CO_2 CAPTURE TECHNOLOGY MEETING 2014

AIR LIQUIDE

CO_2 Capture by Cold Membrane Operation with actual Coal-Fired Power Plant Flue Gas

31st July, 2014

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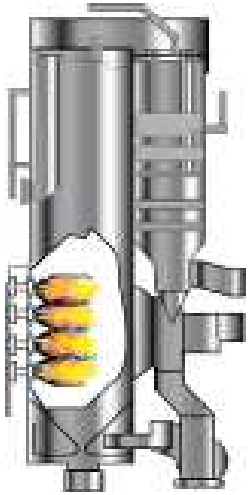
Project Summary

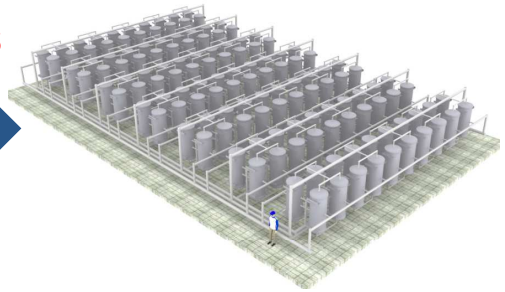
- Air Liquide Hybrid Cold membrane - Liquefaction Process plant for 550 MWe scale



POWER PLANT

Flue Gas

Improved Performance at Cold Condition



COLD MEMBRANE

LIQUEFACTION

CO_2 for EOR

- Cold membrane testing was completed with synthetic flue gas (TRL4) in 2012
- Current project will test the cold membrane technology with real flue gas at 0.3 MWe (TRL5) using field test unit at National Carbon Capture Center (NCCC)

Agenda

- AL Roadmap for CO_2 Capture Technologies
- Hybrid Cold Membrane Technology
- Project Overview
- Project Scope, Key Deliverables & Progress
- Project Risks
- Next Steps

AL Roadmap for CO_2 Capture Technologies for Power Plants

COMMERCIAL PLANTS

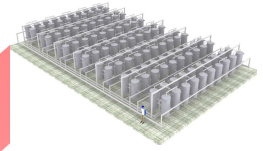
LARGE SCALE PLANTS

PILOT/ FIELD TESTS

CONCEPTUAL/ BENCH SCALE STUDIES

FutureGen 2.0

25 MWe Field Test



Callide

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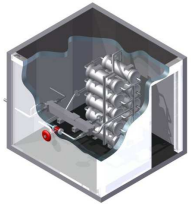
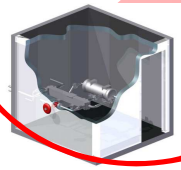
1 MWe Multi-bundle Test



