NETL CO_2 Capture Technology Meeting 2015

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Creative Oxygen

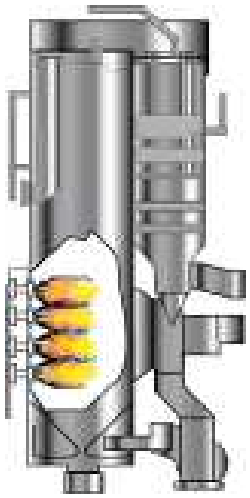
CO_2 Capture by Cold Membrane Operation with actual power plant flue gas (DE-FE0013163)

June 23rd 2015

T. Chaubey, S. Kulkarni, A. Augustine, D. Hasse,
J. Brumback, D. Kratzer, D. Calvetti, J. Ma| R&D

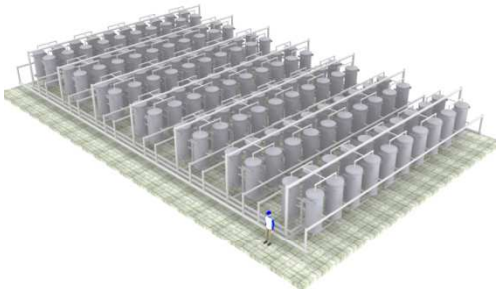
Project Summary

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



Flue Gas

Improved Performance at Cold Condition



CO_2 for sequest. or EOR

POWER PLANT

COLD MEMBRANE

LIQUEFACTION

- Cold membrane testing at 0.1 MWe with synthetic flue gas (TRL4) in 2012
  - CO_2 Capture Cost estimated at 46-52$/tonne (DOE Target - $40/tonne)
- Current project will test the cold membrane technology at 0.3 MWe scale (TRL5) at National Carbon Capture Center (NCCC)

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Project Team

AIR LIQUIDE (R&D, MEDAL, E&C)

- Membrane experts – Sudhir Kulkarni, David Hasse, Karl Beers (MEDAL), Jean-Marie Gauthier (MEDAL)
- Process experts – Trapti Chaubey, Alex Augustine, Paul Terrien (E&C), Alfredo Velasco (MEDAL)
- Modeling expert – Jiefu Ma
- Senior Technicians – Jacob Brumback, Dean Kratzer, Judy Huss
- Engineering Services – Dennis Calvetti, Robert Sokola, Hwanho Kim
- AL management – Robert Gagliano, David Edwards, Ed Sanders

External Partner - PARSONS GOVERNMENT SERVICES

- Brad Knutson

TEST SITE - NATIONAL CARBON CAPTURE CENTER

- Tony Wu, Eric Fleming, Barton Pate, Max Phillips, Bob Lambrecht, Mike England

Agenda

- AL Motivation & Roadmap
- Hybrid Cold Membrane Technology
- Project Overview
- Project Progress
- Project Risks
- Next Steps

Air Liquide Motivation

MARKET

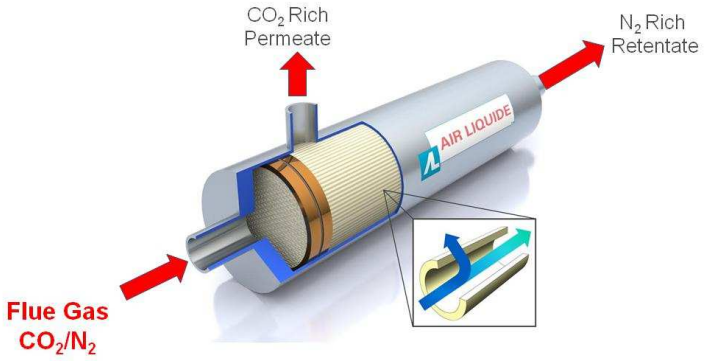
- CO_2 as a Product - 12 CO_2 plants in US
- CO_2 for EOR application – Huge potential market

SOLUTION

- CO_2 Separation technologies such as cold membrane hybrid process, liquefaction plants, adsorption and absorption

PROBLEM

- CO_2 Generator – 22.9 MMt of CO_2 emitted in 2014 worldwide
  - AL SMR plants, cogen plants, Electricity for ASU and other applications
- CO_2 emission equivalent to 7 Commercial power plants



