Mechanical Engineer)
  - Pingjiao “Annie” Hao (Sr. Research Scientist)
- **U. Texas - Austin:**
  - Gary Rochelle (co-PI)
  - Eric Chen (Research Associate)
  - Frank Seibert (Sr. Research Engineer)
  - Darshan Sache (Graduate Student)
  - Yu-jeng Lin (Graduate Student)
  - Yue Zhang (Graduate Student)
  - Junyuan Ding (Graduate Student)

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About Membrane Technology & Research, Inc. (MTR)

MTR designs, manufactures, and sells membrane systems for industrial gas separations

80 Employees
2013 Sales: $35 million

MTR

About UT – Austin and the Texas Carbon Management Program

- Texas Carbon Management Program (TxCMP)
  - 25 companies, $750,000/yr
  - 6 PhD students
  - CO_2 rates, thermo, degradation, aerosols, modeling
- CO_2 Capture Pilot Plant Project (C2P3)
  - 4 companies (B&W, LG&E, Chevron, Southern), $250k/yr
  - Located at Separations Research Program (SRP)
  - 0.1 MW pilot with air/CO_2
  - One 4-6 week campaign/yr
  - DOE project to test PZ flash stripping at NCCC in 2015

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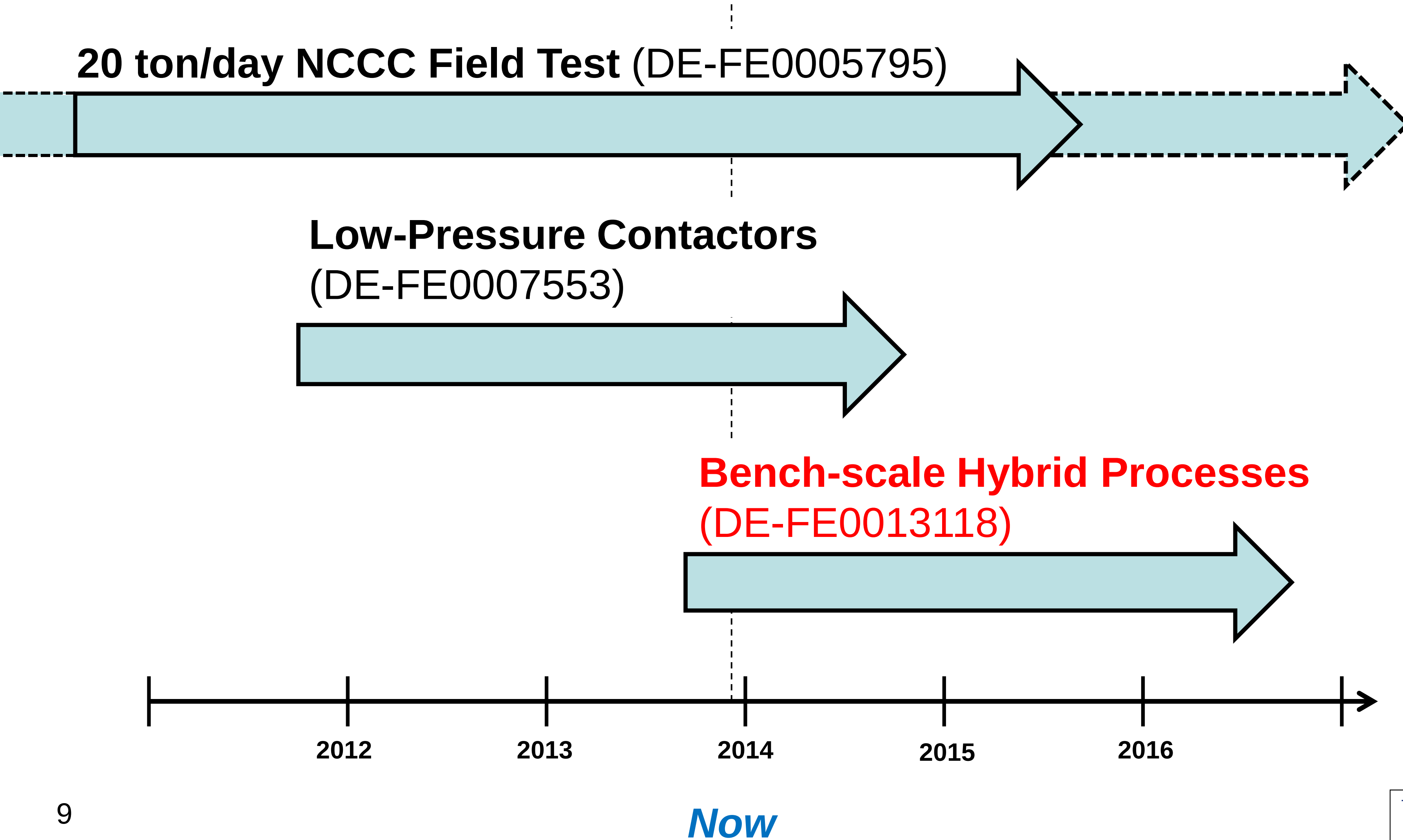
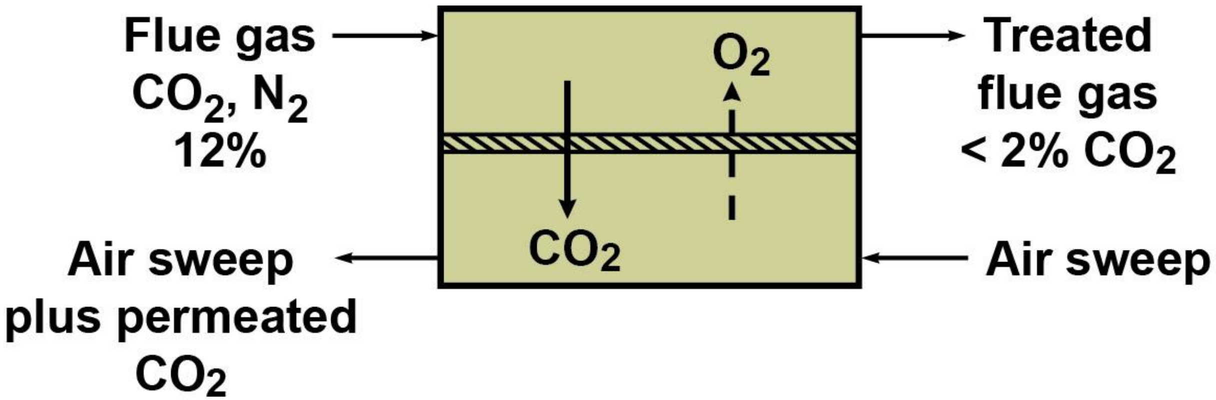
Active MTR CO_2 Post-Combustion Membrane Development Programs



