2019 NETL CO_2 Capture Technology Project Review Meeting:

Bench Scale Testing of Next Generation Hollow Fiber Membrane Modules (DE-FE0026422)

Shilu Fu

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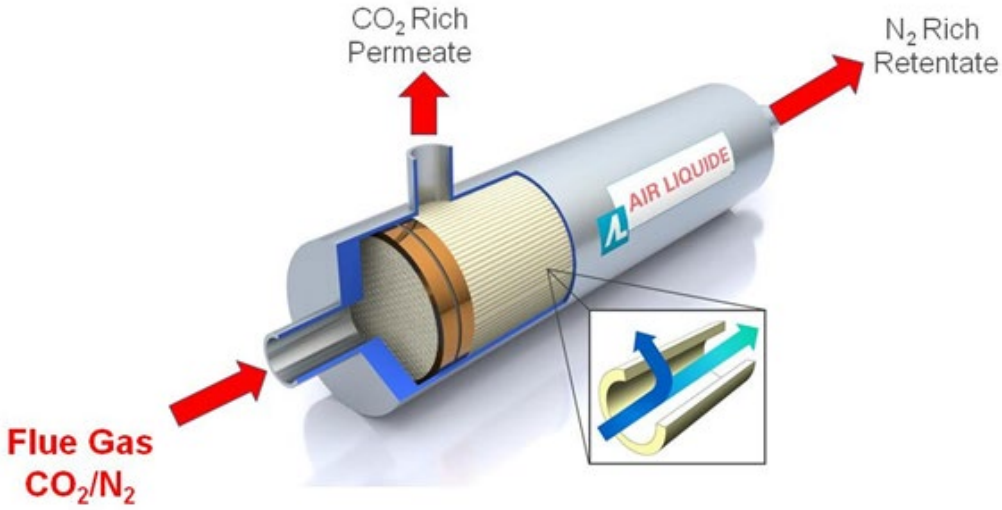
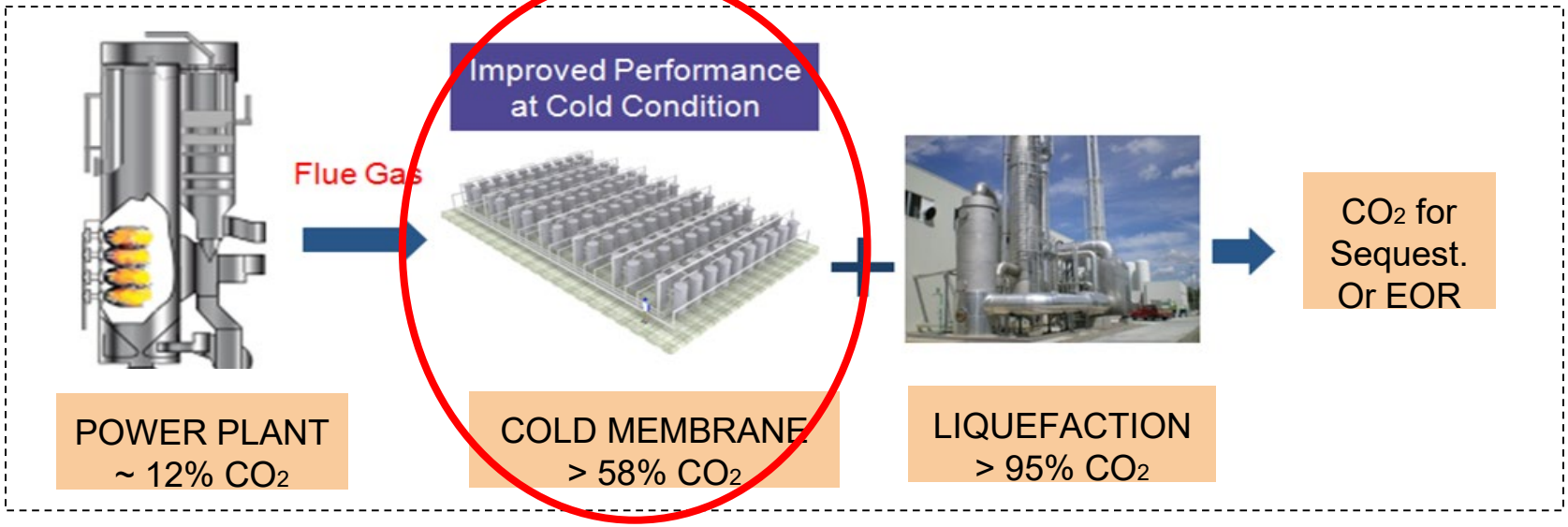
Aug. 26th, 2019

