IEA 4th Post Combustion Capture Conference:

CO_2 Capture by Cold Membrane Operation (DE-FE0013163 & FE0026422)

Air Liquide
Creative Oxygen

September 5, 2017

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Air Liquide and MEDAL

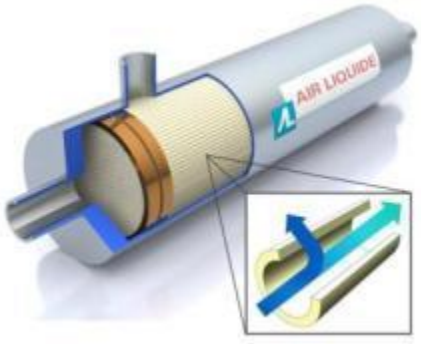
World leader in industrial and medical gases

68,000 employees

$19 billion sales (2016)

N_2 applications / markets

- OBIGGS
- Maritime
- Food & Bev
- CB Inerting
- UB Oil Drilling



H_2 applications / markets

- Refinery Off-gas Streams
- Chemical Synthesis

CO_2 applications / markets

- CO_2 Capture / CO_2 Sourcing
- Fuel Gas
- Biogas
- NG Sweetening
- EOR
- NG Trimming

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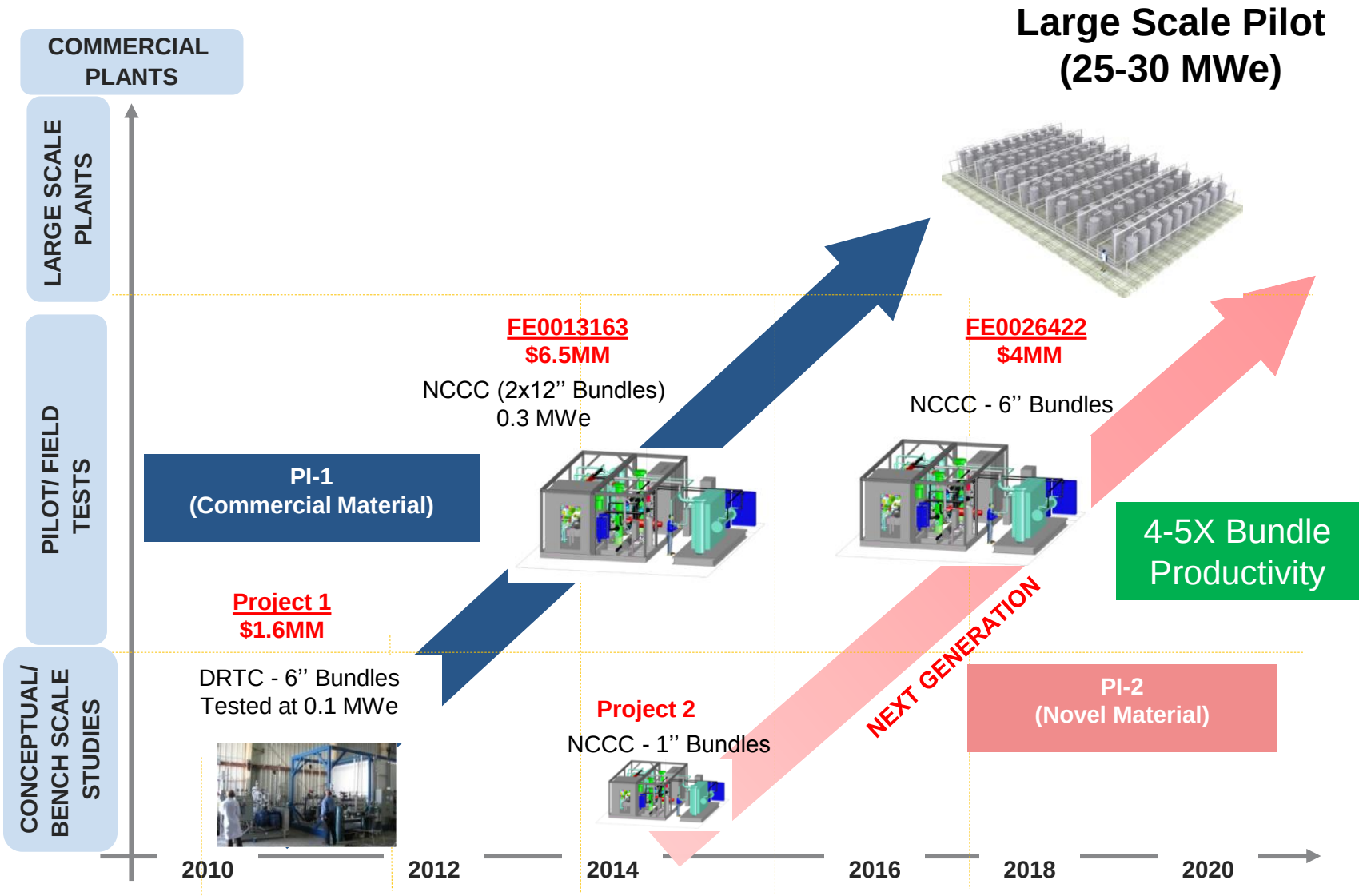
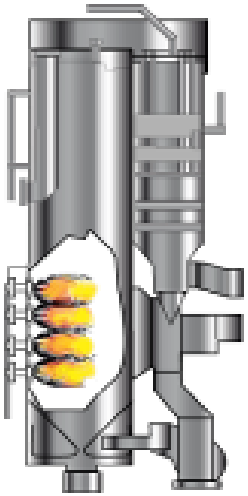
Cold Membrane Technology Roadmap



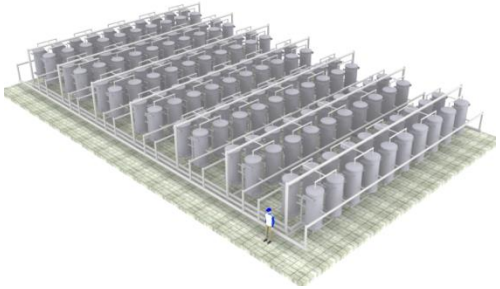
Technology Summary

- Air Liquide hybrid cold membrane / liquefaction process for 550 MWe scale



Flue Gas

Improved performance at cold temperature



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)
- Tested PI-1 material at 0.3 MWe scale (TRL5) at the NCCC
- Plan to test novel PI-2 material at 0.3 MWe scale at the NCCC, late 2017

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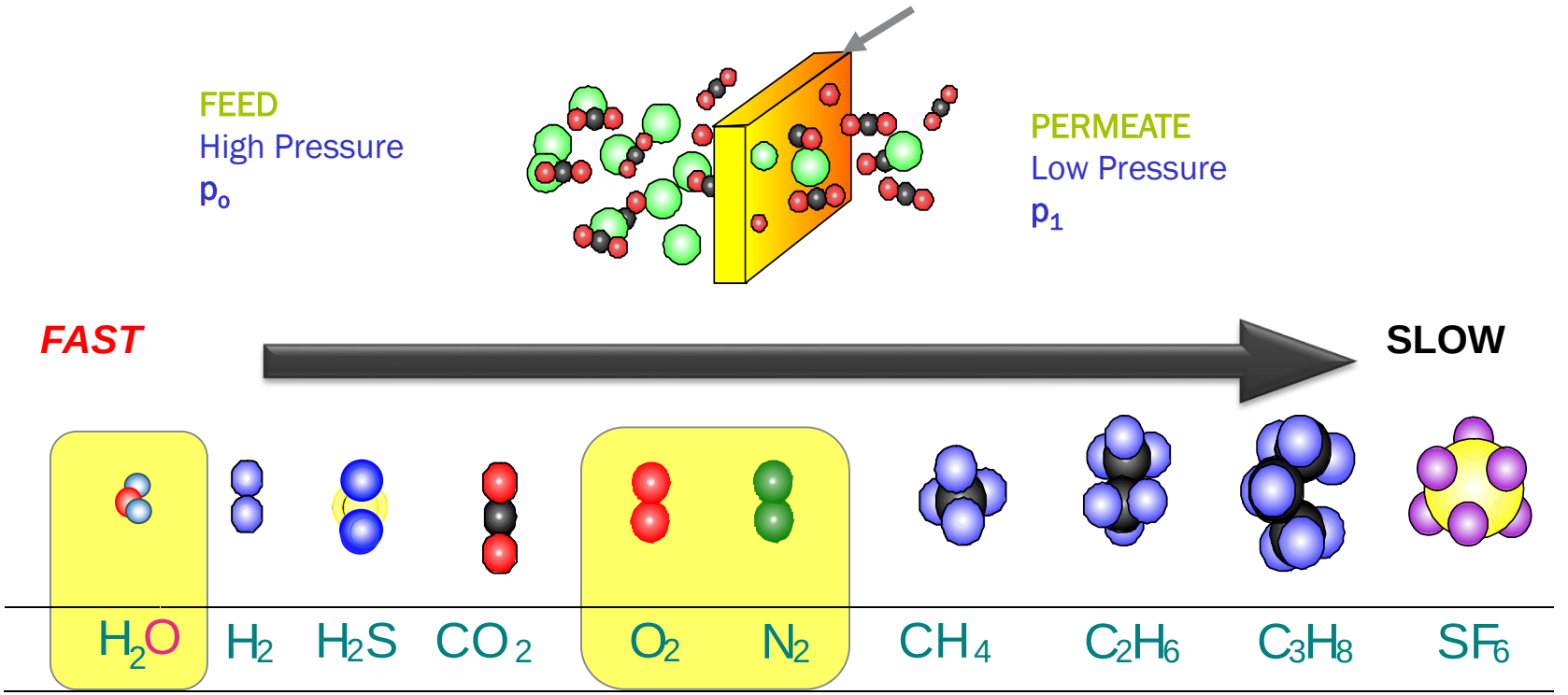
Membranes at a Glance

