the Energy to Lead

Pilot Test of a Nanoporous, Super-hydrophobic Membrane Contactor Process for Post-combustion CO_2 Capture

DOE Contract No. DE-FE0012829

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Presentation for Kickoff Meeting

November 13, 2013

gti PoroGen INNOVATIVE MEMBRANE PRODUCTS HITACHI Inspire the Next TRIMERIC CORPORATION

Outline

- Introduction to team members
- Technology overview
- Background: bench-scale development
- Pilot-scale project overview
- Plans for each budget period

Introduction to GTI and PoroGen

gti

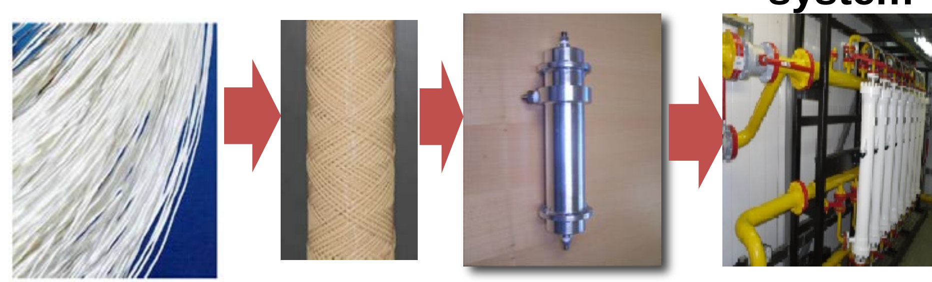
- Not-for-profit research company, providing energy and natural gas solutions to the industry since 1941
- Facilities
  - 18 acre campus near Chicago
  - 250 staff

Energy & Environmental Technology Center

PoroGen
INNOVATIVE MEMBRANE PRODUCTS

- Materials technology company commercially manufacturing products from high performance plastic PEEK (poly (ether ether ketone))
- Products ranging from membrane separation filters to heat transfer devices

PEEK Fiber + Cartridge + Module = Separation system



Introduction to Hitachi and Trimeric

HITACHI
Inspire the Next

- Global leader in the energy market with over 20,000 products
- Over 20 years of R&D of CO_2 capture technologies from lab-scale to pilot-scale and demonstrations with various fossil-fired flue gases
- Collaborations with utilities, industry, universities and governments including US DOE for testing of CO_2 capture technologies

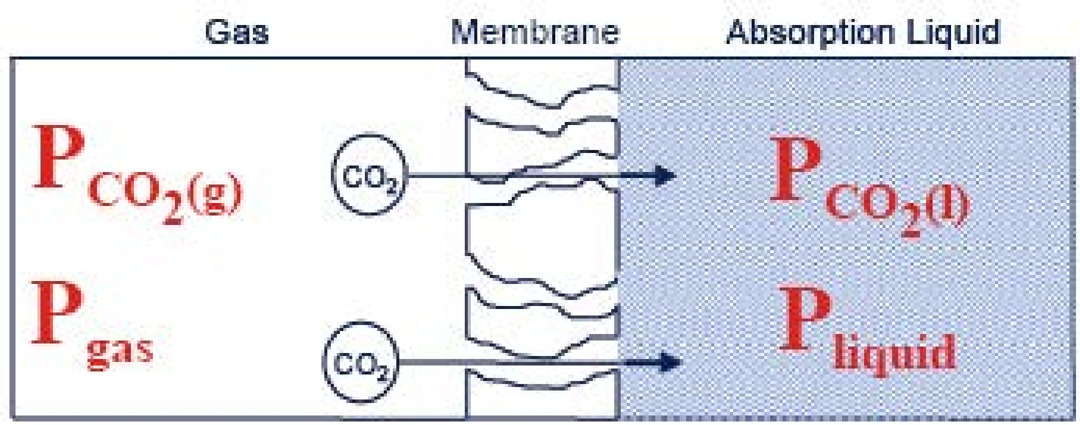
TRIMERIC CORPORATION

- Provides chemical process engineering, research and development, and other specialized technical services to public and private clients
- Extensive experience assisting clients to design, build, troubleshoot, and operate CO_2 processing facilities, which include systems used for enhanced oil recovery, CO_2 capture, sequestration and storage.
- Several staff members have led carbon capture technoeconomic evaluation projects for the DOE

Technology Overview

What is a membrane contactor?

- High surface area membrane device that facilitates mass transfer
- Gas on one side, liquid on other side



- Membrane does not wet out in contact with liquid
- **<u>Separation mechanism</u>**: CO_2 permeates through membrane and reacts with the solvent; N_2 does not react and has low solubility in solvent

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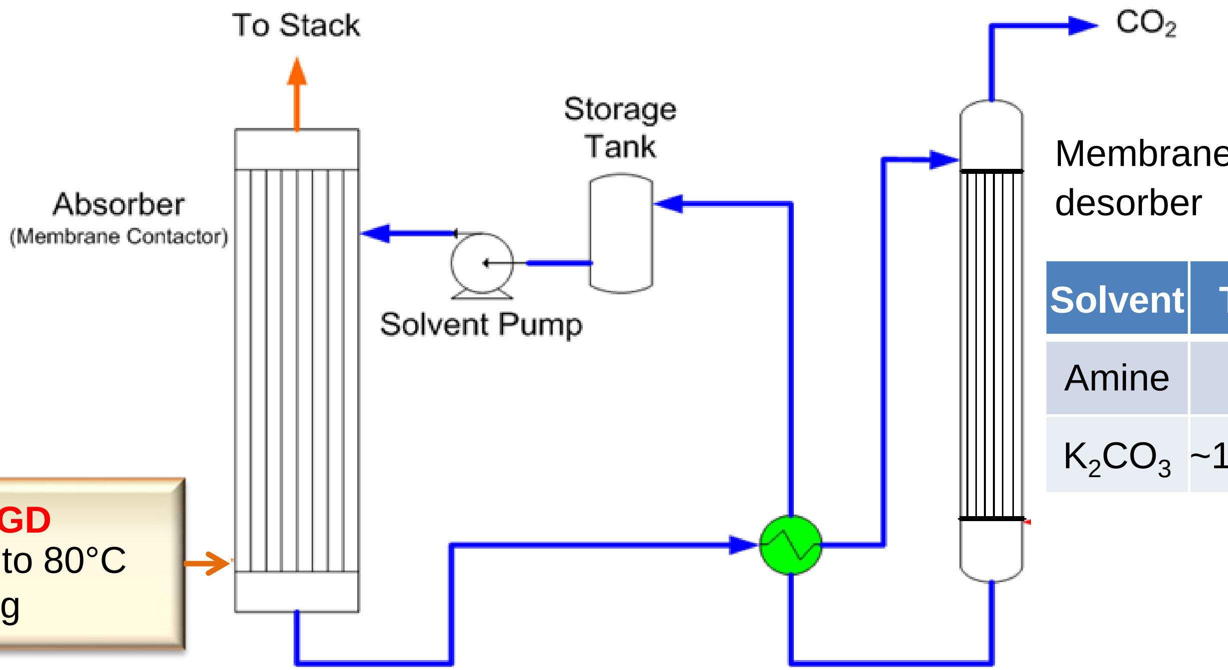
Process description



Solvent	T (ºC)	P (psig)
Amine	~120	1-50+
K_2CO_3	~120-150	1-50+

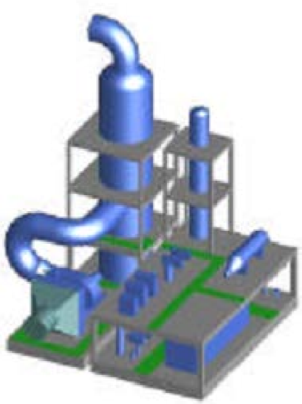
Flue gas after FGD
Temperature: 40 to 80°C
Pressure: 1-4 psig

Polymer	Max service temperature (°C)
Teflon™	250
PVDF	150
Polysulfone	160
PEEK	**271**

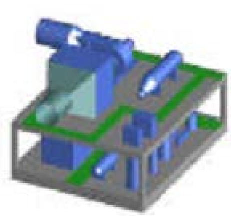
- The PEEK hollow fibers exhibit exceptional solvent resistance: exposure of fibers to MEA solution (30%) for 1,500 hours at 120 °C had no adverse effect on the mechanical properties or gas transport

Membrane contactor advantages as compared with conventional absorbers

Gas-liquid contactor	Specific surface area, (cm^2/cm^3)	Volumetric mass transfer coefficient, $(sec)^{-1}$
Packed column (Countercurrent)	0.1 – 3.5	0.0004 – 0.07
Bubble column (Agitated)	1 – 20	0.003 – 0.04
Spray column	0.1 – 4	0.0007 – 0.075
Membrane contactor	**1 – 70**	**0.3 – 4.0**



Conventional Amine Scrubber Column



Membrane Contactor

- **Our economic analysis (shown later)**
  - Cost 36% lower than DOE's benchmark amine technology
- **Membrane contactor savings (based on Aker Process Systems' analysis*)**
  - Total operating weight: 47%
  - Footprint requirement: 40%
  - Height requirement: 60%

* Olav Falk-Pedersen, Developments of gas/liquid contactors, GRI contract 8325, December, 2002.