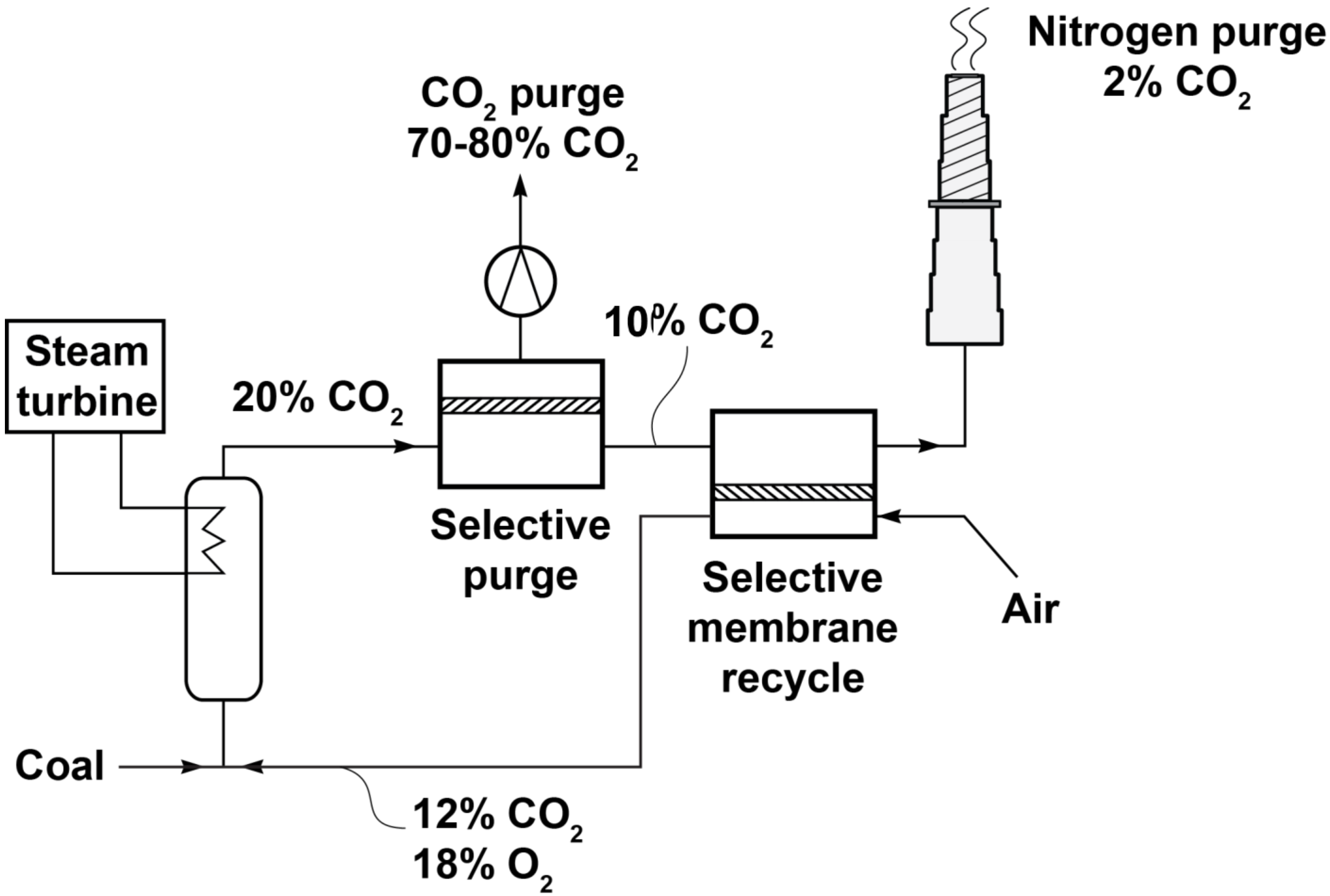
The MTR Membrane Contactor

A Way of Generating an Affordable (Partial) Pressure Difference



A separation is performed at a minimal energy cost

MTR's All-Membrane Solution



500 MW_e plant requires one million m^2 of membrane

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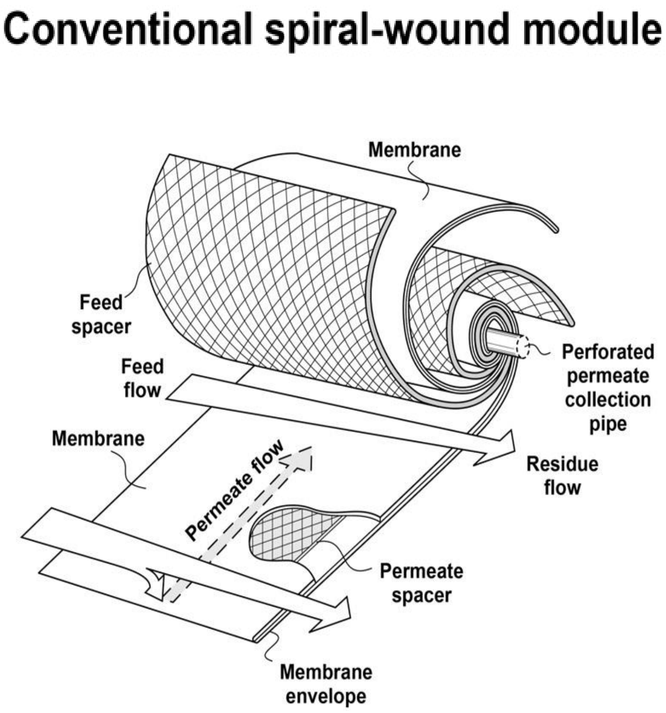
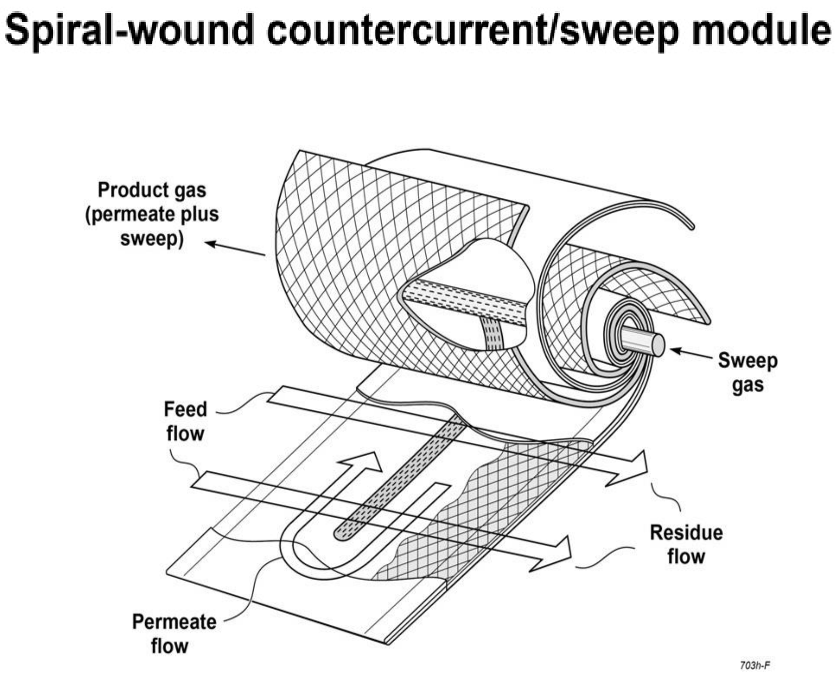
Current Approach Uses Modified Spiral-Wound Modules





Each module contains 20 to 50 m^2 of membrane

Membrane Contactor Modules: Issues and Solutions

Issues	*Solutions*
– **Skid packing density** – **Manifolding** – **Footprint**	Large area modules, compact skids
– **A sweep process** – **Needs low pressure drop**	Needs wide, straight channels on both sides of the membrane

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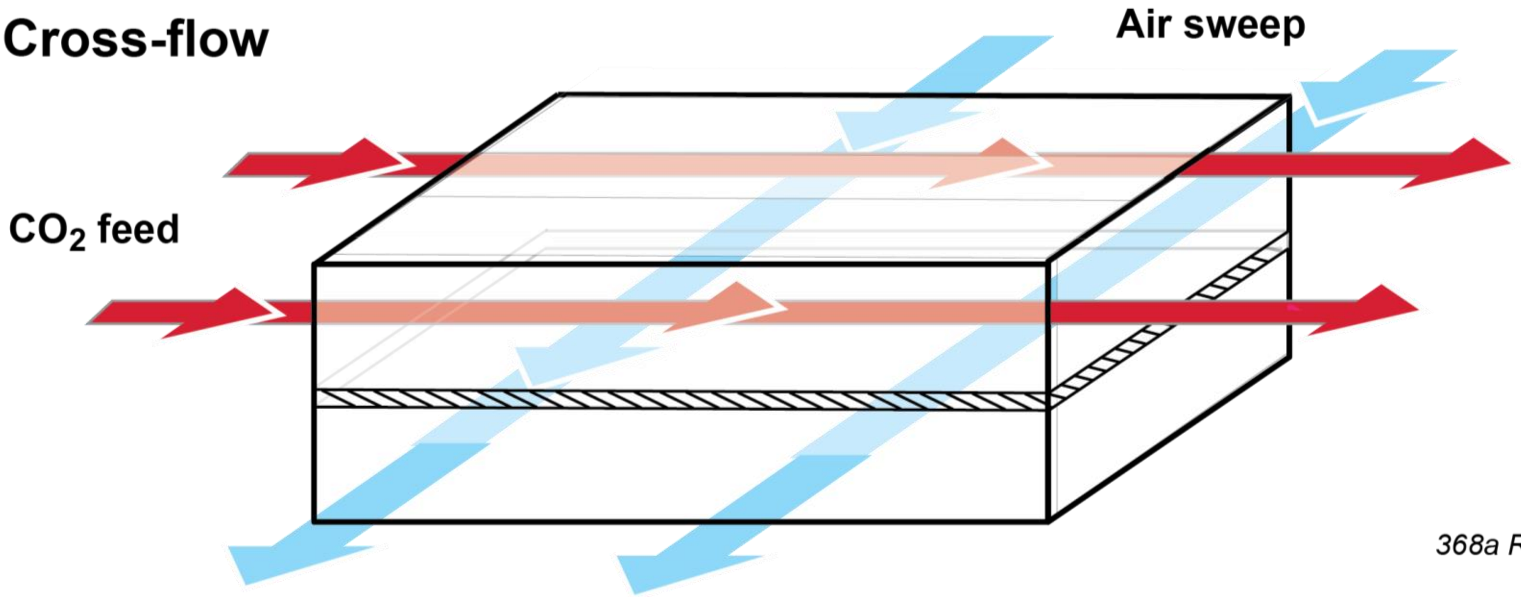
Current Membrane Contactor Design



368a Report Fig

Progress to Date (DE-0007553)