Oxy-combustion & CO_2 Capture

Lacq

0.3 MWe NCCC



Current Project

SaskPower Study

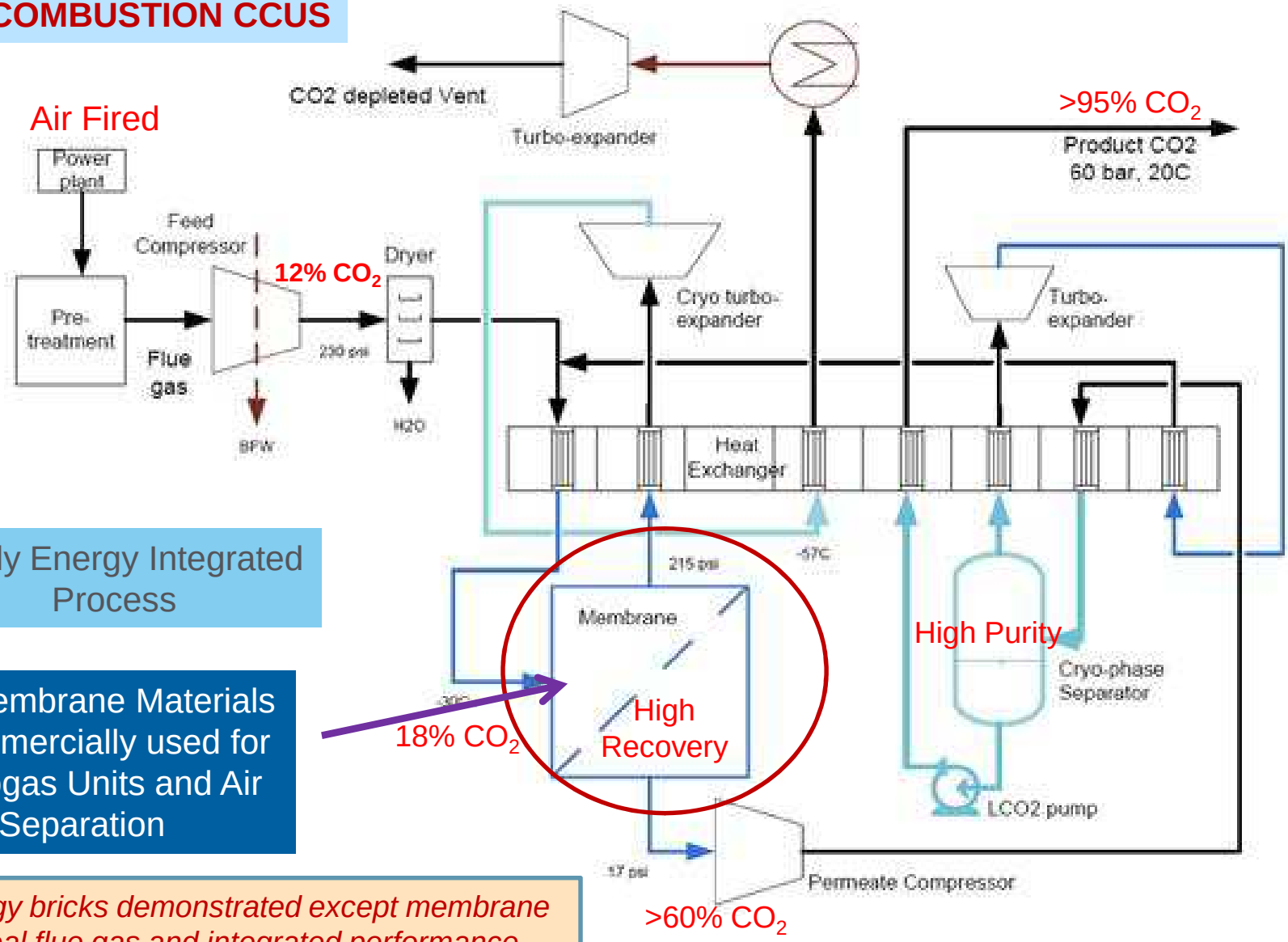
0.1 Mwe - DRTC

Post combustion CO_2 Capture
Cold Membrane + Liquefaction

2006 2008 2010 2012 2014 2016 2018 2020 2022

Hybrid Membrane + Liquefaction Configuration

POST-COMBUSTION CCUS



Highly Energy Integrated Process

PI-1 Membrane Materials is Commercially used for AL Biogas Units and Air Separation

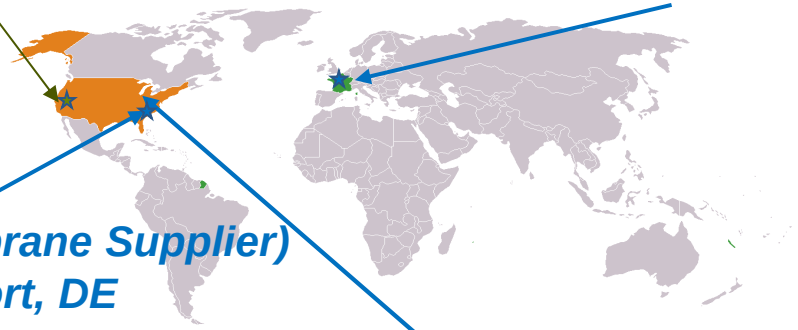
All technology bricks demonstrated except membrane with real flue gas and integrated performance

Project Overview

DOE NETL Award No. DE-FE0013163
Total Budget : $5.8MM, DOE Funding - $4.7MM ; Cost share - $1.1MM
Period of Performance: 10/01/2013 through 3/31/2016 over 2 Budget Periods
NETL Project Manager: Jose Figueroa
Prime Recipient: AL R&D Delaware Research & Technology Center (DRTC)
Project Sub-awardees: MEDAL, E&C, Parsons

E&C - $489K, MEDAL - $361K, Parsons - $96K

Parsons Governmental Services
Pasadena, CA and Philadelphia, PA



Air Liquide Engineering
Champigny, France

MEDAL (Membrane Supplier)
Newport, DE

Delaware Research & Technology Center
Newark, DE

Overall Project Objective / Target

- PI-1 Bundle Optimization Study (Existing commercial material – previously tested)
  - Improve performance by 30%
  - Validate performance on 0.1 MWe unit with simulated flue gas
- PI-2 High Permeance CO_2 fiber preparation and testing (New material)
  - 5X separation performance compared to PI-1
  - Validate performance on with simulated flue gas using 1 inch bundle
- 0.3 MWe field testing at NCCC
  - Perform 500 hours of steady state operation in field
- Techno-economic analysis
  - Evaluate potential to meet DOE target of $40/tonne capture cost

Project Schedule & Planning

Main Tasks	Start	End	Location
BUDGET PERIOD 1 (BP1) Oct 2013 to March 2015			
PI-1 Membrane Bundle Optimization & Testing	Oct 2013	Dec 2014	DRTC, MEDAL
PI-2 High Permeance Fiber Bundle Preparation & Testing	Oct 2013	March 2015	DRTC, MEDAL
Design and Procurement of 0.3 MWe field test unit at NCCC	Oct 2013	March 2015	DRTC, E&C, MEDAL, Sub-contractors
BUDGET PERIOD 2 (BP2) April 2015 to March 2016			
Field Test at NCCC	April 2015	Dec 2015	DRTC, NCCC, MEDAL
TEA	April 2015	March 2016	DRTC, E&C, Parsons
Design Multi-bundle Field Test	April 2015	July 2015	DRTC, E&C

