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

S. James Zhou, Shiguang Li, Travis Pyrzynski, and Howard Meyer, *GTI*
Yong Ding and Ben Bikson, *PoroGen*
Katherine Searcy, *Trimeric*

Project Review at NETL

February 6, 2015

gti

Project objectives and goal

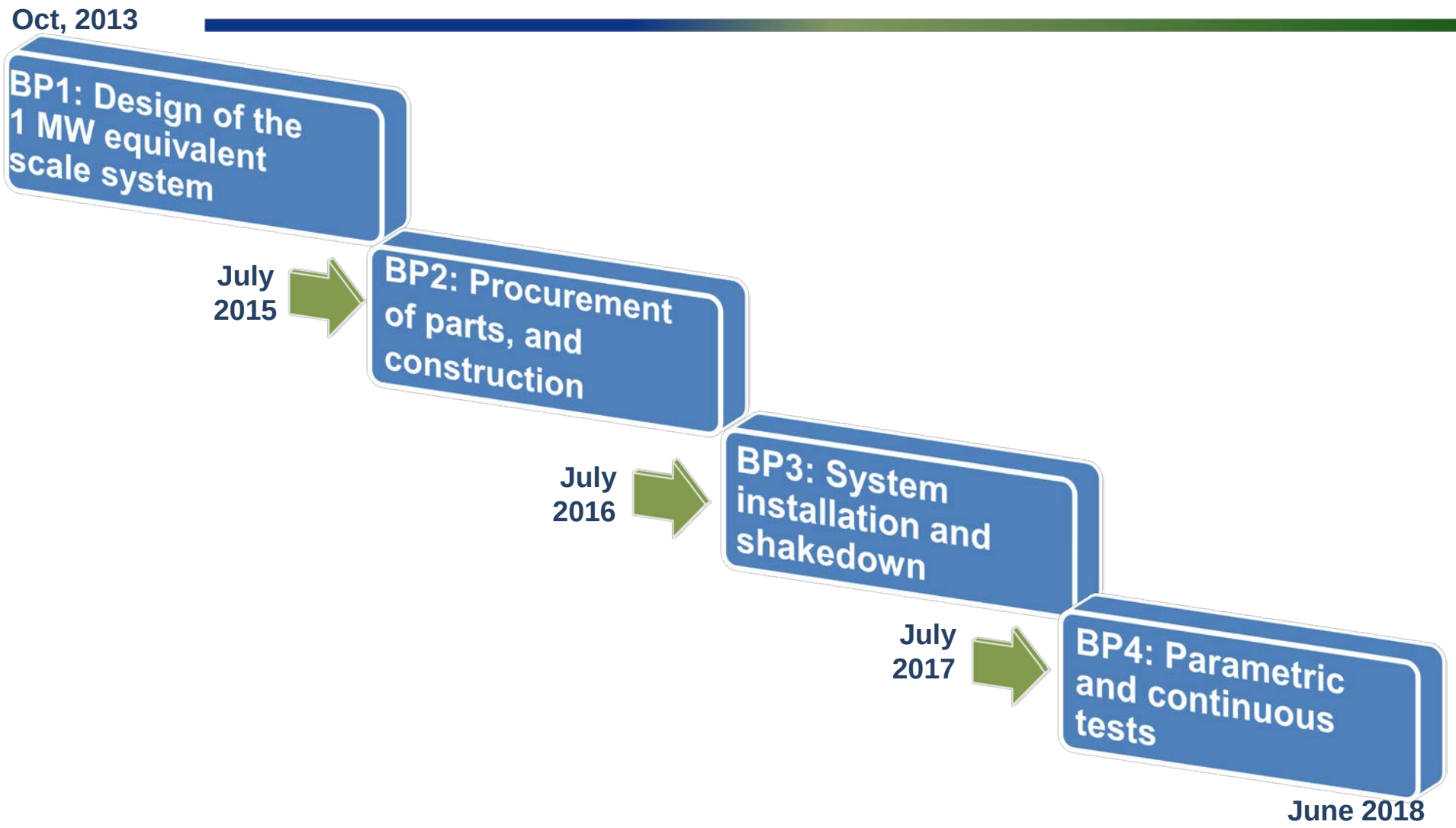
- **Objectives**:
  - Build a 1 MW_e pilot-scale CO_2 capture system (20 ton/day) using PEEK hollow fibers in a membrane contactor and conduct tests on flue gas at the NCCC
  - Test the pilot system under steady-state conditions for a minimum of two months
  - Gather data necessary for process scale-up
- **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)