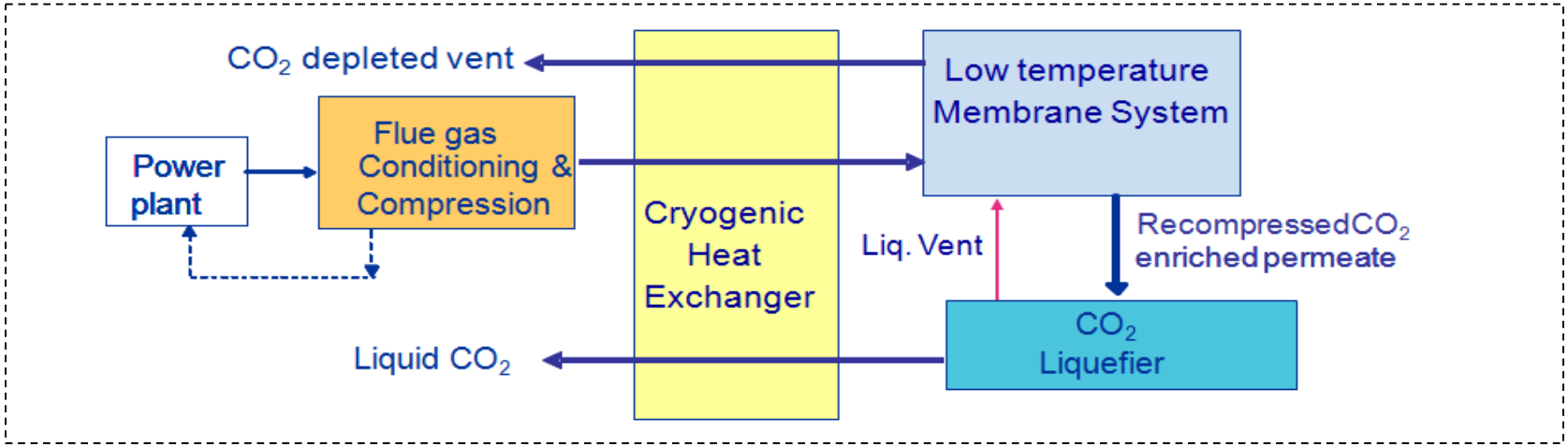


Shilu Fu, D. Hasse, S. Kulkarni, R. Swaidan | R&D
T. Poludniak, J.-M. Gauthier | ALAS
Brad Knutson, Louis Wheat, John Cole| Parsons

Air Liquide Capture Technology Summary

❖ **Air liquide hybrid *cold membrane + liquefaction* process**





Project Overview

Project target: CO_2 capture from coal fired power plant flue gas with AL cold membrane technology at $40/tonne:
Total Budget: $4.3MM, DOE Funding - $3.3MM, AL Cost Shares - $1.0MM
Period of Performance: 10/01/2015 through 06/30/2019 over 2 budget periods (extended to Dec. 2019)

	Expenditures
Budget Period 1 (Oct 2015- June 2017)	$1,600,000
Budget Period 2 (Jul 2017- Dec 2019)	$2,700,000

NETL Project Manager: Andrew O'Palko
Project Partners:

- Air Liquide R&D (project executive) – David Hasse, Andrew Hamilton, Sudhir Kulkarni, Trapti Chaubey, Ted Li, Alex Augustine, Jiefu Ma, Dean Kratzer, Judy Huss, Dennis Calvetti, Gerard Gagliano, Deborah Hutchinson, Raja Swaidan
- MEDAL/ALAS (Membrane manufacturing) - Tim Południak, Jean-Marie Gauthier
- E&C (Engineering support)– Pierre-philippe Guerif, Abigail Bonifacio
- Parsons (TEA validation) - Brad Knutson, Louis Wheat, John Cole

Test partner – National Carbon Capture Center

Project Schedule & Status

Main Tasks	Milestones/ Success Criteria	Status
BUDGET PERIOD 1 (BP1) Oct 2015 to June 2017		
Design/manufacture 4” PI-2 bundles	✓ Four bundles fabricated ✓ Performance achieved target: >90 Nm^3/h feed, 90% CO_2 recovery, >58% CO_2 purity	**COMPLETED**
Identify other hybrid processes with possibility of economic feasibility	✓ Eight cases considered, five evaluated	**COMPLETED**
BUDGET PERIOD 2 (BP2) July 2017 to December 2019		
Design/manufacture 6” PI-2 bundles	✓ Seven bundles fabricated	**COMPLETED**
Field Test at NCCC at 0.3 MWe scale	✓ Performance achieved: >400 Nm^3/h feed, 90% CO_2 recovery, >58% CO_2 purity ✓ 500-hour long-term stability test	**COMPLETED**
	❑ Extended parametric testing to investigate industrial CO_2 source applications	Dec. 2019
TEA	✓ CO_2 capture cost evaluated for five cases	**COMPLETED**