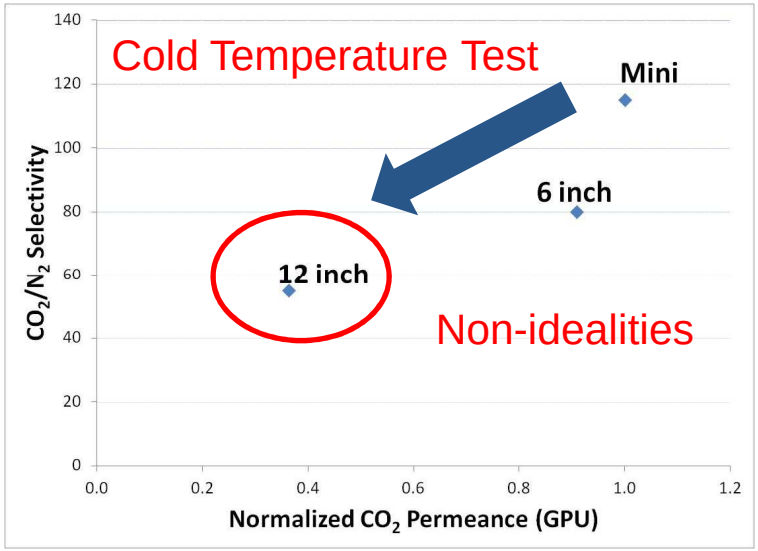
Project Scope, Deliverables & Progress for BP1

PI-1 Bundle Optimization & Testing

SCOPE

- CFD simulations to provide guidance for improvement in the 12 inch bundle performance
- Improved configuration bundle will be fabricated and tested using bench scale skid at DRTC with synthetic flue gas (Parametric tests)
- CFD and bundle testing is complementary and iterative process

Cold temperature average membrane data from previous DOE funded project (DE-FE0004278)



SUCCESS CRITERIA

- Improvement in capacity by 30% for 90% CO_2 capture for permeate composition >60% CO_2

Important to improve 12 inch bundle performance by 30% in order to meet the cost target

PI-1 Bundle Optimization& Testing Progress

0.1 MWe Bench Scale Skid Modification

New Vessel & Sweep line installed

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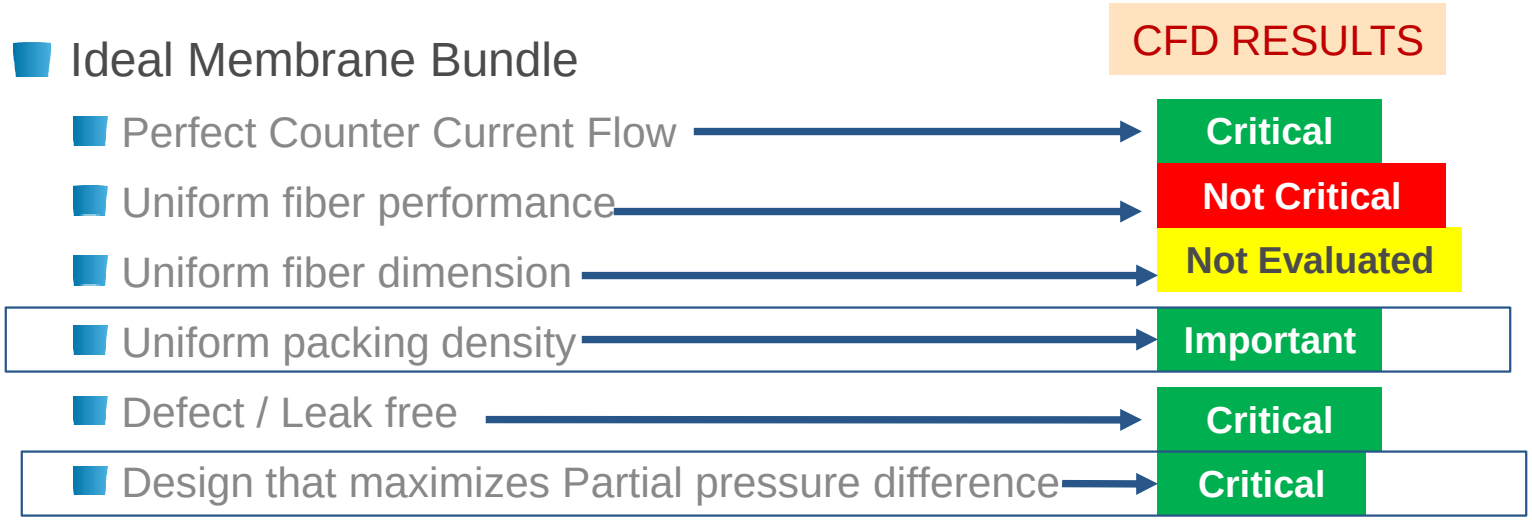
PI-1 Bundle Optimization CFD Model