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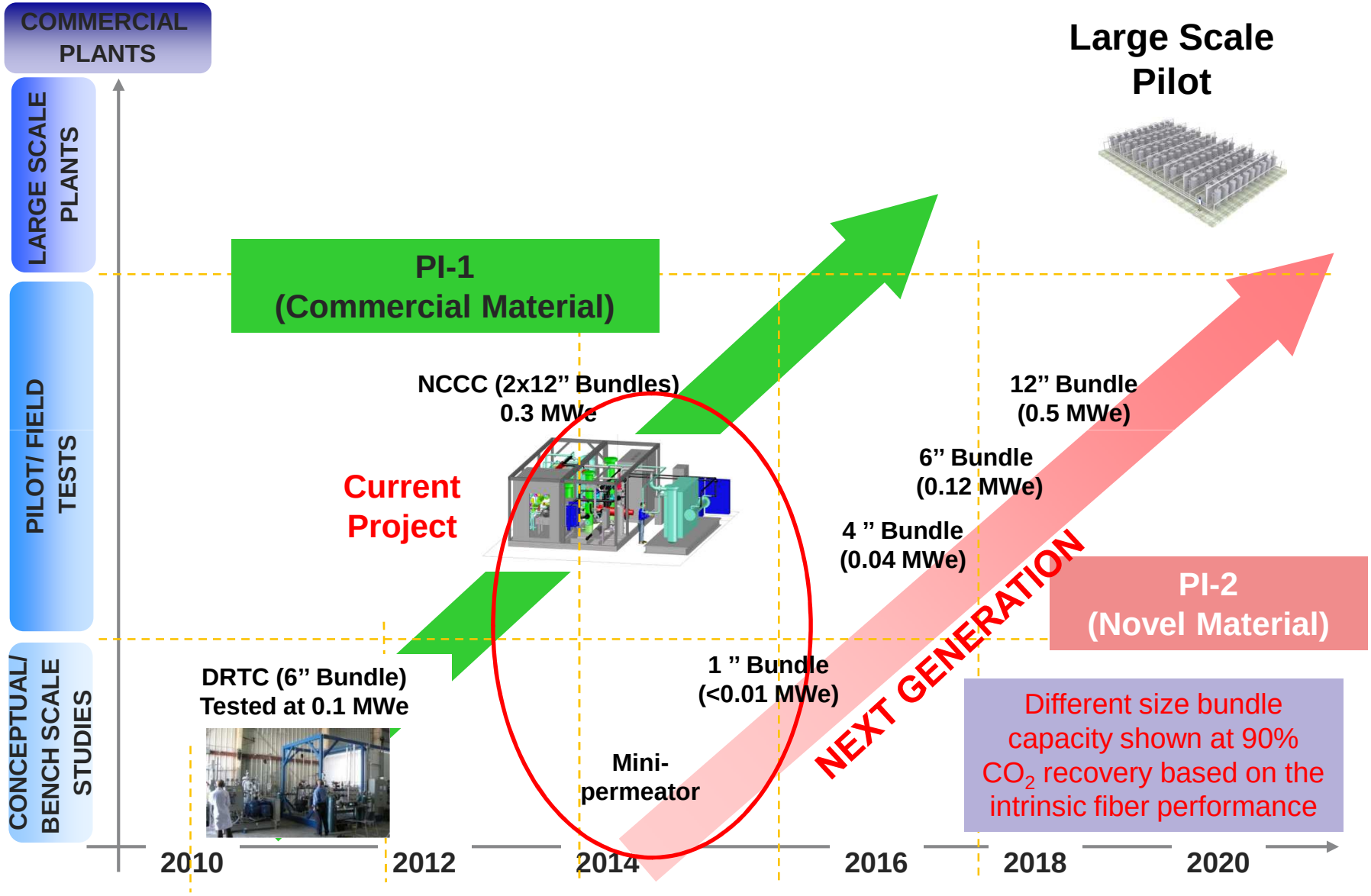
Air Liquide Roadmap for Post-Combustion Capture



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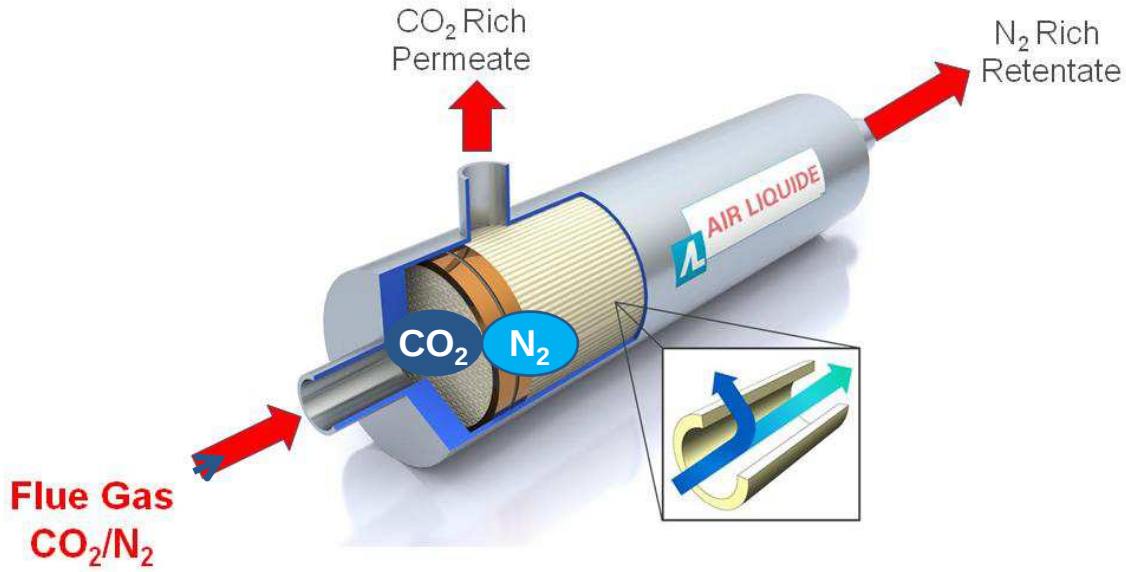
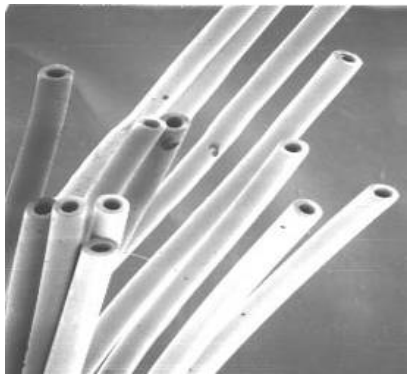
Cold Membrane Process Based on Hollow Fiber Membrane



- Key Parameters for high membrane performance
  - High surface area/vol, Good intrinsic property, very low thickness
  - High productivity/bundle is critical meeting the permeate purity spec



>5X Surface area/volume compared to spiral membranes.