A thin barrier that allows selective passage of molecules at different rates



A simple technology which requires

… no moving parts

… no external energy

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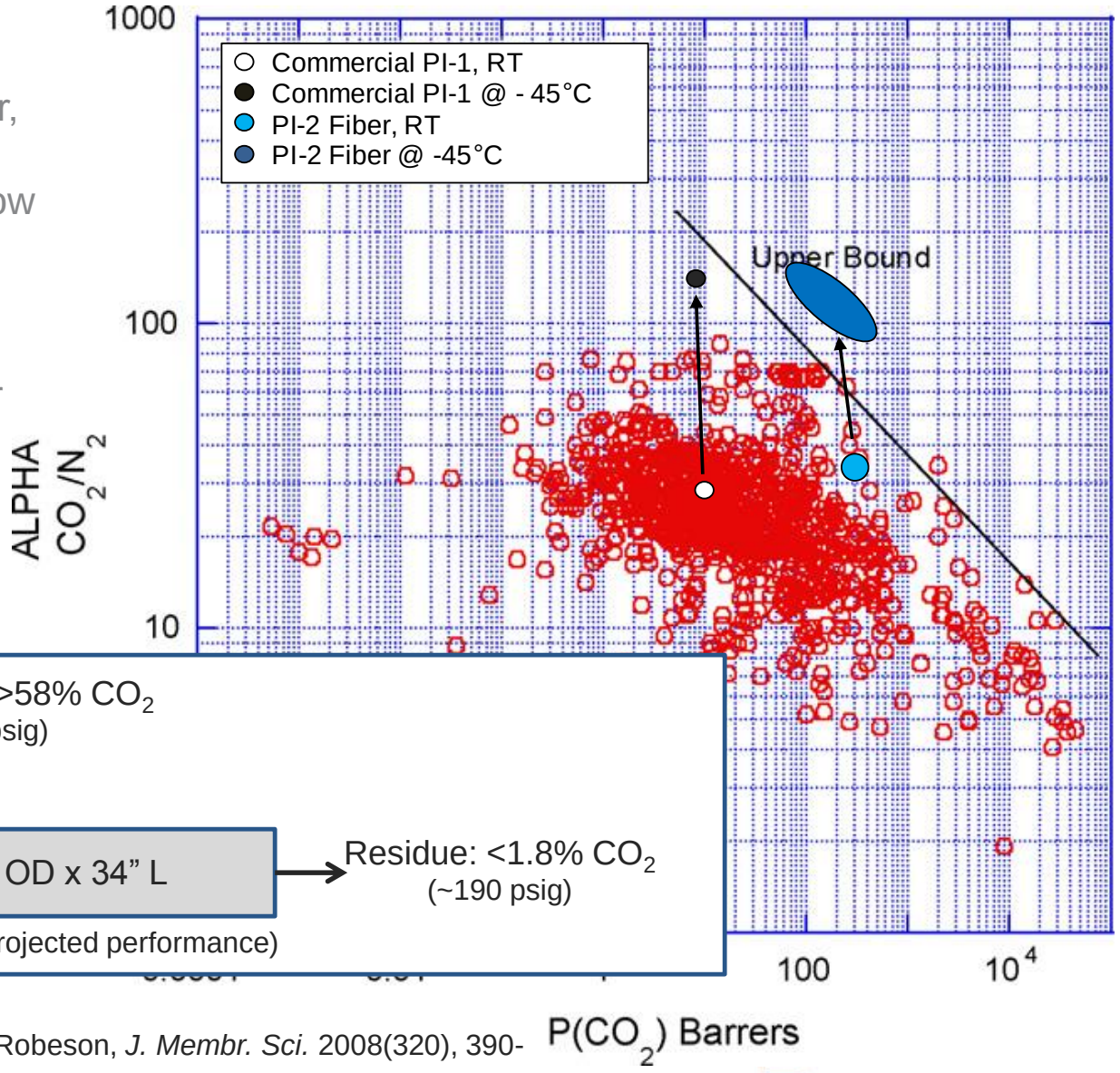
Background: Novel PI-2 Membrane Material

PI-1 standard product

- 1,000's of modules per year, dozens of applications
- Performance improves at low temperature

PI-2 novel material

- Permeation properties near Robeson* upper bound
- Spinnable
- Performance at NCCC over 500+ hours



Permeate: >58% CO_2
(~1 psig)

Feed: 3,300 Nm^3/h
(0.6 MWe eq.)
18% CO_2, 200 psig, -45°C

12" OD x 34" L

(1 module, projected performance)

Residue: <1.8% CO_2
(~190 psig)

*Robeson, *J. Membr. Sci.* 2008(320), 390-

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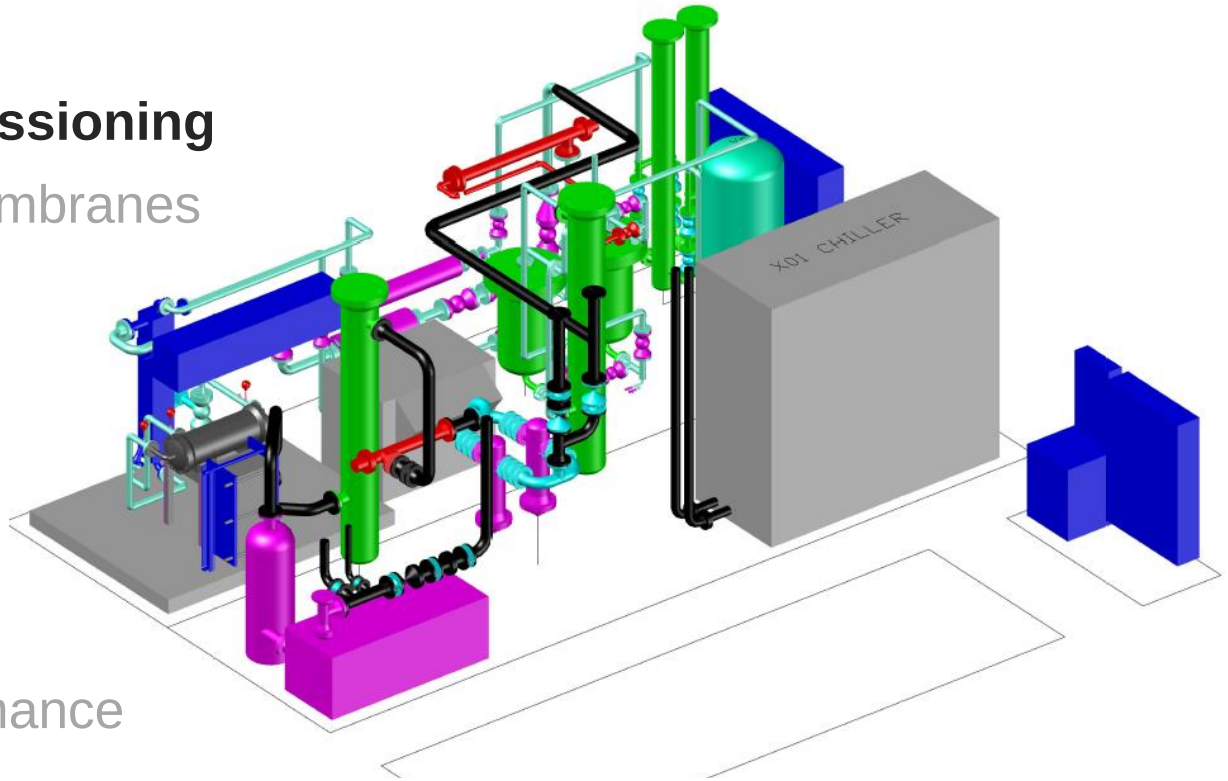
Agenda

- Project & Technology Overview
- **NCCC Testing**
  - **Installation/Commissioning**
  - PI-1 commercial membranes
  - PI-2 novel material
- 550 MWe TEA
- Next Steps
  - PI-2 manufacturing
  - Bench scale performance
  - NCCC test plan



(early 3-D mock-up of 0.3 MWe skid)