- Ideal Membrane Bundle



- 2-D Axi-symmetric CFD model was developed for bore-feed counter current membrane bundle
- Several parameters were studied to identify the cause of non-ideality
- Non-idealities are more critical for high selectivity membranes operating at high recovery
  - Critical elements are different for air separation & CO_2 separation

Variable Packing Density impacts bundle performance

CAT Scan verifies radial variation in packing density for 12 inch bundle

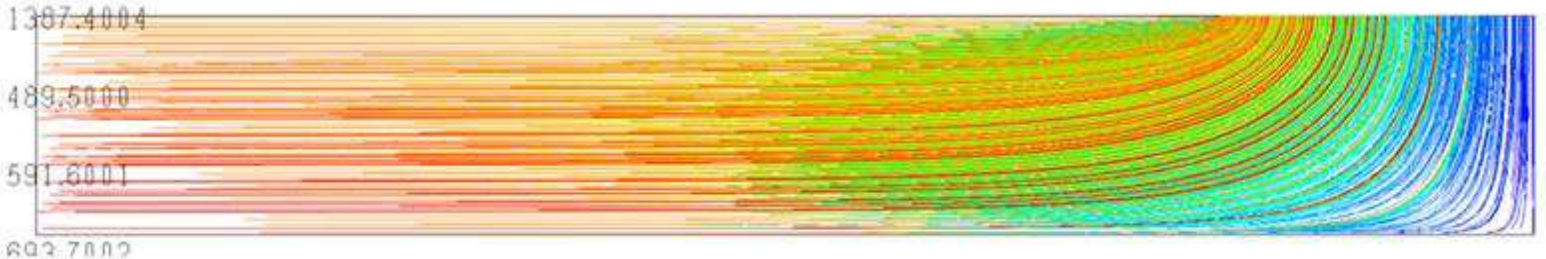
Permeate

N_2 rich Residue

Feed

Radially varying packing

Increased Cross Flow



Constant packing

Perfect Counter-current Flow

Perfect counter-current flow is important to achieve high separation performance at high CO_2 recovery

