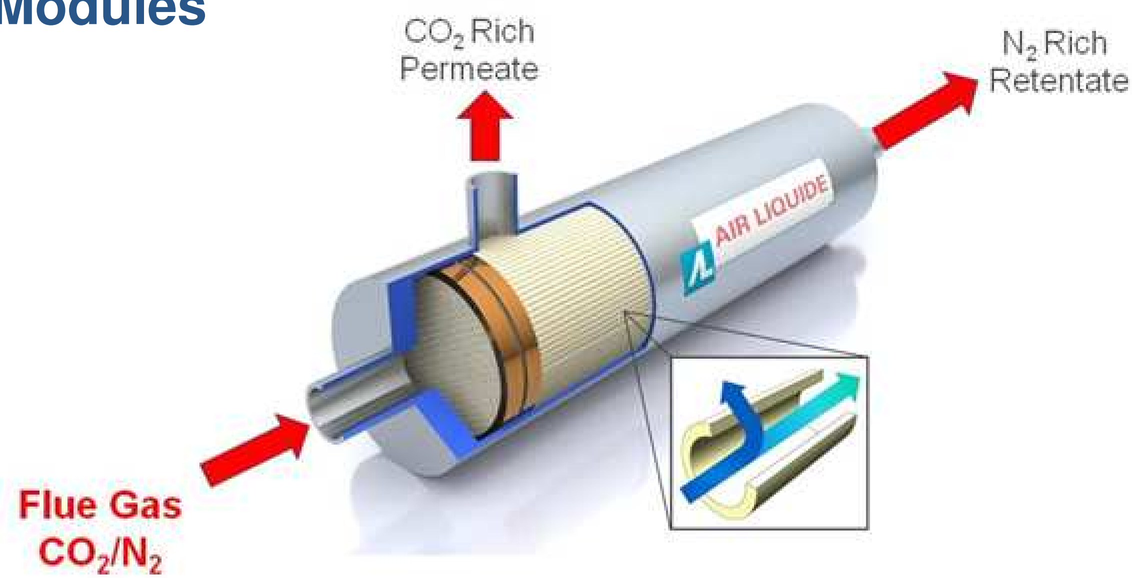
2018 NETL CO_2 Capture Technology Project Review Meeting:

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



August 15, 2018

A. Augustine, S. Kulkarni, S. Fu, A. Hamilton, D. Hasse, J. Ma, M. Bennett, T. Chaubey, R. Gagliano, | R&D
T. Poludniak, J.-M. Gauthier | ALAS

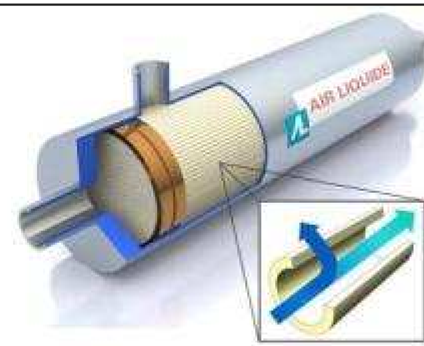
Air Liquide & ALAS

Air Liquide: world leader in industrial and medical gases

65,000 employees

$20 billion sales (2017)

Air Liquide Advanced Separations, ALAS



N_2 applications / markets

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

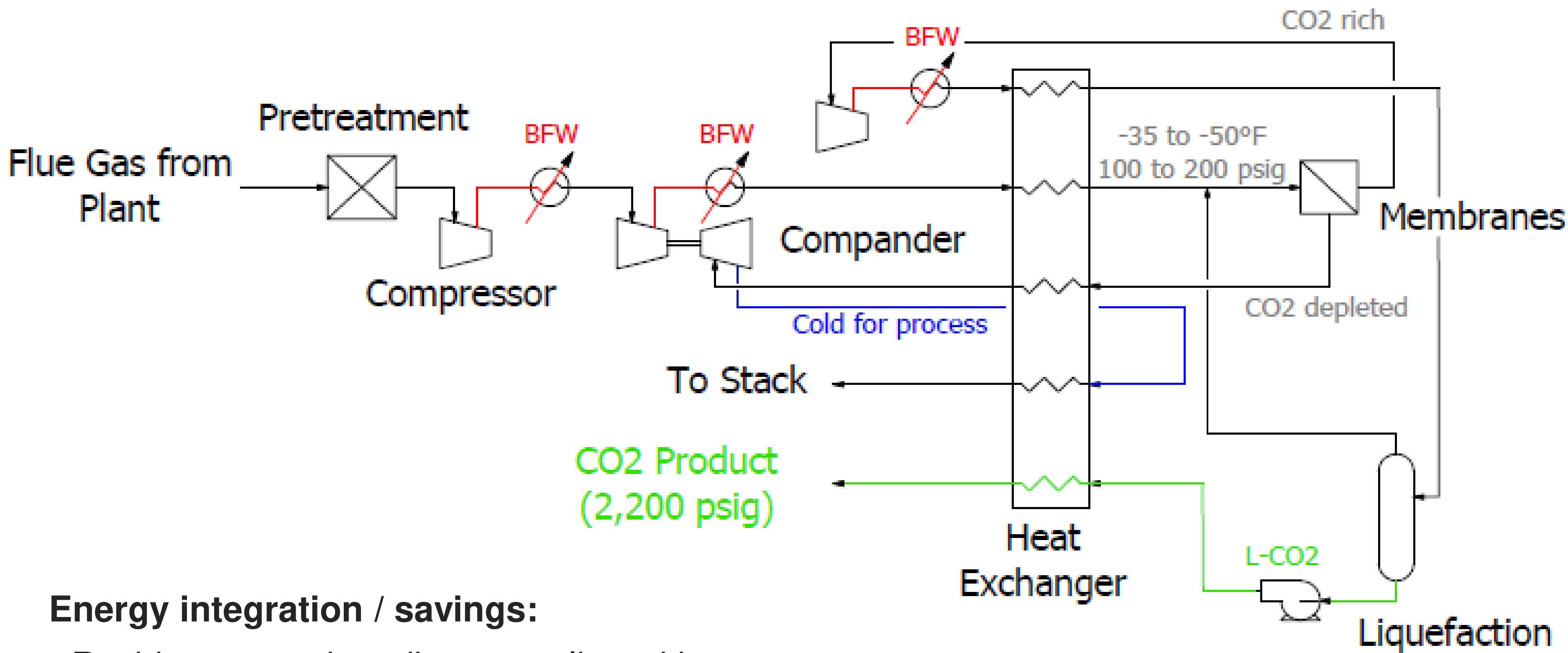
H_2 applications / markets

- Refinery Off-gas Streams
- Chemical Synthesis

CO_2 applications / markets

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

Background: Cold Membrane Process



Energy integration / savings:

- Residue expansion, direct coupling with compression
- Pumping of liquid CO_2
- Boiler feed water (BFW) sufficient for entire power plant steam cycle

Drawbacks:

- High membrane capital cost
- Energy intensive

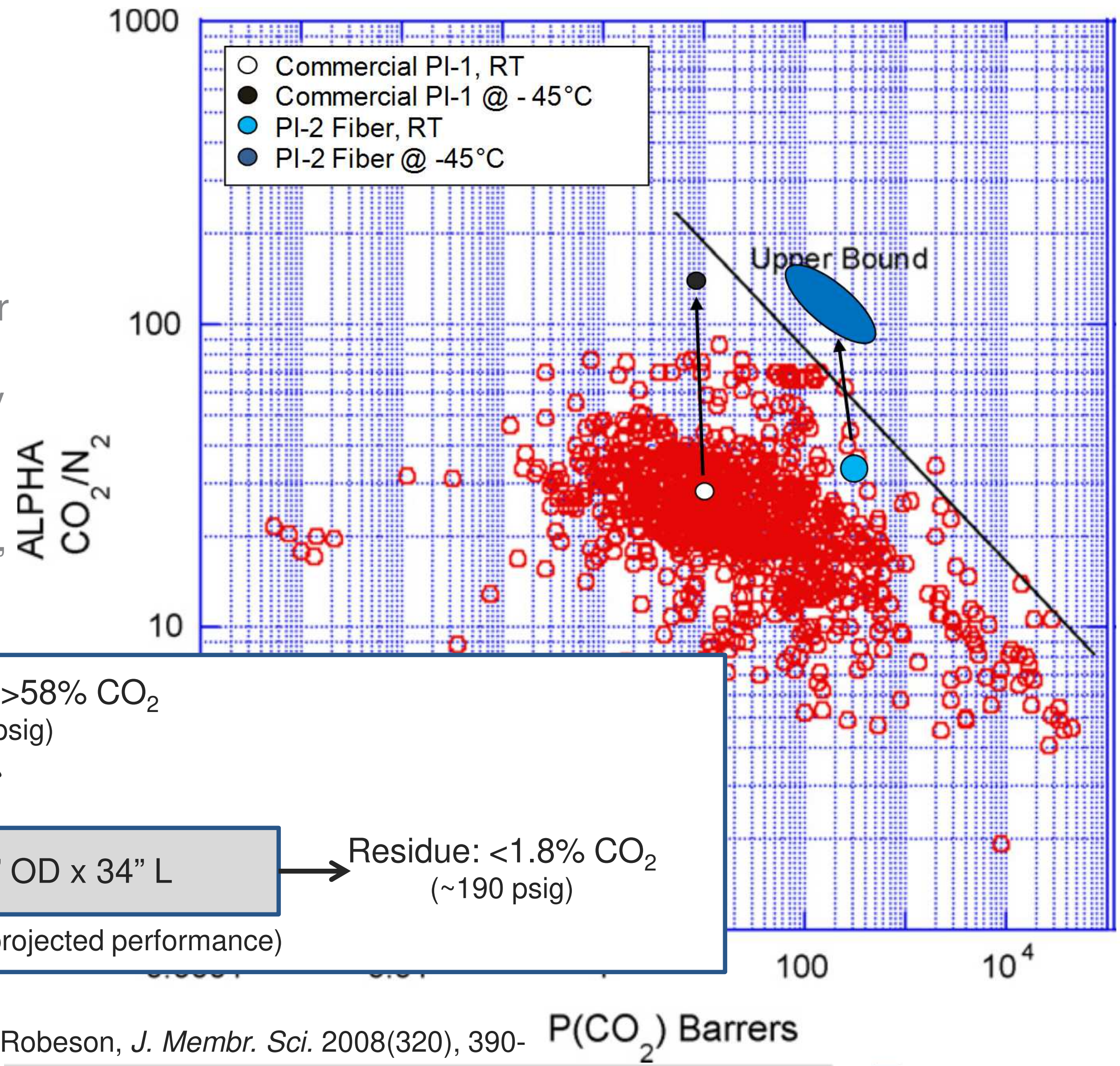
Background: Novel PI-2 Membrane Material

PI-1 standard product

- Commercial product
- Well developed for CO_2 capture under FE0013163

PI-2 novel material

- Permeation properties near Robeson* upper bound
- Developed to commercially viable status in past 2 years
- Performance at NCCC over 2,100 hours at 1” scale, 300+ hours presently at 6”



Permeate: >58% CO_2
(~1 psig)

Feed: 3,300 Nm^3/h
(1.1 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-

Project Status

Objectives (Success Criteria):

- Design/manufacture 4” bundle(s)
  - >90 Nm^3/h feed @ 90% CO_2 recovery, >58% CO_2 purity
- Identify other hybrid processes with possibility of economic feasibility
- Design/manufacture 6” bundle(s)
  - >400 Nm^3/h feed @ 90% CO_2 recovery, >58% CO_2 purity
- Field-test 6” bundles at 0.3 MWe scale with real flue gas at NCCC
- TEA achieving >90% capture at a cost of electricity 30% less than DOE baseline

Oct ’15 → Jun ‘17

✓ Four bundles fabricated, performance achieved

✓ Eight cases considered, five evaluated

Jul ’17 → Dec ’18*

✓ Seven bundles fabricated, first three exceeded targets

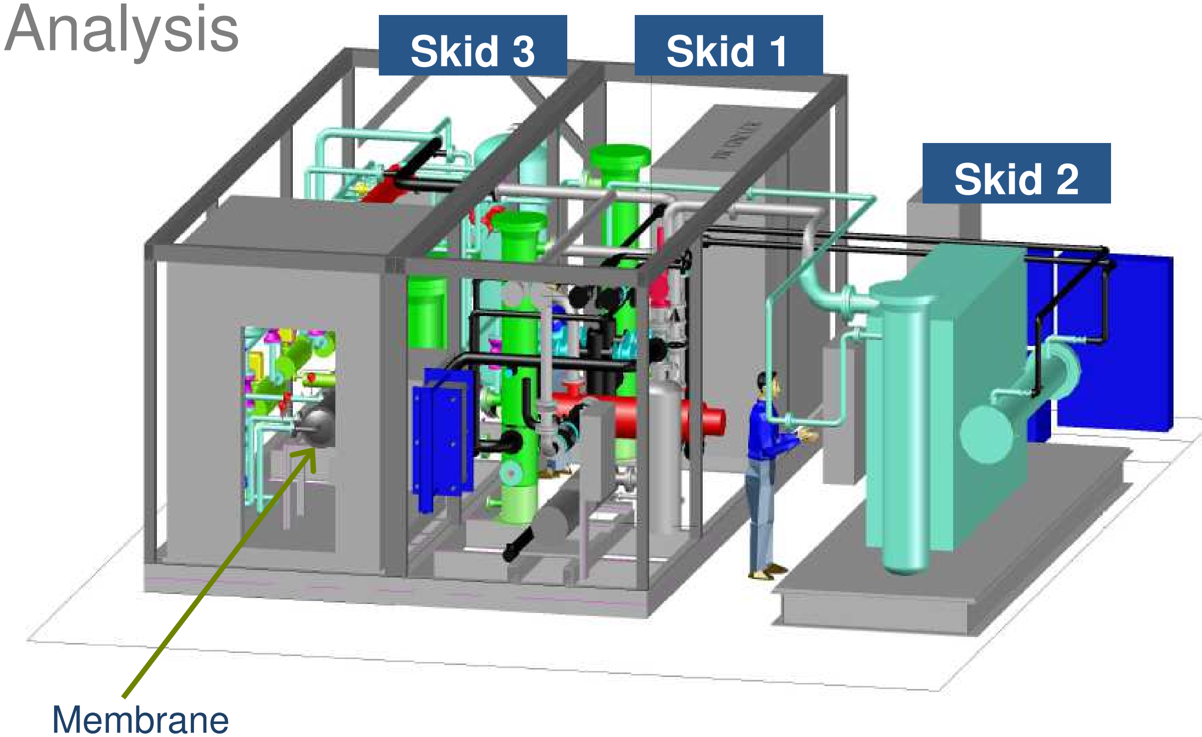
- Two bundles tested at NCCC in real flue gas
- Work progress