- **BP1**
  - Footprint: .3 m x .6 m
  - Modules: 20 m^2
- **BP2**
  - Footprint: 1m x 1m
  - Modules: 100 m^2

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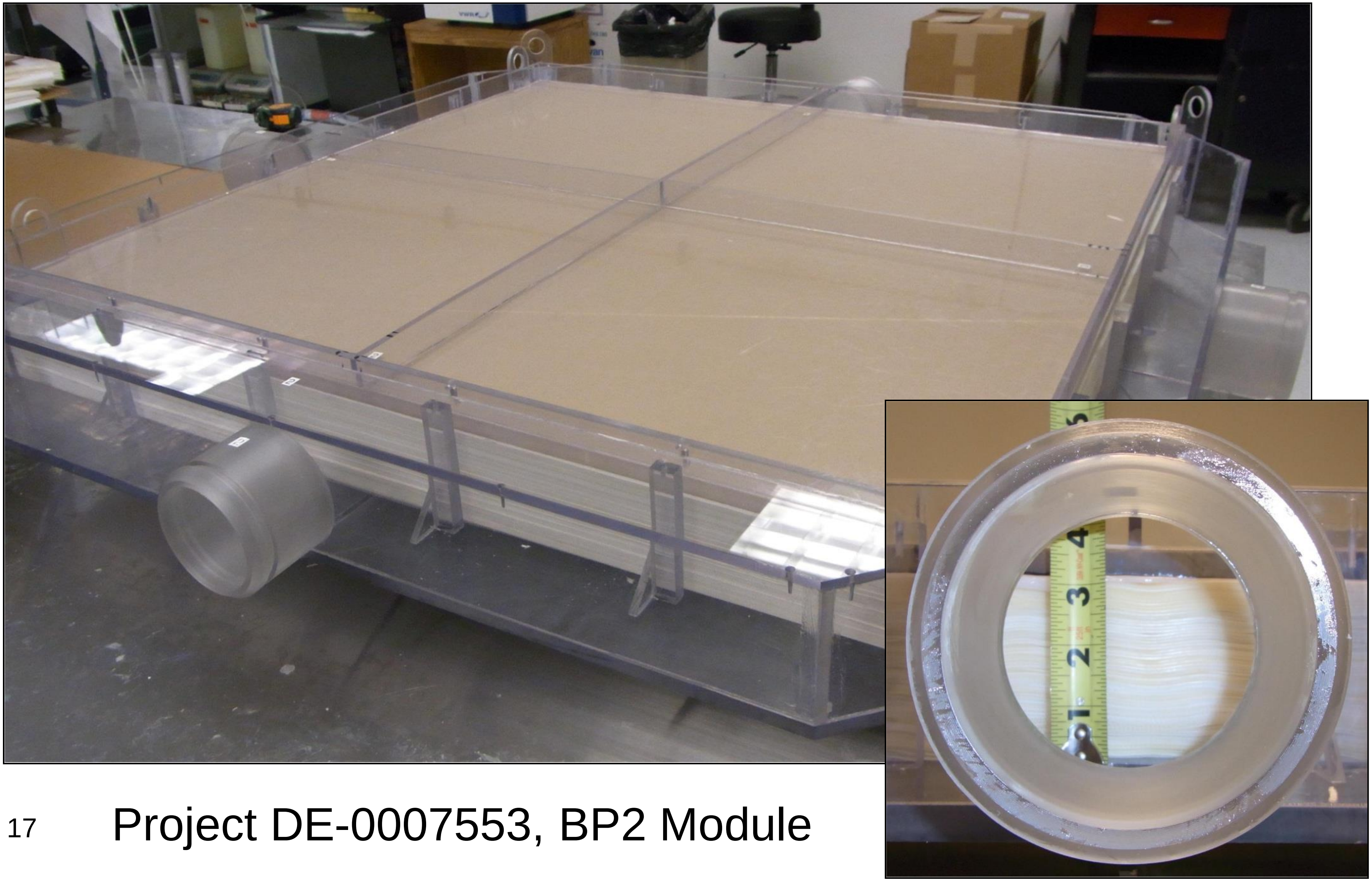
20 m^2 Membrane Modules

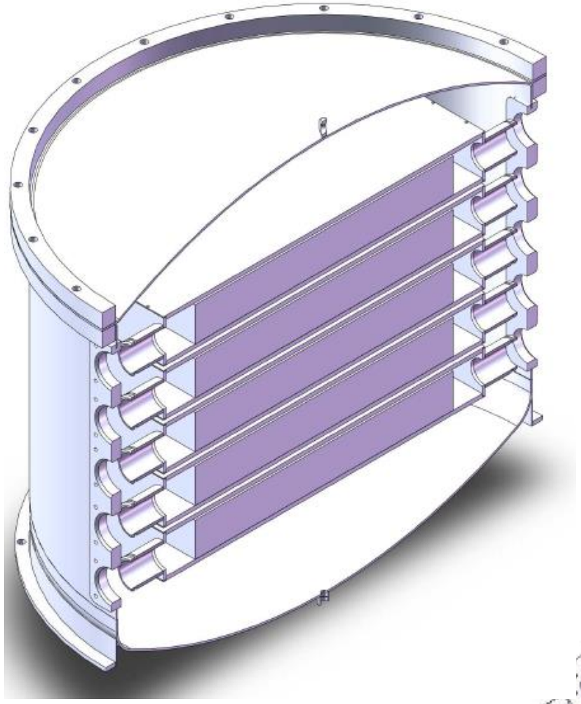
- **Spiral-wound module**
  - **8 in diameter, 40 in long**
  - **20 to 25 envelopes**
  - **Spacers vary with application**
- **Plate-and-frame module**
  - **2 ft x 1 ft x 4.25 in**
  - **62 to 80 envelopes**
  - **Various spacers tested**