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Membrane contactor advantages for flue gas CO_2 capture compared to conventional membrane process

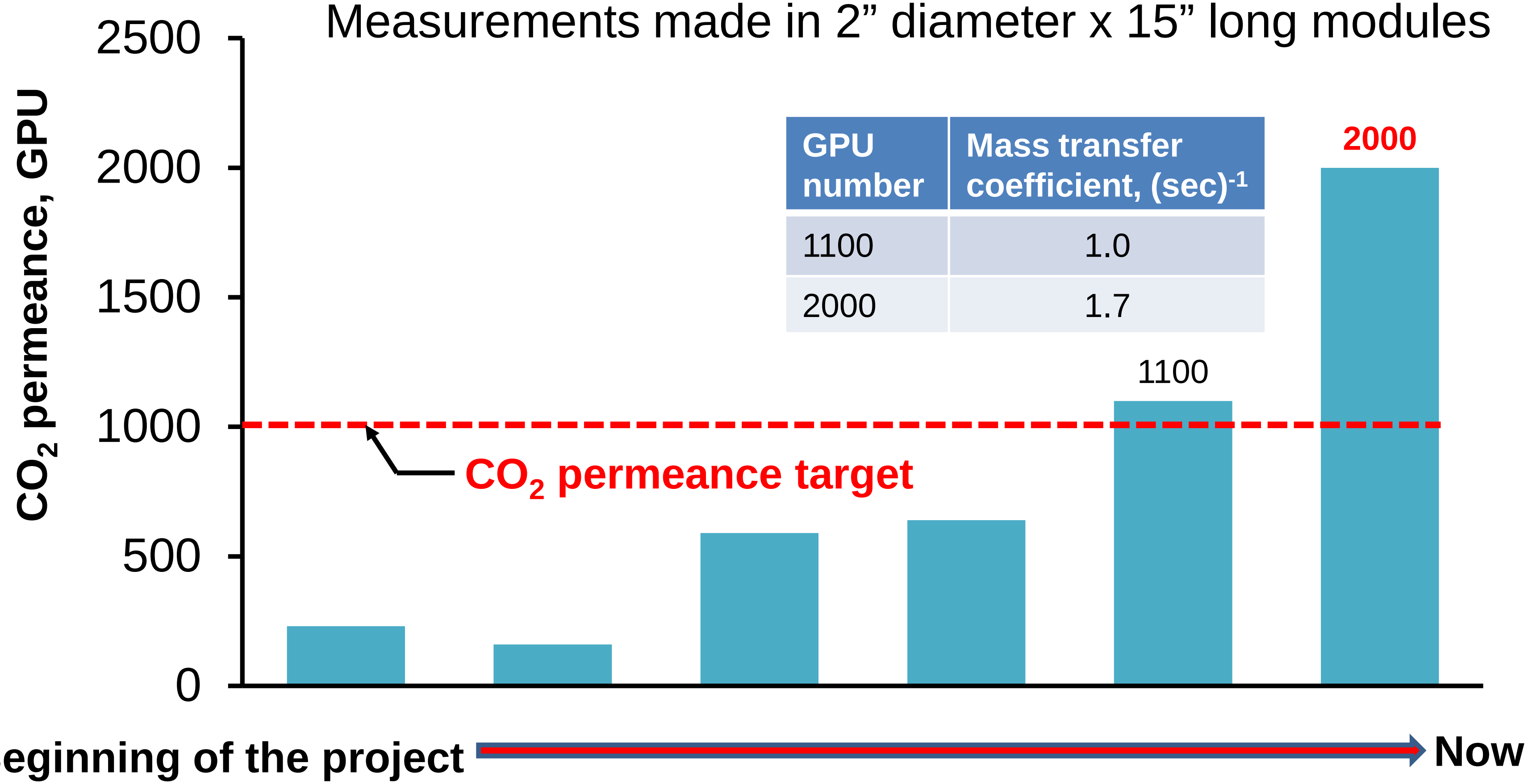
Membrane technology	Need to create driving force?	CO_2/N_2 selectivity (α)	Can achieve >90% CO_2 removal and high CO_2 purity in one stage?
Conventional membrane process	Yes. Feed compression or permeate vacuum required	Determined by the dense "skin layer", typically $\alpha = 50$	No. Limited by pressure ratio, multi-step process required*
Membrane contactor	No. Liquid side partial pressure of CO_2 close to zero	Determined by the solvent, $\alpha > 1000$	Yes

* DOE/NETL Advanced Carbon Dioxide Capture R&D Program: Technology Update, May 2011

Membrane modules achieved 2,000 GPU membrane intrinsic CO_2 permeance

More than 200 modules constructed by PoroGen

Measurements made in 2” diameter x 15” long modules



GPU number	Mass transfer coefficient, $(sec)^{-1}$
1100	1.0
2000	1.7

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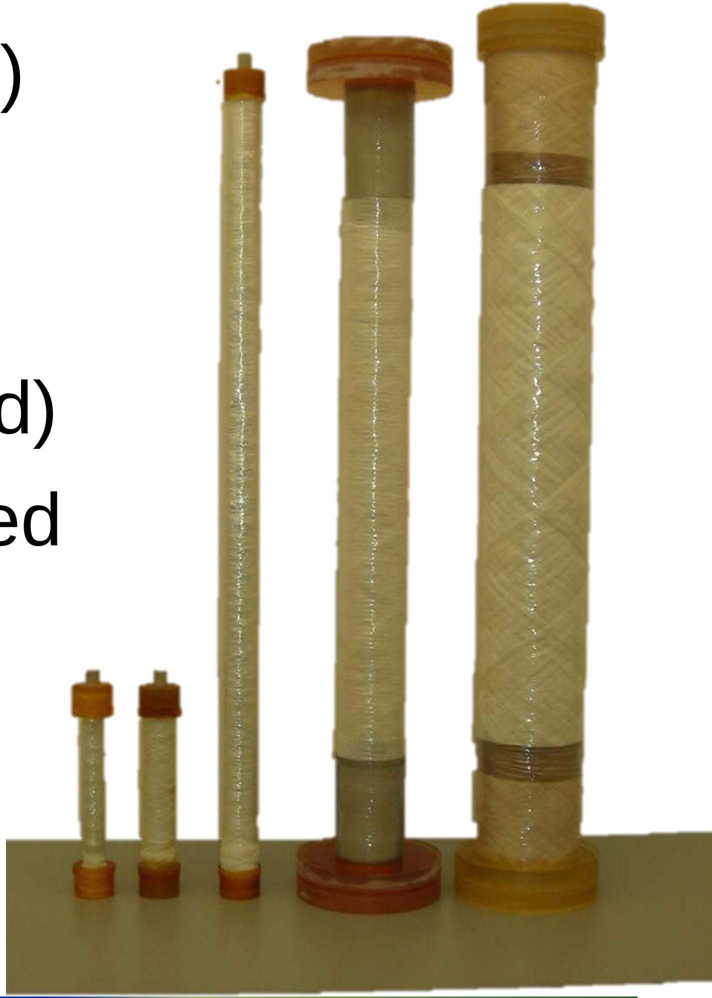
Module cartridge scale-up from bench to commercial

- 2” bench – 0.12 m^2 (tested in lab)
- 2” bench – 0.5 m^2 (tested in lab)
- 2” bench – 3 m^2 (tested in lab)
- 4” field – 15 m^2 (tested in the field)
- 8” commercial – 60 m^2 (to be used in the pilot-scale program)