Cost effective solution at large scale application

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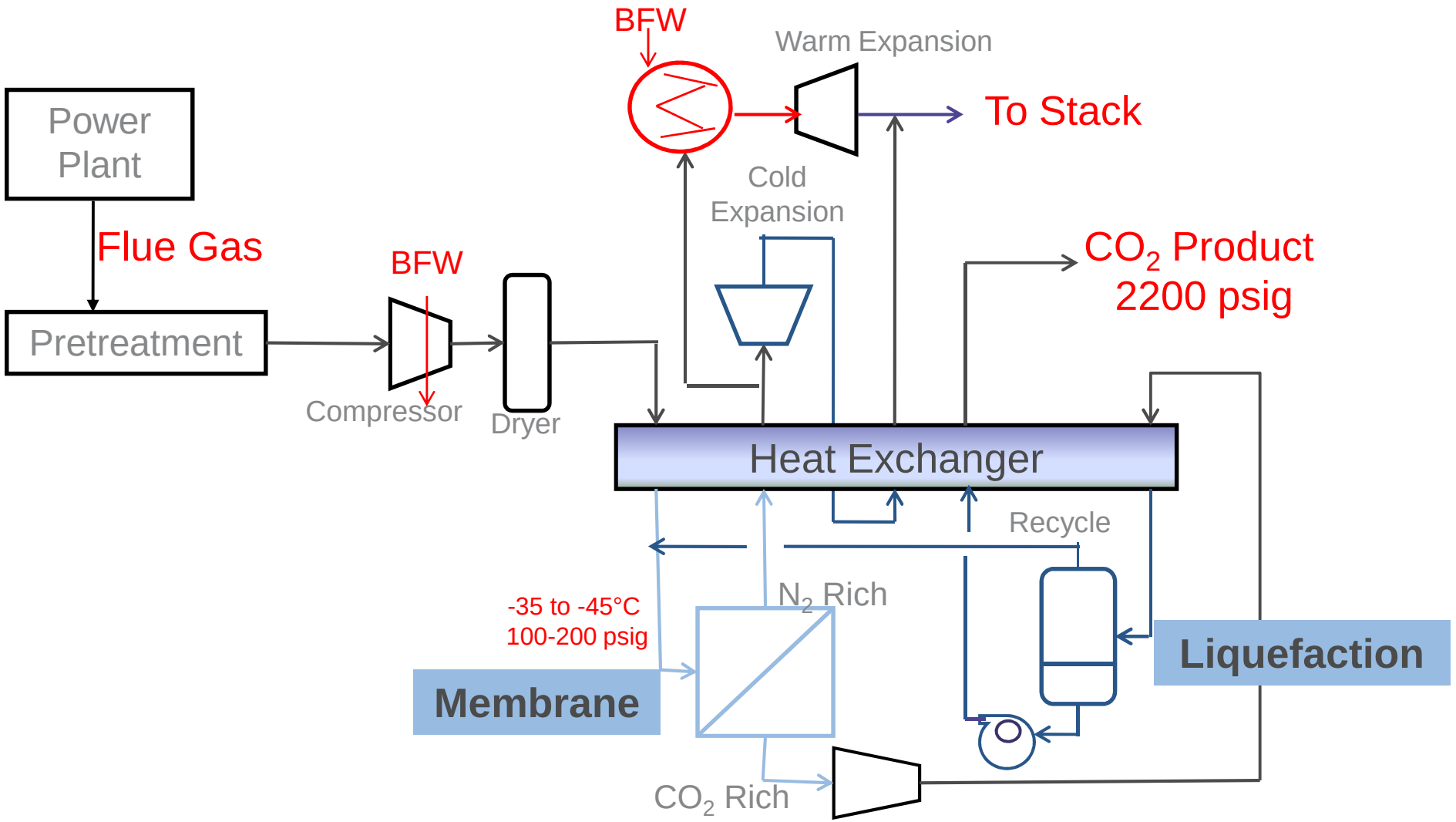
Hybrid Membrane + Liquefaction Configuration



All technology bricks have been demonstrated with the exception of membrane with real flue gas

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Project Overview: DOE NETL Award No. DE-FE0013163

Total Budget : $5.88MM, DOE Funding - $4.7MM ; Cost share - $1.17MM

	DOE Share	AL Cost Share
Budget Period 1 (Oct 2013 – June 2015)	$3,369,528	$842,382
Budget Period 2 (July 2015 – Dec 2016)	$1,338,964	$334,741

Period of Performance: 10/01/2013 through 12/31/2016 over 2 Budget Periods

NETL Project Manager: José Figueroa

Prime Recipient: American Air Liquide DRTC

Project Sub-awardees: MEDAL (Bundle Optimization support, Detailed engineering), E&C (Basic Engineering & TEA), Parsons (TEA Review)

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

Project Schedule & Status

Main Tasks	Start	End	Milestones/ Success Criteria	Status
BUDGET PERIOD 1 (BP1) Oct 2013 to June 2015				
PI-1 Optimization & Testing	Oct 2013	March 2014	>30% improvement in bundle productivity	**COMPLETED**
PI-2 Bundle Preparation & Testing	Oct 2013	June 2015	4-5X Projected Bundle Productivity compared to PI-1	**COMPLETED**
Design and fabrication of 0.3 MWe field test unit	Oct 2013	June 2015	Fabrication, Installation, Acceptant Testing of FTU	**COMPLETED**
BUDGET PERIOD 2 (BP2) July 2015 to December 2016				
Field Test at NCCC	July 2015	July 2016	500 hours of steady state testing	Target 2016
TEA	July 2015	Dec 2016	$40/tonne CO2 capture cost	Target 2016
Preliminary design next phase	July 2015	July 2016	Preliminary design and costing of next phase	Target 2016