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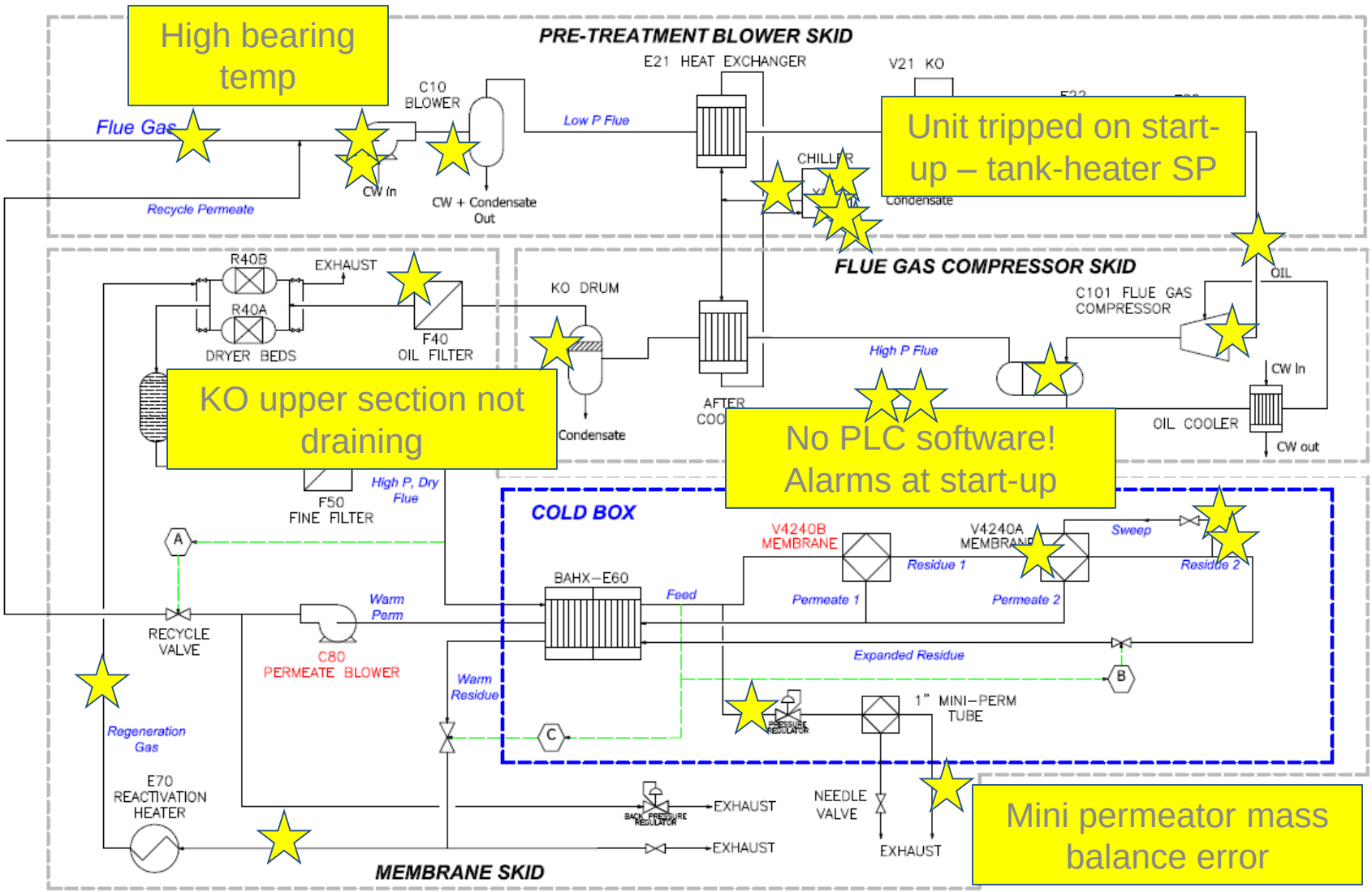
Field Test Unit Commissioning at NCCC



Key takeaway: thorough acceptance test and commissioning!

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DRTC TEAM AT NCCC:
Install: Aug-2015, Testing: Oct-2015

Testing at the NCCC

PO-4 (Oct – Dec 2015) Objectives:

- Validate enhanced performance with real flue gas — **Complete**
- Long term test with PI-1 and small (1”) PI-2 — **Complete**

PO-5 (May – Nov 2016):

- Parametric testing 6” and 12” PI-1 bundle, 1” PI-2 — **Complete**
- Flue gas contaminants analytical campaign — **Complete**

PO-7 (Nov’17 – Dec’17):

- Parametric testing 6” PI-2 bundles — **Planned**
- Long term test (500 hours, 90% capture) — **Planned**

PO-8 (mid-2018?):

- Some interesting stuff! — **Planned**

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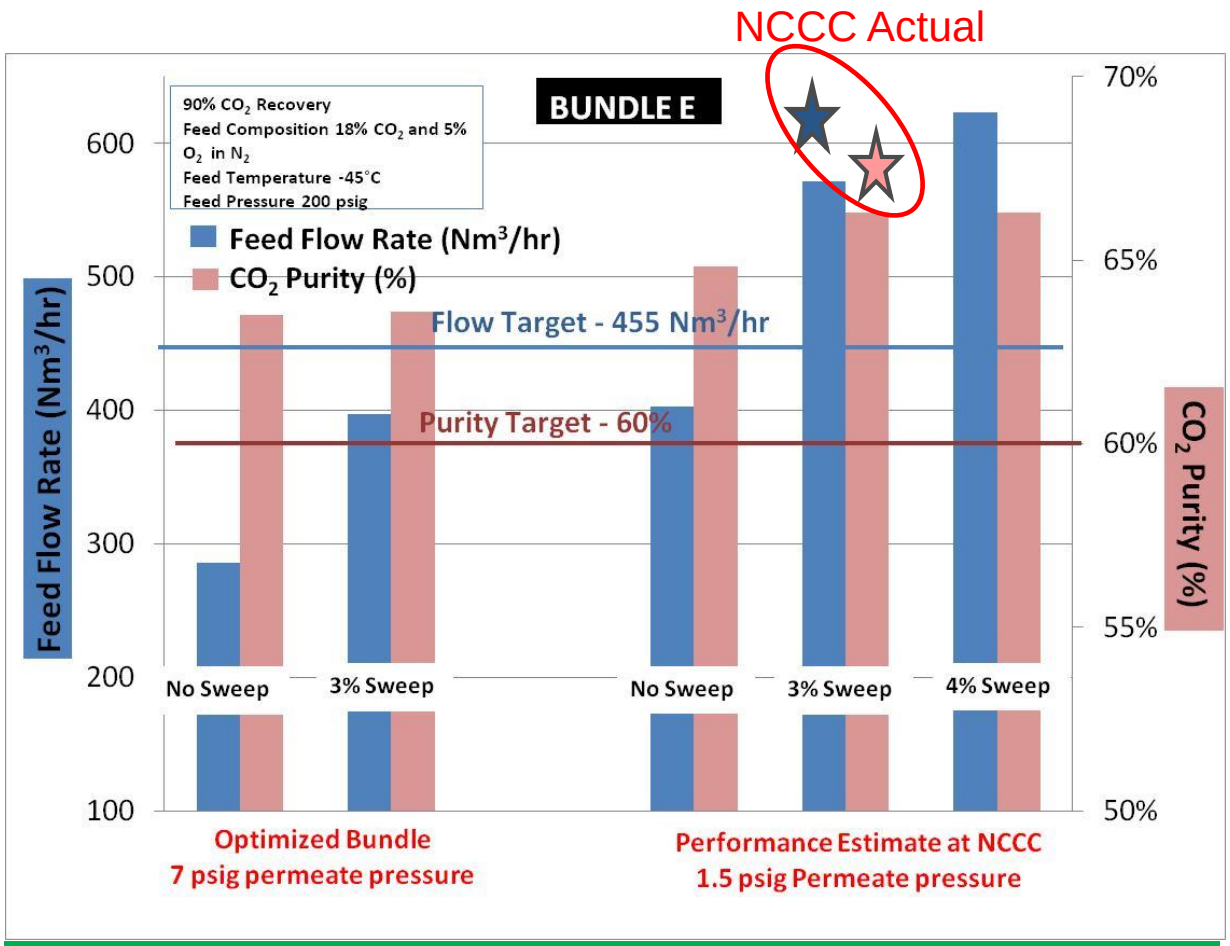
Performance Validation (12” Commercial Bundle)

- Bundle performance in field was projected from 0.1 MW bench scale skid
- Actual performance was even better than predicted



Enhanced membrane performance validated in field!