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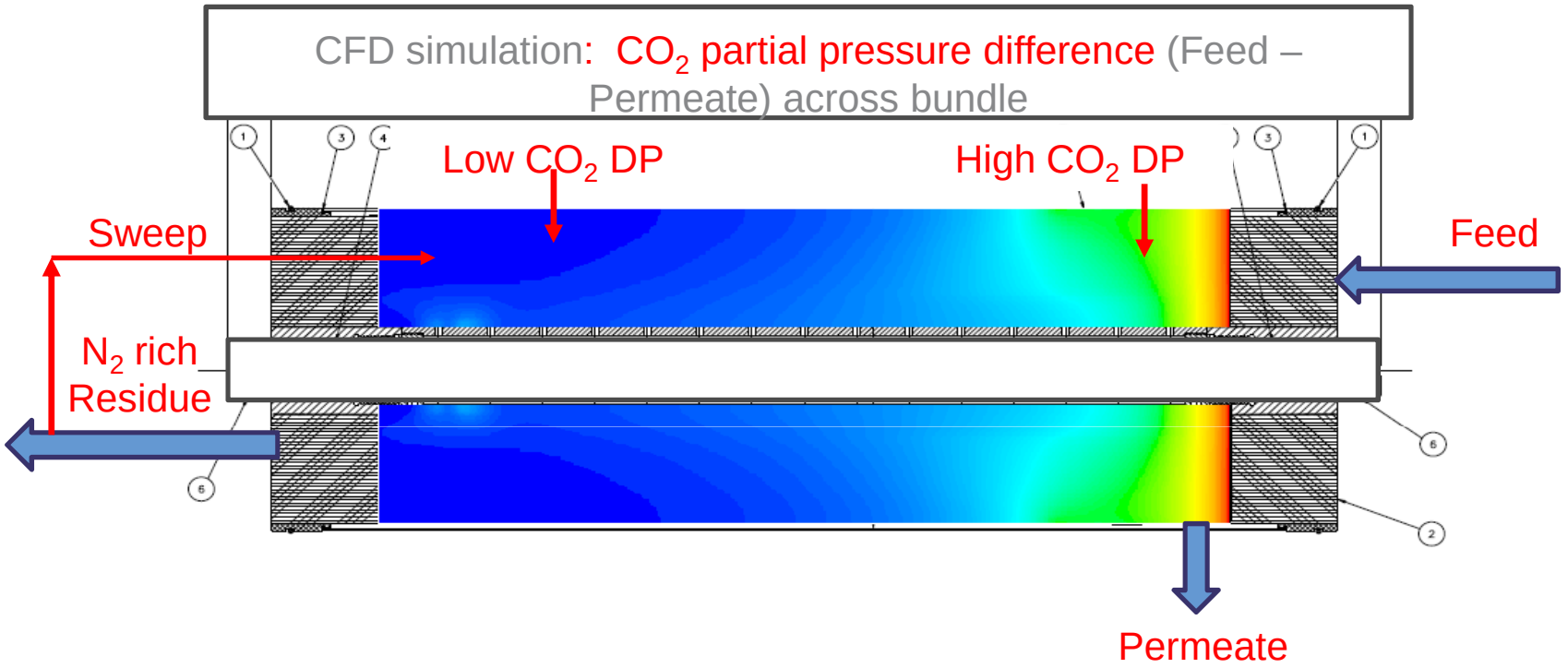
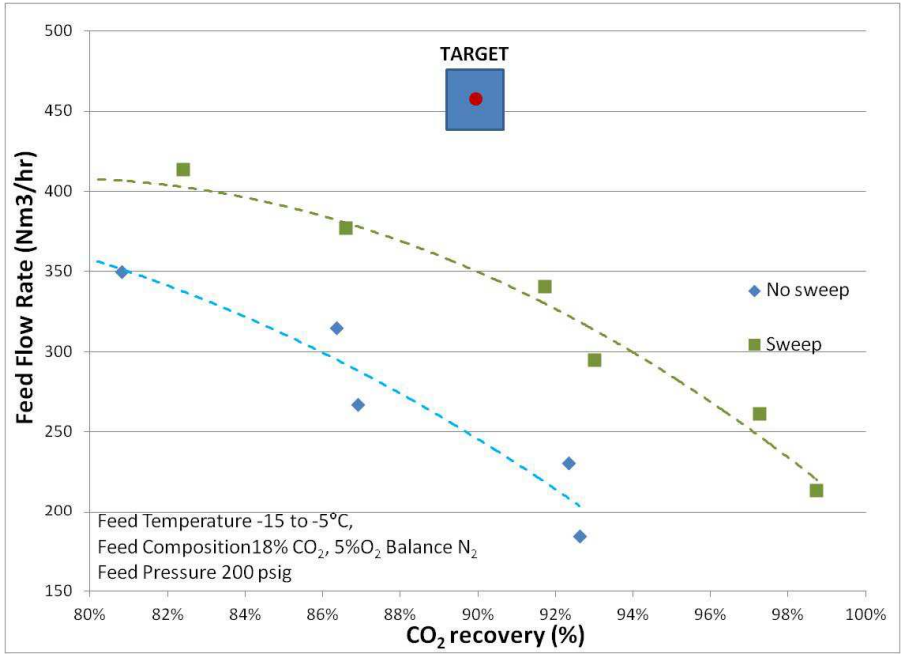
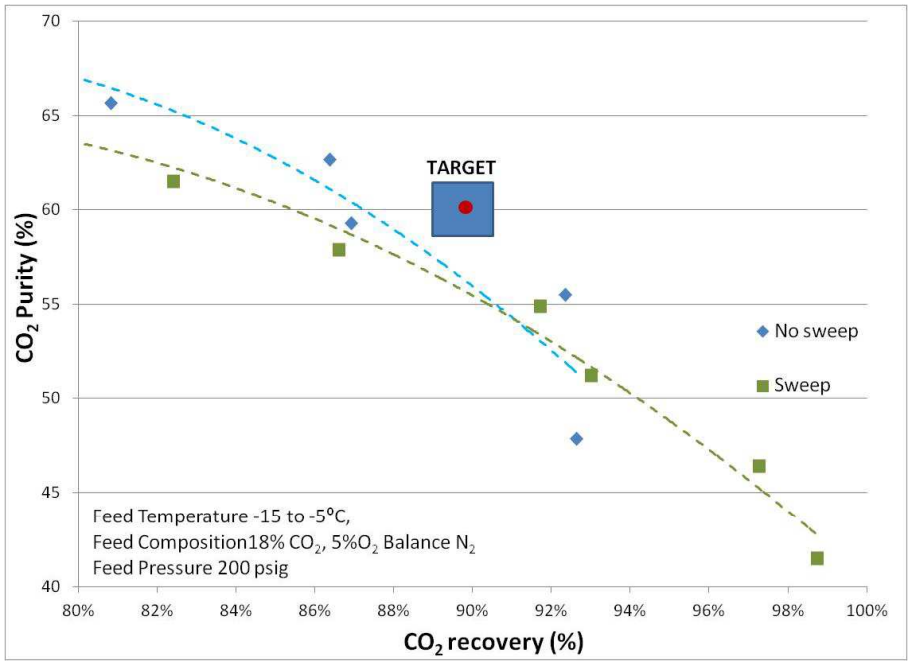
CO_2 partial pressure difference is critical



Addition of Sweep increases driving force across membrane for efficient flue gas separation

PI-1 Bench Scale Testing





- Impact of Sweep addition has been studied on the Flue gas at **-5 to -15ºC**
- Further studies will be continued at -45ºC to evaluate full potential of the cold membrane technology

ON TRACK 40% Completed – 30% capacity increase using sweep (Further Tests at -45ºC)