100 m^2 Membrane Module

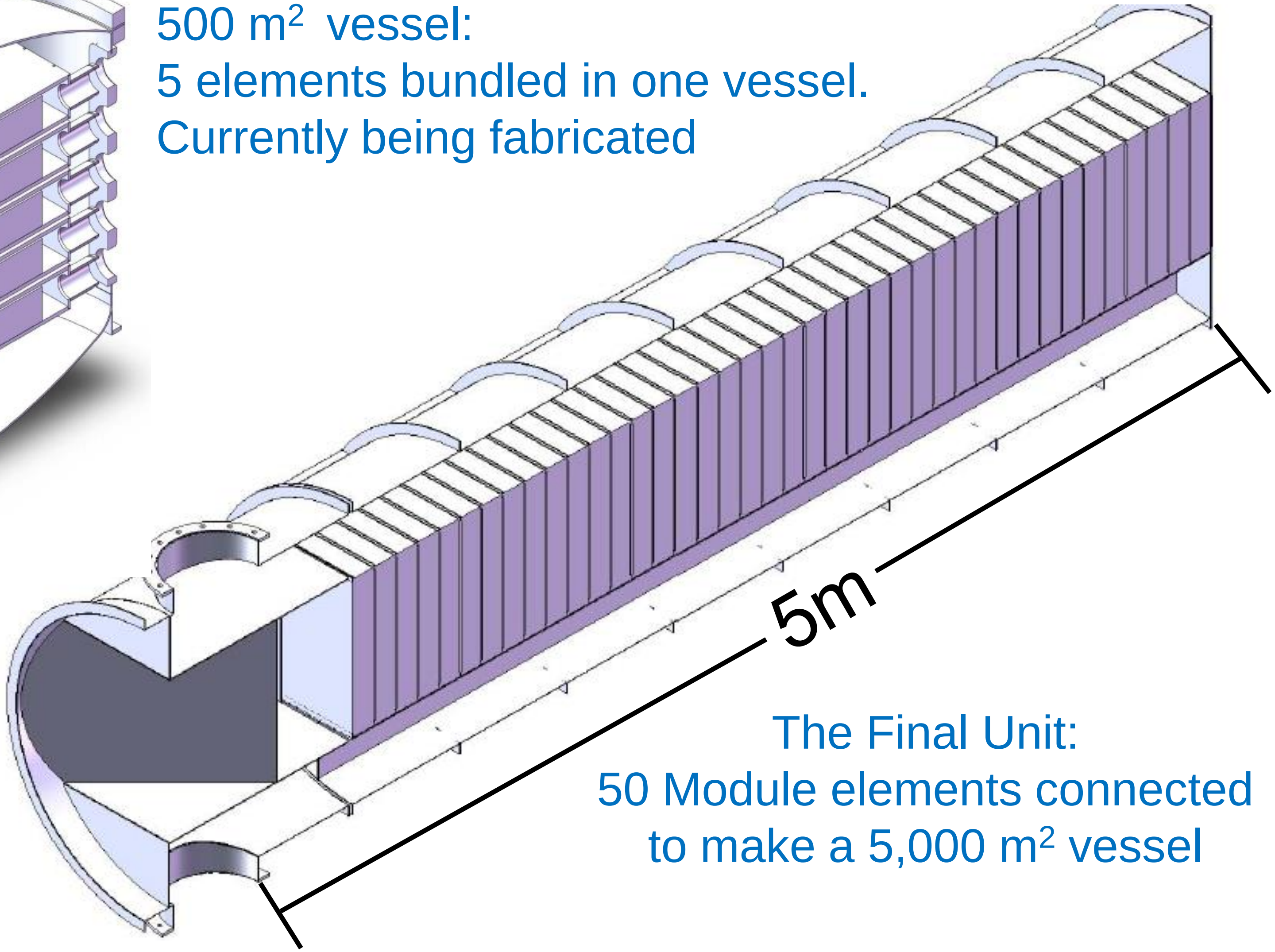


Project DE-0007553, BP2 Module

MTR Concepts for Commercial-Sized Module Vessels

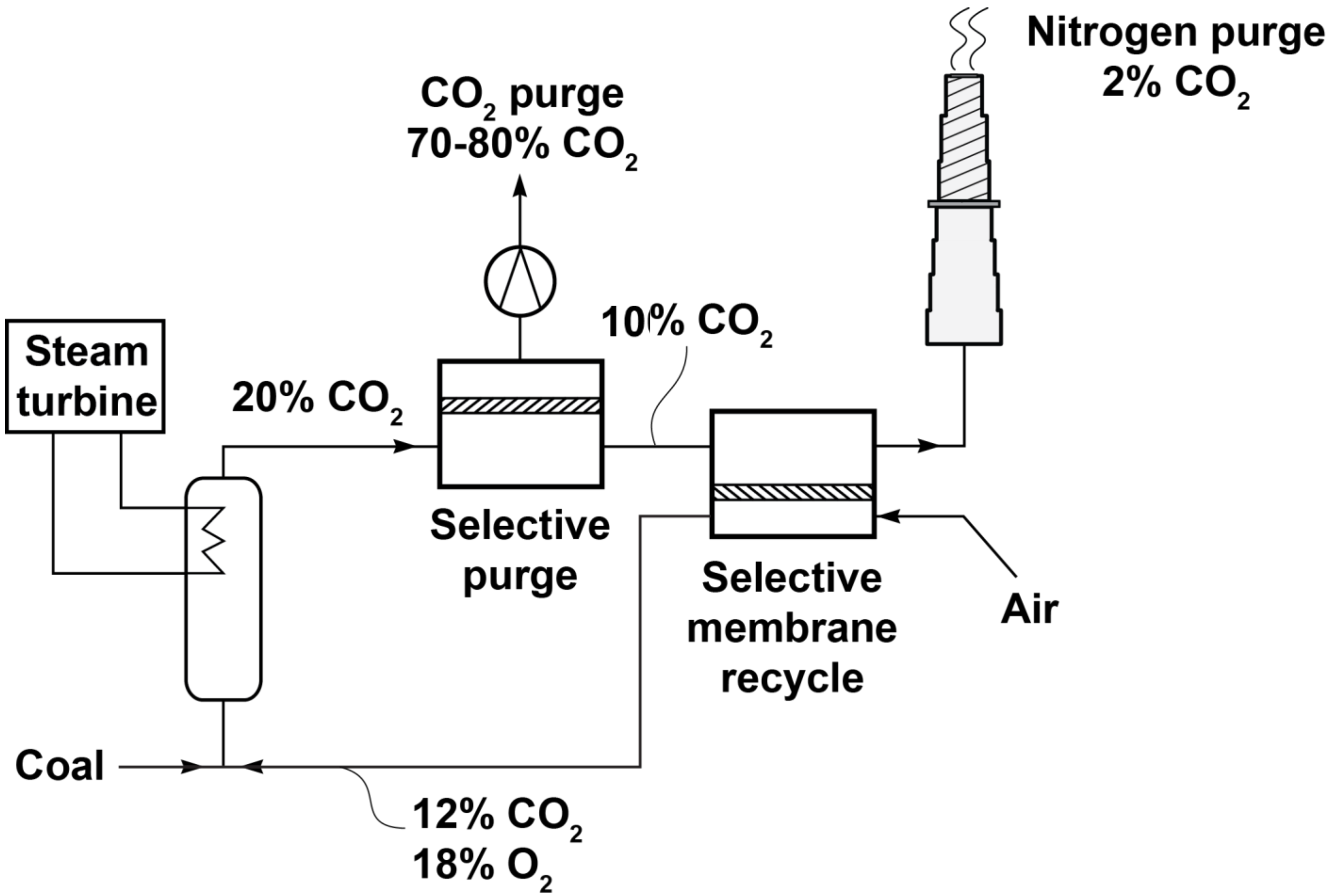


500 m^2 vessel:
5 elements bundled in one vessel.
Currently being fabricated



The Final Unit:
50 Module elements connected to make a 5,000 m^2 vessel

MTR All-Membrane Solution



500 MW_e plant requires one million m^2 of membrane

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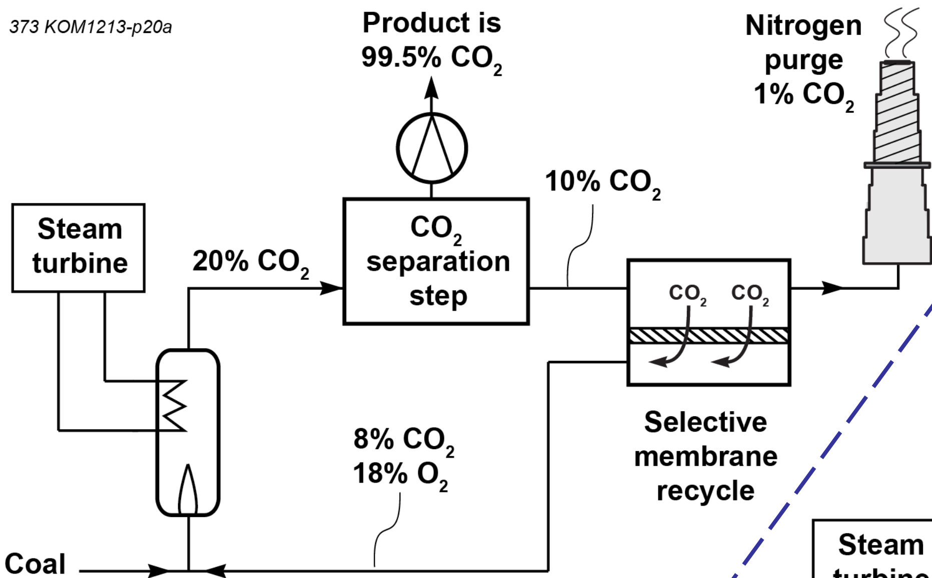
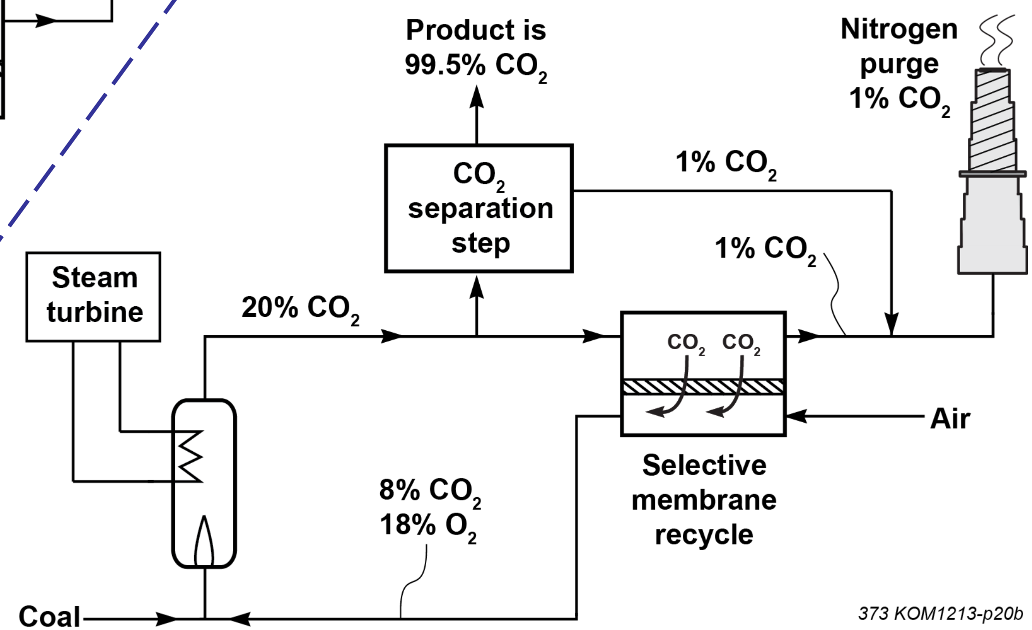
Combination (Hybrid) Process Options Show Promise