Total Budget - $3.98 MM (25% cost share), 9.4 man-years total**
Partners – AL R&D, NCCC, ALAS, and Parsons

Revision in progress:
***Jun ‘19**
****$4.37 MM**

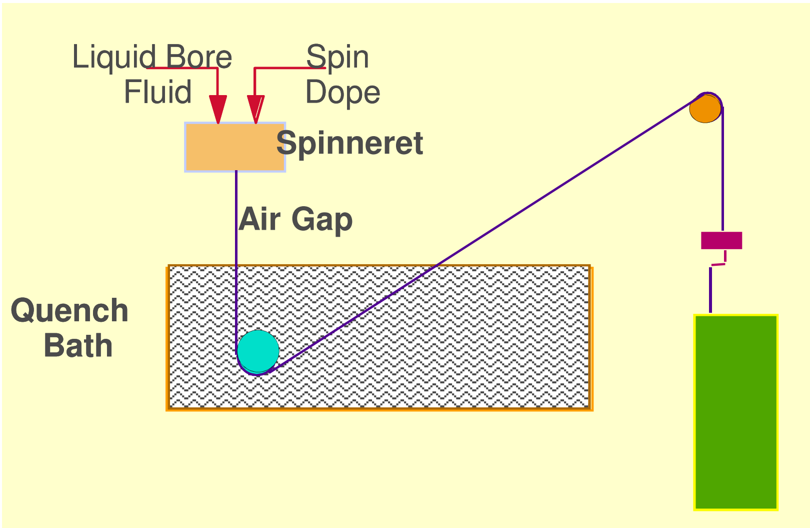
Agenda

- Technology & Project Overview
- **PI-2 Scale-up**
  - **Manufacturing development**
  - Membrane bundle fabrication and testing
- Techno-Economic Analysis
  - Process development
  - Manufacturing cost
  - Economic model and preliminary results
- Conclusions & Next Steps



Manufacturing Development

Dry jet wet quench fiber spinning



12-filament Development Spin Unit

2-gallon mixer

15-gallon mixer

Batches of fiber

ALAS manufacturing equipment for processing

Manufacturing Development

	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 (commercial)	6”		50 – 90x	24/36-hole production unit	
12” bundle (commercial)	12”		>200x		

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

Fiber Processing / Handling
- Washing
- Drying
- Bobbin winding

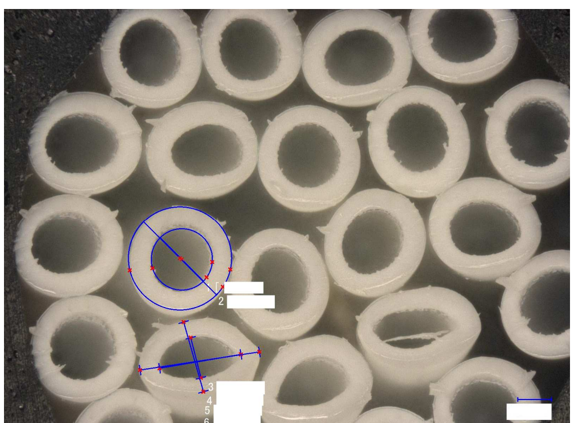
Forming Equipment
- Tube-sheet forming
- Machining





Membrane Bundle Fabrication

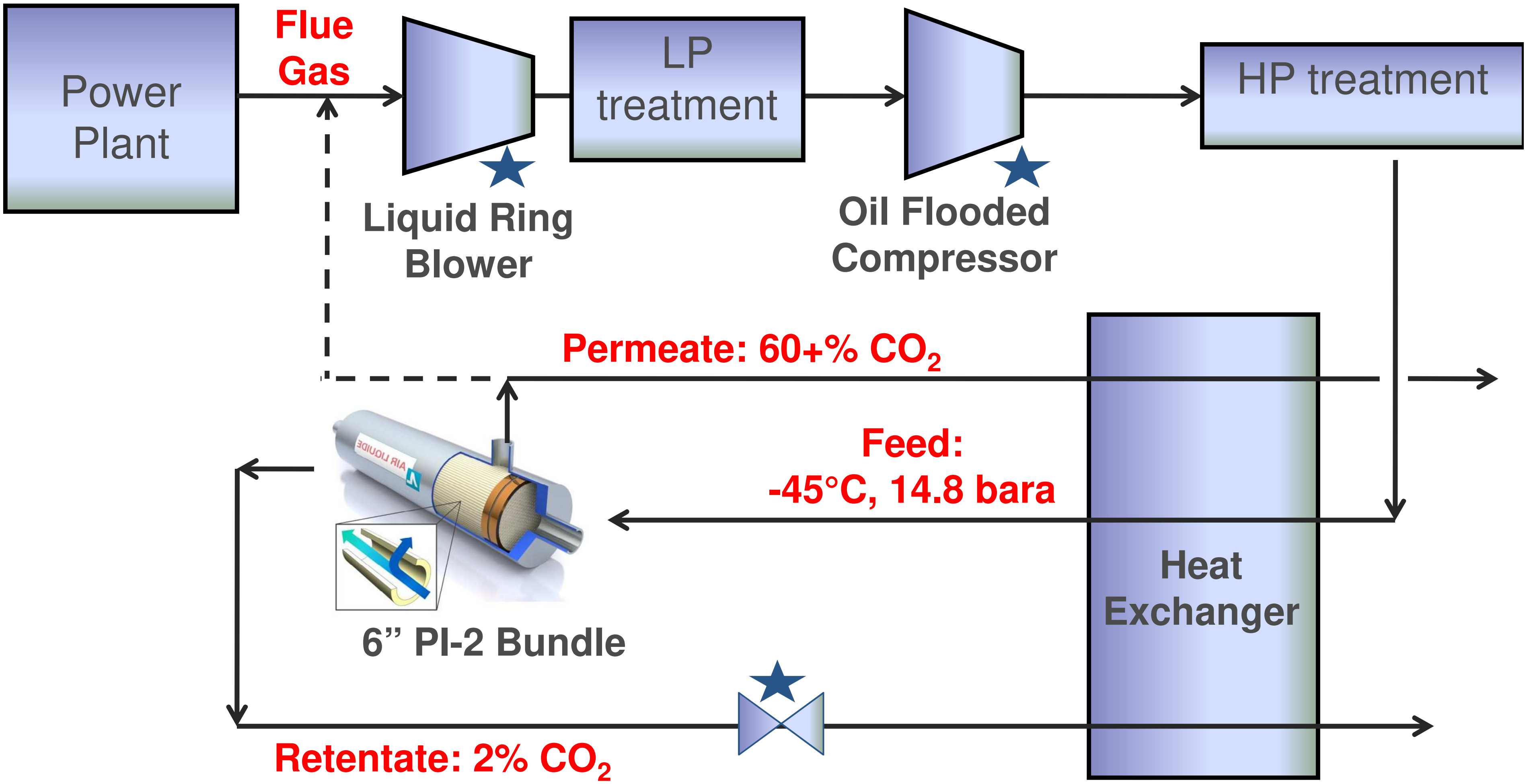
Date	Equipment	Polymer Quantity / Fiber Yeild	Comments
May-2016	DSU (12 fil)	0.5 lbs / 20%	Core pump cavitation, needed rebuild
Jun-2016	DSU	2.2 lbs / 93%	1st forming campaign (2 x 4”) – good
Jun-2016	DSU	0.6 lbs / 25%	Multiple fiber breaks, bore pump rebuild
Dec-2016	DSU	2.7 lbs / 90%	2nd forming campaign (2 x 4”) – good
May-2017	DSU	11 lbs / 80%	3rd forming campaign (1 x 6”) – good
Oct-2017	DSU	18 lbs / 90%	4th forming campaign (2 x 6”) – good
Feb-2018	Manuf. (24 fil)	29 lbs / 85%	5th forming campaign (4 x 6”) – good