Our team

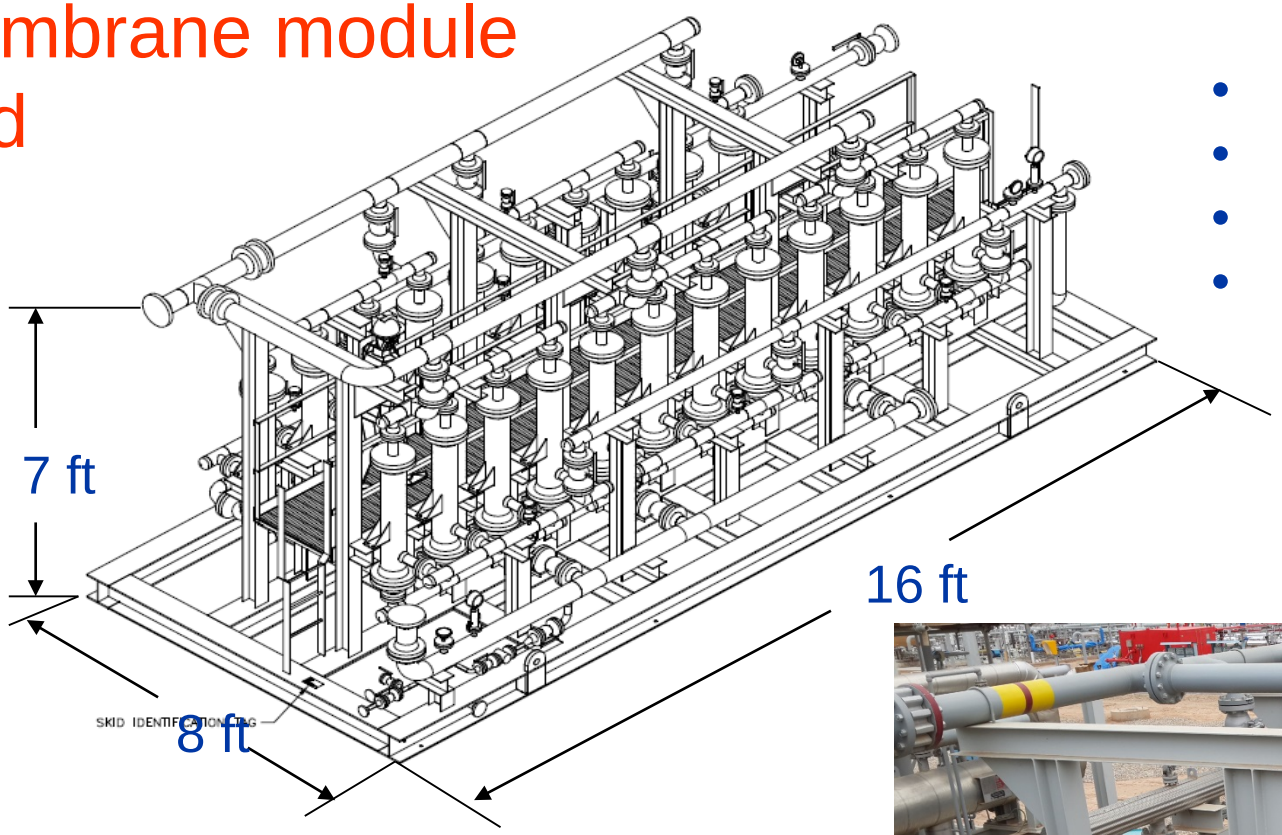
Member	Specific Project Roles
gti	• Project management and planning • EH&S analysis • System design and construction • Site preparation, system installation, and shakedown • Pilot test at the NCCC
PoroGen INNOVATIVE MEMBRANE PRODUCTS	• PEEK hollow fiber and module development • Supporting system design and construction
TRIMERIC CORPORATION	• Techno-Economic Analysis
TBD	• Consulting support on gas compression
NATIONAL CARBON CAPTURE CENTER	• Site host