Background: bench-scale development

Oct. 1, 2010 – Dec. 31, 2013

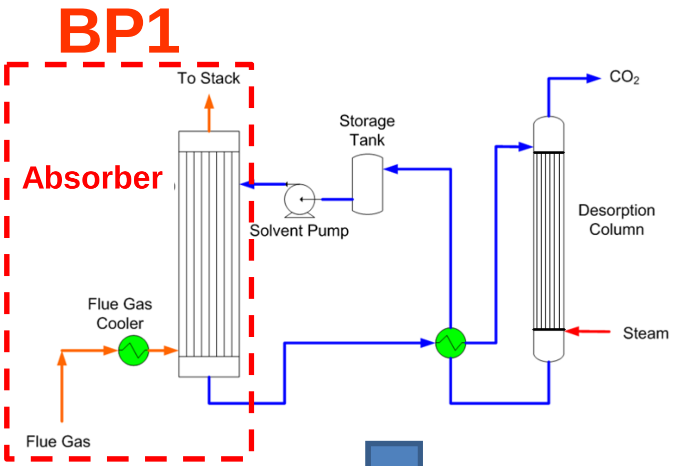
Project participants:

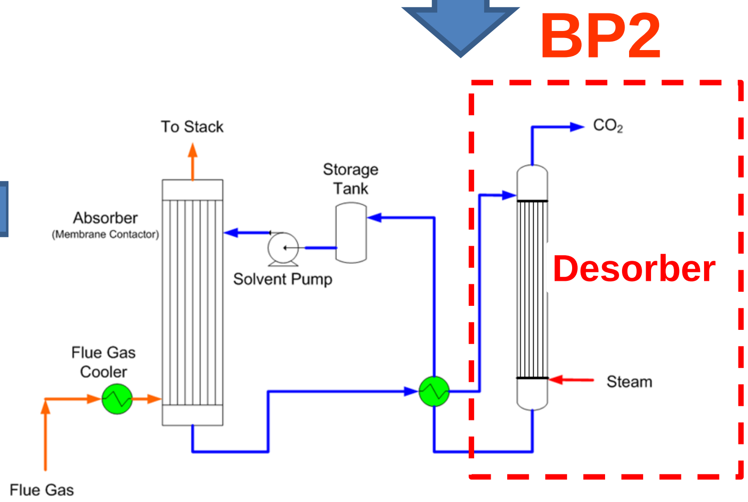
- GTI: process design and testing
- PoroGen: membrane and membrane module development
- Midwest Generation: providing field test site

Objective and scope

2010

Objective: develop PEEK membrane contactor technology to meet DOE's target of ≥ 90% CO_2 capture, < 35% increase in COE





BP3

Integrate absorption/regeneration

Field testing

BP1 Membrane Absorber Study

Technical goals achieved

Parameters	Goal	aMDEA	K_2CO_3
CO_2 removal in one stage	≥ 90%	90%	94%
Gas side ΔP, psi	≤ 2	1.6	1.3
Mass transfer coefficient,$(sec)^{-1}$	≥ 1	1.7	1.8

BP1 membrane absorber CO_2 capture performance demonstration

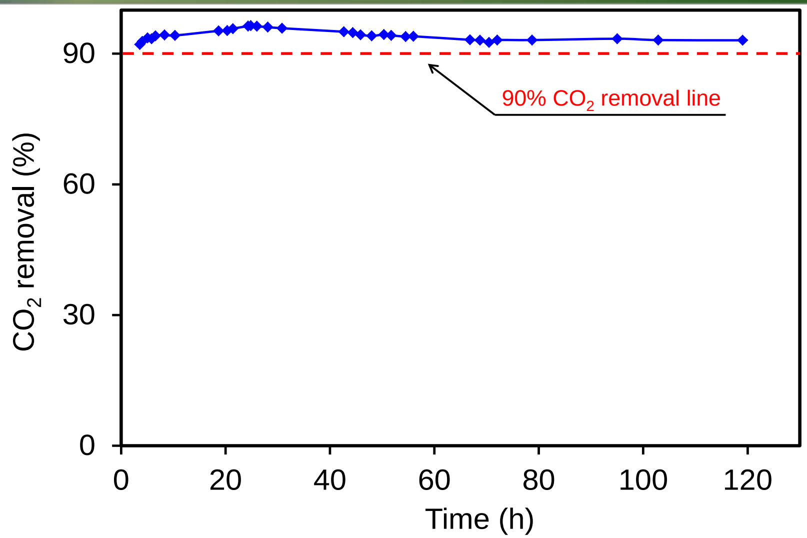
- **Feed**: Simulated flue gas compositions (N_2 + CO_2 saturated H_2O, SOx, NOx, O_2) at temperature and pressure conditions after FGD
- **Membrane module**: Performance can be essentially linearly scaled to commercial size modules
  - Uncertainty exists because of gas/liquid contactor interface issues
  - Additional factors affect mass transfer coefficient
- **Solvents**: DEA, MDEA, aMDEA (40 wt%) and activated K_2CO_3 (20 wt%)
- **Use of design of experiment test matrix**: **over 140 tests**

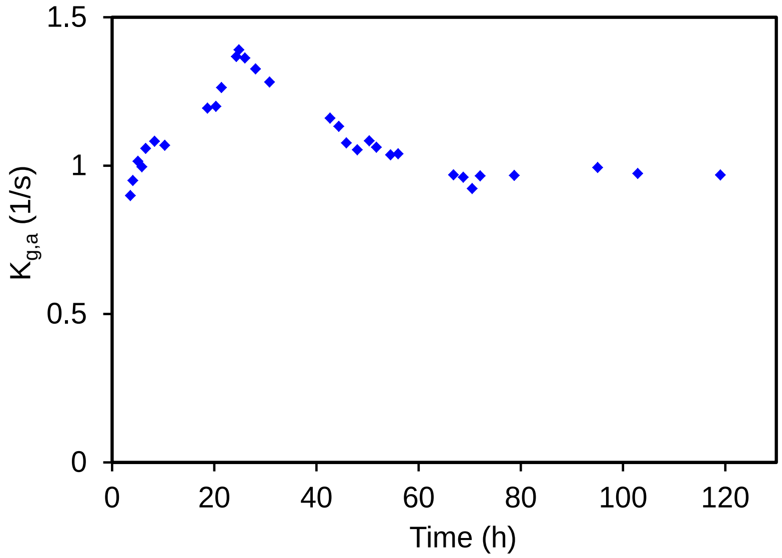
Module for lab testing (Ø2” x 15” long, 0.5m^2)

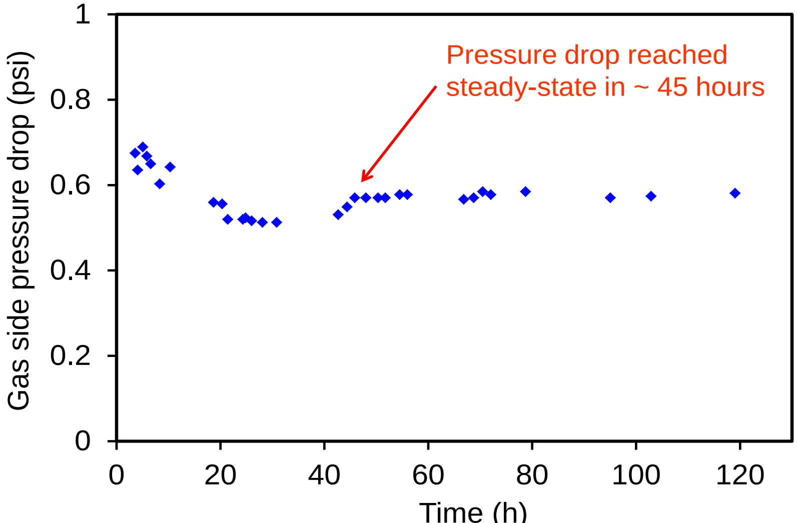
Activated **m**ethyl**d**i**e**thanol**a**mine = **aMDEA**

BP1 sample testing data: membrane for adsorption only, packed column for desorption

Membrane intrinsic CO_2 permeance	**1,100 GPU**
Solvent	**40 wt% aMDEA**







BP2 Membrane Desorber Study

Technical goals achieved

Parameters	Goal	Mode III	Mode IV
CO_2 purity	≥ 95%	97%	97%
Solvent lean enough for membrane absorber	Achieve	Achieved	Achieved

Notes:

- 97% CO_2 purity, the rest is condensable water vapor

BP2 membrane desorber CO_2 stripping performance demonstration

- **Membrane module**: performance can be linearly scaled to commercial size modules
- **Liquid feed**: CO_2 loaded aMDEA and activated K_2CO_3 rich solvents
- **Four flow configurations (Modes) investigated: over 80 tests**

Module for lab testing (Ø2” x 15” long, $0.5m^2$)

Economic evaluation at the end of BP2 (Dec. 15, 2012)

Bases:

- Lab testing data
- Membrane module cost for commercial size (8-inch): $80/m^2
- DOE/NETL-2007/1281"Cost and Performance Baseline for Fossil Energy Plants"

Case	COE, $/MWhr	Increase in COE	$/Tonne CO_2 Captured*
DOE Case 9 no capture	64.00	--	
DOE Case 10 benchmark amine plant	118.36	85%	$65.30
Our membrane contactor	**98.67**	**54%**	**$41.50**
R&D strategy to meet DOE's target of $40.00			
1) Module cost from $80 to $30/m^2	95.64	48%	$36.87
2) Advanced solvent	More energy saving		

* In 2011 dollars

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BP3: Integrated Absorber/ Regeneration and Field Testing

Technical goals achieved

Parameters	Goal	Testing results
Continuous operation time in the lab	≥ 100 h	104 h with >90% CO_2 removal
Mass transfer coefficient of the 4" 2,000 GPU module in the field	>1.0 $(sec)^{-1}$	1.2 $(sec)^{-1}$, within 30% of the maximum achieved with 2-inch modules in the lab

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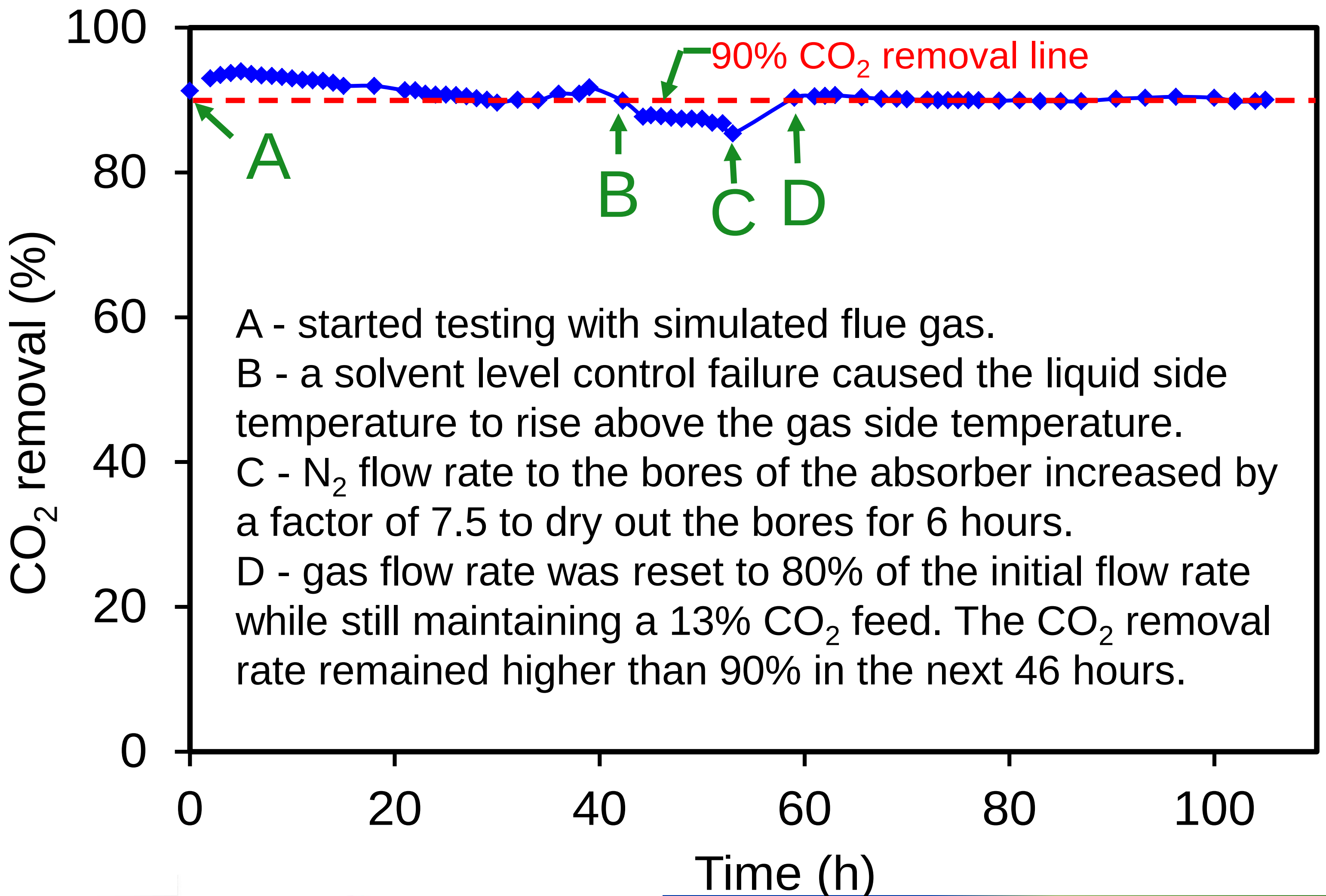
100-hour integrated membrane contactor absorption/regeneration lab testing completed



Performance can be linearly scaled

- **1st evidence**: CO_2 removal rate remained constant with aMDEA solvent as membrane area increased from 1.2 ft^2 to 4.4 ft^2 (full-scale 2-inch module)

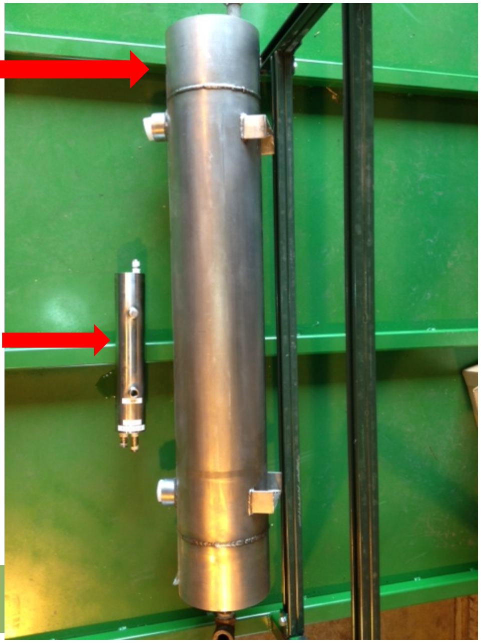
Module	Membrane area, ft^2	Intrinsic CO_2 permeance, GPU	Mass transfer coefficient, *(sec)*$^{-1}$
2PG471	1.2	2,000	1.7
2PG472	4.4	2,000	1.7

- **2nd evidence:** Intrinsic CO_2 permeance remained constant as module scaled from 2-inch to 4-inch diameter

Module	Module length, inch	Intrinsic CO_2 permeance, GPU
2" (2PG472)	15	2,000
4" (347)	60	2,000