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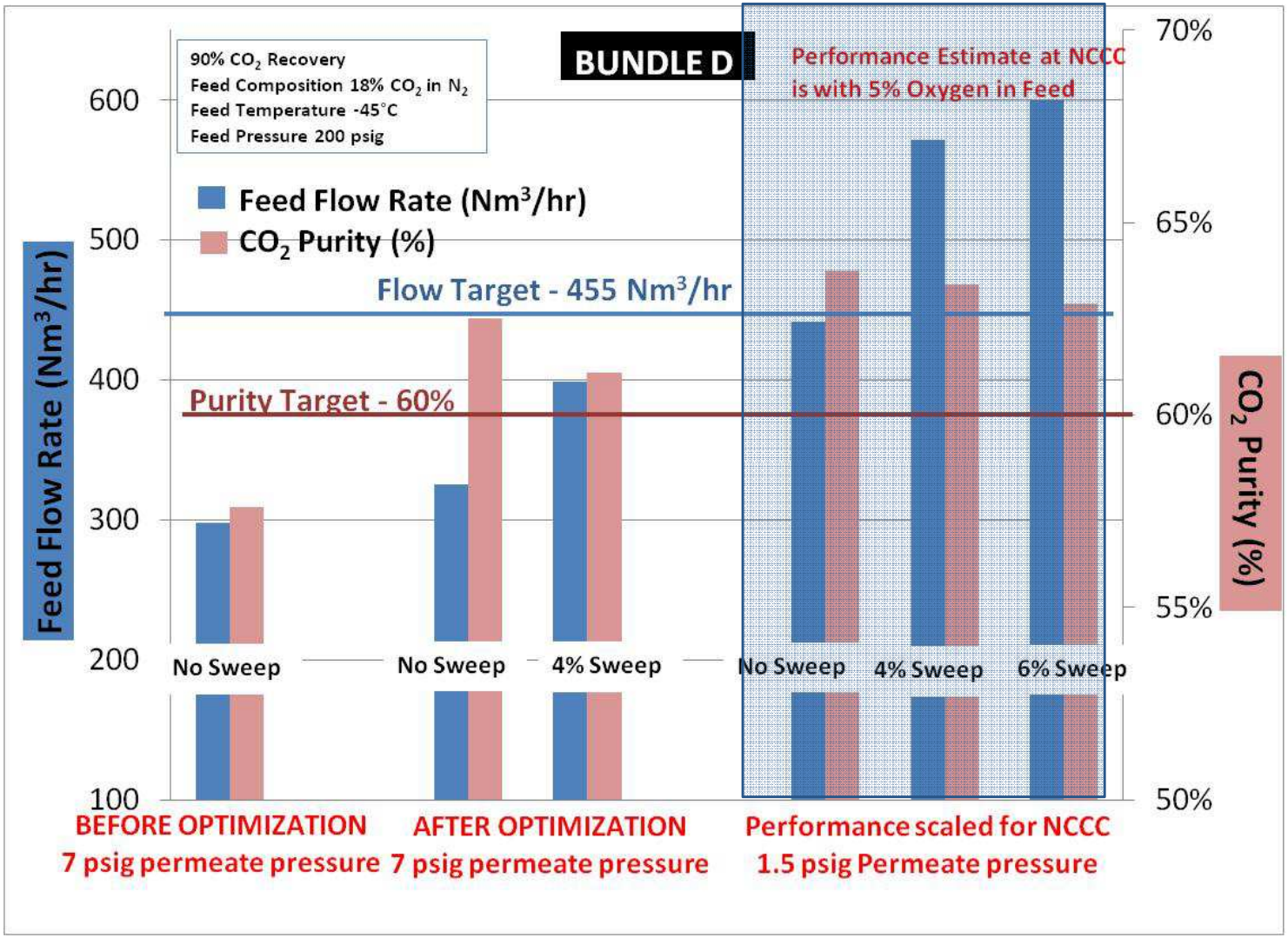
PI-1 Bundle Testing Summary

- PI-1 Commercial Bundles tested for >13,700 hours
  - Current Project - Six 12 inch bundles ~6500 hours
    - 4 Bundles Qualified for field
  - Previous Project - Two 6 inch bundles – 7200 hours
- Completed Bundle Optimization and testing with synthetic flue gas
- Process simulation used due to current bench scale skid (0.1 MWe) limitations:
  - Feed flow rate 400 Nm3/hr
  - Permeate pressure 7-8 psig
- Process Performance is scaled to NCCC conditions
  - Feed flow capacity at NCCC~1000 Nm^3/hr (0.3 MWe)
  - Lower permeate pressure at NCCC test conditions (Target – 1.5 psig with single bundle)

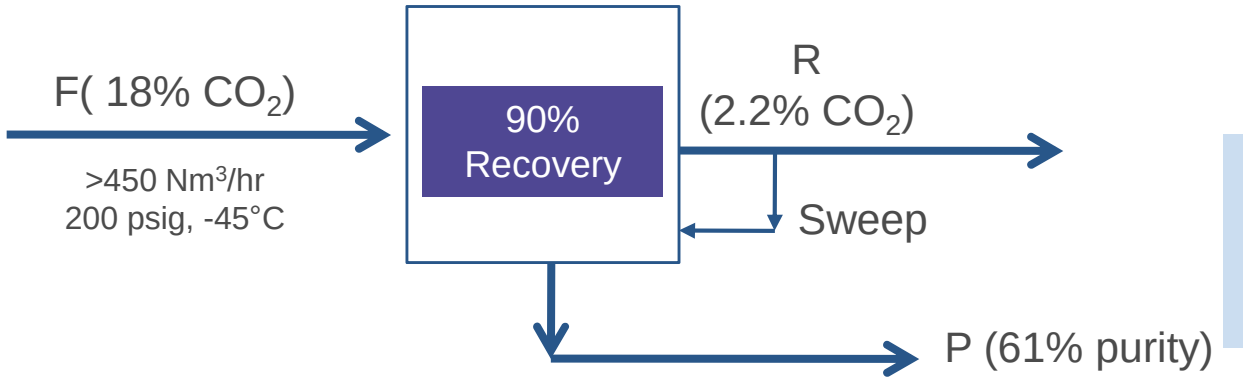
90% CO_2 Capture Data & Performance scaled for NCCC



>30% Improvement in Bundle Productivity has been achieved with the combination of simulation and experiments