Timeline and scope



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

Membrane module skid



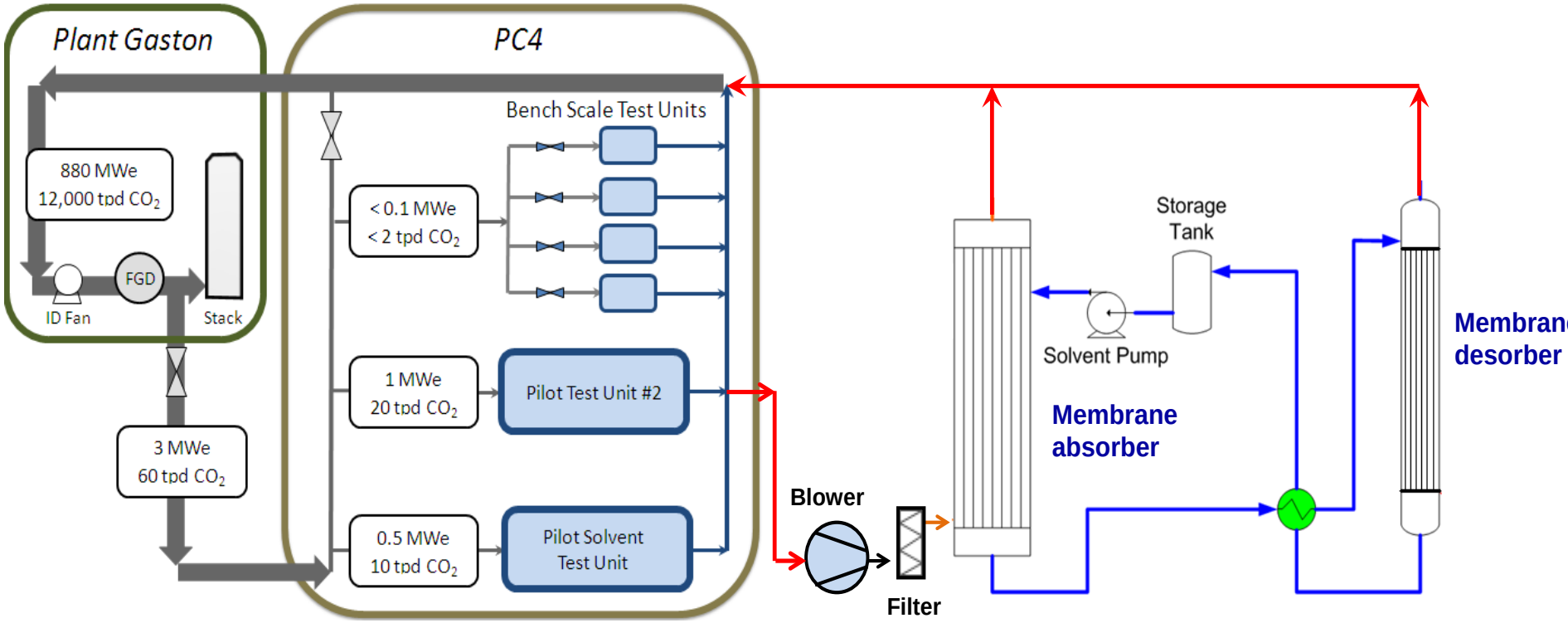
- Skids:
- 1-2- absorber skid
- 1- desorber skid
- 1-2 BOP skids

Anticipated slipstream feed conditions at NCCC

Parameter	Condition
Pressure	~ atmospheric pressure
Temperature	~ 40 °C (100 °F) after cooling
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
Total flue gas flow rate	Max. 10,000 lb./hr.