4-inch diameter module in 8-inch shell for field testing

2-inch diameter module for lab testing



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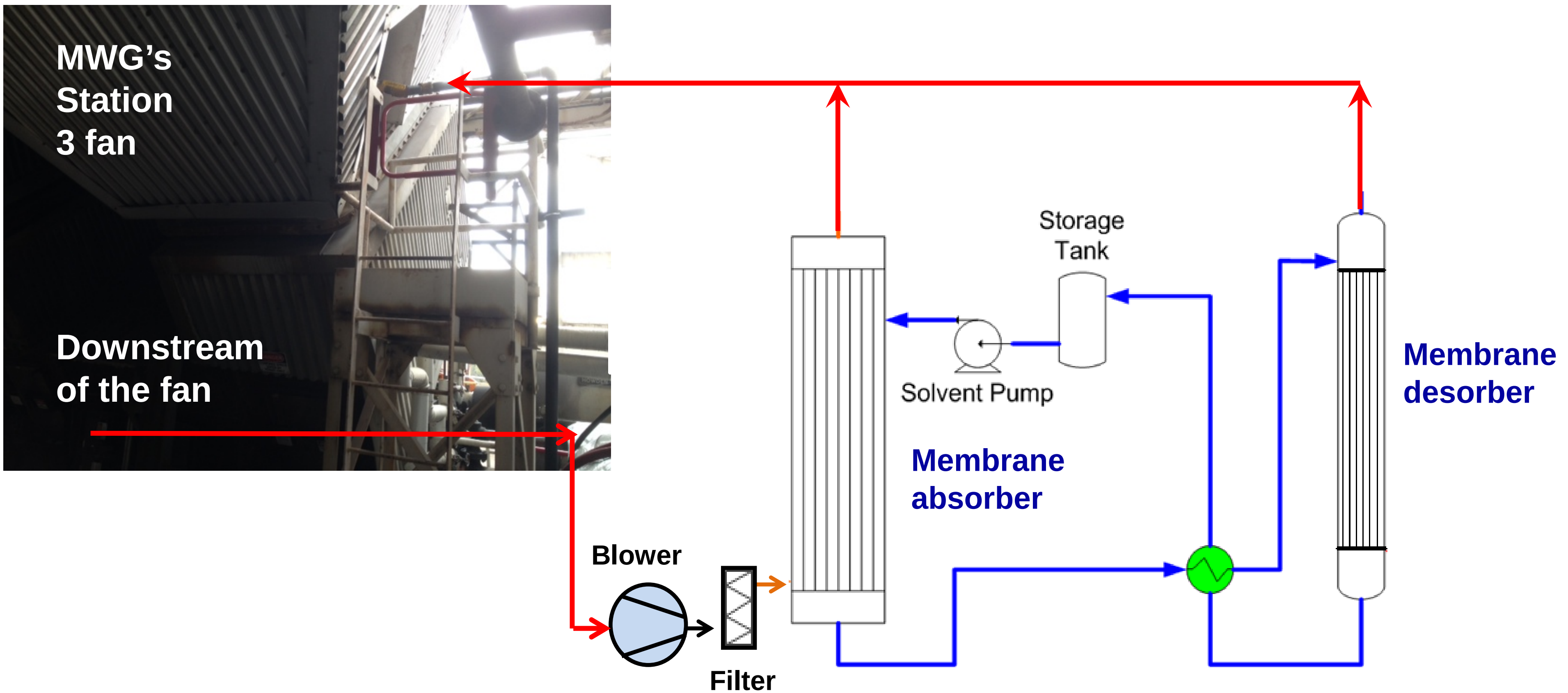
Field test system construction and shakedown completed at GTI

Midwest installed skid with all necessary connections, cooling water supply and return, and electricity

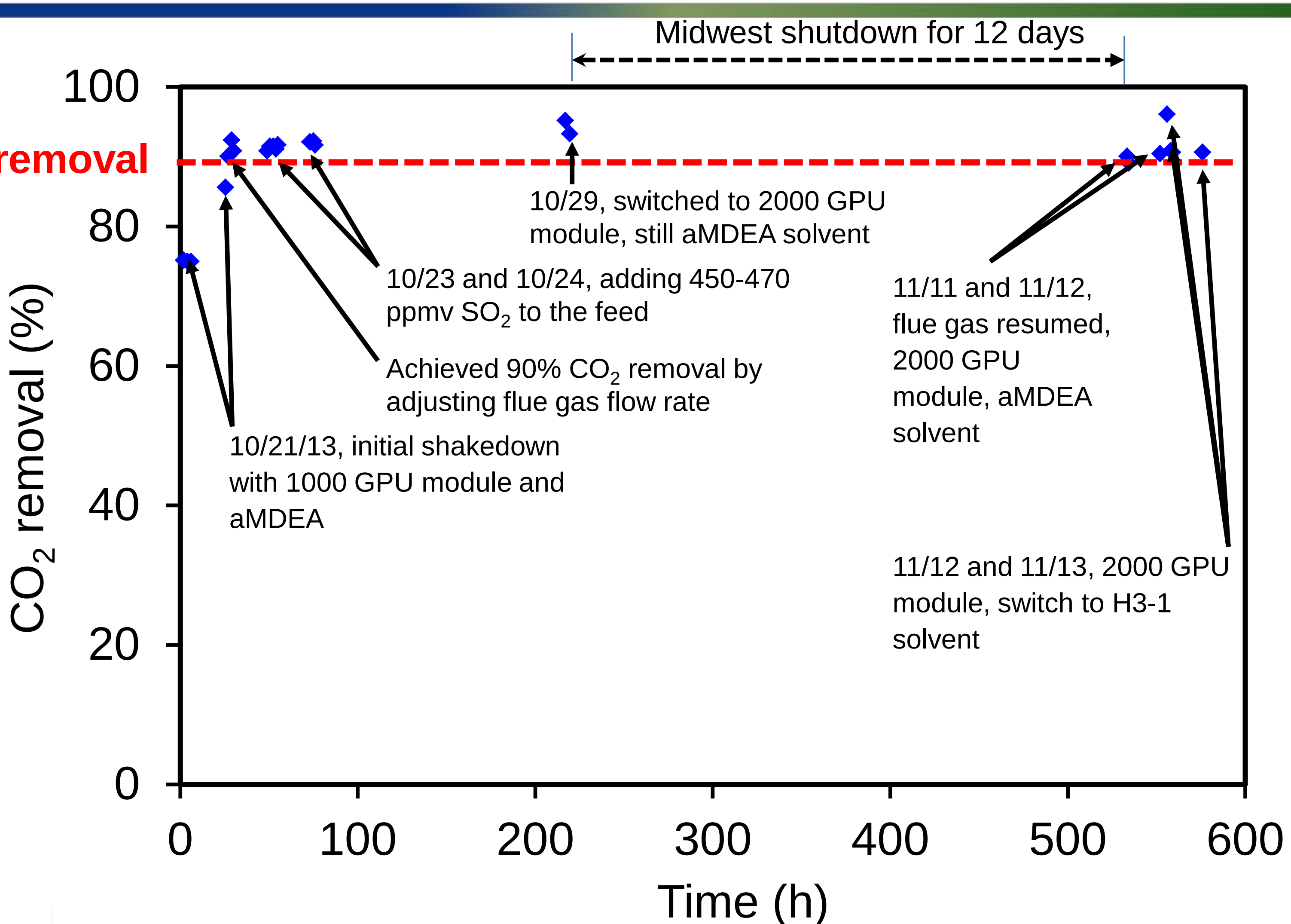
Process flow diagram



Flue gas composition

Element	Concentration
CO_2	7.4-9.6 vol%
NO_x	40-60 ppmv
SO_2	0.4-0.6 ppmv
CO	100-600 ppmv
O_2	8.5-11 vol%
Balance: N_2 , water vapor and trace elements	

Field test results with aMDEA and H3-1 solvents



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2,000 GPU module performance with aMDEA solvent and real flue gas in the field

Inlet CO_2 vol%	CO_2 removal %	Volumetric mass transfer coefficient, $(sec)^{-1}$
9.5	93.2	1.2

Mass transfer coefficient for conventional contactors: 0.0004-0.075 $(sec)^{-1}$

Mass transfer coefficient for 2-inch diameter modules: **1.7** $(sec)^{-1}$

- Desorber CO_2 stripping rate sufficient to keep steady state operation at 90% CO_2 removal

Mass transfer coefficient and rich solvent CO_2 loading obtained in the field

- Mass transfer coefficient of 1.2 $(sec)^{-1}$ is more than one order of magnitude higher than those of conventional contactors
- Rich solvent CO_2 loading of 0.33 mol/mol (65% of saturation) is comparable to that of packed columns. That is, similar regeneration duty, but much smaller equipment when using PEEK membrane desorber

Summary of bench-scale development

- **BP1** membrane absorbers
  - Technical goal achieved: ≥ 90% CO_2 removal in one stage; gas side pressure drop: 1.6 psi; mass transfer coefficient: 1.7 $(sec)^{-1}$
- **BP2** membrane desorbers
  - Technical goal for CO_2 purity (97%) and solvent lean enough for membrane absorber
  - Economic evaluation indicates a 54% increase in COE
- **BP3** integrated absorber/regeneration and field testing
  - A 100-hour, integrated absorber/desorber test completed in the lab, and CO_2 removal above 90% has been achieved
  - Membrane performance improvements continue
  - Field test unit with 4-inch 2,000 GPU module tested at Midwest
    - ≥ 90% CO_2 removal in one stage
    - Mass transfer coefficient of 1.2 $(sec)^{-1}$, which is over one order of magnitude greater than conventional contactors