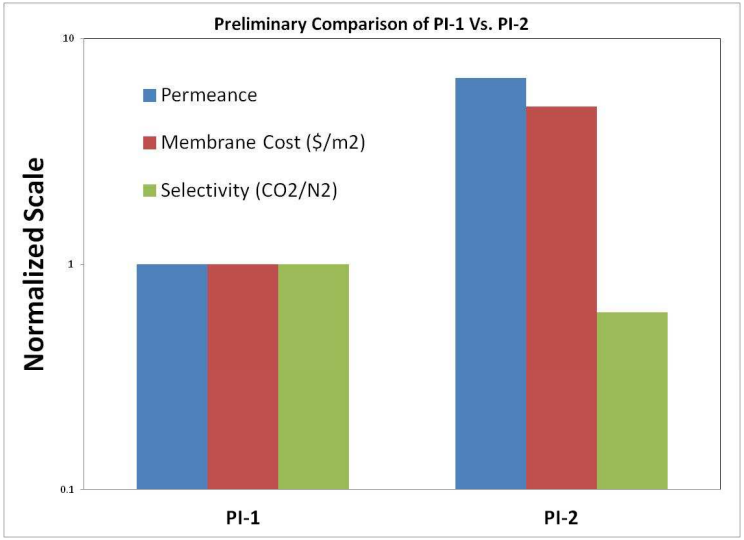
PI-2 Membrane Bundle Preparation & Testing

SCOPE

- PI-2 Laboratory trials to develop spinning techniques
- Synthetic Flue gas testing using 1 inch diameter bundle (Parametric test)
- Field test using PI-2 membrane will depend on the outcome of techno-economic comparison and performance criteria

Deliverable 1 – Bundle definition and Techno-economic comparison for PI-1 & PI-2 membrane bundle performance

PI-2 – New Material with potential 5X higher permeance



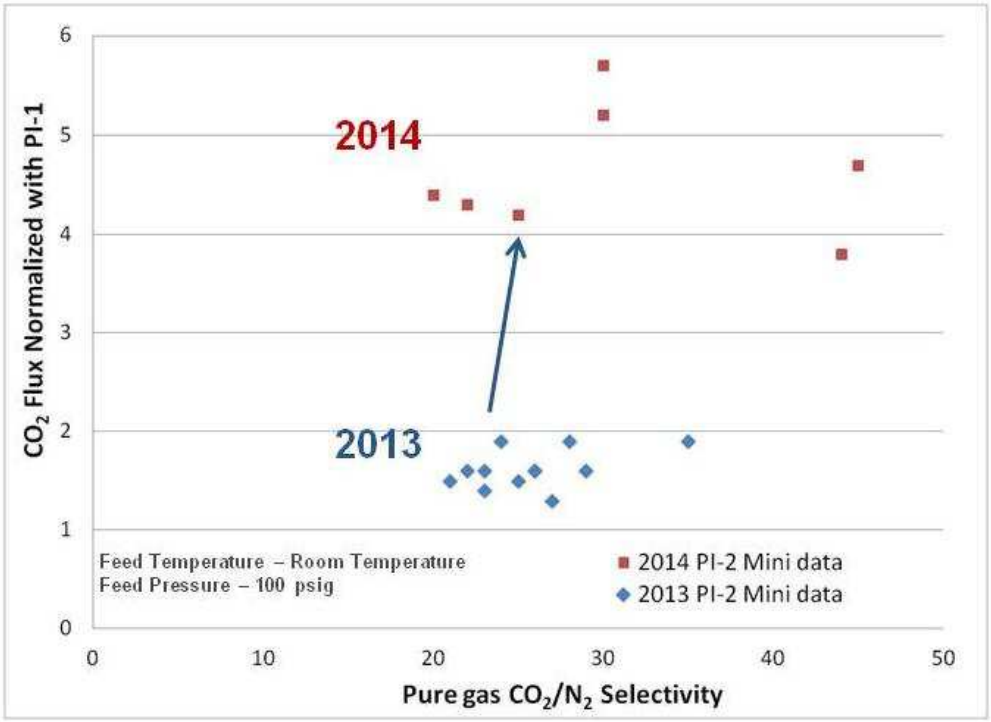
Preliminary Lab testing shows similar trend as PI-1 at low temperature

Success Criteria

- PI-2 membrane permeance-selectivity projecting to a 12” bundle with 5X feed capacity of PI-1 for 90% CO_2 capture with permeate composition >60% CO_2

PI-2 Fiber Spinning Progress

- PI-2 Spin formulation & Post-treatment procedures have been studied
  - Room temperature performance was enhanced by using different spin condition and solvent change
  - Cold temperature test in progress to reach our target performance



ON TRACK 20% Completed– 5X Performance achieved at room temperature (Further tests at cold temperature)