Tests will also be conducted with ~ 150 ppm SO_2 in the feed to mimic the flue gas compositions of burning Illinois coal

Integration of membrane contactor 1MW pilot plant at NCCC



NCCC's PC4

Our 1 MW_e system

BP1: performance period and funding

- **Funding**: $2,979,497 in total
  - DOE: $2,176,897 (72%)
  - Cost share: $802,600 (28%)
    - GTI: $515,519
    - ICCI: $150,000
    - PoroGen: $100,000
    - MHPS: $37,081
- **Performance period**: Oct. 1, 2013 – June 30, 2015
- **Project participants:**
  - GTI PoroGen Trimeric MHPS

BP1 objectives

- Develop preliminary Techno-Economic Analysis (TEA) and Environmental, Health & Safety study (EH&S) based on bench-scale test data
- Determine scaling parameters for 2,000 GPU hollow fiber membrane modules to 8-inch diameter by 60-inch long commercial modules
- Design an HFMC pilot system for flue gas CO_2 capture at 1 MW_e equivalent scale (20 ton CO_2/day)

BP1 tasks

- Task 1 - Project management
- Task 2 - Preliminary TEA and EH&S study
- Task 3 - Determination of scaling parameters for 2,000 GPU hollow fiber membrane modules
- Task 4 – Bench-scale testing in support of the pilot-scale design effort
- Task 5 – Design and costing of the 1MW_e equivalent CO_2 capture system

Task 1 scope: project management

- GTI will coordinate all project activities with Team Members and will report technical progress and financial results to DOE throughout the duration of the project

Status for the DOE DE-FE0012829 project

- TEA and EH&S reported submitted and approved
- Test solvent switched from **H3-1 to aMDEA** due to the difficulties in completing process modeling for the H3-1 solvent with available data
- A GO decision was reached on 10/1/2014 for our team to start work on BP1 Tasks 3-5
- A **9-month extension** was requested and approved for completing Tasks 3-5 for the design of the 1MW_e equivalent membrane contactor pilot CO_2 capture test system with additional funding of $186 K from DOE and $46 K from recipient

BP1 schedule and milestones

Task No.	Milestone Description	Planned Completion	Actual Completion	Verification Method
1	Updated Project Management Plan (PMP)	11/30/13	11/06/2013	PMP file
1	Kickoff Meeting	12/31/13	11/13/2013	Presentation file
2	Complete preliminary TEA and EH&S study	12/24/13	09/29/2014	Topical Reports
3,4	Achieve membrane intrinsic CO_2 permeances of 2,000 GPU in 8-inch diameter modules	03/30/15	on target	Quarterly Report
5	Issue pilot-plant design package	05/01/15	on target	Topical Report
	Complete Design and TEA	06/30/15		Annual Report

BP1 success criteria

1. Target performance demonstrated with the PEEK hollow fiber membrane: membrane intrinsic permeance > 2,000 GPU; and

2. Final pilot-plant design package design review with DOE and NCCC HAZOP and DHR finalized

Task 2 scope: preliminary TEA and EH&S study

- **Subtask 2.1: Preliminary TEA**
  - Basis for the analysis: a net 550 MW_e power plant
  - Complete a preliminary process design that includes major equipment sizing and energy and mass balances
- **Subtask 2.2: Preliminary EH&S study**
  - Identify significant EH&S risks
  - Evaluate emissions types, levels, and properties, and safe handling and storage procedures