Pilot-scale project overview

Funding and performance period

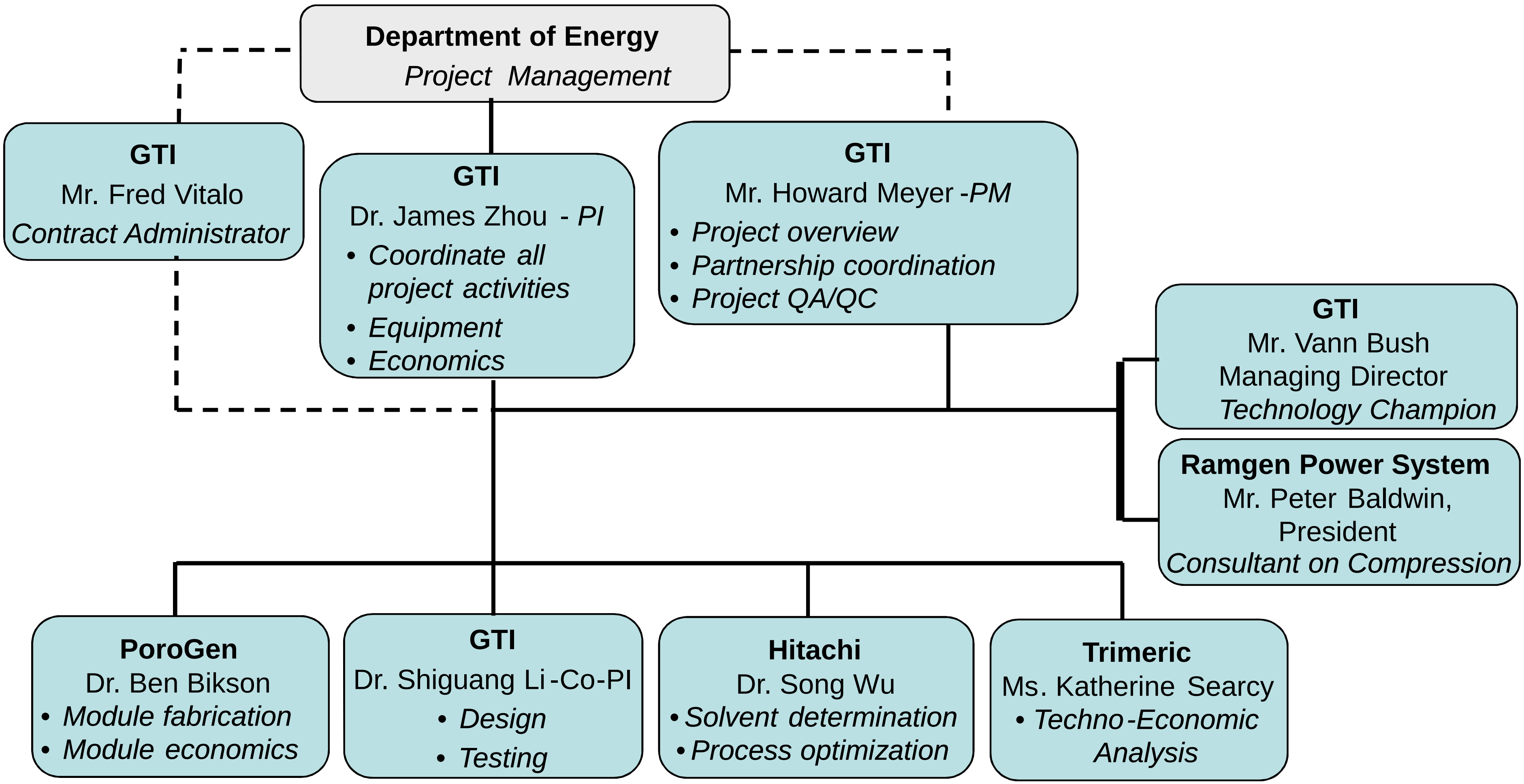
- **Funding**: $12,544,638
  - DOE: $10M
  - Cost share: $2.54M (20% of the total budget)
- **Performance period**: Oct. 1, 2013 – Sep. 30, 2017

Project objectives and goal

- **Objectives**:
  - Build a 1 MW_e equivalent pilot-scale CO_2 capture system (20 ton/day) using PEEK hollow fibers in a membrane contactor and conduct tests on flue gas at the NCCC
  - Demonstrate a continuous, steady-state operation for a minimum of two months
  - Gather data necessary for process scale-up
- **Goal**
  - Achieve DOE's Carbon Capture performance goal of 90% CO_2 capture rate with 95% CO_2 purity at a cost of $40/tonne of CO_2 captured by 2025

NCCC= National Carbon Capture Center (Southern Company, Wilsonville, AL)

The project organization and structure



Each team member's role

Member	Specific Project Roles
gti	• Project management and planning • System design and construction • Site preparation, system installation, and shakedown • Pilot test at the NCCC
PoroGen INNOVATIVE MEMBRANE PRODUCTS	• Membrane and module development • Supporting system design and construction
HITACHI Inspire the Next	• Development of advanced solvents for HFC application • Supporting techno-economic analysis
TRIMERIC CORPORATION	• Techno-Economic and EH&S Analyses
RAMGEN POWER SYSTEMS	• Consulting support on gas compression
NATIONAL CARBON CAPTURE CENTER	• Site host