(microscope image of 24-filaments PI-2)

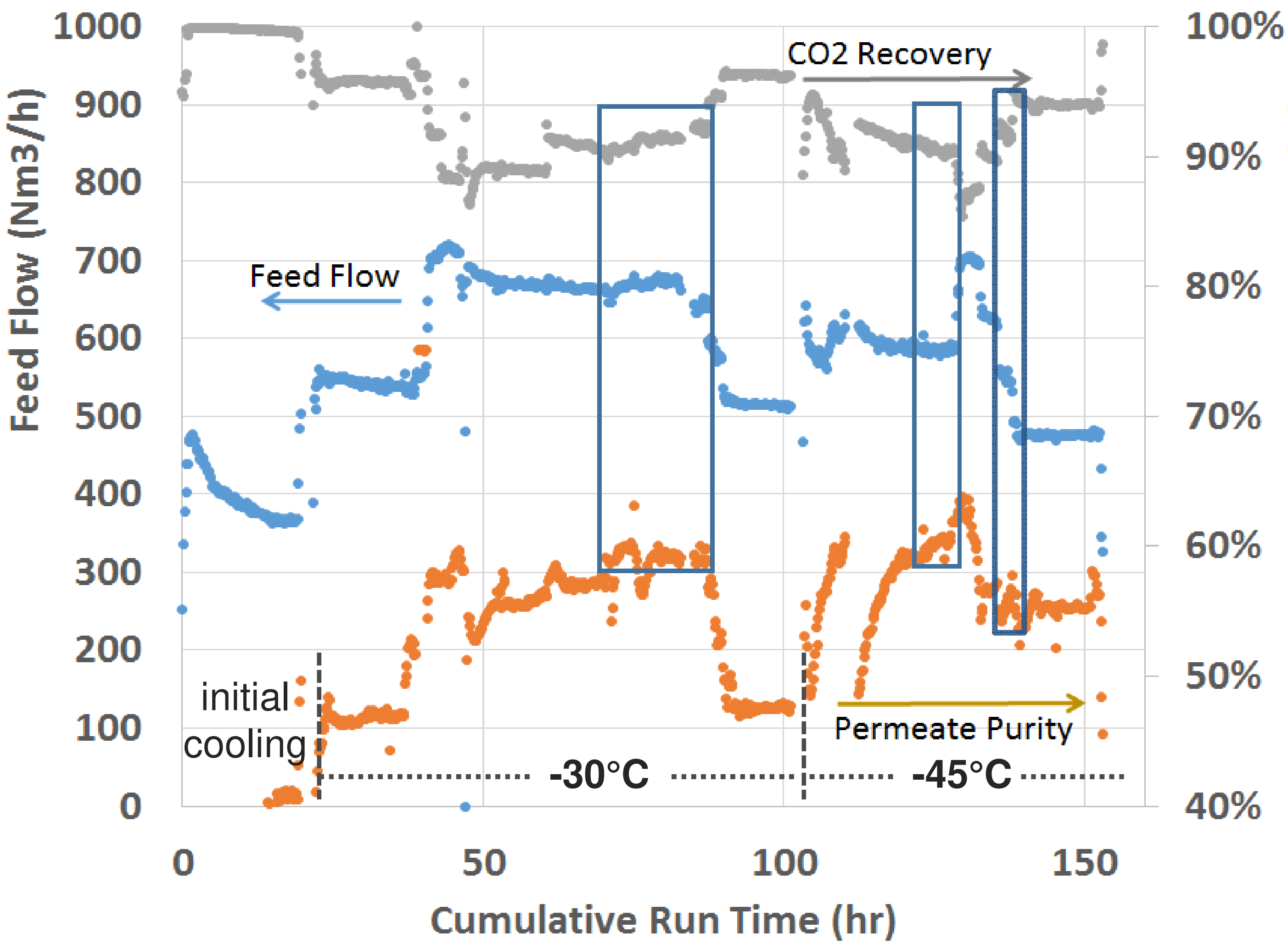
(wash can of PI-2 fiber)

Process Flow Diagram - NCCC



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

6” Membrane Bundle Test Data (6IN-PI-2-01)



- Range of conditions tested at NCCC in real flue gas
- One 6” bundle processes >600 Nm^3/h of gas (0.2 Mwe)
- Success criteria exceeded in three different ranges (indicated)
- Long-term steady state testing still desirable