Agenda

1. Technology Overview
2. Membrane Manufacturing
3. NCCC Field Test
4. TEA

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1. Technology Overview

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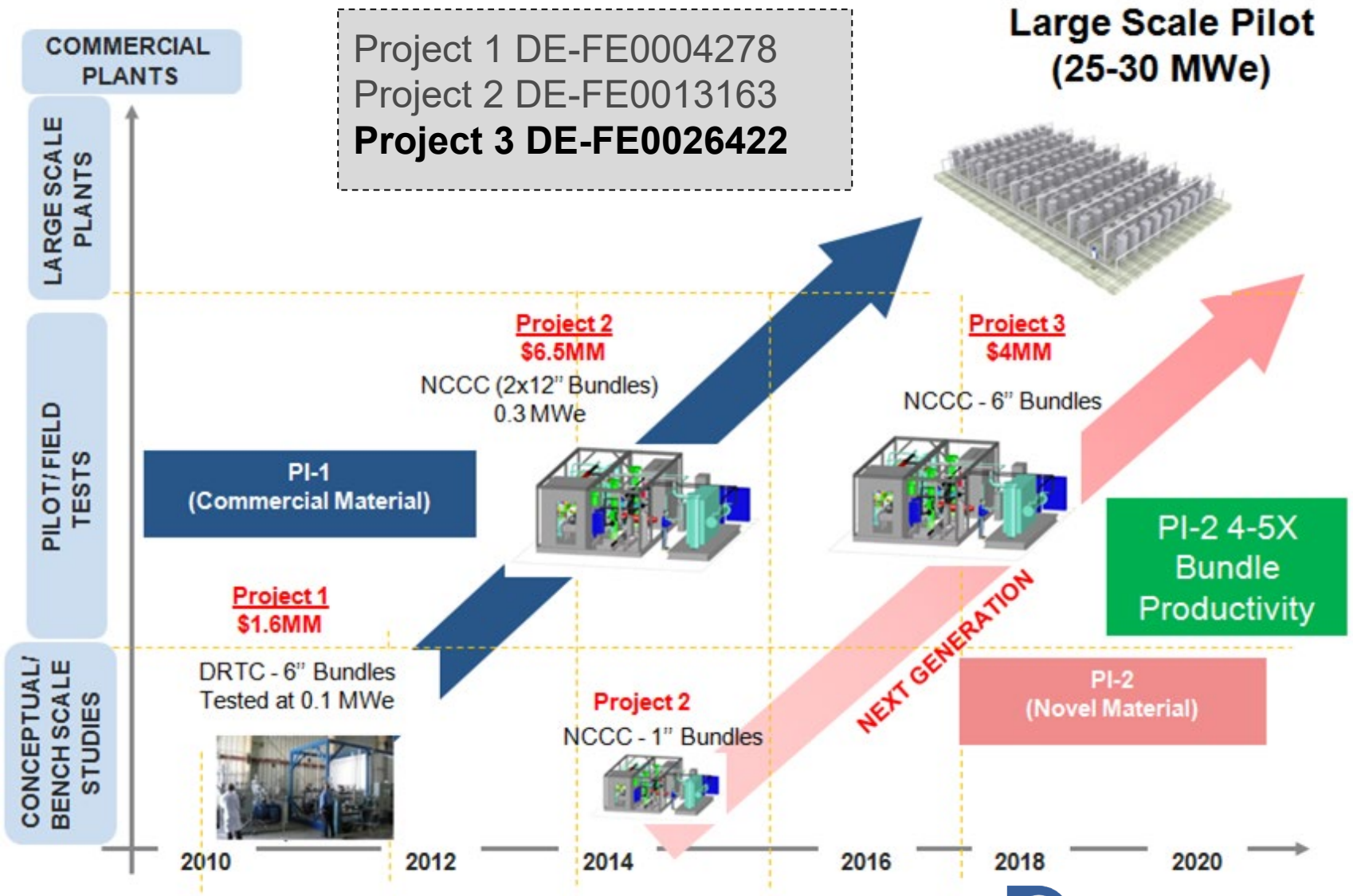
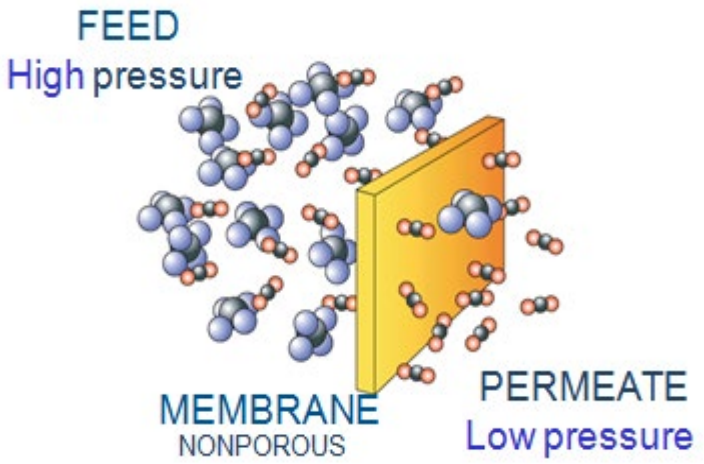
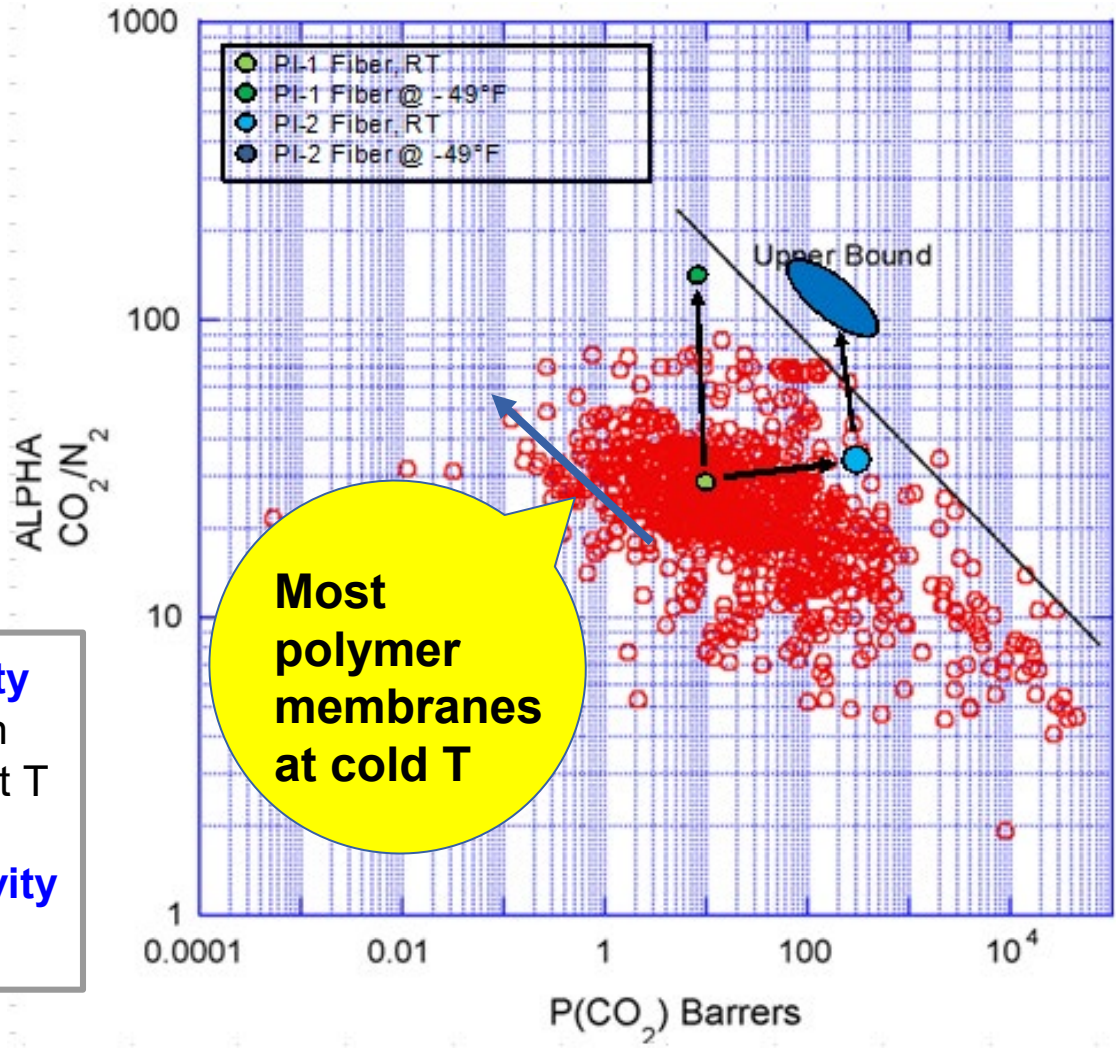
AL Cold Membrane -CO_2 capture Technology Roadmap