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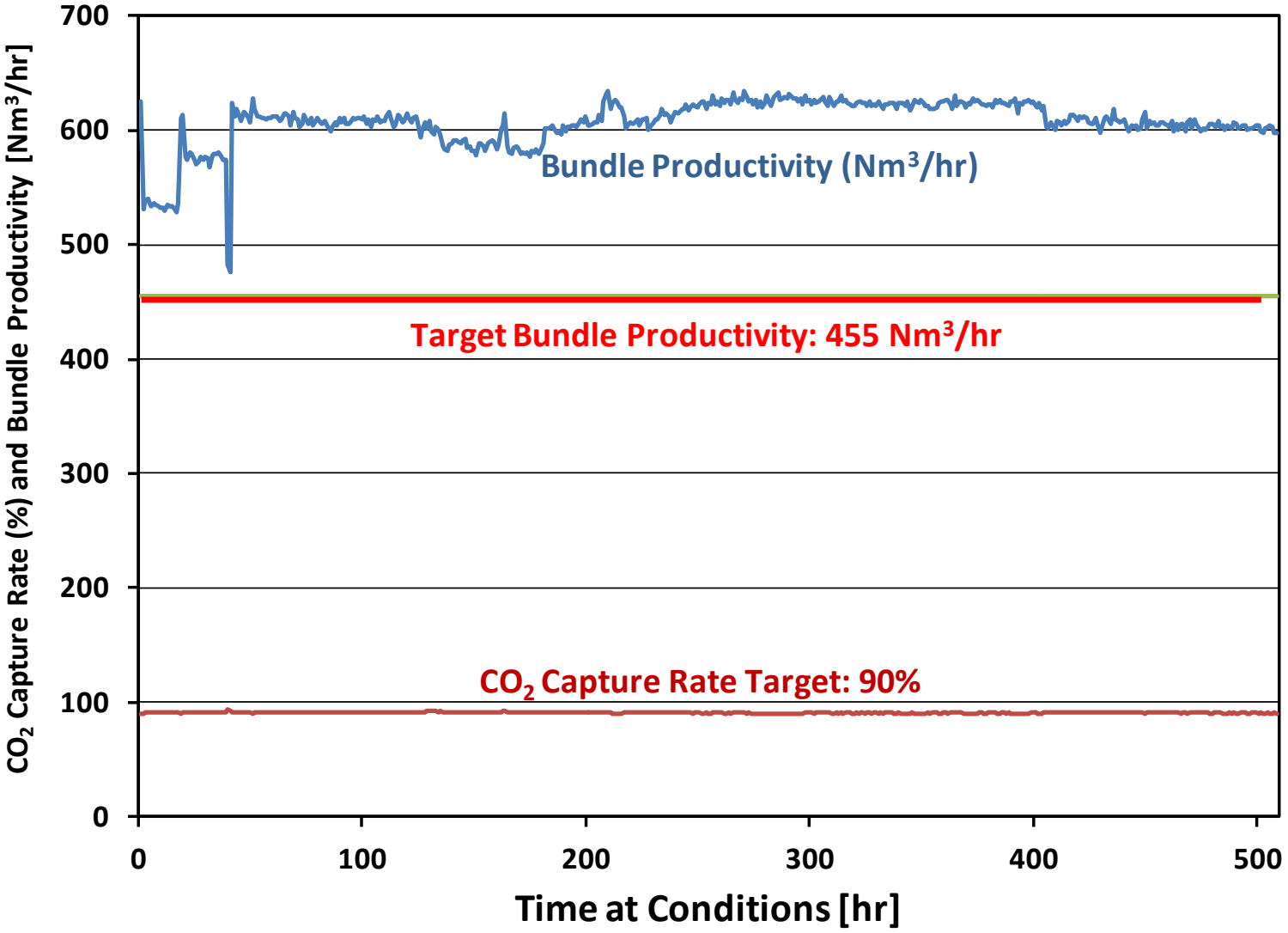
12” PI-1 Commercial Bundle Steady State Test



30% better performance than target!

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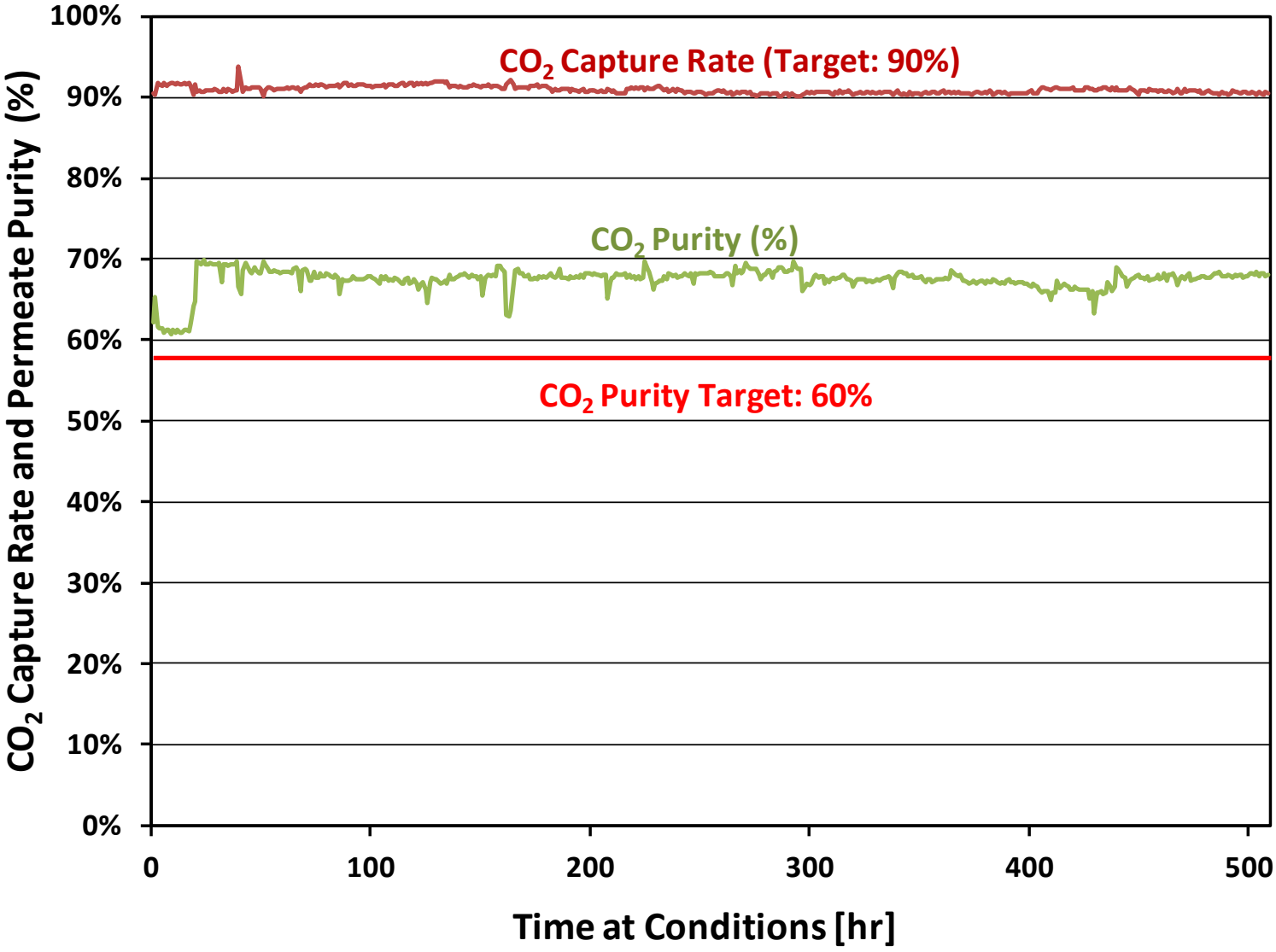
12” PI-1 Commercial Bundle Steady State Test



Steady state operation demonstrated

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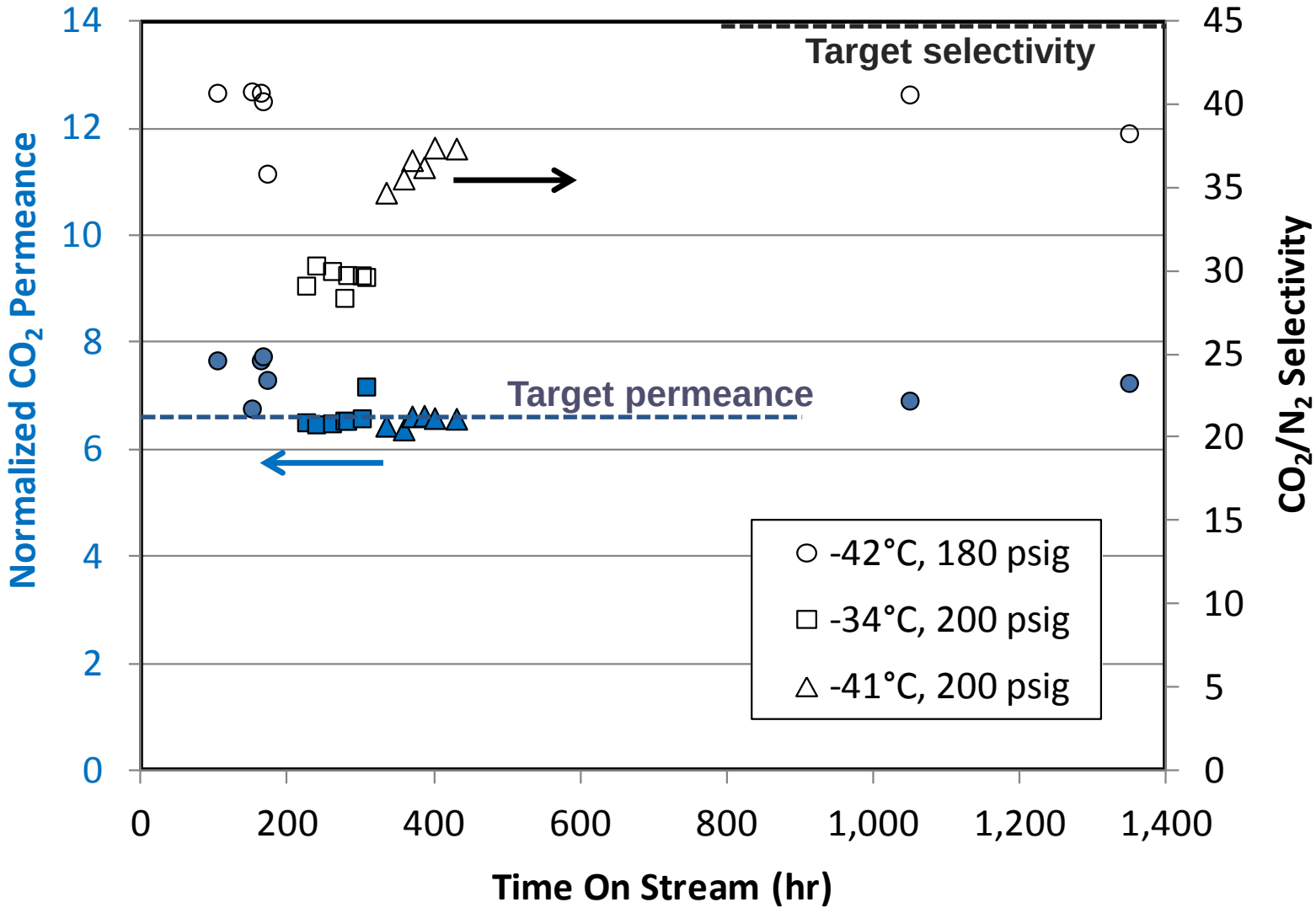
PI-2 Steady State Test (1” Bundle: 10x More Fibers)