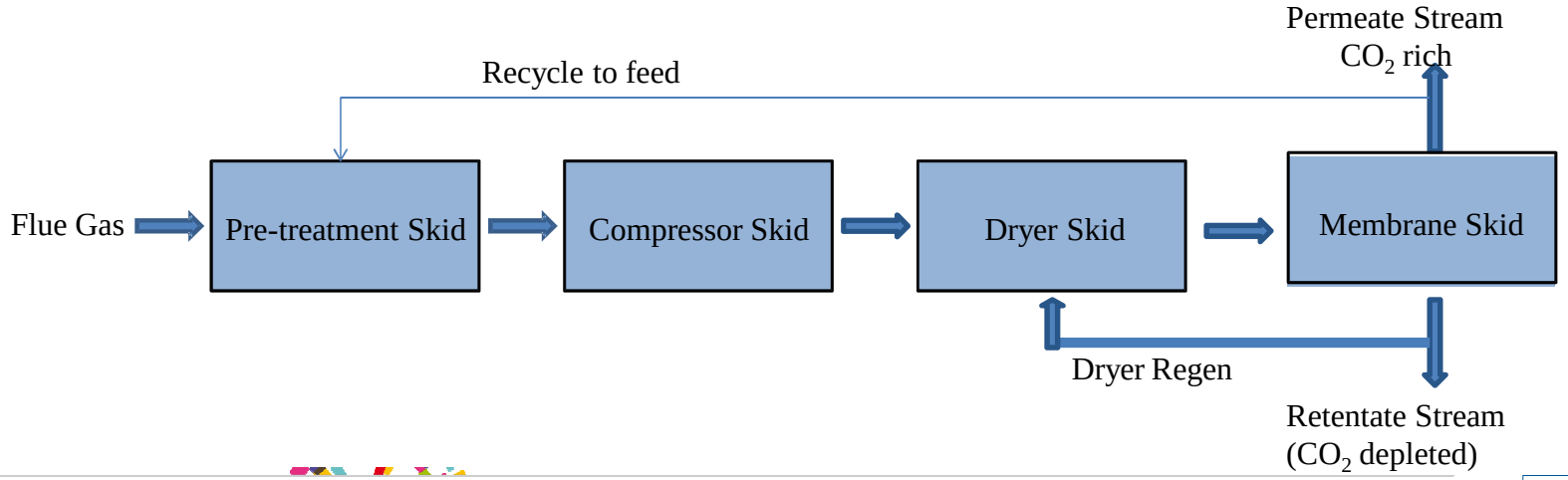
0.3 MWe Field Test at NCCC

- Scope –
  - **BP1** - Field Test Engineering Design, Procurement, Fabrication, Acceptance Testing

    Deliverable 2 – Detailed design package for 0.3 MWe Field test unit
  - **BP2** – Equipment Delivery, Installation & Commissioning, PI-1 and PI-2 testing
    - 2 month parametric tests and steady state testing

Deliverable 3 – CO_2 Capture Field Test Report for cold membrane performance at 0.3 MWe

- Success Criteria –
  - Field testing at 0.3 MW_e scale with steady state testing for 500 hours
  - Verification of process operability by processing actual treated flue gas