Series Hybrid Case



- *Double the CO_2 concentration*
- *50% removal required*

- *Double the CO_2 concentration*
- *Half the flow*
- *95% removal required*



Parallel Hybrid Case

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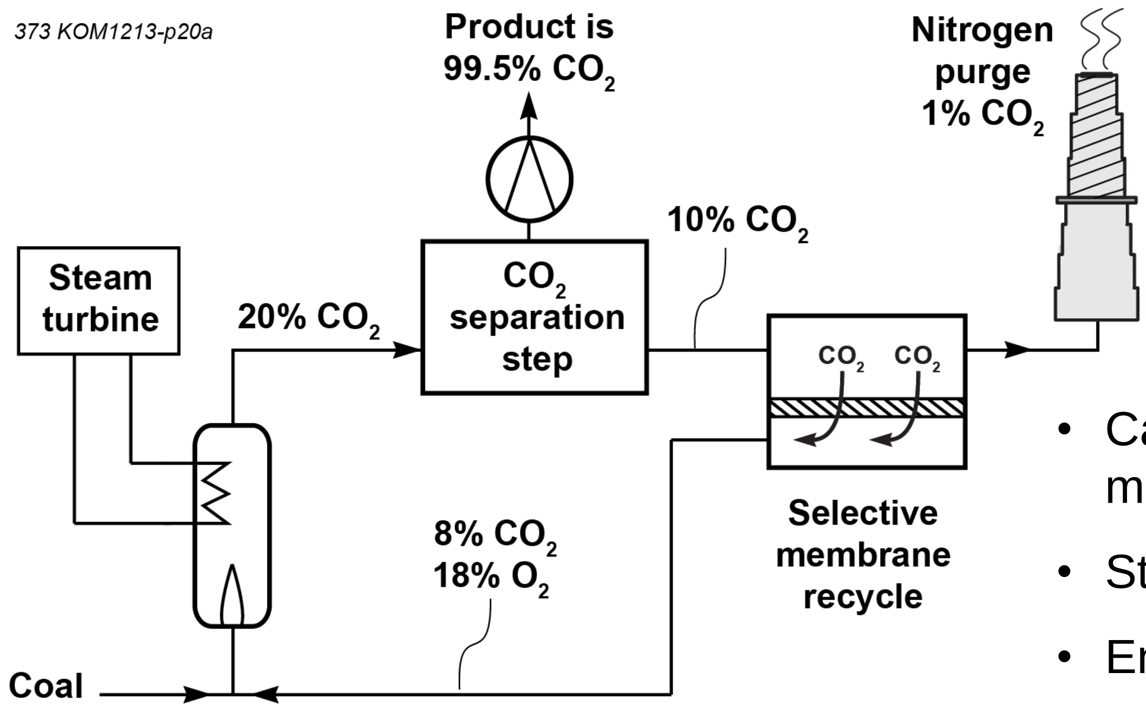
Series Hybrid Case

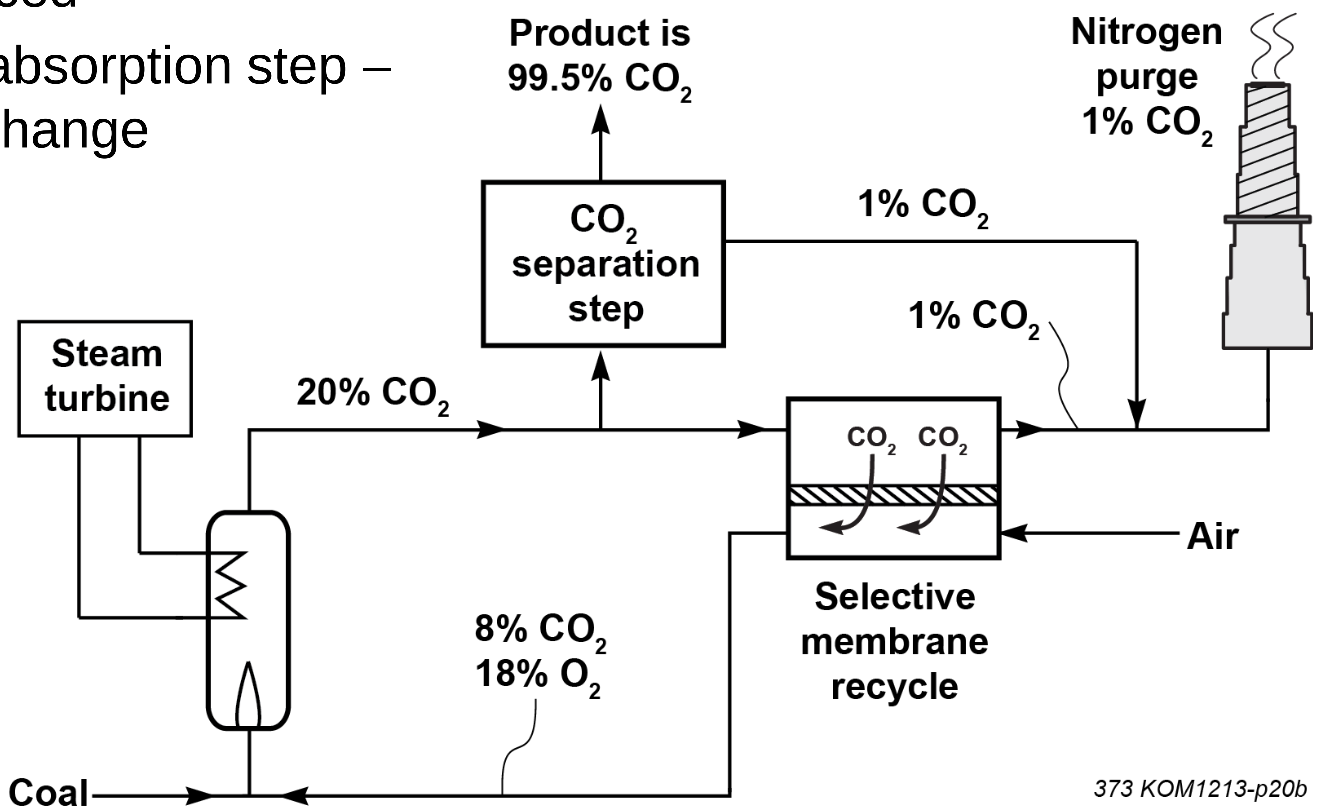


- CapEx of absorption step – not much change
- Stripper can operate at 10 bar
- Energy of stripping step reduced
- Energy and CapEx of CO_2 compression much reduced
- Membrane removes amine carryover (?)

  – *Double the CO_2 concentration*
  – *50% removal required*

Parallel Hybrid Case

- Membrane contactor smaller (better sweep ratio)
  - *Double the CO_2 concentration*
  - *Half the flow*
  - *95% removal required*
- CapEx of absorber step much reduced
- Energy of absorption step – not much change



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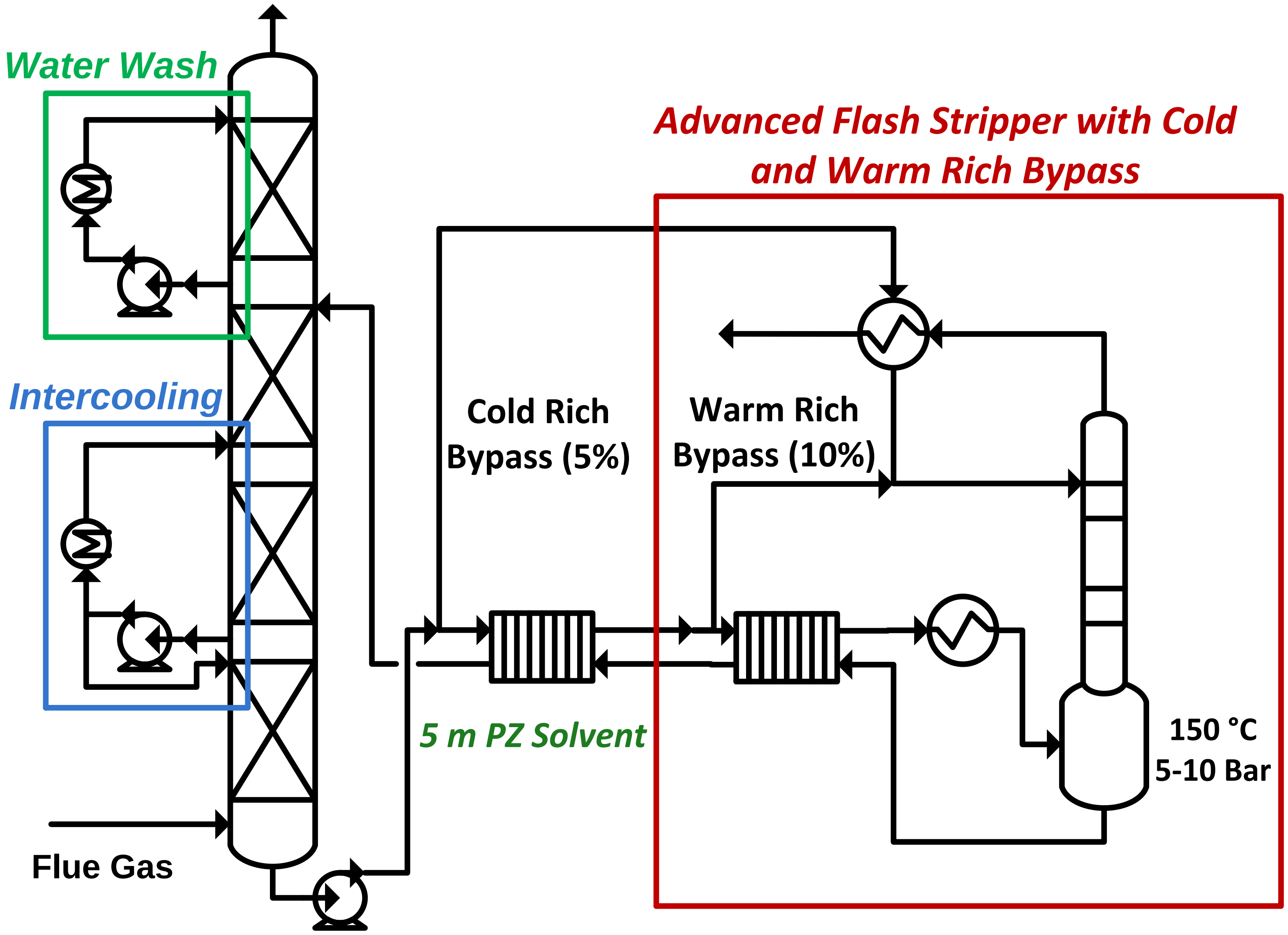
UT: Advanced Flash Stripper (AFS) with Advanced Intercooling/Water Sash