Stable performance for PI-2 bundle in flue gas

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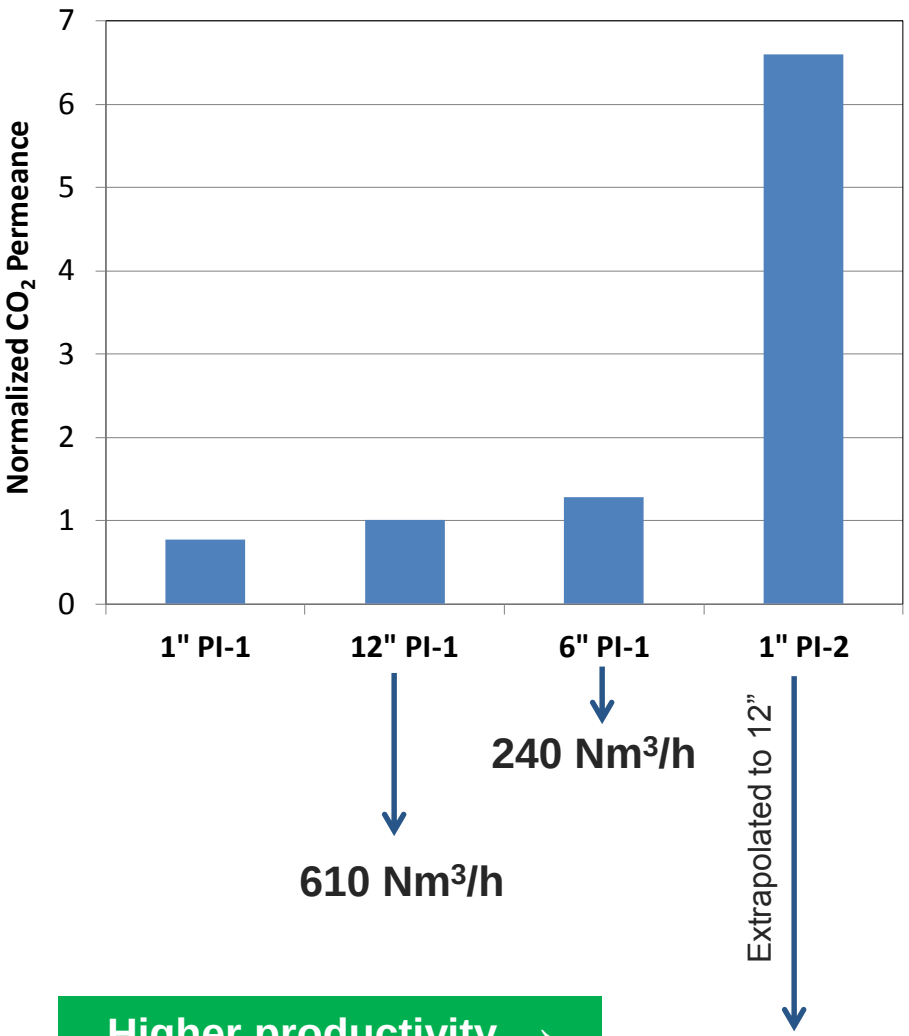
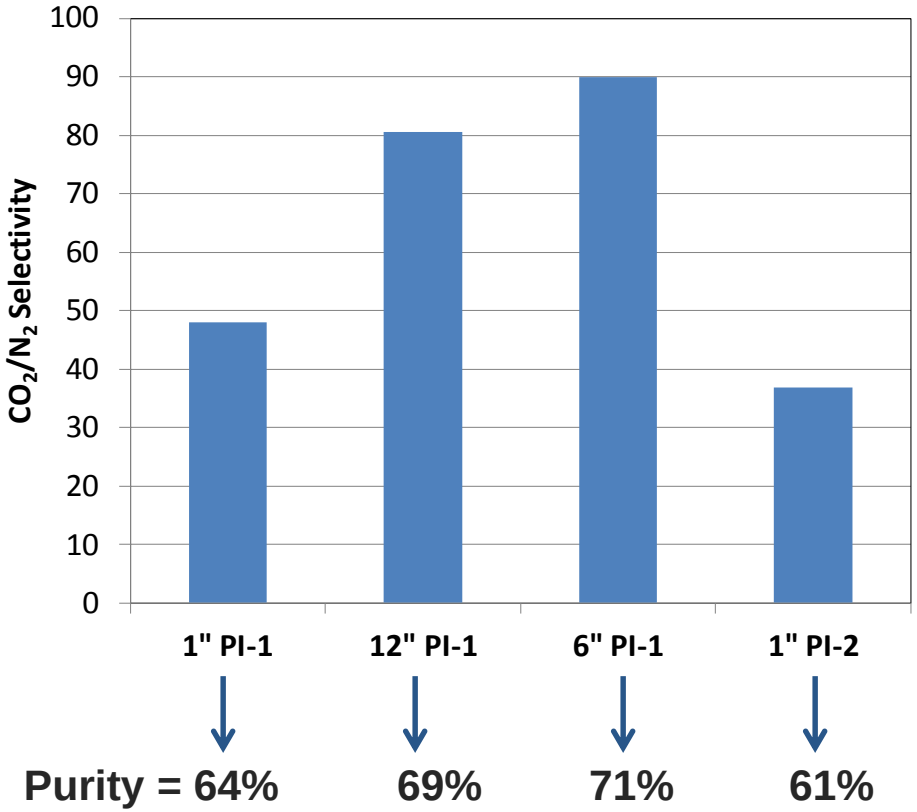
12” PI-1 vs PI-2 Bundle Performance