Motivation: Membrane? Why cold? Why PI-2





- ❖ **Why cold? -- improve selectivity**
- ★ Discovered by Air Liquide R&D in 2008: Improved CO_2 selectivity at T below ambient
- ❖ **Why PI-2? -- improve productivity**
- ★ 4-5 X higher CO_2 productivity

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2. Membrane Manufacturing

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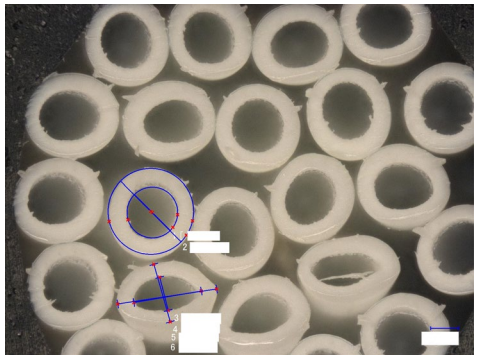
Membrane Bundle Fabrication

Date	Equipment	Comments
Jun-2016	DSU	1st forming campaign (2 x 4”) – good
Dec-2016	DSU	2nd forming campaign (2 x 4”) – good
May-2017	DSU	3rd forming campaign (1 x 6”) – good
Oct-2017	DSU	4th forming campaign (2 x 6”) – good
Feb-2018	Manuf. (24 fil)	5th forming campaign (4 x 6”) – good