Key results from the preliminary EH&S study

- No significant EH&S risks to pilot plant operators, test center employees, and surrounding area environment
- The pilot CO_2 capture project will not generate appreciable new air emissions
- aMDEA has an LD50 value of 4,680 mg/kg (BASF-Test) indicating low toxicity
- The aMDEA aqueous solution is not flammable
- The membrane contactor process with aMDEA solvent can be safely operated in compliance with all applicable laws and regulations.
- Nitrosamine will pose no significant risk from inhalation
- A HAZOP review meeting will be held with NCCC personnel during the final design review process and a letter from SCS/NCCC affirming process safety compliance will be obtained before fabrication or procurement of equipment begins

Preliminary TEA was based on field test results at Midwest with aMDEA solvent

- Feed conditions

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	

- High mass transfer coefficient achieved

Total gas flow rate, L(STP)/min	CO_2 removal, %	Volumetric mass transfer coefficient, $(sec)^{-1}$
245	93.2	1.2

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

Cost of CO_2 capture for HFMC technology with aMDEA vs. DOE Case 12

Item	Unit	Bench scale field test data	Target mass transfer coefficient achieved	DOE Case 12 (Econamine™)
COE - No TS&M	mills/kWh	127.1	122.1	137.3
COE - Total	mills/kWh	137.1	132.1	147.3
Incremental Cost of CO_2 Capture - No TS&M	mills/kWh	46.2	41.2	56.3
Increase in COE - No TS&M	%	57.0%	50.9%	69.6%
Increase in COE - Total	%	69.4%	63.2%	81.9%
Cost of CO_2 Capture - No TS&M	$/tonne	**49.35**	**44.00**	**56.47**
% Change		**-13%**	**-22%**	**0%**
Cost of CO_2 Capture – No TS&M with H3-1 solvent	$/tonne	**41.89**	**40.42**	**56.47**

Steps to take for the cost of CO_2 capture for HFMC technology to reach DOE target

- PEEK contactor mass transfer increase beyond the current target of 1.7 $(sec)^{-1}$ to reduce CAPEX
- Integration of PEEK membrane contactor technology with other advanced carbon capture technologies
- Use of lower regeneration energy solvent
- Use of new, energy efficient solvent regeneration processes

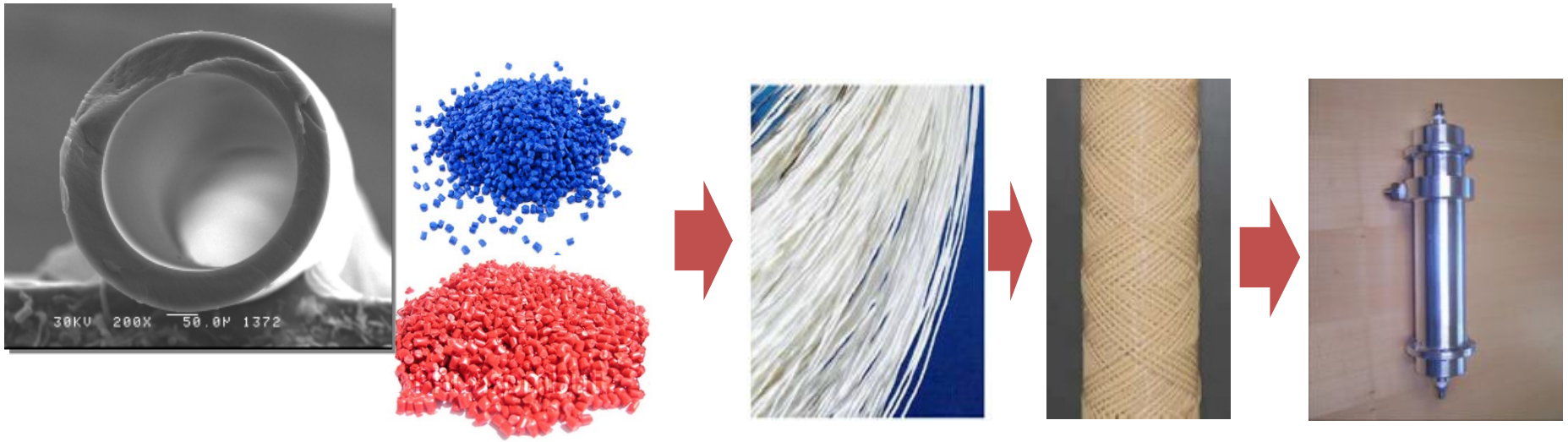
Task 3 scope: determination of scaling parameters for 2,000 GPU hollow fiber membrane modules