Higher productivity → Lower CAPEX

Higher purity → Lower OPEX

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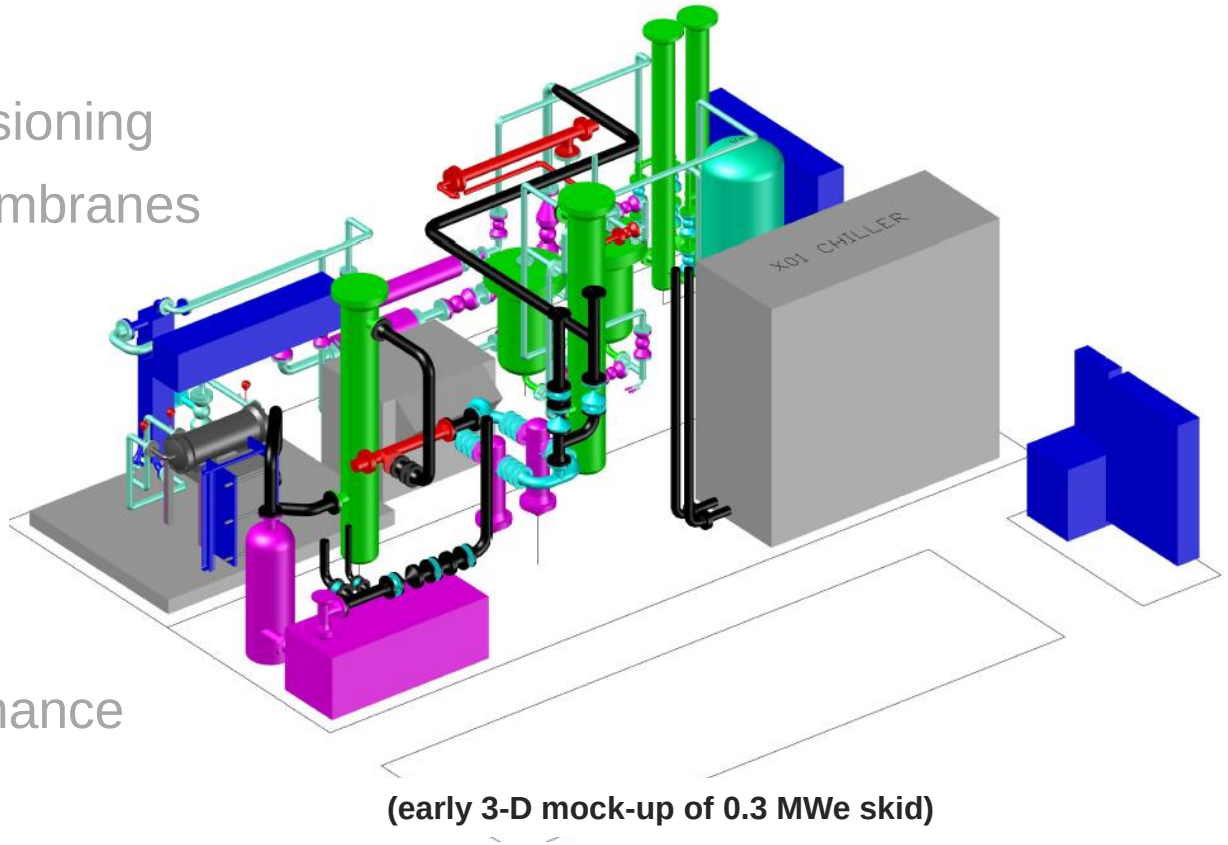

(early 3-D mock-up of 0.3 MWe skid)

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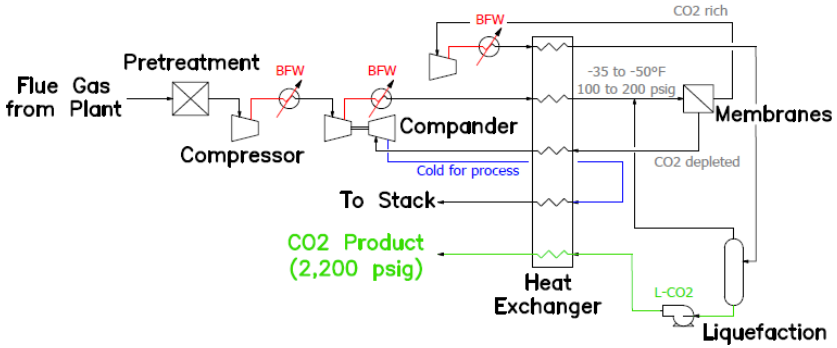
Techno-Economic Analysis (TEA)

Objective: CO_2 capture from a commercial power plant, 550MWe (net), 12,000 tpd, at $40/tonne by 2025

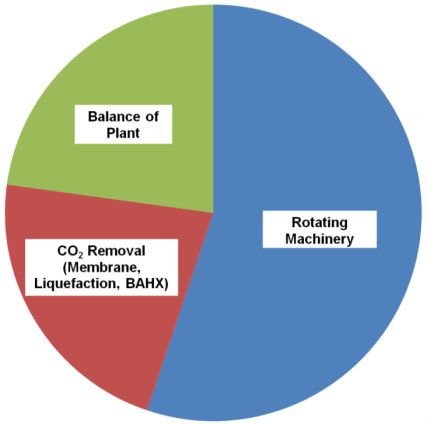


- Process optimization
  (PFD → HYSYS model, mass-energy balance)

- Equipment costing
  (vendor quotes, scaling method)

Major Equipment	Scaling Factor	Cost Reference
Pre-FGD heat recovery	UA value	AL database
2-stage contact tower	Molar flow	AL database
Particulate filter	Molar flow	Vendor quote
Feed compressor	Molar flow	Vendor quote
Equipment 5, 6, 7, etc.	…	…

- DOE cost methodology
- Parsons review and feedback



(cost analysis)

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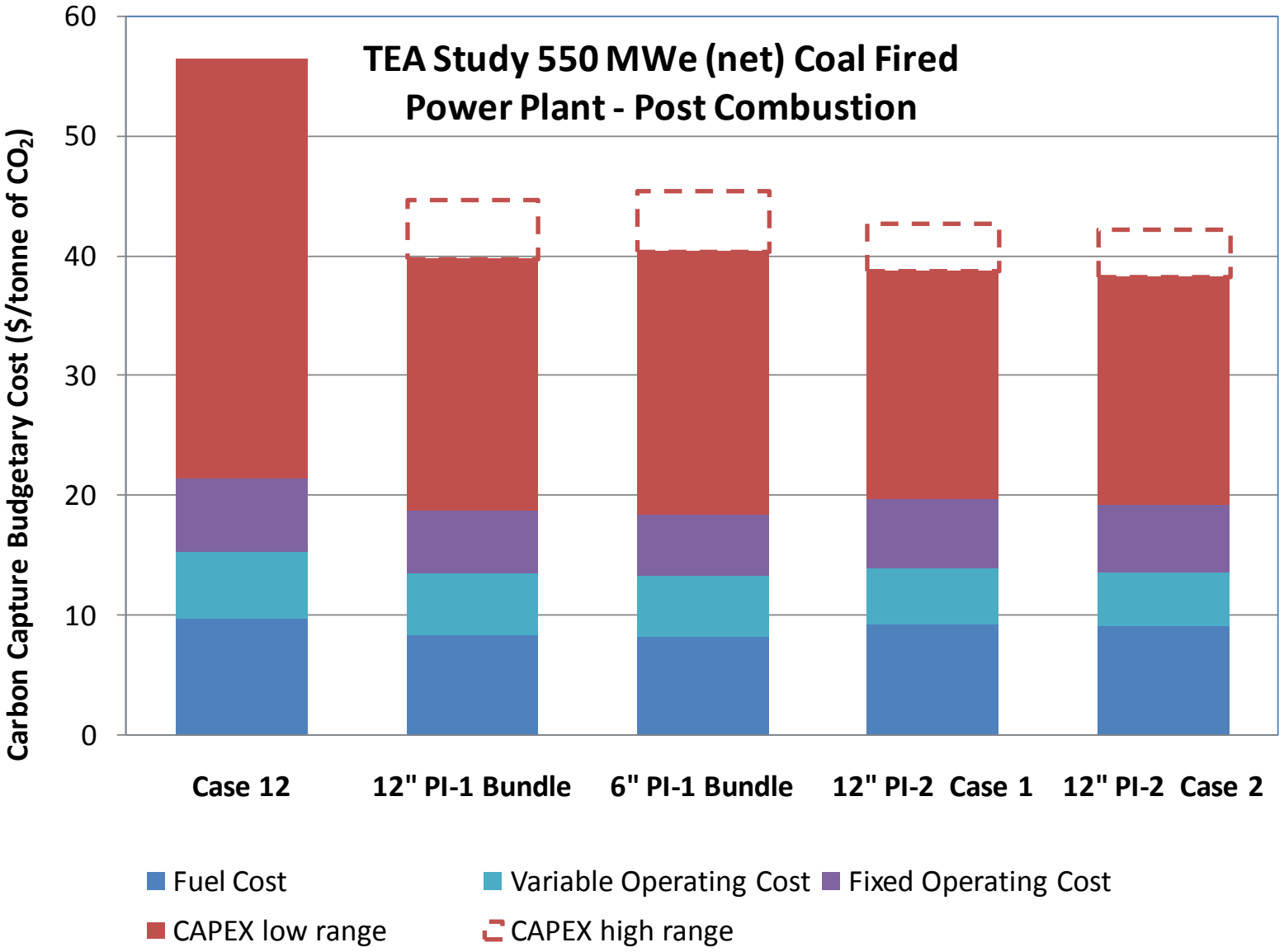
Carbon Capture Cost Estimate