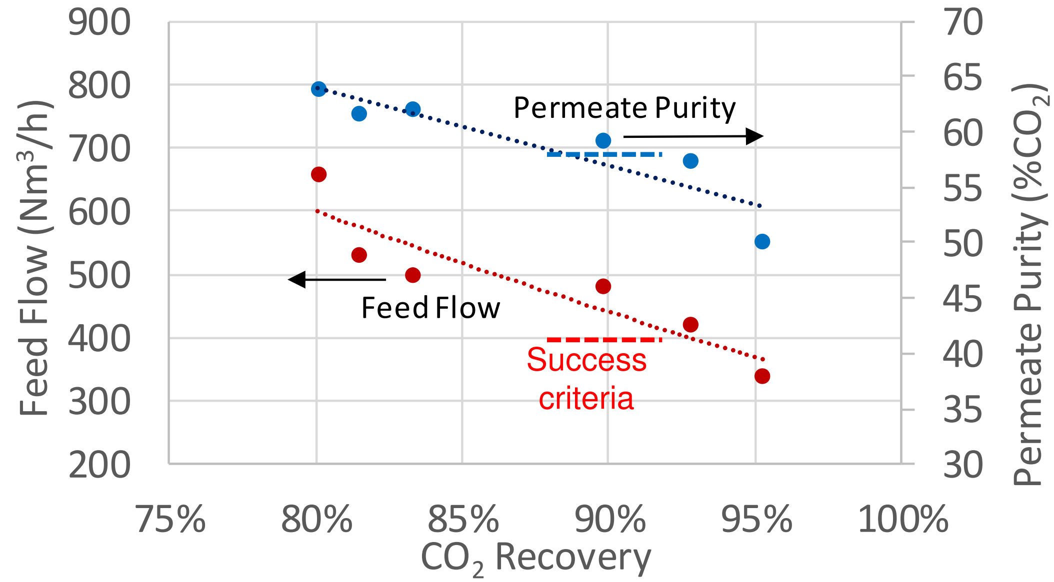
All: 14.8 bara, 18% CO_2

Parametric Test Data (6IN-PI-2-01)

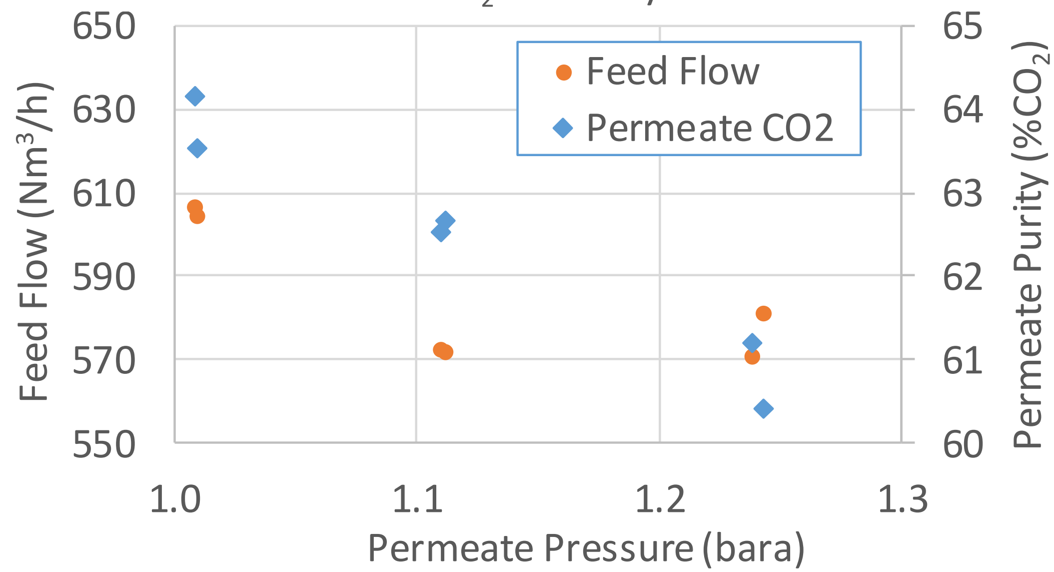
- Feed flow and permeate purity dependence on CO_2 recover – in line with expectations

- Success criteria exceeded at target conditions!

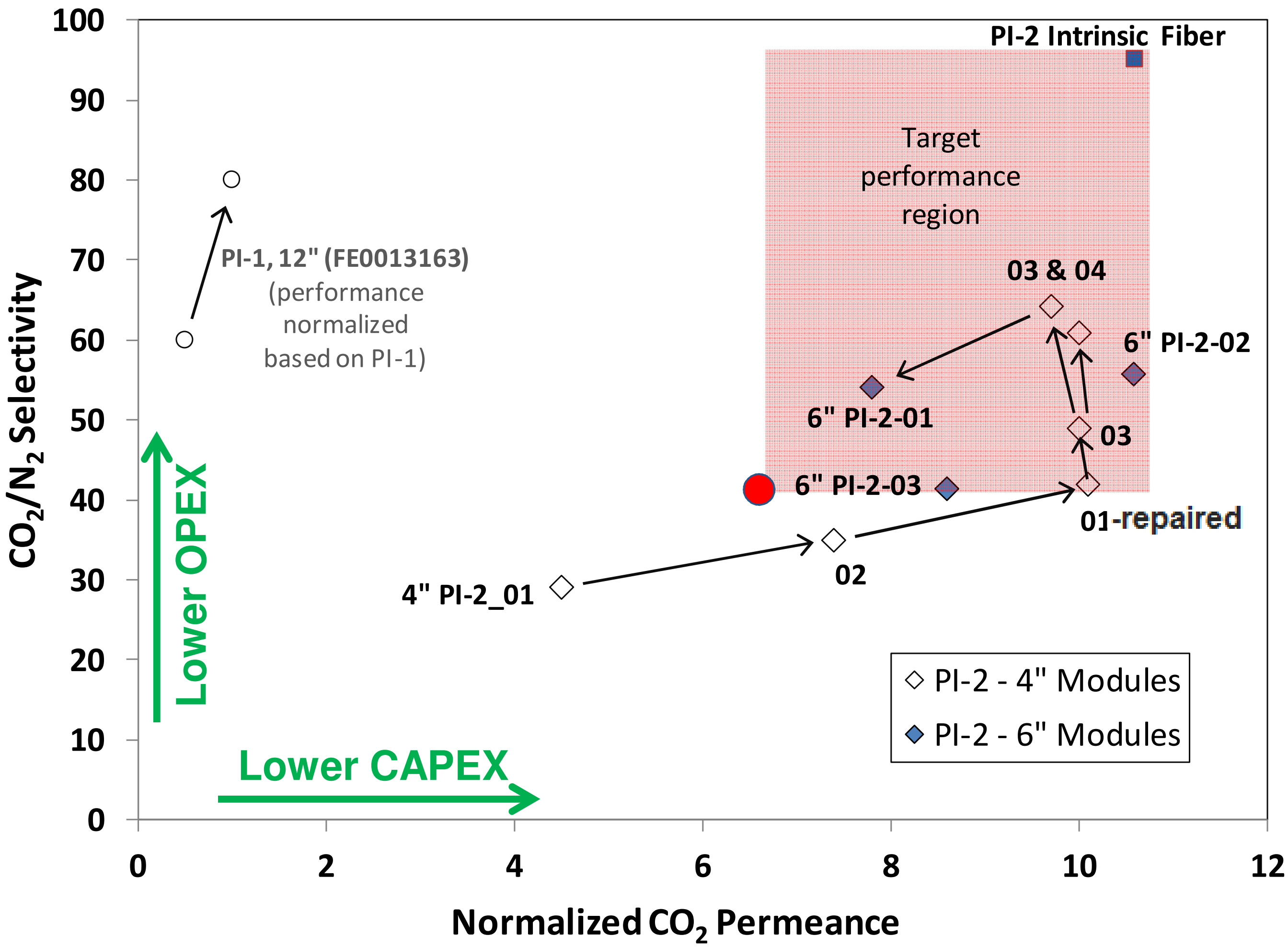
(400 Nm3/h, 58% permeate purity, 90% recovery)