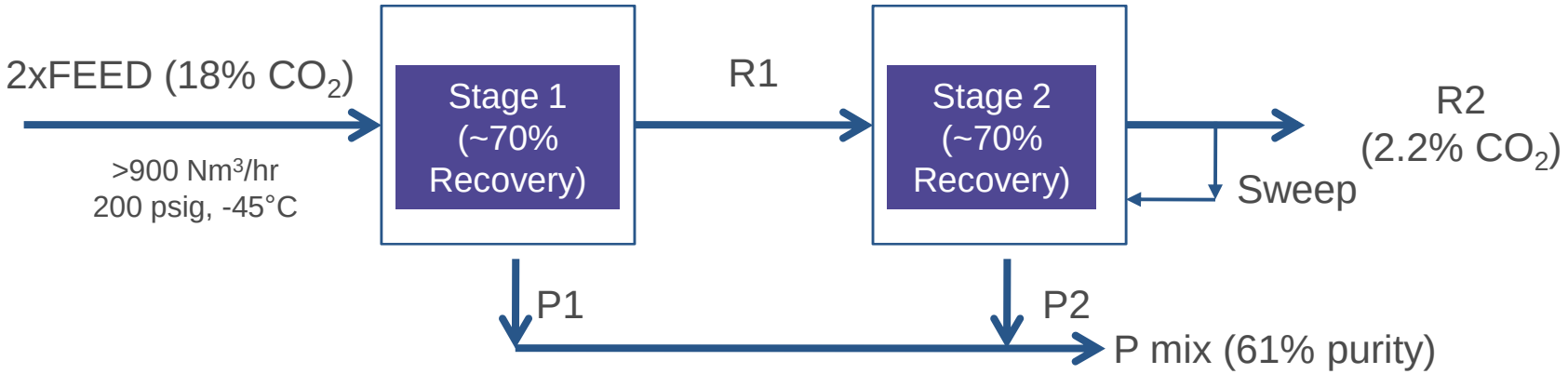
Membrane Bundle Configurations at NCCC

- Single Stage Configuration



Permeate is further purified in a liquefier

- 2 Stage Configuration in Series – Completed bench scale test (0.1 MWe) at different feed composition to validate the concept



Multiple Configurations will be tested at NCCC
Single stage, 2 bundles in series or parallel

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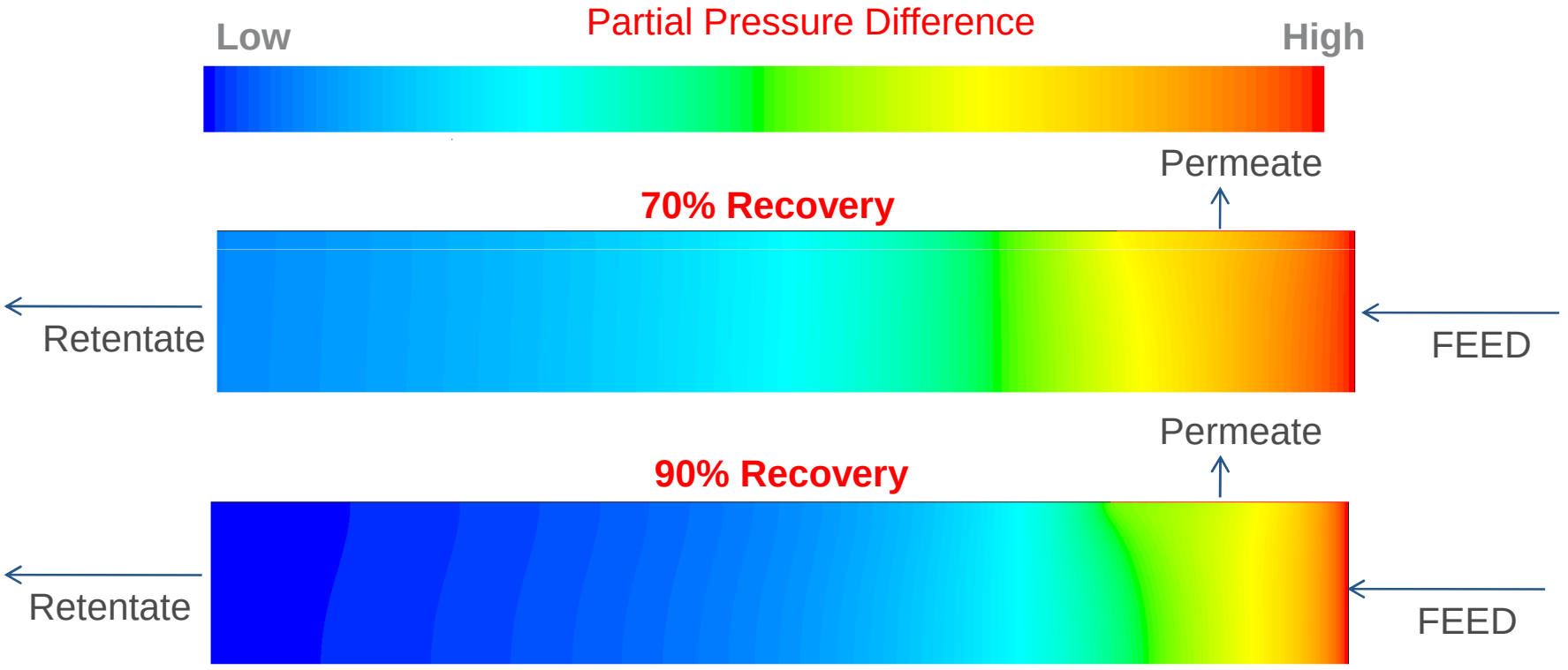
2 Stage Configuration – CFD Analysis

- Both stages will operate at 65-70% CO_2 recovery for overall 90% recovery
- Total number of bundles will be reduced for the final solution