Timeline and scope

Oct, 2013

BP1: Design of the 1 MW equivalent scale system

Oct 2014

BP2: Procurement of parts, and construction

Oct 2015

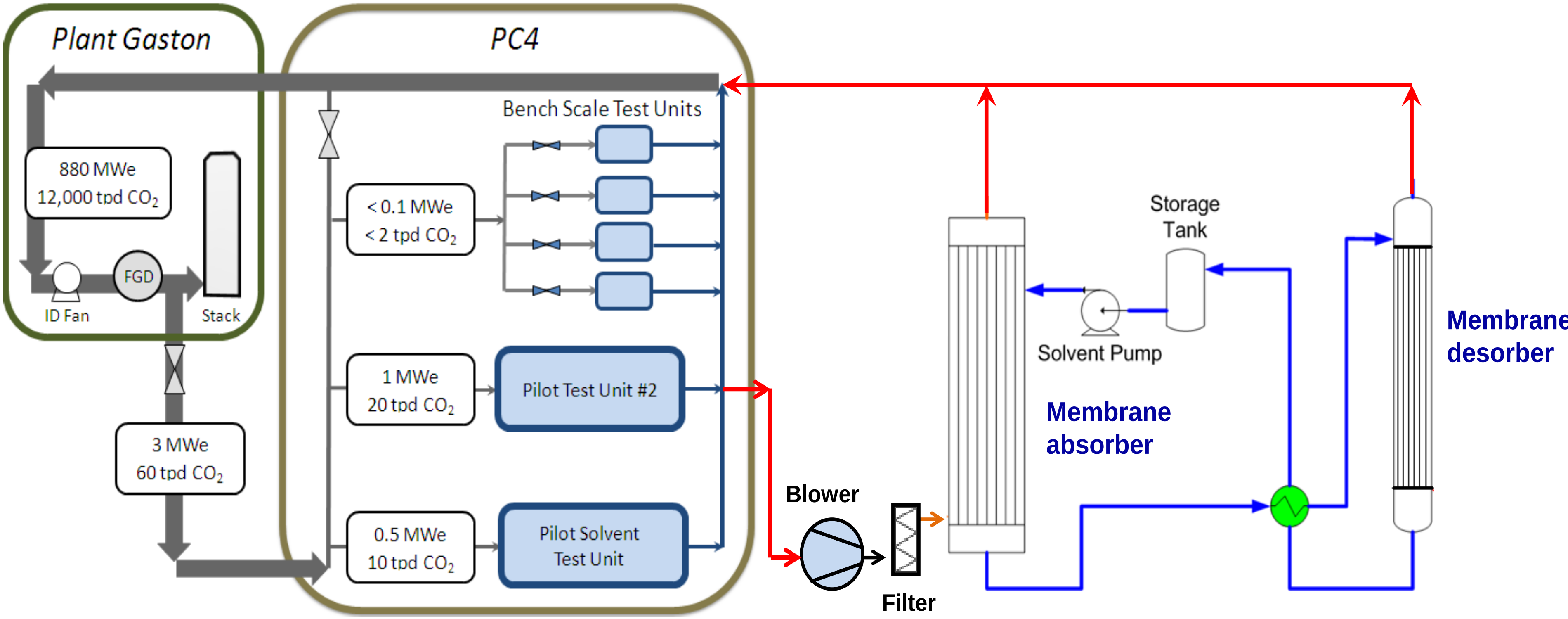
BP3: System installation and shakedown

Oct 2016

BP4: Parametric and continuous tests

Sep 2017

Preliminary process flow diagram



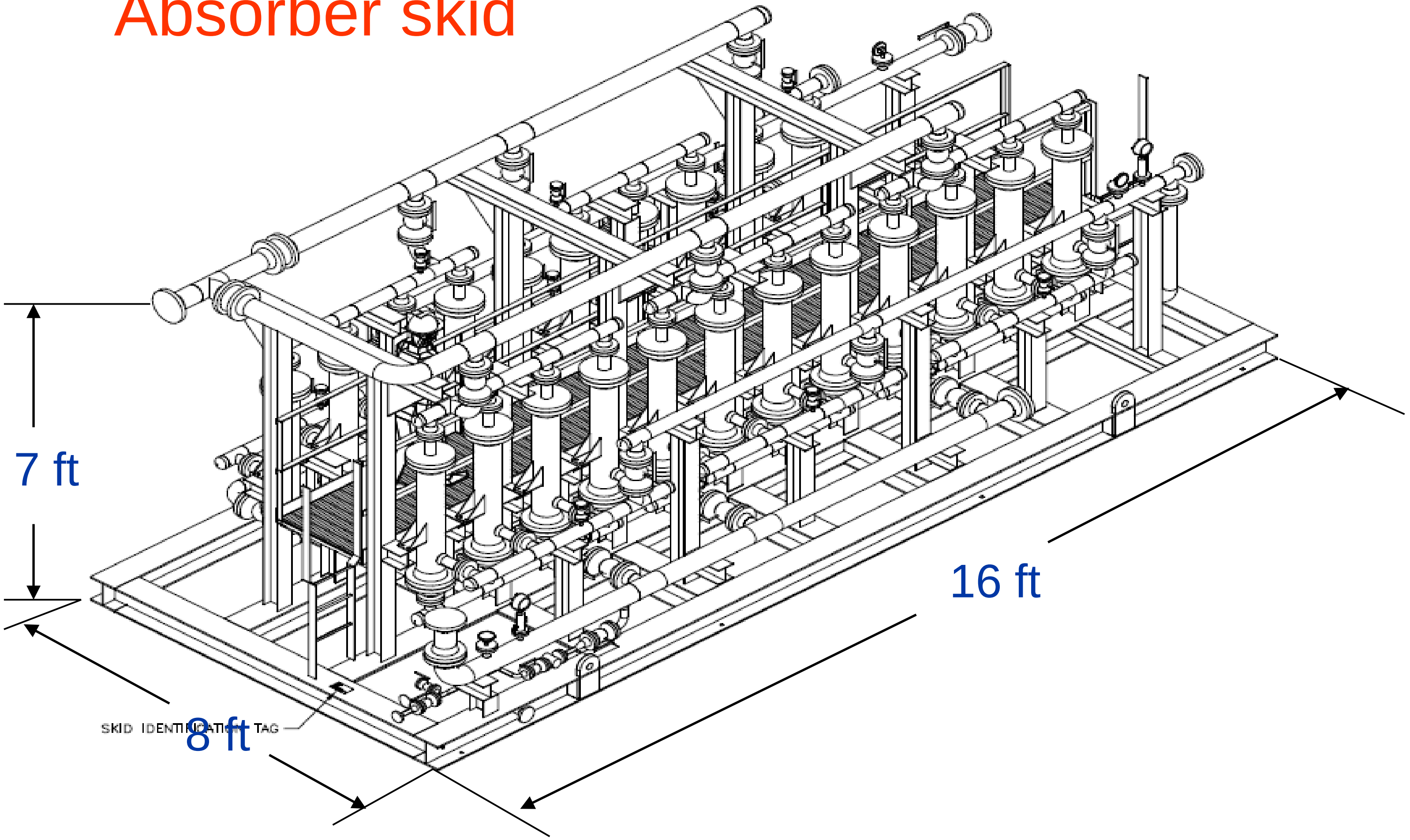
NCCC's PC4 **Our 1 MW_e system**

Anticipated slipstream feed conditions

Parameter	Condition
Pressure	~ atmospheric pressure
Temperature	~ 40 °C (100 °F)
Gas composition	CO_2 concentration: ~13 vol%
Water vapor in feed stream	Fully saturated
Contaminant levels	SO_2 level: 20-30 ppm or ~1 ppm

Conceptual diagram for a 24 module skid for 8-inch diameter modules

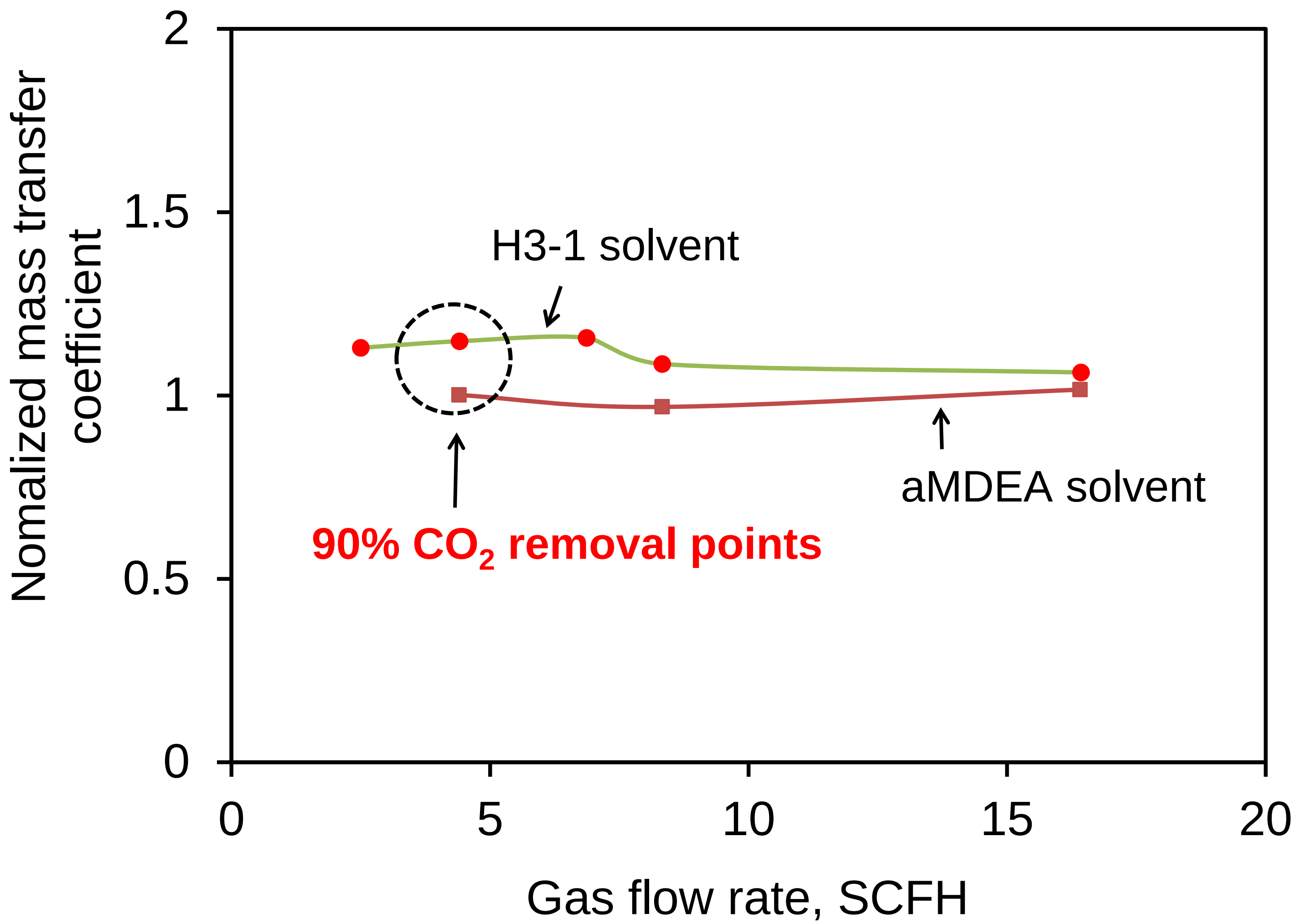
Absorber skid



Solvent to be used: Hitachi's advanced H3-1

- H3-1 solvent has been tested in our PEEK membrane contactors
- H3-1 test results show higher mass transfer coefficients than the aMDEA solvent
- Published data show that the required solvent flow rate and heat duty of H3-1 are 42% and 26% lower than DOE benchmark technology MEA plant
- All tests in BP1 will be performed with H3-1 solvent and 8-inch diameter modules to support design of pilot plant