- 2,000 GPU hollow fibers will be prepared and installed into commercial-sized 8-inch diameter modules and determine scaling parameters
  - ✓ Gas and liquid flow distribution
  - ✓ Gas and liquid side pressure drops
  - ✓ CO_2 removal performance/mass transfer coefficients
  - ✓ Temperature distributions

Membrane and module development

- PoroGen fabricated larger ID fibers in 2-inch modules to achieve 2,000 GPU CO_2 permeance and lower gas-side pressure drop
- GTI tested modules in contactor mode, provided feedback to PoroGen for membrane and module scale up
- GTI tested performance stability during startup/shutdown cycles
- Fabrication of modules to 8-inch diameter ongoing

Module manufacture cycle time: 6-8 weeks



- PoroGen: from PEEK pellets to fiber to cartridge to module takes 5 to 6 weeks
- GTI: performance (including stability) tests take 1-2 weeks
- Total cycle time 6 to 8 weeks for each variation of module
- 1 MWe is expected to need 50 to 60 8-inch diameter modules
- PoroGen's current capacity is about 1,000 module/year

Larger inner diameter fibers produced to decrease pressure drop

- The requirement related to pressure of HFMC process: inlet flue gas pressure must be slightly higher than the ambient pressure in order to ensure uniform flue gas flow through the hollow fibers
- Field test: ΔP = ~ 5 psi, needs to decrease to < 2 psi (our target)
- The Hagen–Poiseuille equation:

$$\Delta P = \frac{8Q\eta L}{\pi \cdot r^4}$$

  - *Q:* volumetric flow rate, η*:* absolute viscosity of the fluid, *L:* length of the hollow fiber, and *r:* radius of the hollow fiber

Low gas-side pressure drop for larger ID fibers modules

- Fiber inner diameter is being increased from current 13 mil to at least 17 mil to meet the ΔP target
- Larger ID (20 mil) fiber module has been fabricated and tested

Cartridge No.	Number of Fibers	Active Fiber Area (inside, cm^2)	2” gas-side Δp, psid	8” gas-side Δp, psid
2PG-664	448	3,161	0.28	0.74
2PG-665	448	3,161	0.28	0.74

High performance for the larger ID fibers confirmed

- Intrinsic CO_2 permeance as high as 2,600 GPU (our target: 2,000 GPU)

Cartridge No.	Number of Fibers	Active Fiber Area (inside, cm^2)	Pure CO_2 Permeance (GPU)
2PG-664	448	3,161	2,600
2PG-665	448	3,161	2,500

- Contactor testing with aMDEA solvent: mass transfer coefficient of 1.61 sec^{-1} (close to our target of 1.7 sec^{-1}) at 90% CO_2 removal
- Low gas-side ΔP of 0.28 psi was observed for the 2-inch module
  - ΔP as low as 0.74 psi (our target: less than 2 psi) is predicted for the 8-inch diameter module

Task 4 scope: 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

Factors affecting CO_2 capture performance have been tested at PoroGen and GTI

- O-rings/other components
- Epoxy/fiber interface in tubesheets
- Wet out of hydrophobic surface in long-term operation
- Module startup/shutdown procedures

Addressing epoxy/fiber interface adhesion (continued)

Cross sections of fractured tubesheets

Tubesheet with poor fiber epoxy adhesion

Tubesheet with good fiber epoxy adhesion

Progress has been made for the first three factors

- No problems with O-ring seals were noted through tests of multiple 2” diameter modules, some after prolonged operation
- Completed development of tubesheet fabrication procedure