All 4-4” & 7-6” bundles passed QC, proving the robustness of ALAS technique in manufacturing PI-2 membranes



microscope image of 24-filaments PI-2

wash can of PI-2 fiber

Two prototype bundles

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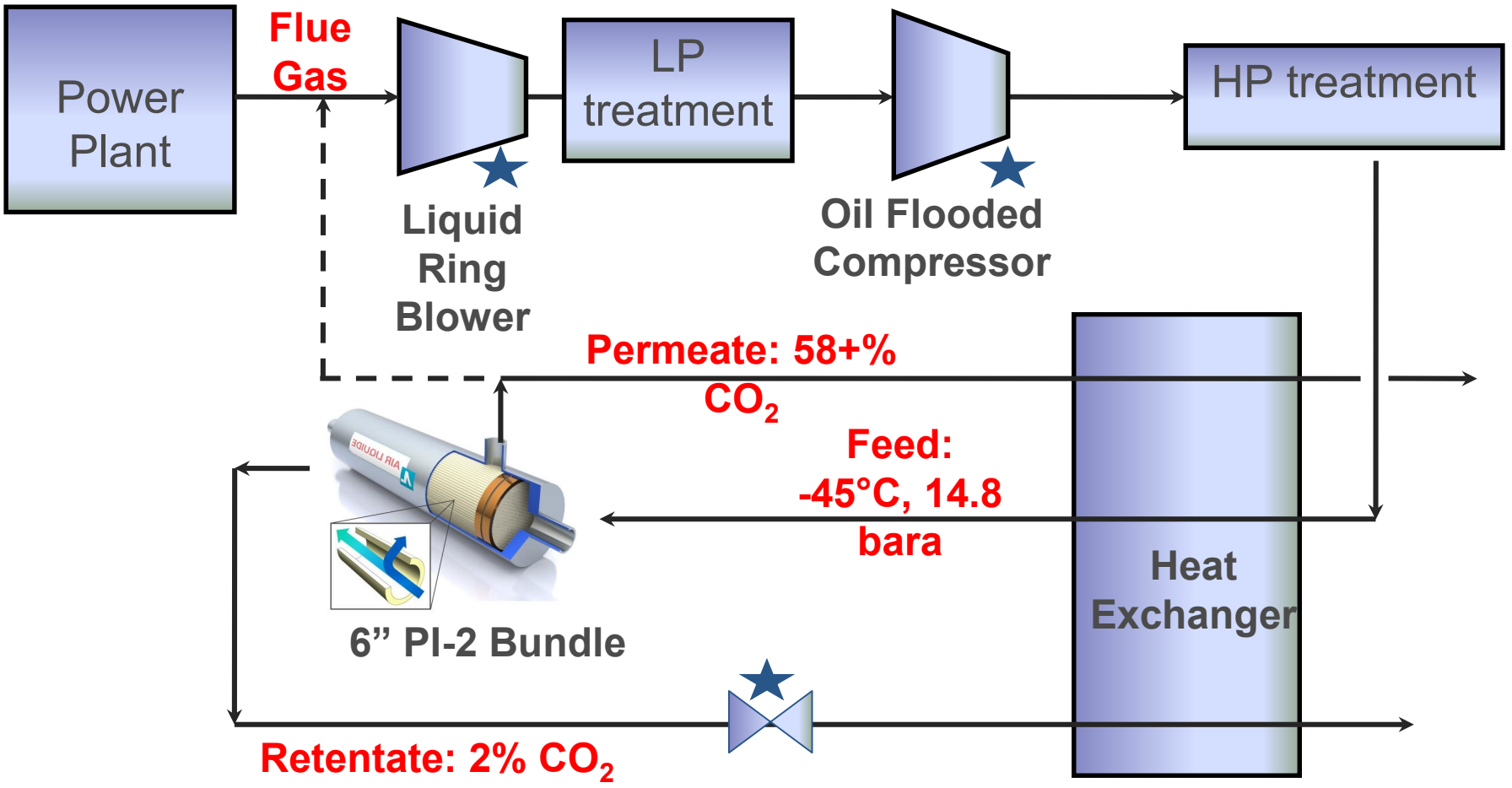
3. NCCC Field Test

Process Flow Diagram - NCCC 0.3 MWe field test unit



★ Different technology utilized at full scale: axial compressor and turbo-expanders

CO_2 Capture by Cold Membrane Operation, Energy Procedia, Volume 63, Pages 1-8184 (2014)