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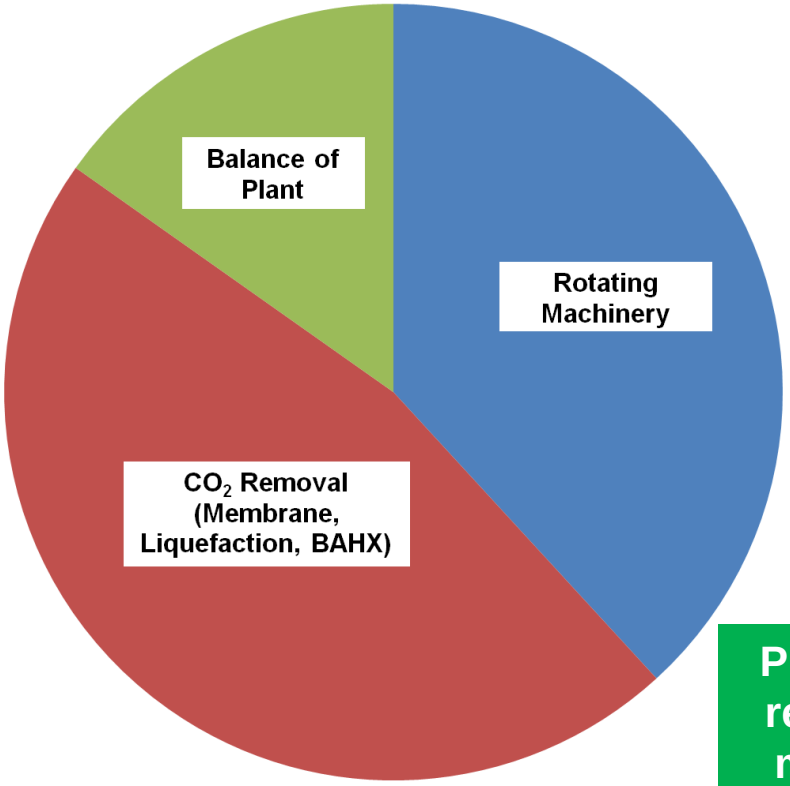
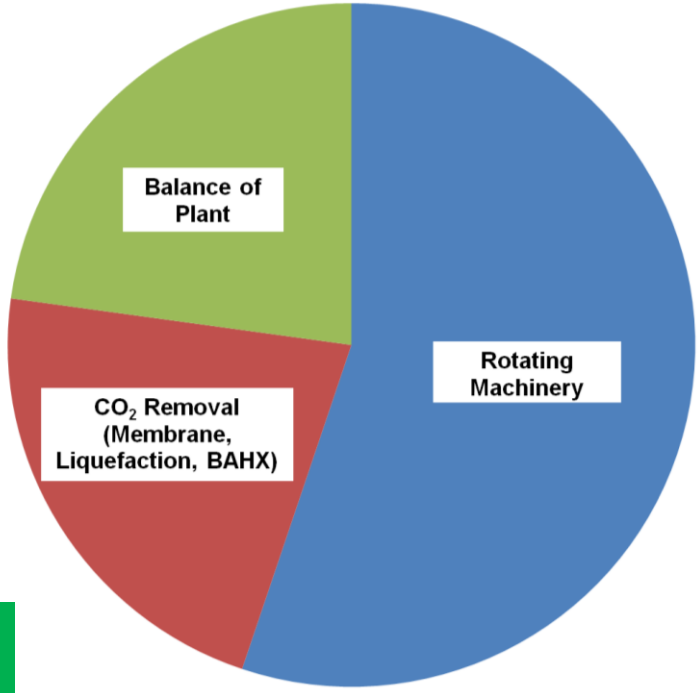
Techno Economic Analysis (TEA) Study

	Case 12 (Amine)	Cold Membrane (PI-1)	PI-2
Power Plant Cost (MM$)	1,366	1,305	1,326
CO_2 Capture System (MM$)	593	357	254
Total Plant Cost (MM$)	**1,959**	**1,662**	**1,580**



Cold Membrane (PI-1)

PI-2: big cost reduction on membranes



Projected PI-2

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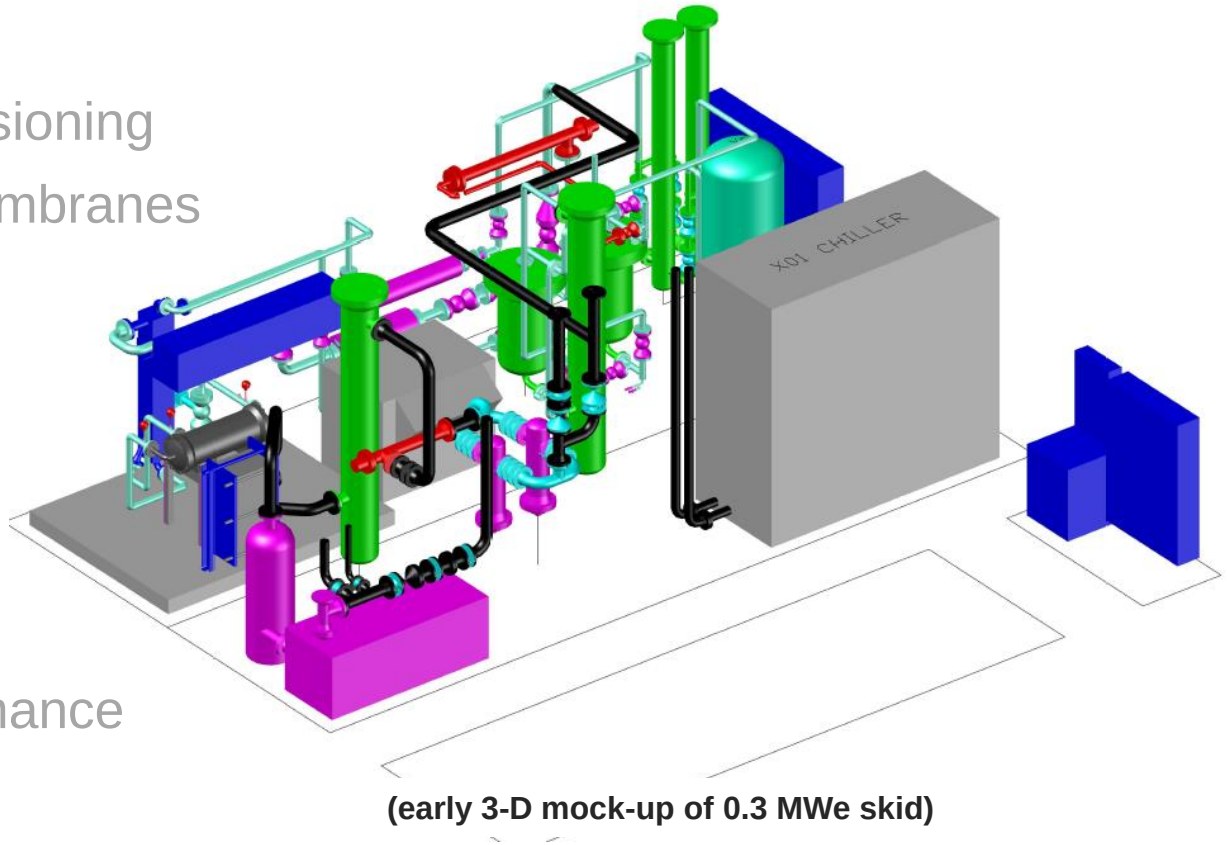

(early 3-D mock-up of 0.3 MWe skid)

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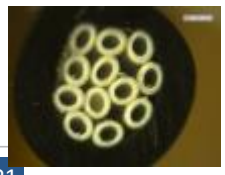
Membrane Manufacturing Scale-up, DE-FE0026422

	OD (in)	Length (ft)	Fiber Count	Spinning Device	Fabrication Technique
Mini permeator	0.25 - 0.5”	1.6’	<1000	1-hole lab unit	Hand
Permeator	1”		1 – 5x		Skein
Skein module	2.5”	2.8’	15 – 20x	12-hole “DSU”	
R&D prototype bundle	2.5 - 4”		15 – 20x		Forming
6” bundle	6”		50 – 90x	24/36-hole production unit	
In progress, ready Oct - 2017					
12” bundle (commercial)	12”		>200x		