Higher Driving force at 70% CO_2 Recovery

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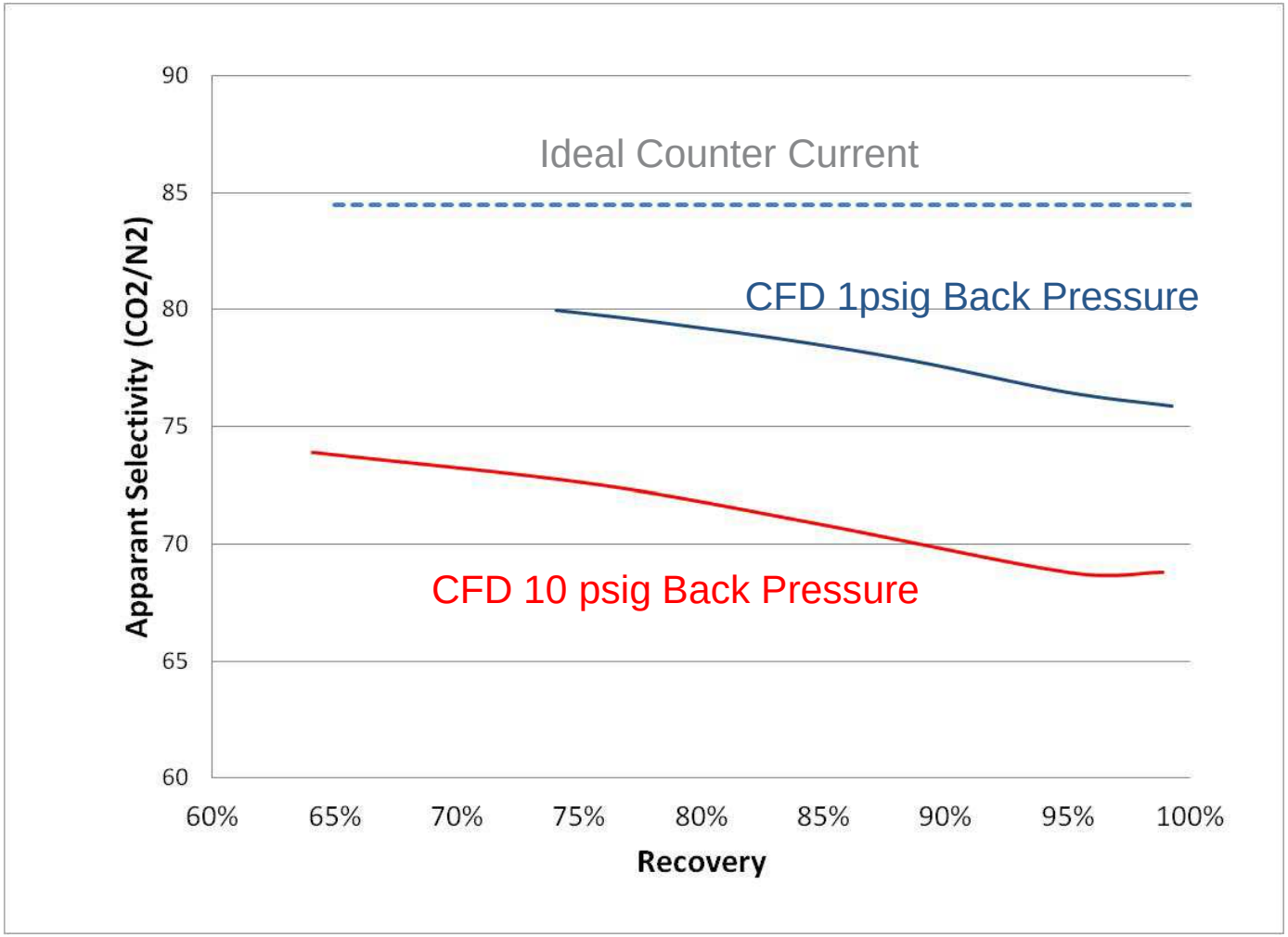
2 Stage Configuration – CFD Analysis



Bundle Non-ideality is dominant at high CO_2 recovery and accentuated at higher permeate pressure

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PI-2 Membrane Development Summary

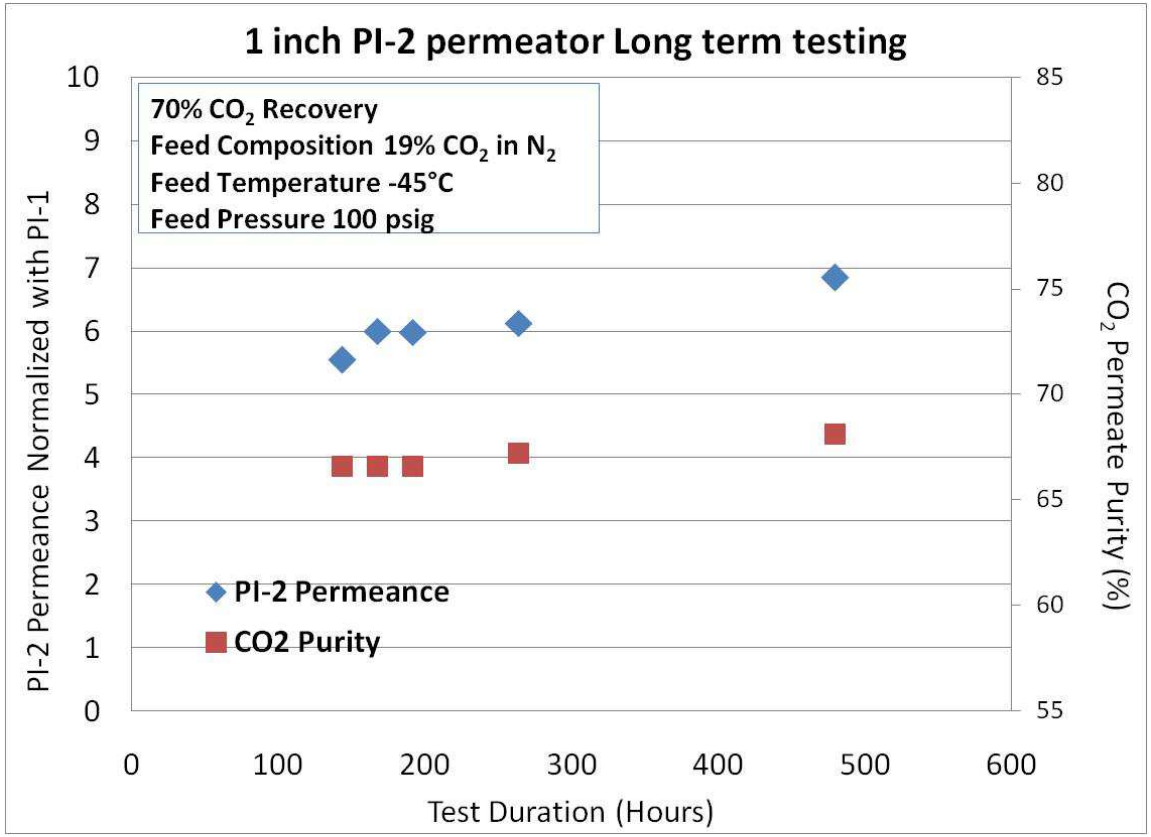
- Laboratory trials to develop spinning techniques for PI-2 membranes
  - CO_2 permeance is >5X compared to PI-1 material
  - Increase in membrane separation performance at lower temperature consistent to PI-1
- Scale-up in the current project