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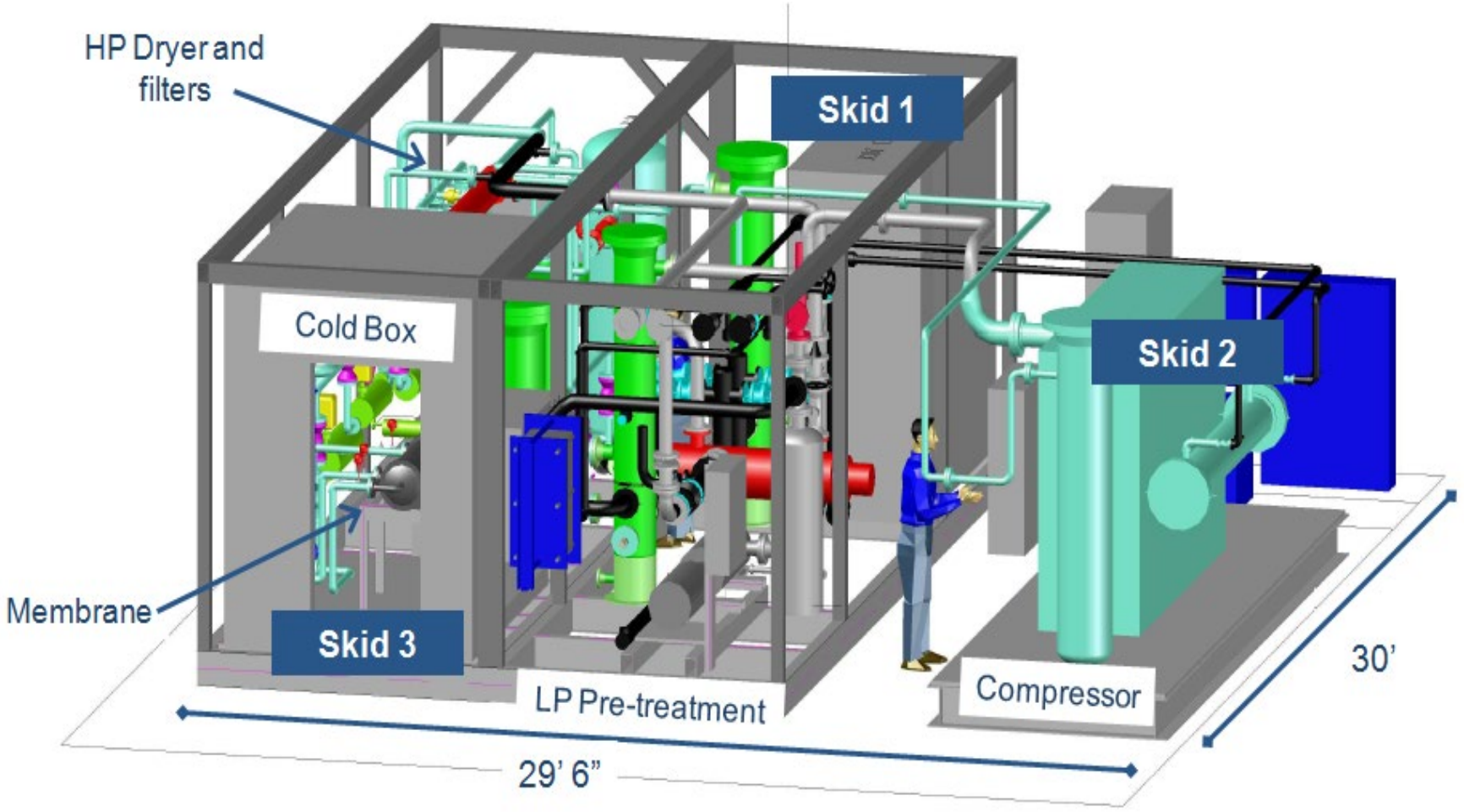
Membrane skid at NCCC

0.3MWe (TRL 5) field test unit



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Membrane skid at NCCC

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PI-2 validation with real flue gas at NCCC

PO-5 (May – Nov 2016)

under the previous DOE-AL project of DE-FE0013163

- Long term test PI-2 1” permeator (~ 500 hours, 50% CO_2 capture) — **Complete**

PO-7 (Oct 17 – May 18):

- Validate enhanced performance with real flue gas — **Complete**
- Parametric testing 6” PI-2 bundles — **Complete**

PO-8 (Feb 19 – May 19):

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

PO-8 (Current):

- Extended parametric testing on 6” PI-2 bundles to investigate industrial CO_2 source application — **On-going Dec. 2019**