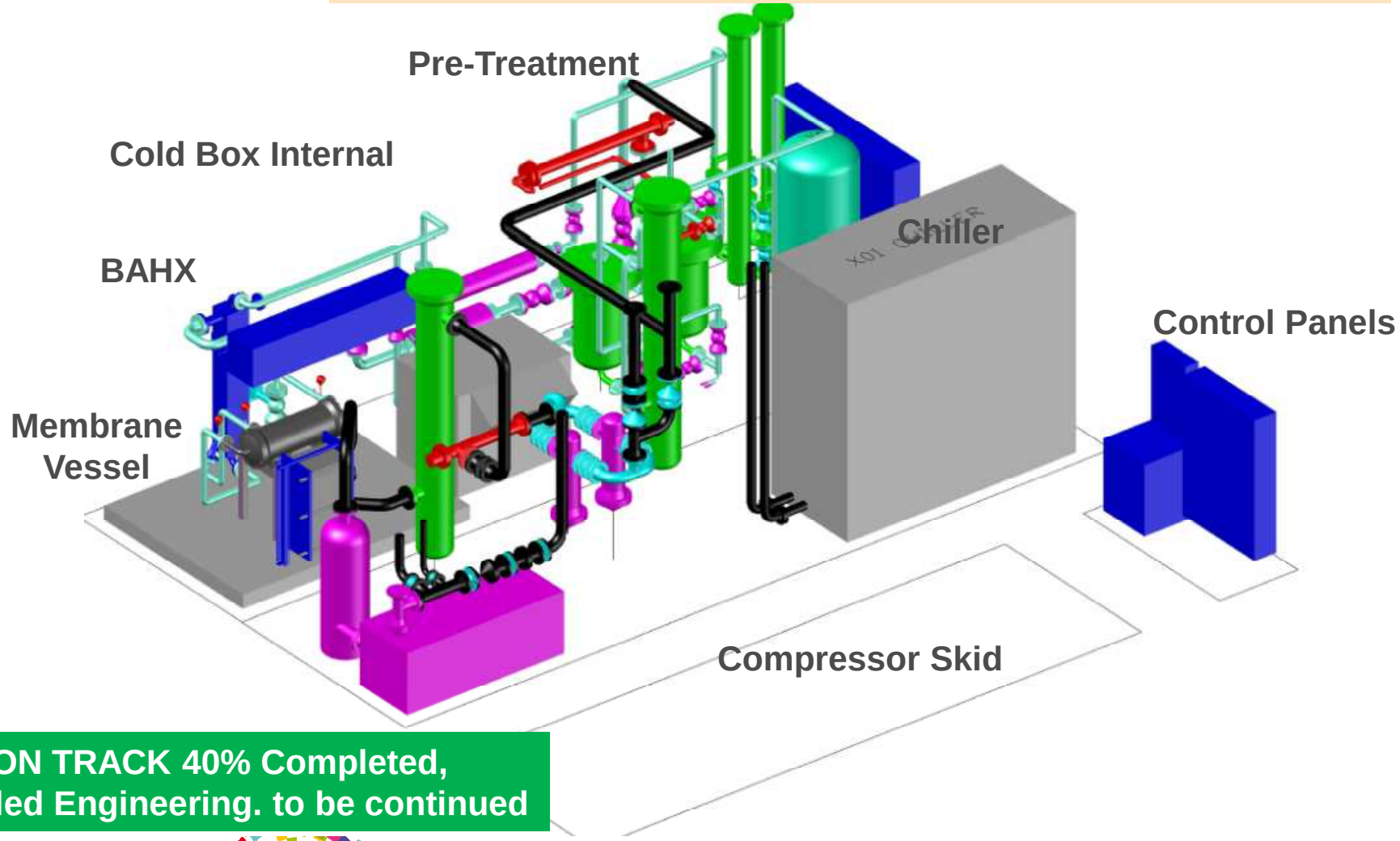


0.3 MWe Field Test at NCCC Progress

- Conceptual Engineering package is completed
  - P&ID, Process control & automation, Line & Vessel sizing
- Safety & Process Review was completed with NCCC at DRTC in March 2014
- >90% of Major equipment have been procured
- Analytical test plan is developed to identify various components to be tested at different locations during the test campaign
- Detail Eng/ Fabrication drawings – in progress
  - Detailed fabrication drawings with information such as piping, plumbing, duct work, electrical and support structure and material specifications
  - Skid Fabricator has been selected

0.3 MWe Field Test 3-D Layout

Engineering design for compressor and dryer will be used from Air Liquide Liquid CO_2 Plants for the field test at NCCC



ON TRACK 40% Completed, Detailed Engineering. to be continued

Scope for Budget Period 2

- Scope – TEA to calculate CO_2 capture cost from a 550 MWe net power plant and EH&S analysis
  - TEA will be reviewed by Parsons Government Services
- Success Criteria – CO_2 capture cost to reach DOE target of $40/tonne for 90% capture (n^{th} of a kind estimate)

Deliverable 4 – Final Techno-Economic Analysis Report

Preliminary design of Multi-Bundle pilot test for cold temperature operation

- Scope – Design multi-bundle pilot test at1-5 MWe scale
  - Preliminary design will be the basis for future project
- Status – Above tasks will be performed in Budget Period 2 (2015)

Project Risks

Project Risks	Mitigation Strategy
PI-1 Risks • 12 inch bundle lower performance compared to 6 inch bundle • Compressor limitation on existing bench-scale skid – limits low recovery test range •Project time line limits number of optimized bundles that can be manufactured & tested	**PI-1 Mitigation Strategy** • Optimization of 12 inch bundle or 6 inch bundle based solution • Some test configurations will be pushed to field test • Selective testing & CFD modeling
PI-2 Risks • Bundle manufacturing and viability for test at low temperature is unknown	**PI-2 Mitigation Strategy** • PI-1 is a commercial product, validated for low temperature
Field Test Risks • Particulates can foul the compressor or blind the hollow fiber membrane • Compressor corrosion due to acid contaminants • Acid contaminants in the presence of moisture may lead to long term hydrolysis of membrane • Design related safety issues • Final schedule for field test is TBD	**Field Test Mitigation Strategy** • Dust filtration to remove the particulates • Water knock-out and de-saturation before compressor • Dryer upstream of membrane • Detailed HAZOP review •Working closely with NCCC

Next Steps for BP1

- PI-1 Bundle Optimization
  - PI-1 Bundle testing at cold condition will continue
  - New bundles with features that address critical non-idealities
- PI-2 Fiber Preparation & Testing
  - Cold temperature test with PI-2 minis
  - 1 inch PI-2 bundle testing at cold temperature and parametric test
- 0.3 MWe Field Test design
  - Detailed Engineering will continue (3-D drawings, Review of equipment drawings, Electrical drawings and controls programming)
  - Remaining Equipment procurement
  - Skid Fabrication & Acceptance testing

ON TRACK – ON BUDGET AND ON SCHEDULE

Acknowledgement

- US DOE – José Figueroa, Lynn Brickett, Andrew O'Palko
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