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Challenges of Richer Solvent & Variable Removal – 5 m PZ

- 15-20% inlet CO_2 in both hybrid configurations
- Richer loading may result in solids precipitation
  - HPZCOO (solid) at loading = 0.42-0.45 in 8 m PZ
  - No rich precipitate in 5 m PZ
  - With lower viscosity 5 m PZ will provide same good W_{eq}
- Kg' for CO_2 absorption will be smaller
  - 5 m PZ = faster diffusion of reactant and products
- T bulge and demand for intercooling increases
- Modeling & pilot plant testing necessary to address
- 80-95% removal minimizes $/ton CO_2 removed
- Lower lean loading may precipitate PZ.6H_2O - 5 m PZ will minimize this risk

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Parallel Hybrid Case – 95% CO_2 Removal

- Solvent Concentration - 5 m PZ
  - Eliminate lean and rich precipitation issues (vs. 8 m PZ)
  - Lower viscosity than 8 m PZ
- Absorption – Advanced Split Flow Absorber Intercooling
  - Similar absorption rate as 8 m PZ (lower solvent viscosity)
  - Reduced column diameter - reduced gas flow (50%, optimize split ratio)
  - Increased packing height - higher CO_2 removal rates (95%+)
  - Absorber intercooling placement critical
- Regeneration – Advanced Flash Stripper
  - Regeneration Pressure @ 150°C ~ 5 bar
  - Reduced compression cost (opposed to MEA)
  - 5% Cold Rich bypass / 10% Warm Rich Bypass (not optimized)
- No membrane protection by absorber water wash

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Series Hybrid Case – 50% CO_2 Removal

- Solvent Concentration - 5 m PZ
  - Eliminate rich end precipitation issues (vs. 8 m PZ)
  - Lower viscosity than 8 m PZ
- Absorption – Advanced Split Flow Absorber Intercooling
  - Similar absorption rate as 8 m PZ (lower solvent viscosity)
  - Reduced packing height – 50% CO_2 removal rates
- Regeneration – Advanced Flash Stripper
  - Regeneration Pressure @ 150°C ~ 10 bar (higher lean loading)
  - Reduced compression cost (~10% or more energy reduction)
  - Reduced Δloading reduces solvent capacity
  - Improved exchanger to minimize loss of sensible Q
  - 5% Cold Rich bypass / 10% Warm Rich Bypass (not optimized)
- Membrane protected from FGD flue gas by water wash

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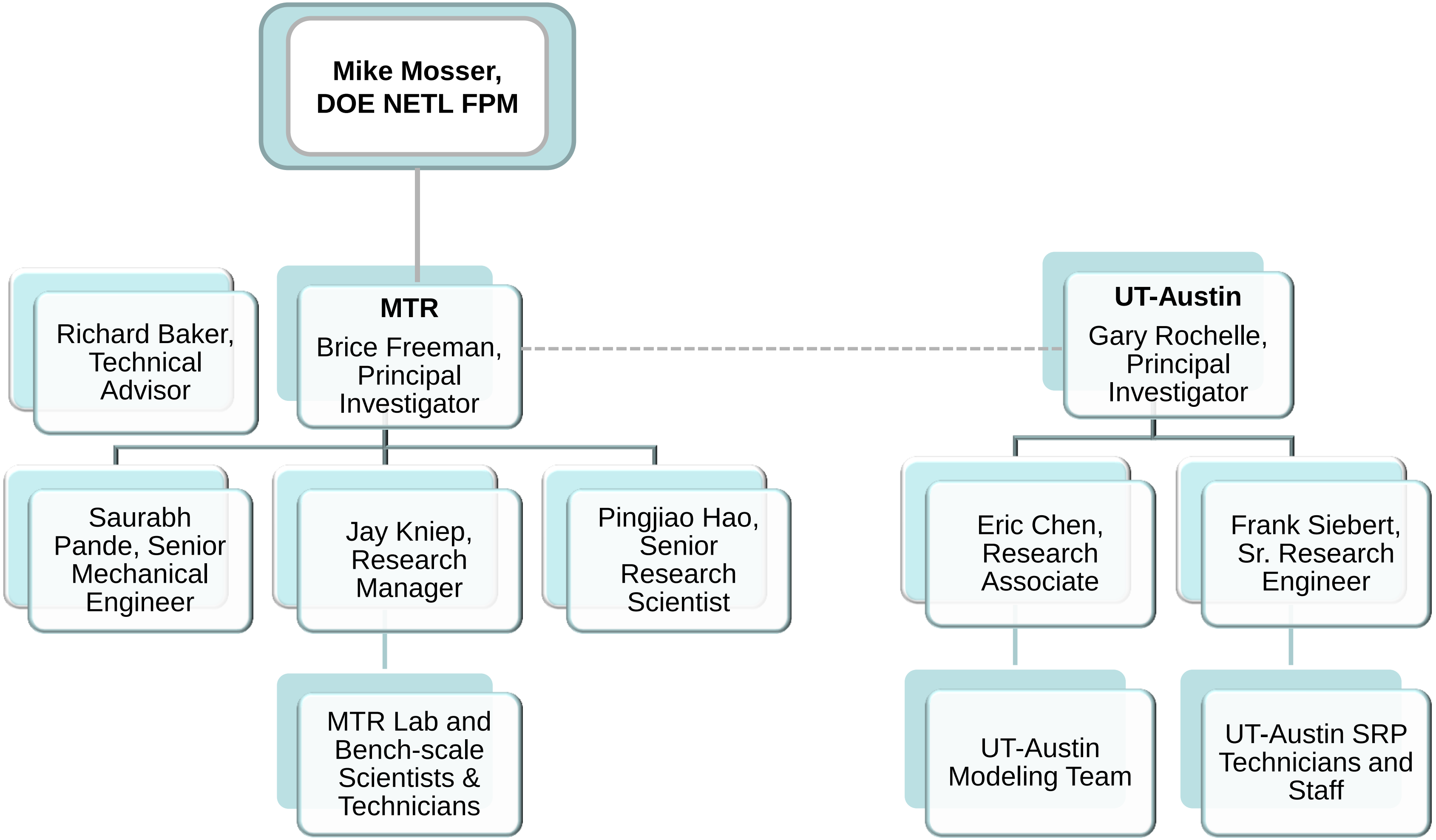
Project Organization Structure



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Statement of Work – BP 1 + 2

- **BP1**
  - Develop process simulation models for the hybrid system and initial techno-economic analysis.
  - Fabricate a 200-300 m^2 membrane CO_2 separation test unit at MTR.
- **BP2**
  - Conduct comprehensive parametric test programs separately at MTR (membrane system) and UT Austin (absorption/stripper system).
    - Tests will cover full range of operating conditions for serial and parallel designs.
  - Refine predictive simulation program and define optimum operating conditions for operation of the integrated membrane-absorption system.
  - Modify the SRP pilot plant with new packing and water wash sections
  - Prepare comprehensive BP3 parametric test program plan.
  - Ship membrane test unit to UT Austin and integrate with absorber-stripper.