Spinning Equipment (DSU): Spinning; Post-spin handling

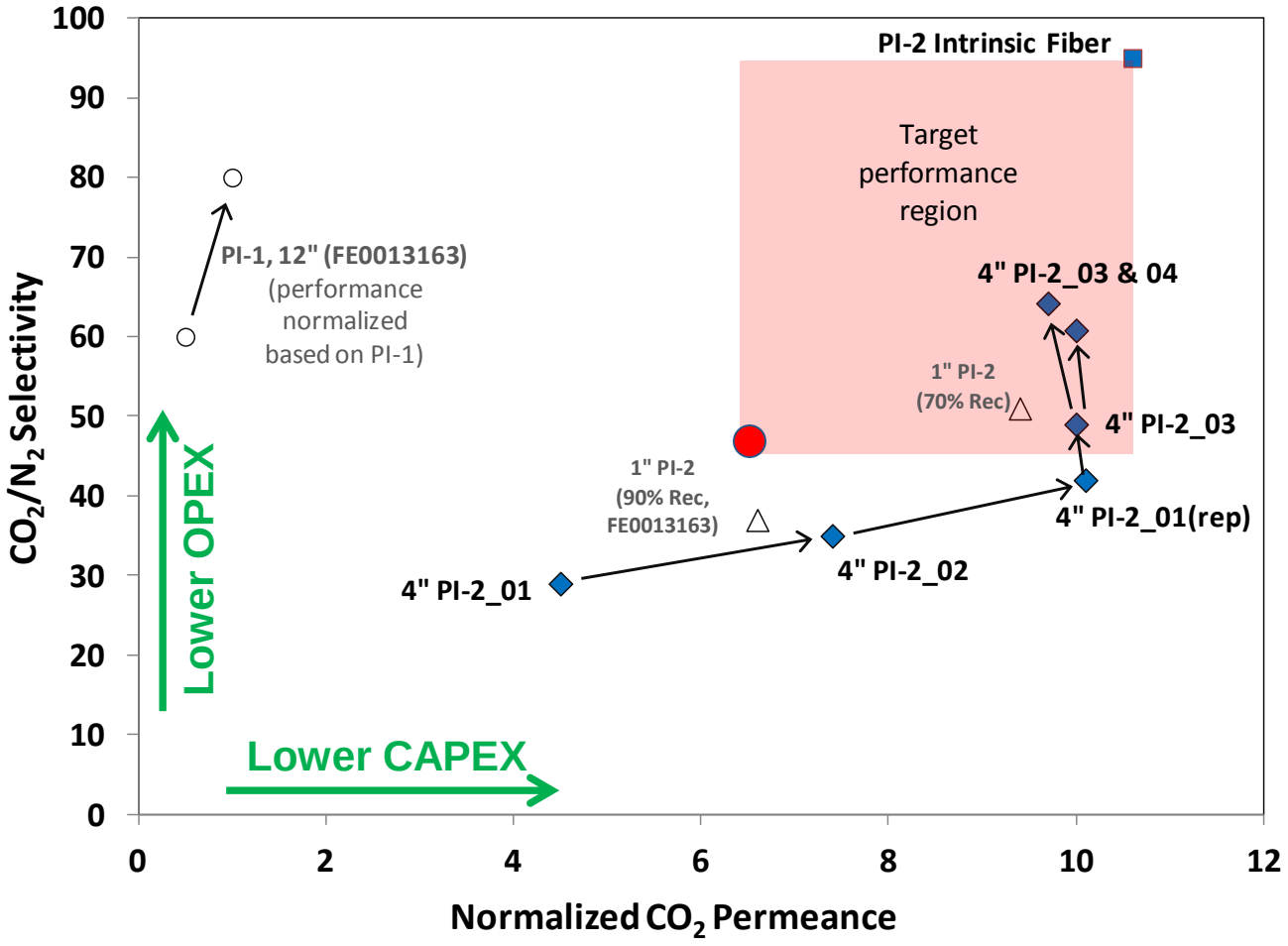
Fiber Processing / Handling: Washing; Drying; Bobbin winding

Forming Equipment: Tube-sheet forming; Machining





4” Prototype Bundle Performance



- Significant improvement by using ‘forming’ method in scale-up
- Lessons learned resulting in further performance gains

1) Epoxy application for tubesheet
2) Post-treatment solution concentration
3) Outer wrap layer positioning
4) Optimize fiber OD

Success criteria:
90 Nm^3/h feed flow,
90% CO_2 recovery,
58% permeate purity

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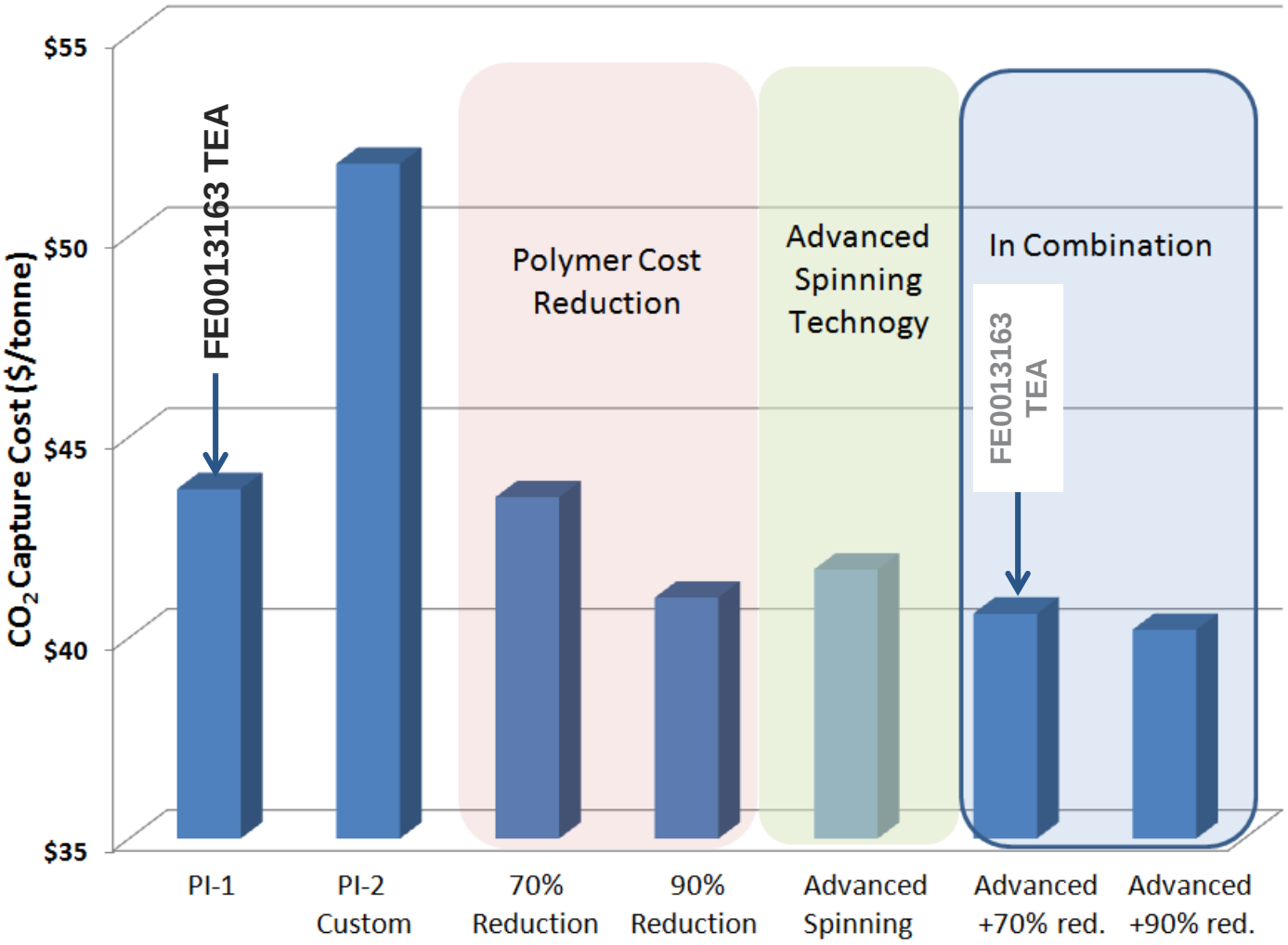
Fiber Manufacturing Cost Analysis

What are relative merits of cost-saving approaches?

- Best value is composite formulation
- With low polymer price monolith fiber yields CO_2 capture cost savings
- Pursuing both approaches



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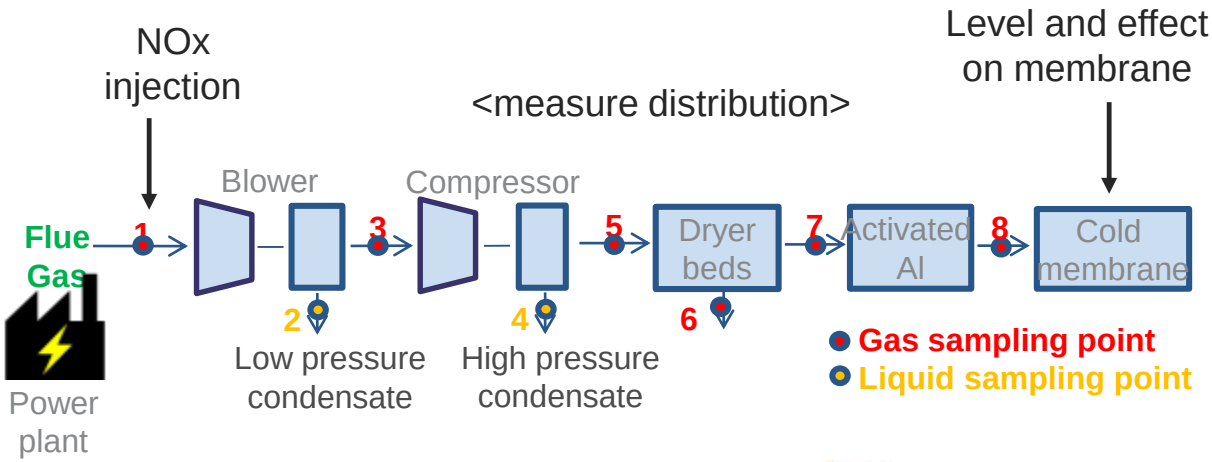
Next Steps

- Manufacturing several 6” bundles (6 – 8), test on 0.1 MWe skid in Newark, DE
- Field-test at NCCC, 0.3 MWe scale
  - Parametric testing
  - Long-term stability
  - Dynamic testing: start / stop / cool / warm / moisture breakthrough – evaluate bundle integrity
  - NO/NO_2 injection to simulate SCR failure/removal

0.3 MWe Field-Test Unit at NCCC, Pilot Bay 3 (DE-FE0013163)



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Research & Development

Opening new ways

THANK YOU FOR YOUR ATTENTION