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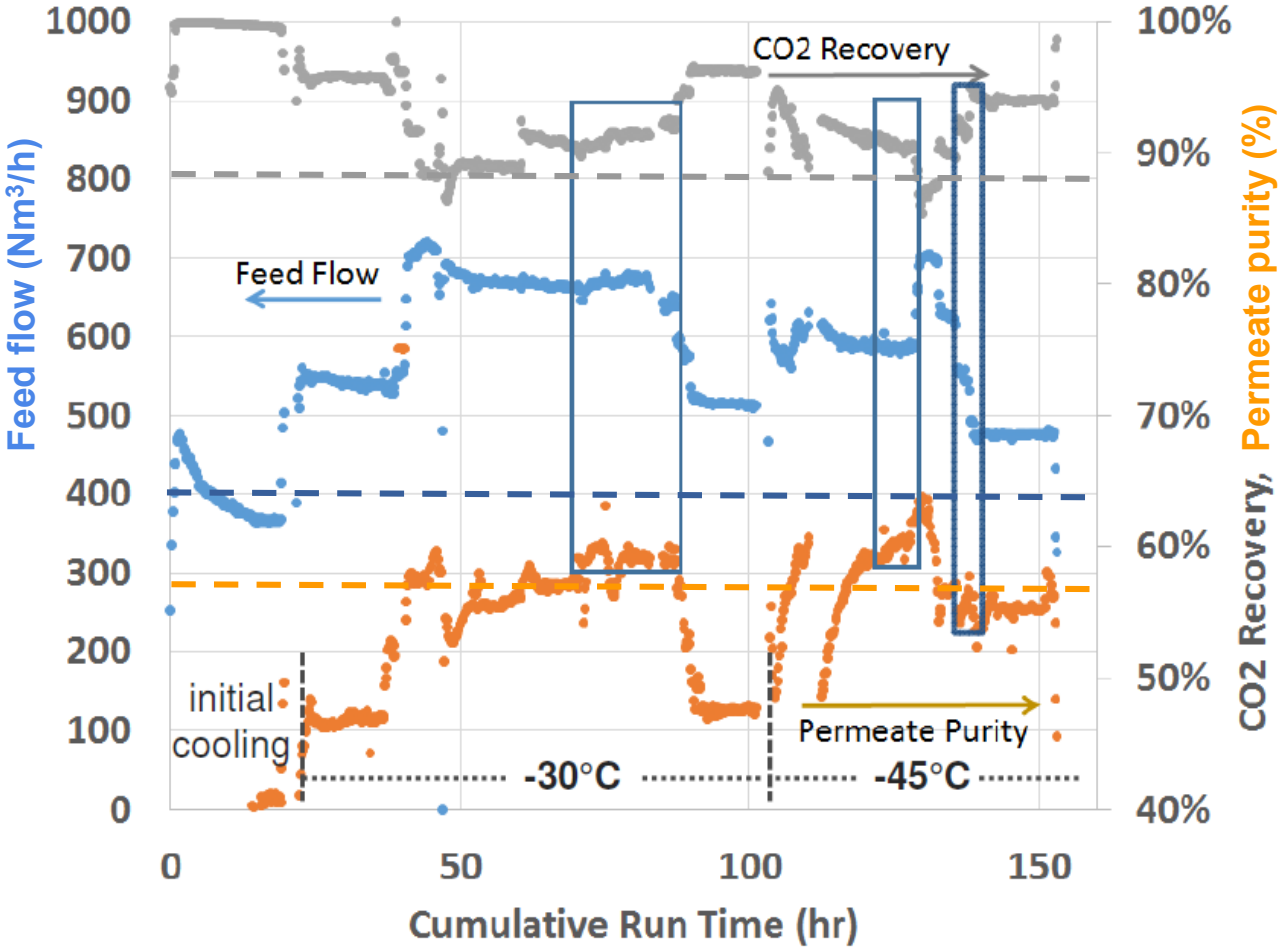
PI-2 6'' membrane bundle test at NCCC (2018)



- ★ Parametric: T, feed flow
- ★ Significant high processability of >600 Nm^3/h
- ★ Reached target at T of -30 °C, potential further energy saving

All: 14.8 bara, 18% CO_2

Performance target: >400 Nm^3/h feed @ 90% CO_2 recovery, >58% CO_2 purity

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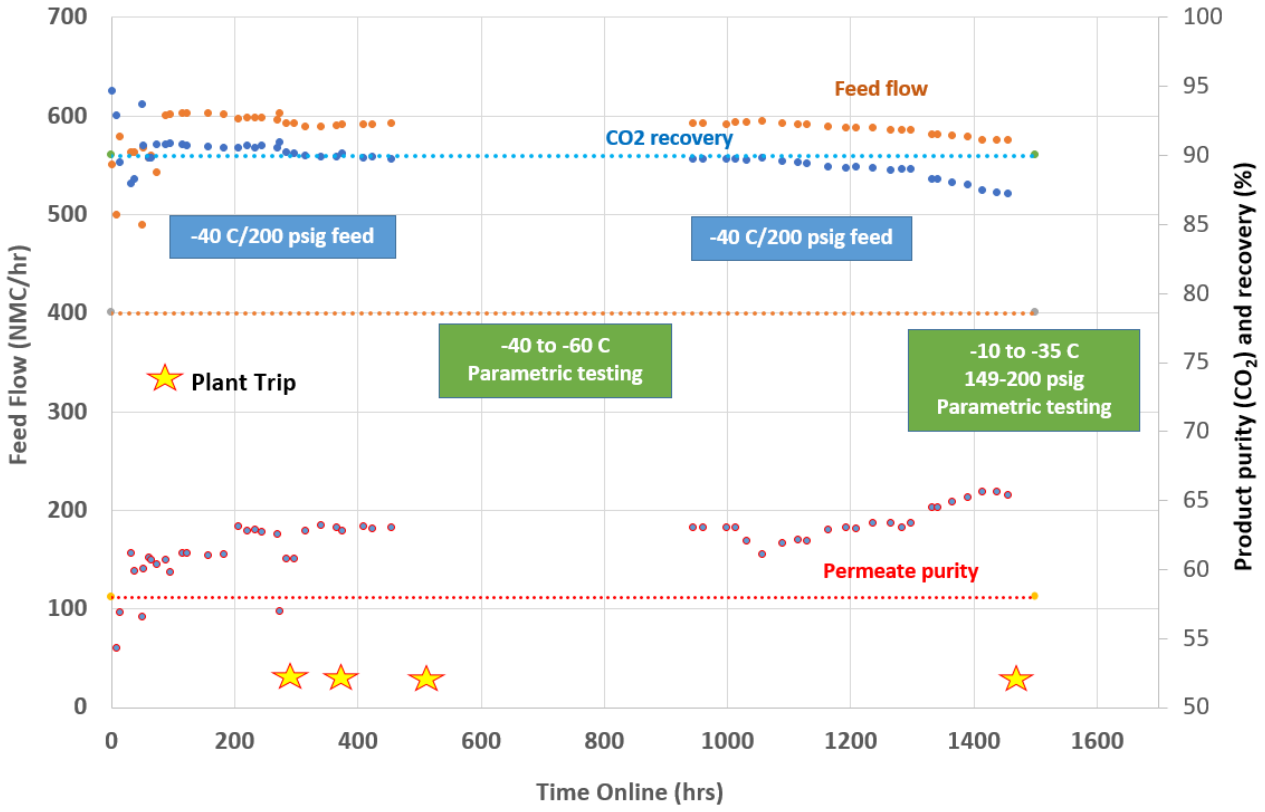
PI-2 6'' membrane bundle stability test at NCCC (2019)