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Statement of Work – BP 3

- **BP3**
  - Conduct comprehensive parametric test program plan prepared in BP2.
    - Change absorption solution chemistry, stripper operations as needed in the 5 m PZ-AFS.
    - Change operation of membrane system to optimize process performance.
  - Use test data to further refine the predictive simulation model.
  - Select and evaluate optimized operating conditions and absorption chemistry for the best process design.
  - Prepare final techno-economic analysis of the technology.
    - Use DOE/NETL cost estimating methodologies in the evaluations.
    - Incorporate road map outlining integration of the technology into the DOE/NETL development program.

Project Schedule

BP1 Tasks

Project Tasks	Year One (10/1/13-9/30/14) BP1	Year Two (10/1/14-9/30/15) BP2	Year Three (10/1/15-9/30/16) BP3	Task Start Date	Task End Date	Est. Total Cost Per Task (DOE+Cost Share)
Task 1. Project Management and Planning	1 2			10/1/2013	9/30/2016	$ 450,725
BP1 Tasks						
Task 2. Initial Techno-Economic Analysis and 5 m PZ Modeling						$ 143,140
Task 2.1. Initial Techno-Economic Modeling	3			11/1/2013	3/31/2014	
Task 2.2. Develop 5 m PZ Process Model	4			10/1/2013	3/31/2014	
Task 3. Make Membrane Rolls with High CO2 Permeance						$ 102,792
Task 3.1. Manufacture Membrane	5			10/1/2013	3/31/2014	
Task 3.2. Determine Membrane Batch Characteristics				10/1/2013	3/31/2014	
Task 3.3. Validate Membrane Improvements				11/1/2013	6/30/2014	
Task 4. Prepare Large-Area Modules						$ 215,426
Task 4.1. Make Modules	6			2/1/2014	6/30/2014	
Task 4.2. Test Modules				5/1/2014	9/30/2014	
Task 5. Design and Construct Large Module System	7			12/1/2013	9/30/2014	$ 291,813
Task 6. Hybrid Process Model Development and Integration Optimization	8			4/1/2014	9/30/2014	$ 447,796

Project Schedule

BP2 and BP3 Tasks

Project Tasks	Year One (10/1/13-9/30/14) BP1	Year Two (10/1/14-9/30/15) BP2	Year Three (10/1/15-9/30/16) BP3		Task Start Date	Task End Date	Est. Total Cost Per Task (DOE+Cost Share)
BP2 Tasks							
Task 7. Operation of Membrane Test System		9a, 9b			10/1/2014	9/30/2015	$ 462,262
Task 8. Modify the SRP Pilot and Test with 20% CO2							$ 584,324
Task 8.1. Modify the SRP Pilot Plant		10			10/1/2014	5/31/2015	
Task 8.2. Operation of the Absorber/Stripper Test Unit		11			6/1/2015	9/30/2015	
Task 9. Revise Techno-Economic Analysis and Prepare Parametric Test Plan for Hybrid Process		12, 13			10/1/2014	9/30/2015	$ 198,000
BP3 Tasks							
Task 10. Install Membrane System at UT Austin's Pilot Plant & Conduct Parametric Testing							$ 538,204
Task 10.1. Install Membrane Module at Pilot Plant			14		1/1/2016	4/30/2016	
Task 10.2. Parametric Test of Integrated Membrane-Absorption Test Unit			15		5/1/2016	8/31/2016	
Task 11. Final Techno-Economic Analysis Prepared			16, 17		7/1/2016	9/30/2016	$ 315,298

Total **$ 3,749,780**

(BP1,2,3) Task 1 – Project Management and Planning

- Develop initial updates to the Project Management Plan (PMP) and maintain the PMP throughout the project.
- Internal monthly reports prepared to monitor technical progress and budgets.
- Periodic and topical progress reports will be submitted in accordance with the contract requirements, and a final report will be prepared upon completion of the project.
- Regular bi-weekly telephone meetings with the FMP, supplemented with PowerPoint presentations.
- **End Product of Task 1**: Project Management Plan updates and reports submitted.

(BP1) Task 2 – Initial TEA and 5 m PZ Modeling

- **Subtask 2.1. Initial Techno-economic Modeling.**
  - Develop preliminary techno-economic model assumptions
  - Update with empirical data as obtained; described in Tasks 9 and 11
- **Subtask 2.2. Develop 5 m PZ Aspen Plus Process Model.**
  - Adapt "Independence" PZ Aspen Plus process simulation to 5 m PZ from 8 m PZ
  - Model 15-20% inlet CO_2 flue gas with advanced flash stripper and absorber intercooling
  - Optimize advanced flash stripper at 150°C, high lean loadings (P_{CO2} equilibrium = 5-8%)
  - Evaluate alternative advanced flash stripper configurations
- **End Product of Task 2:** Initial techno-economic analysis topical report prepared and 5 m PZ process model developed.

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(BP1) Task 3 – Make Membranes with High CO_2 Permeance

- **Subtask 3.1. Manufacture Membrane.** MTR will fabricate membrane rolls using commercial-scale membrane equipment.
- **Subtask 3.2. Determine Membrane Batch Characteristics.** Membranes will be checked for integrity by measuring pure-gas CO_2 and N_2 permeances.
- **Subtask 3.3. Validate Membrane Improvements.** The membranes used in this program will have a CO_2/N_2 selectivity of ~50 and CO_2 permeance of 1,000-1,500 gpu. MTR has an ongoing program to improve these membranes outside of this program. Improved membranes may be used in this project as they become available from other R&D activities.
- **End Product of Task 3:** High CO_2 permeance membranes manufactured and characterized.

(BP1) Task 4 – Prepare Large-Area Modules

- **Subtask 4.1. Make Modules.** 100 m^2 membrane contactor modules with very low pressure drop (< 0.1 bar) will be produced. The membrane test unit will require 2-3 modules; 200-300 m^2 of total membrane area.
- **Subtask 4.2. Test Modules.** Module performance will be verified by sending air with 2-5% CO_2 to the feed side of the membrane, while sweeping the permeate side with CO_2-free air. The permeance and selectivity are determined by measuring CO_2 removal from the feed.
- **End Product of Task 4:** Membrane modules produced and tested.

(BP1) Task 5 – Design and Construct Large Module System

- MTR will design a pilot test system containing the low-pressure membrane contactors (200-300 m^2), necessary piping, balance of plant, and controls.
- Skid includes fans and low-resistance filters on the feed and air sweep streams.
- A Hazard and Operability analysis of the unit will be performed, involving both MTR and UT Austin engineers, to identify any possible safety issues.
- The system will be built at a fabricator. After inspection and hydro-testing, the system will be shipped to MTR for installation.
- **End Product of Task 5:** Membrane test system produced.

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(BP1) Task 6 – Hybrid Process Model Development and Integration Optimization

- MTR's CHEMCAD membrane process simulation models will be adapted to Aspen Plus® for the hybrid membrane-series and parallel configurations to support the techno-economic analysis.
- A range of operating conditions will be simulated including varying flue gas splits and CO_2 removal rates by the membrane and 5 m PZ-AFS capture plant.
- **End Product of Task 6:** Functioning computational model of integrated hybrid system.

(BP2) Task 7 – Operation of Membrane Test System

- MTR will test the membrane system over a range of conditions expected in both series and parallel operating modes to predict its operational performance. Example variables include:
  - Flue gas feed CO_2 concentration
  - Flue gas flow rate
  - Fraction of CO_2 removal from the flue gas
  - Ratio of feed flow to sweep flow
  - Feed and sweep air pressures
- The data obtained will be correlated with membrane module simulation programs used at MTR. This data will be incorporated into the process simulation model created in Task 2.
- **End Product of Task 7:** Membrane unit parametric test data obtained.

(BP2) Task 8 – Modify the SRP Pilot Plant and Test with 20-25% CO_2

Subtask 8.1. Modify the SRP Pilot Plant.

- Extend existing SRP absorber column by 25 ft. (7.62 m)
  - 10 ft. section of absorber packing for higher CO_2 removal rates (~95%+ removal; 20% inlet and 1% outlet CO_2)
  - 10 ft. (3.05 m) section for the water wash
- Install high-pressure gas blower
  - Pressure drop (~1.5 psi [10.3 kPa]) for the series configuration
  - Additional pressure drop in absorber -10 ft. packing and 10 ft. water wash
- Upgrade existing FTIR gas analyzer system at the SRP pilot plant
  - Automated multiplexer sampling system for sampling at seven locations
  - Absorber gas inlet, three points along the absorber column, one point inside the water wash, absorber gas outlet, and fiber filter knockout outlet.

Task 8 – Continued

Subtask 8.2. Operation of the Absorber/Stripper Test Unit with 15-20% CO_2.