Tubesheet with good fiber epoxy adhesion

- No wet out of hydrophobic membrane surface after long-term operation based on single-gas CO_2 permeation measurements before and after contactor testing

Task 5 scope: design and costing of the 1MW$_e$ equivalent CO_2 capture system

Final design package includes:

- Cost to build with a +/- 10% accuracy
- Final PFD, P&ID, general arrangement and elevation drawings
- Slipstream feed conditions
- Liquid side conditions
- Estimated CO_2 delivery conditions
- Start-up, steady-state operation, and shut-down procedures
- Protocols, methods, measurements, and quality assurance for baseline and performance testing

Design and costing ongoing

- Some items identified through preliminary TEA
  - Slipstream feed conditions
  - Liquid side conditions
  - Estimated CO_2 delivery conditions
- Discussed with the host site (NCCC) engineers
  - Utility needs
  - Operating philosophy and duties for each party
  - HAZOP review

Plan and status

- Preliminary design package
  - Developed by GTI (with NCCC and PoroGen)
  - Deliverable: bid package for potential system fabricators
- Firm bids from skid fabricators
  - Pre-screen several potential bidders
  - Deliverable: firm bids by late-February
- Cost estimate +/- 10 % (by mid-March)

Preliminary design package

- PFD and material/energy balances
  - Completed for NCCC (20 tons/day CO_2 captured) 11/14/14
- P&ID's
  - Second review with NCCC engineers completed 1/23/15
- Equipment sizing and instrumentation
  - Completed equipment and instrument data sheets 2/4/15
- Final HAZOP with NCCC
  - To take place at NCCC 02/23 to 02/25/15