- Permeate CO_2 concentration and feed flow dependent on permeate pressure (at fixed CO_2 recovery)



Manufacturing Progress



- 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% CO_2 recovery,
58% permeate purity
4" – 90 Nm^3/h (feed)
6" – 400 Nm^3/h

6” Bundle Performance vs. Success Criteria

	6IN-PI-2-01	6IN-PI-2-02	6IN-PI-2-03		Success Criteria
Conditions	18.4% CO_2, 14.8 bara, -45°C, P_{perm}: 1.1 bara	18.0% CO_2, 13.1 bara, -45°C, P_{perm}: 1.2 bara	Experimental: 16% CO_2, 11.9 bara, -42°C, P_{perm}: 1.1 bara	Projected: 18% CO_2, 14.8 bara, -45°C, P_{perm}: 1.1 bara	
CO_2 Permeance [$P_{CO2}/P_{PI\text{-}1}$]	7.3	10.6	8.6*		
CO_2/N_2 Selectivity	51.5	55.8	41.3*		
CO_2 Recovery	91%	90%	99%	90%	90%
Productivity, Feed [Nm^3/h]	577	646	247	647	400
Permeate CO_2 Purity	62%	60%	44.4%	59%	58%

*Measured at high recovery, low accuracy

- First two 6” bundles met the success criteria in real flue gas
- Third 6” bundle, tested in synthetic gas at a high stage cut, to be further tested at NCCC

- Lessons learned in 4” module fabrication resulted in excellent performance at 6” size