	Fiber Count Compared to Mini-Permeator	Synthetic Flue gas test	Real Flue Gas Test (NCCC)
Mini-Permeator	1X	Test Completed	-
1 inch Permeator	25X – 45X	Test in progress (3 Permeators qualified for NCCC)	BP2 (Campaign 1)
1 inch Bundle	250X – 350X	BP2	BP2 (Campaign 2)

- Challenges with PI-2
  - Polymer qualification
  - Fabrication scale-up

1 inch PI-2 Permeator Testing

- MEDAL commercial 1 inch bundle design is used to prepare PI-2 permeators
- 1 inch permeator testing is in progress
  - Long term testing is continuing for >500 hours



Performance is stable after >500 hours long term testing at cold temperature

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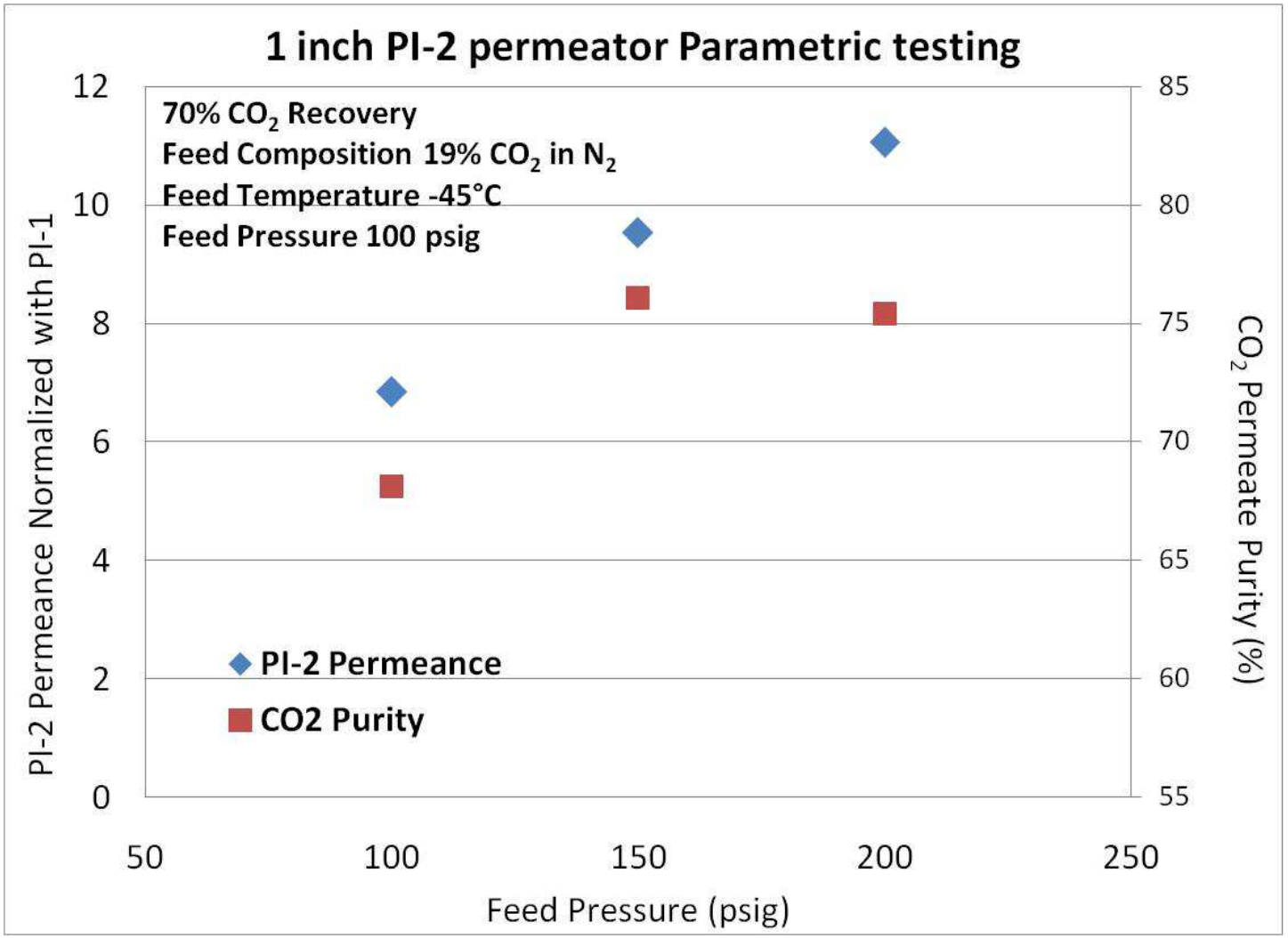
PI-2 Permeator Parametric Testing