- ★ Bundle performance significantly exceeded target
- ★ > 700-hour stable performance
- ★ Performance drop due to extreme cold temp. at -60 °C

All: 14.8 bara, 18% CO_2

Performance target: >400 Nm^3/h feed @ 90% CO_2 recovery, >58% CO_2 purity

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4. TEA

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Techno-Economic Analysis

1. **PI-2 membrane development**
2. **Process design optimization**

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

	Case 11	Case 12	PI-1 (90%) Previous DOE-AL Project of DE-FE0013163	PI-2 (90%) Current DOE-AL Project of DE-FE0026422
Power Plant Cost (MM$)	906	1,602	1,440	1,349
CO_2 Capture System (MM$)		469	355	244
CO_2 Capture Cost w/o T&S ($/tonne)		**42**	**36**	**32**
LCOE w/o T&S (mills/kWh)	75	141	130	127

Base case provided by DOE reference:

- Case 11 -- base case, current coal fire power plant without CO_2 capture
- Case 12 -- CO_2 capture with Amine adsorption

★ Both PI-1 and PI-2 cold membrane capture technologies exceed the target of $40/tonne.

★ With 3 years of development within AL, PI-2 membrane further lower the CO_2 capture cost for ~ $4/tonne.

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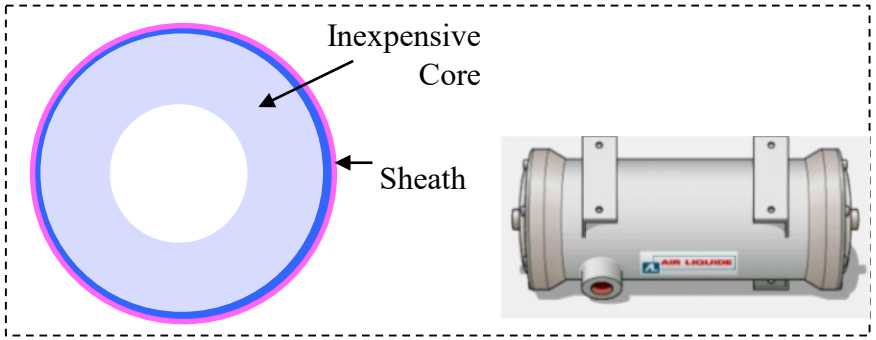
Conclusions

1. **AL next generation PI-2 cold membrane CO_2 capture technology is a Low-Cost solution with ~ $32/tonne.**
   - ❖ Ground-breaking membrane with high productivity
1. **The membrane performance has been validated with > 3000 hours testing with real flue gas at NCCC.**
2. **Full scale TEA has been conducted and validated by a third party.**
   - ❖ ALAS has well-established membrane manufacturing technology
   - ❖ All major equipment are standard and being utilized by AL ASUs, not FOAK.
1. **Future/ongoing:**
   - ❖ Actively seeking for future partner for larger scale testing.



Acknowledgement / Disclaimer

- US DOE: Andrew O'Palko, Sheldon Funk, José Figueroa
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- Air Liquide: Andrew Hamilton, Dave Hasse, Dennis Calvetti, Gerard Gagliano, Alex Augustine, Trapti Chaubey, Sudhir Kulkarni, Tim Poludniak, Ted Li, Judy Huss, Raja Swaidan
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Research & Development

Opening new ways

THANK YOU FOR YOUR ATTENTION