1) Epoxy application for tubesheet
2) Post-treatment solution concentration

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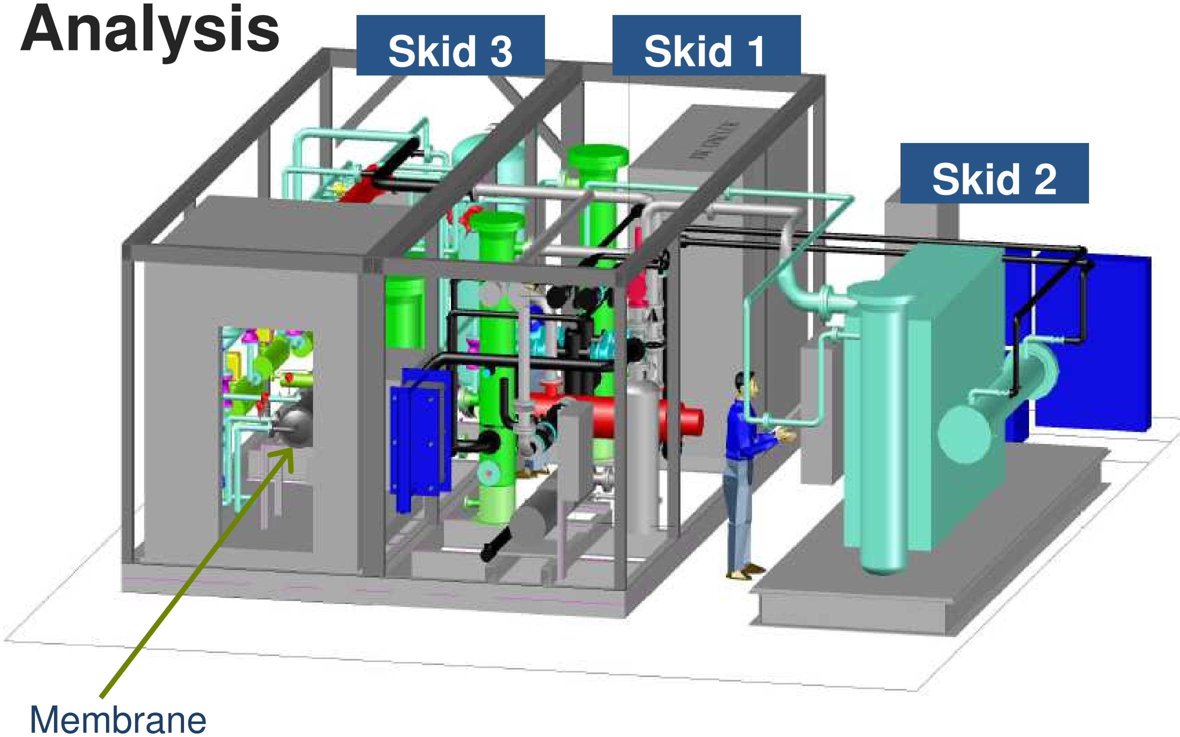
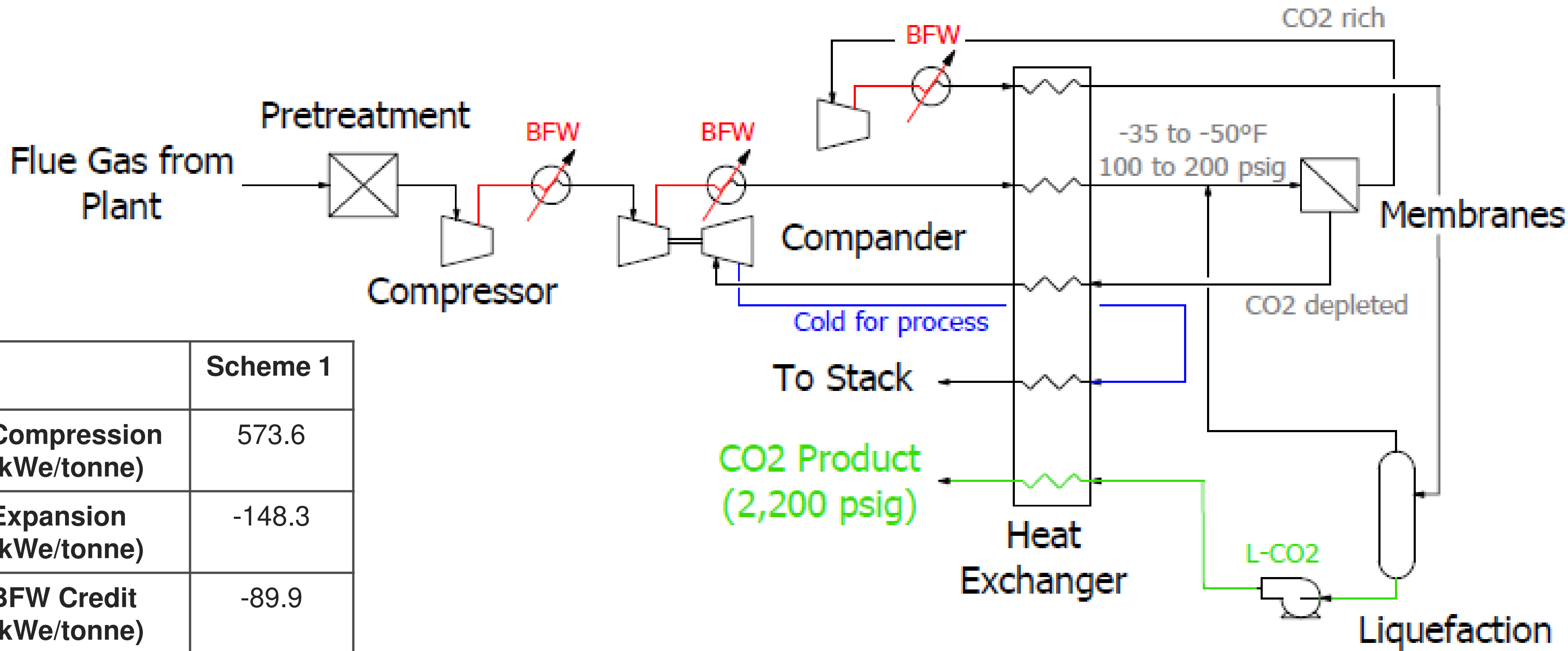
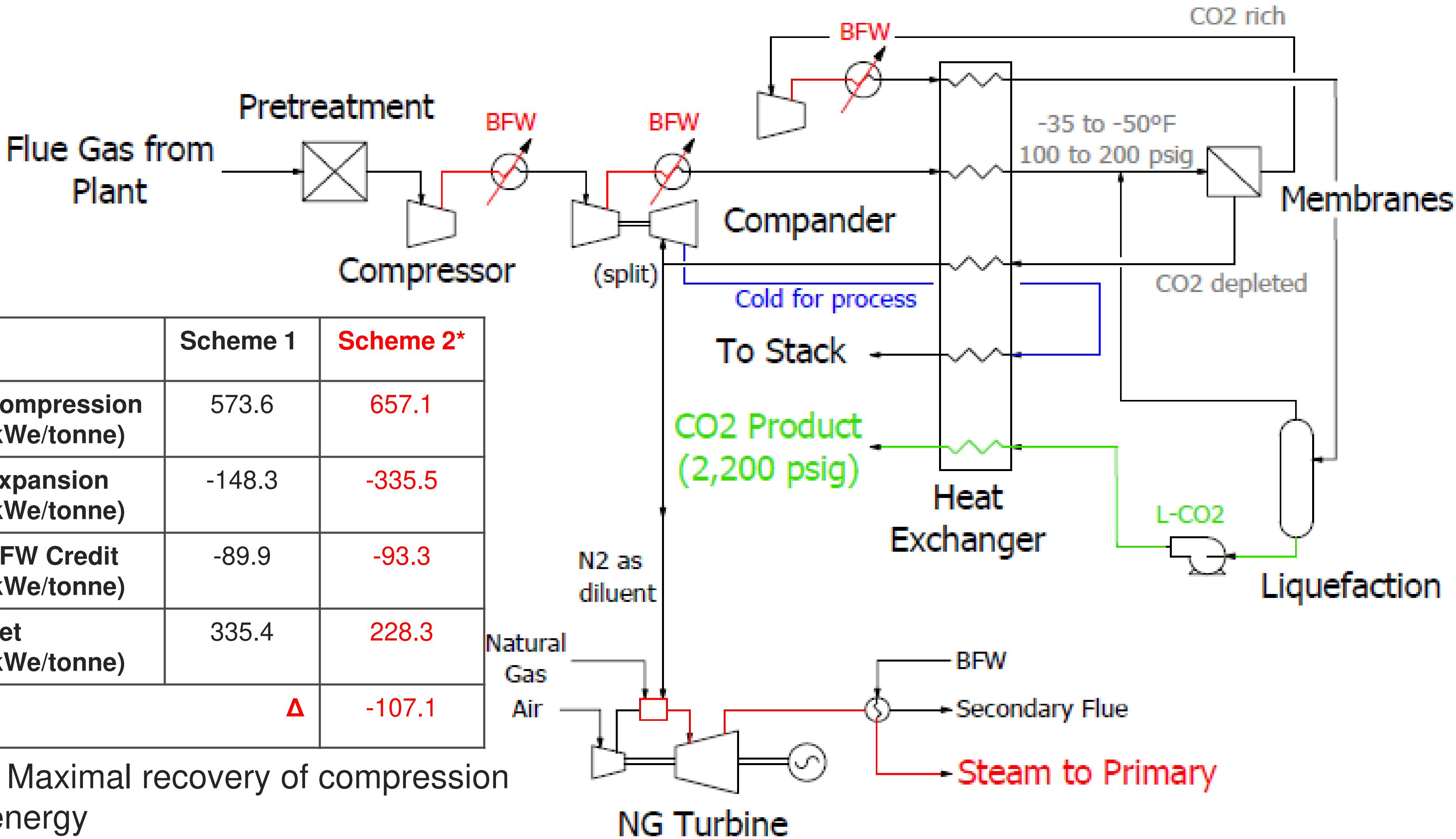


Process Design (Scheme 1 – Cold Membrane Process)



	Scheme 1
Compression (kWe/tonne)	573.6
Expansion (kWe/tonne)	-148.3
BFW Credit (kWe/tonne)	-89.9
Net (kWe/tonne)	335.4

Process Design (Scheme 2 – Energy Recovery with NG Turbine)