Fiber Performance target has been met.
Projected 4-5X Bundle Productivity compared to PI-1

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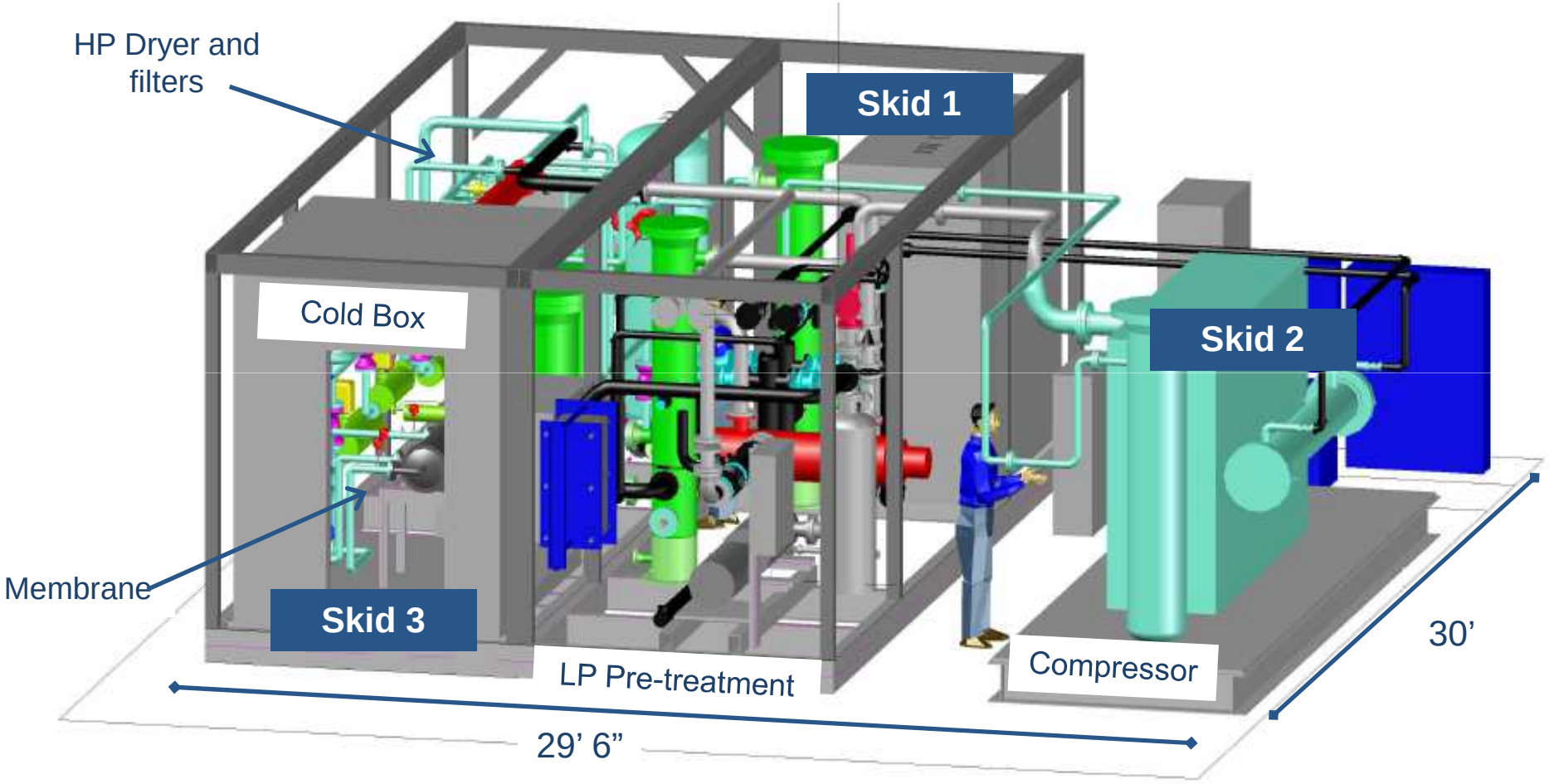
FIELD TEST UNIT

0.3 MWe Field Testing at NCCC



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0.3 MWe Field Test Unit Design and Construction

Process equipment installation and acceptance testing is complete

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0.3 MWe Field Test Unit Design and Construction

Compressor Skid is ready and stored at NCCC

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Project Risks

Project Risks	Mitigation Strategy
PI-1 Risks • Lower performance of 12 inch bundle compared to 6 inch	**PI-1 Mitigation Strategy** • Bundle Optimization
• Bench scale skid limitation	• Process simulation used. Validation by field testing
•Optimized bundle testing limited due to time	• Selective testing & CFD modeling
PI-2 Risks • Bundle manufacturing and viability for test at low temperature is unknown	**PI-2 Mitigation Strategy** • Laboratory Testing at low temperature
• Polymer Qualification for membrane • Scale-up	• Close Collaboration with supplier • Different phases of development

Project Risks

Project Risks	Mitigation Strategy
Field Test Risks	**Field Test Mitigation Strategy**
• Particulates can foul the compressor or blind the hollow fiber membrane	• Dust filtration to remove the particulates
• Compressor corrosion due to acid contaminants	• Water knock-out and de-saturation before compressor
• Acid contaminants in the presence of moisture may lead to long term hydrolysis of membrane	• Dryer upstream of membrane
• Design related safety issues	• Detailed HAZOP review
• Uncertainty in field	• Extensive acceptance testing, AL experience and close collaboration with NCCC

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Next Steps - Budget Period 2 (July 2015 – Dec 2016)

- 0.3 MWe Field testing at NCCC (October 2015 – July 2016)
- PI-2 bundle fabrication
- TEA and EH&S analysis for CO_2 capture using cold membrane technology
  - Comparison between different membrane configurations
  - PI-1 versus PI-2 membrane material
- Preliminary design of next phase

Acknowledgements & Disclaimer

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