- Simulate series and parallel operating modes varying:
  - Inlet CO_2 concentration and CO_2 removal
  - Temperature and pressure of the stripper
  - CO_2 Loading and solvent recirculation rate
- Pilot plant campaign #1 at SRP
  - Operate with 5 m PZ and an inlet CO_2 gas concentration between 15-20%
  - Simulate test conditions expected with membrane in series & parallel configuration
  - Optimize lean and rich CO_2 loading, stripper temperatures, stripper pressures to minimize equivalent work
  - Series configuration – absorber operate at 50% removal (outlet CO_2 =10%)
  - Parallel configuration – absorber operate at 95% removal (outlet CO_2 = 1%)
  - FTIR measurements for amine aerosols and volatility at the inlet, outlet and middle of the wash section
  - Evaluated effects of circulation rate, feed temperatures, and packing selection in the water wash
- **End Product of Task 8:** Absorber/stripper unit parametric test data obtained.

(BP2) Task 9 – Revise TEA and Prepare Parametric Test Plan

- Results from parametric studies performed in Tasks 7 and 8 will be incorporated into the predictive computer simulations of the process and used to update the Initial TEA prepared in Task 2.
- The simulation and the results of this analysis will then be used to determine the likely best case operating mode, operating conditions and absorbent solution chemistry.
- Based on this analysis, the best mode of operation of an integrated membrane-absorption system will be selected and a parametric test plan prepared.
- **End Product of Task 9.0:** Revised TEA prepared and parametric test plan for hybrid process operation created.

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(BP3) Task 10 – Install Membrane System at SRP, Conduct Parametric Testing

Subtask 10.1. Install Membrane System at the UT Austin Pilot Plant.

- The membrane test system will be installed at the UT Austin's SRP.
- MTR and UT will review the system hardware and operating programs and then unit run through its various operating modes.

Subtask 10.2. Parametric Test of Integrated Membrane-Absorption Test Unit.

- The integrated membrane-absorption system will be operated for a full campaign. The objective will be to demonstrate optimal performance and operation of the hybrid membrane-absorber/stripper process with 5 m PZ.
- The campaign will characterize optimal operating conditions of the water wash to reduce amine aerosol emissions.
- FTIR measurements will be made at the inlet and outlet streams of the membrane in the series configuration to monitor amine emissions and CO_2 concentrations. FTIR measurements will also help evaluate the performance of the water wash section.

End Product of Task 10: Performance of integrated hybrid process test unit measured.

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(BP3) Task 11 – Final TEA and Process Model Prepared

- The membrane, absorber and stripper process models will be updated and refined based on the operation of the pilot tests.
- The models will be scaled to develop heat and material balances to the NETL 550 MW_e base-case power plant.
- Using the pilot plant test results findings and updated process models, the techno-economic analysis prepared in Task 2 and refined in Task 8 will be updated to final form.
- If the results are sufficiently encouraging, a roadmap to carry the technology forward will be prepared.
- **End Product of Task 11.0:** Final techno-economic analysis and process model of the hybrid capture system completed.

Milestone Log – BP1

Milestone Number	Task/ Subtask No.	Milestone Description	Planned Completion*	Actual Completion	Verification Method
Budget Period 1 Milestones					
1	1	Updated Project Management Plan completed	11/30/2013		Project Management Plan file
2	1	Kickoff Meeting held	12/31/2013		Presentation file
3	2.1	Initial Techno-Economic Assessment completed	3/31/2014		Topical report file (see Success Criteria below)
4	2.2	Development of 5 m PZ process model completed	3/31/2014		Presentation file (see Success Criteria below)
5	3.1	Manufacture membrane	3/31/2014		Quarterly report file and photos
6	4.1	Engineering design of large are membrane module and pressure vessel completed	6/30/2014		Engineering drawings
7	5	Fabrication of membrane module and pressure vessel complete and at MTR	9/30/2014		Photos
8	6	Integrated hybrid process model, initial optimization study complete	9/30/2014		Topical report file

Milestone Log – BP2

Milestone Number	Task/ Subtask No.	Milestone Description	Planned Completion*	Actual Completion	Verification Method
Budget Period 2 Milestones					
9a	7	Membrane module completely assembled and ready for parametric testing at MTR	3/31/2015		Photos
10	8.1	Complete modifications of SRP Absorber	5/31/2015		Quarterly report file and photos
9b	7	Complete parametric testing operation of membrane module in large test system	9/30/2015		Quarterly report and test data (see Success Criteria below)
11	8.2	Complete operation of pilot plant at 20% CO_2 conditions	9/30/2015		Quarterly report and test data (see Success Criteria below)
12	9	Techno-economic model updated	9/30/2015		Updated Topical Report
13	9	Hybrid testing plan prepared	9/30/2015		Topical Report

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Milestone Log – BP3

Milestone Number	Task/ Subtask No.	Milestone Description	Planned Completion*	Actual Completion	Verification Method
Budget Period 3 Milestones					
14	10.1	Membrane system installed at SRP Pilot Plant	4/30/2016		Presentation file and photos
15	10.2	Parametric testing of hybrid membrane-absorption system completed	8/31/2016		Topical report with test data (see Success Criteria below)
16	11	Updated Techno-Economic Assessment completed	9/30/2016		Updated Topical report file (see Success Criteria below)
17	11	Final Report including EH&S Assessment completed	9/30/2016		Final Report file

Outline

- Project Overview & Objectives
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- Project Budget
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Project Budget

	Budget Period 1 10/01/13- 9/30/14		Budget Period 2 10/01/14- 9/30/15		Budget Period 3 10/01/15- 9/30/15		Total
	Government Share	Cost Share	Government Share	Cost Share	Government Share	Cost Share	
Prime Applicant (Recipient): MTR	650,490	162,510	525,371	131,558	323,963	80,685	1,874,577
Subcontractor 1: UT Austin	450,861	112,828	576,783	143,980	472,356	118,395	1,875,203
Total	1,101,351	275,338	1,102,154	275,538	796,319	199,080	3,749,780
Cost Share %	80%	20%	80%	20%	80%	20%	

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Risk Management

Description of Risks	Probability (L, M, H)	Impact Probability (L, M, H)	Risk Management Mitigation and Response Strategies
Technical Risks (p. 1 of 3)			
Large plate-and-frame modules cannot be made	Low	Low	If unforeseen and insoluble problems develop with this module design, we will switch to modified spiral-wound modules from our development work to-date.
Carryover of piperazine amine absorbent damages to the membrane	Moderate	Moderate	This is only a potential problem with the series-membrane design. No problem occurs if the parallel design is used. Pre-treatment of the gas going to the membrane unit and modifications of membrane can both be used.

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Risk Management

Description of Risks	Probability (L, M, H)	Impact Probability (L, M, H)	Risk Management Mitigation and Response Strategies
Technical Risks (p. 2 of 3)			
Performance calculations show that energy and cost savings produced by adding the membrane system to the amine plants do not outweigh the cost of the membrane system	Low	High	To minimize this risk, the cost of the membrane unit should be low. Our target is \$50/m^2 for installed membrane skid cost. We should be able to meet this target in large plants.

Risk Management

Description of Risks	Probability Probability (L, M, H)	Impact Probability (L, M, H)	Risk Management Mitigation and Response Strategies
Technical Risks (p. 3 of 3)			
Changes to air stream going to the boiler caused by the membrane unit will degrade boiler performance.	Moderate	Moderate	Depending on the process design, the oxygen concentration of air going to the boiler is reduced, partially by dilution with recycled CO_2 and load of oxygen to the flue gas. Boiler manufacturer (Babcock and Wilcox) has told us 18% O_2 is adequate. If this changes, the process design must be modified to accommodate the new value.
Formation of PZ solids (precipitation) at extreme CO_2 loading	Moderate	Moderate	This could be a problem. We propose to reduce the concentration of the piperazine solvent from 8 molar to 5 molar. This should be enough.
Inadequate CO_2 removal	Moderate	Moderate	The first response will be to reduce the flow rate of the gas. Second measure will be to replace the absorber packing with finer grade packing material.

Success Criteria

Decision Point	Date	Success Criteria
End of BP 1: Continue with modifications to the SRP Pilot Plant	9/30/2014	• Preliminary TEA shows promise of meeting DOE capture target of \$40/tonne CO_2 captured. • Predicted 90% CO_2 removal is achievable at 20% CO_2 inlet concentration.
End of BP 2: Continue with integrated membrane testing at the Pilot Plant	9/30/2015	• Parametric test of membrane system and absorber/stripper successful; 90% CO_2 removal is achieved at conditions that simulate the hybrid process with membrane. • SRP Pilot Plant modifications are complete.
End of BP 3: Hybrid testing completed	9/30/2016	• Hybrid system shakedown operations completed. • Steady-state testing of the hybrid capture system demonstrates stable 90% CO_2 capture. • Updated TEA shows process can meet \$40/tonne CO_2 capture target.

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