Lab testing with H3-1 showed it has 15% higher mass transfer coefficient than the aMDEA solvent



Technology implementation timeline

Time	Development	Module diameter	Shell diameter
By 2013	Bench-scale	4-inch	8-inch
By 2017	1 MWe pilot scale	8-inch	8-inch
By 2020	25 MWe demonstration	8-inch	36-inch

PoroGen's new facility currently has equipment capacity to produce 1,000 eight-inch membrane modules annually

Plans for each budget period

BP1 details and plans

Oct, 2013

BP1: Design of the 1 MW equivalent scale system

Oct 2014 →

BP2: Procurement of parts, and construction

Oct 2015 →

BP3: System installation and shakedown

Oct 2016 →

BP4: Parametric and continuous tests

Sep 2017

BP1 scope

- Develop a preliminary Techno-Economic Analysis (TEA) and Environmental Health & Safety (EH&S) study
- Determine scaling parameters for 2,000 GPU hollow fiber membrane modules
- Submit a topical report on 2,000 GPU 8-inch diameter module in conjunction with Hitachi's H3-1 solvent
- Issue a detailed 1 MW_e pilot-plant design package

Team member task roles and responsibilities

Task	Organization	Responsibilities
1	All members	Project management and planning
2	Trimeric, GTI	Preliminary TEA and EH&S study
3	PoroGen	Fabricate 2000 GPU, 8-inch diameter membrane modules
4	GTI, Hitachi	Tests in support of the pilot-scale design effort
5	All members	Design of the 1MW$_e$ equivalent CO_2 capture system

Task 1: Project Management

- Subtask 1.1 – Project management and execution
- Subtask 1.2 – Update project management plan and revision
- Subtask 1.3 – Briefings and reports

Task 2: Preliminary TEA and EH&S Study

- **Subtask 2.1: Preliminary TEA**
  - Submit topical report of the proposed process design based on existing laboratory and field test data 12 weeks after award (12/31/2013)
  - Basis for the analysis will be a net 550 MW_e power plant
  - Complete a preliminary process design that includes major equipment sizing and energy and mass balances
  - Estimate the cost impact of using Hitachi's H3-1 solvent on the base case
- **Subtask 2.2: Preliminary EH&S study**
  - Submit a preliminary EH&S study 12 weeks after award
  - Identify significant EH&S risks that may prevent implementation or environmental permitting of the technology with Hitachi's H3-1 solvent
  - Evaluate emissions types, levels, and properties, regulatory compliance and implications, and safe handling and storage procedures

Task 3: Determination of scaling parameters for 2,000 GPU hollow fiber membrane modules

- PoroGen will fabricate 2,000 GPU hollow fibers into commercial-sized 8-inch diameter modules and determine scaling parameters
- PoroGen will provide the 8-inch diameter modules to GTI for QC and contactor performance testing using Hitachi's H3-1 solvent

Task 4: Bench-scale testing in support of the pilot-scale design effort

- Subtask 4.1: QC testing of the PEEK hollow fiber membrane
- Subtask 4.2: Membrane contactor testing and modeling
  - GTI will perform membrane contactor performance testing using H3-1 solvent in the field and in the lab
  - Key data to be determined
    - o Mass transfer coefficient and gas side pressure drop at 90% CO_2 removal for the membrane absorber
    - o CO_2 stripping rate and CO_2 purity for the membrane desorber

Task 5: Design and costing of the 1MWe equivalent CO_2 capture system

Final pilot-plant design package includes

- Cost to build with a +/- 10% accuracy
- Final Process Flow Diagram, General Arrangement Sketch, and Elevation Sketch
- Slipstream feed conditions
- Liquid side conditions
- Estimated CO_2 delivery conditions
- Preliminary start-up, steady-state operation, and shut-down procedures
- Protocols, methods, measurements, and quality assurance for baseline and performance testing

BP1 timeline, tasks, milestones and decision points

Month	1	2	3	4	5	6	7	8	9	10	11	12
Task 1 - Project Management		a	b									
			A									B
Task 2 – Preliminary TEA and EH&S study			c									
Task 3 – Determination of scaling parameters for 2,000 GPU hollow fiber membrane modules								d				
Task 4.1 – QC testing of membrane modules								d				
Task 4.2 – Membrane contactor tests												e
Task 5 – Design and costing of the 1MW$_e$ system												e

Milestones		Decision Points	
a	Updated PMP	A	Complete integrated bench-scale testing on actual coal-derived flue gas
b	Kickoff Meeting	B	Successful completion of all work proposed in Phase I, and satisfactory meeting all milestones
c	Complete preliminary Techno-Economic Analysis study and preliminary EH&S study		
d	Achieve intrinsic CO_2 permeance of 2,000 GPU in 8-inch diameter modules		
e	Issue pilot-plant design package		

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Verification method of milestones

Task No.	Milestone Description	Planned Completion	Verification Method
1	Updated Project Management Plan (PMP)	11/06/13	PMP file
1	Kickoff Meeting	11/13/13	Presentation file
2	Complete preliminary TEA and EH&S study	12/24/13	Topical Report
3,4	Achieve membrane intrinsic CO_2 permeance of 2,000 GPU in 8-inch diameter modules	9/30/14	Quarterly Report
5	Issue pilot-plant design package	9/30/14	Topical Report

BP2 – BP4 plans

Oct, 2013

BP1: Design of the 1 MW equivalent scale system

Oct 2014

BP2: Procurement of parts, and construction

Oct 2015

BP3: System installation and shakedown

Oct 2016

BP4: Parametric and continuous tests

Sep 2017

BP2 scope

- 8-inch diameter commercial-sized module fabrication
- Parts and equipment procurement
- 1 MW_e CO_2 capture system construction

BP2 Team member task roles and responsibilities

Task	Organization	Responsibilities
Task 6.0	PoroGen	Fabrication of 8-inch diameter membrane modules
Task 7.0	Hitachi	Determination of advanced solvent conditions for flue gas CO_2 capture using HFC
Task 8.0	GTI	HFC CO_2 capture performance testing with 8-inch modules
Task 9.0	GTI, Contractor	Procurement of parts and subsystems for the 1 MW_e system
Task 10.0	GTI, Contractor	Construction of the 1 MW_e system

BP3 scope

- Site preparation and system installation at the NCCC
- Procure H3-1 solvent for the pilot testing
- Test system shake down at NCCC
- Dynamic parametric testing at NCCC performed prior to continuous testing

BP3 Team member task roles and responsibilities

Task	Organization	Responsibilities
Task 11.0	GTI	Site preparation
Task 12.0	GTI	System installation at the NCCC
Task 13.0	GTI	On-site system shakedown
Task 14.0	PoroGen	Fabrication of replacement 8-inch membrane modules for pilot scale testing
Task 15.0	Hitachi, GTI	Procurement of advanced solvents for pilot scale testing
Task 16.0	GTI	Measurement of key performance properties through pilot testing

BP4 scope

- Identify operational conditions for the continuous steady-state run at NCCC
- Run continuous steady-state tests for a minimum of two months
- Gather data necessary for further process scale-up
- Final Techno-Economic Analysis and EH&S study

BP4 Team member task roles and responsibilities

Task	Organization	Responsibilities
Task 17.0	PoroGen	Support for pilot-scale testing
Task 18.0	GTI, Hitachi	Solvent process conditions for on pilot-scale testing results
Task 19.0	GTI	Identification of continuous steady-state operation conditions
Task 20.0	GTI	Continuous steady-state operation for a minimum of two months
Task 21.0	Trimeric, GTI, PoroGen, Ramgen	Final Techno-Economic Analysis and technology EH&S assessment
Task 22.0	GTI	Removal of pilot system

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