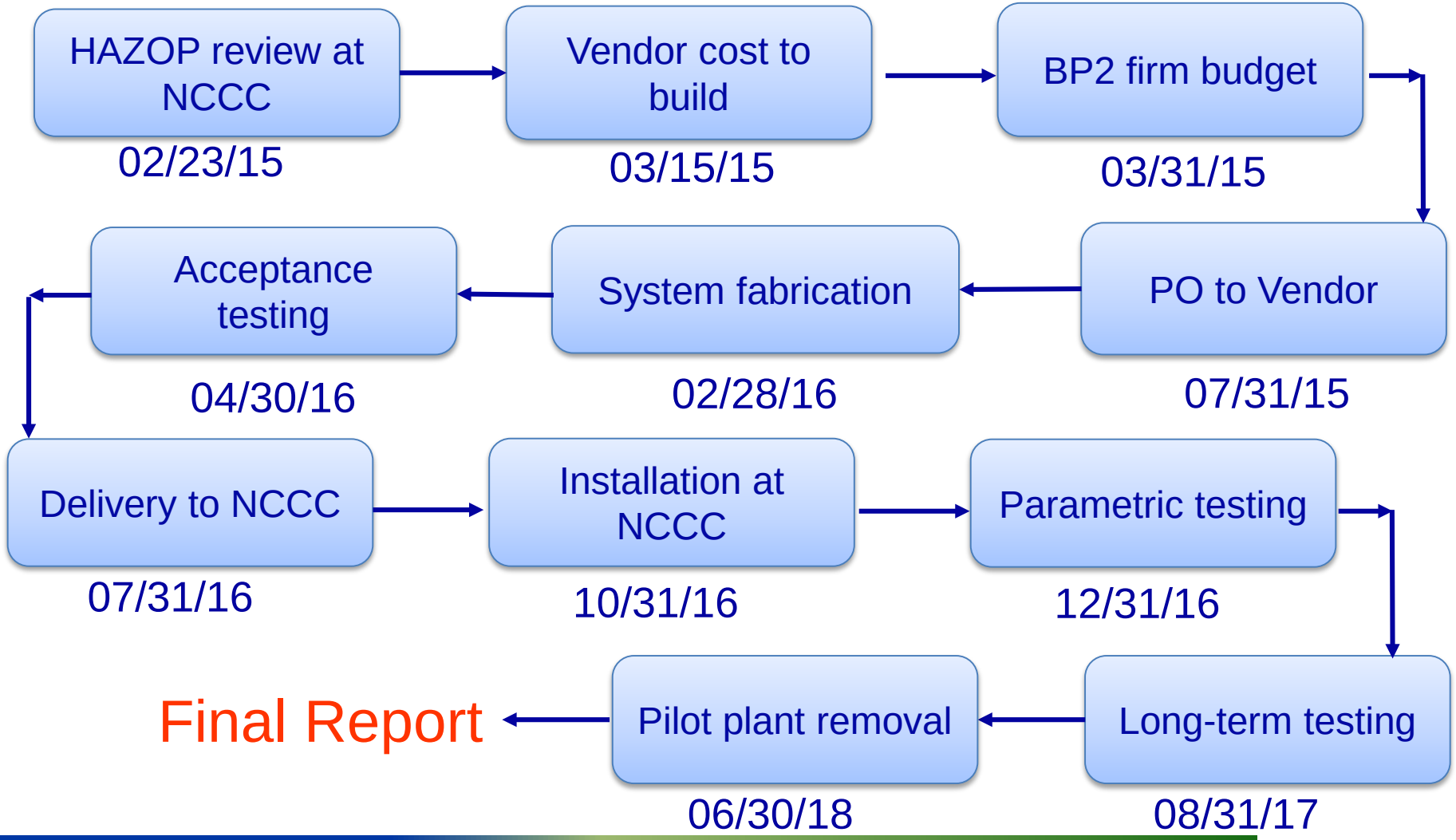
Firm bids from vendors

- Vendors will bid on:
  - Completion of detailed engineering
    - Detailed engineering
    - PFD, P&ID's, utility requirements
    - Final Equipment and instrumentation data sheets
    - Layout/detailed schedule
    - Spec for control system
  - Procurement of equipment and instrumentation
  - Construction of pilot-scale HFMC unit
    - Fabrication of skid(s)
    - Factory acceptance testing
    - Installation and startup

Estimated cost to build

- PFD and P&ID provided to all four fabricators
- Bid package with equipment specifications and instrument list will be delivered to fabricators the week of **02/02/15**
- Meeting with fabricators to take place the week of **02/08/15**
- Firm quote to GTI **03/16/15**
- Continuation application for BP2 with firm budget to build submitted to DOE **03/31/15**

Timeline to pilot test



NCCC test schedule

For GTI pilot test

- PO-5 possibly from Apr/May-Jul/Aug 2016
- PO-6 possibly from Oct/Nov 2016 –Feb/Mar 2017

Summary

- Preliminary EH&S study and TEA completed, cost of HFMC with aMDEA solvent can be 22% lower than the DOE Case 12
- New PEEK fibers targeting low gas side pressure developed
  - Intrinsic CO_2 permeance as high as 2,600 GPU
  - Gas side ΔP as low as 0.74 psi predicted for 8-inch module
- A new process for regeneration designed and tested
- Fabrication of 8-inch module in progress
- Design of 1 MW_e pilot plant is near completion
  - Bid package to vendors by first week of February
  - Firm quote to GTI by 03/16/15
  - Continuation application to DOE by 03/31/15

Scope of work for other budget periods

BP2

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

BP3

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

BP4

- 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

BP2 estimated budget for construction

- Vendor quotes to come in 03/16/2015
- Prior instances show vendor quotes usually higher than original estimates

BP2 success criteria

1. Initial HFC CO_2 capture testing with reduced gas flow and liquid flow using 20-cm (8-inch) diameter modules shows no leaks or other operational issues with the module and solvent;

2. Target performance demonstrated with 20-cm (8-inch) diameter modules: ≥90% CO_2 removal rate, membrane contactor volumetric mass transfer coefficient ≥1.7 $(sec)^{-1}$, gas side pressure drop < 14 kPa (2 psi); and

Acknowledgements

- **Financial support**

- **DOE NETL José Figueroa**
- **ICCI Dr. Debalina Dasgupta**