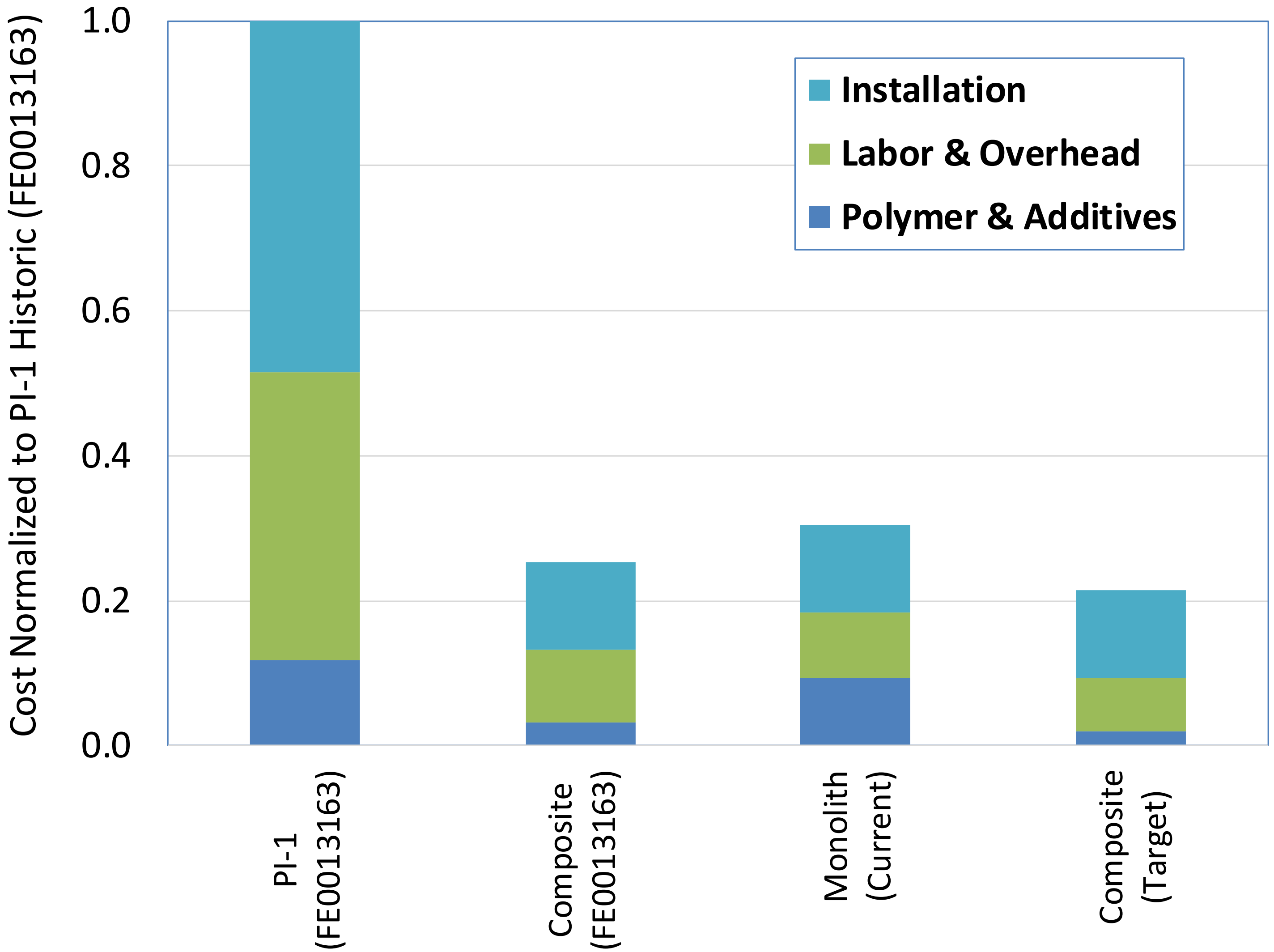
	Scheme 1	Scheme 2*
Compression (kWe/tonne)	573.6	657.1
Expansion (kWe/tonne)	-148.3	-335.5
BFW Credit (kWe/tonne)	-89.9	-93.3
Net (kWe/tonne)	335.4	228.3
	Δ	-107.1

- Maximal recovery of compression energy
- N_2 diluent improves NGCC efficiency

- Membrane operated at 95% CO_2 recovery so overall process meets 90%

Fiber Manufacturing Cost Analysis

- **Huge cost savings by PI-2 productivity per module**
- With low polymer price monolith fiber yields CO_2 capture cost savings
- Some additional savings by manufacturing economy of scale
- For PI-2, best value is composite formulation

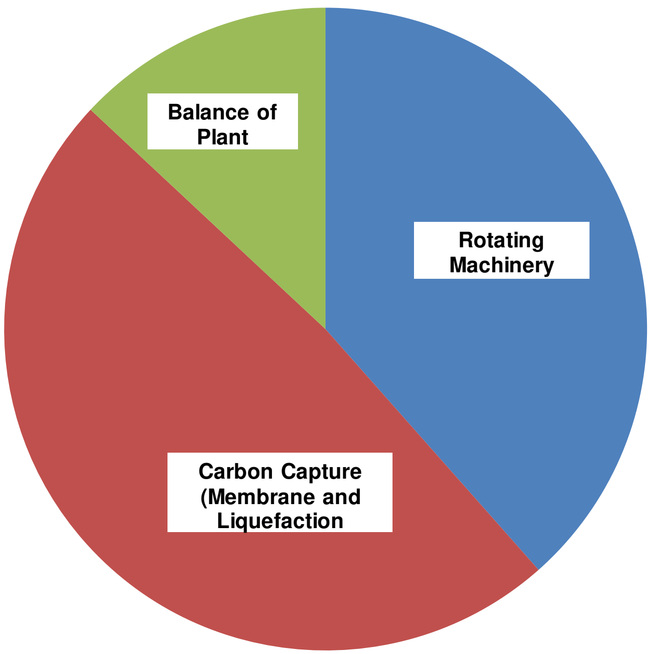


Techno-Economic Analysis

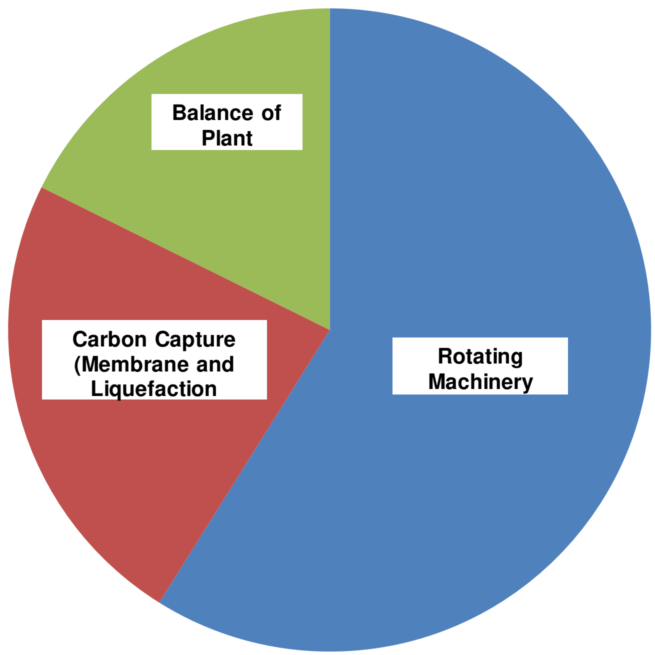
	Case 12 (Amine)	Cold Membrane, PI-1	PI-2**	Change
Power Plant Cost (MM$)	1,602	1,440	1,343	-16%
CO_2 Capture System (MM$)	593	357	242	-59%
CO_2 Capture Cost ($/tonne)	42.2	36	32	-24%
Cost of Electricity (mills/kWh)*	**111**	**103**	**99**	**-11%**

*Not including CO_2 transportation & storage, Cost and Performance Baseline 2013

**Preliminary estimates, not fully vetted



PI-1



PI-2

- Significant cost savings of Cold Membrane system over Amine
- Use of PI-2 results in further capital savings and changes balance of equipment costs

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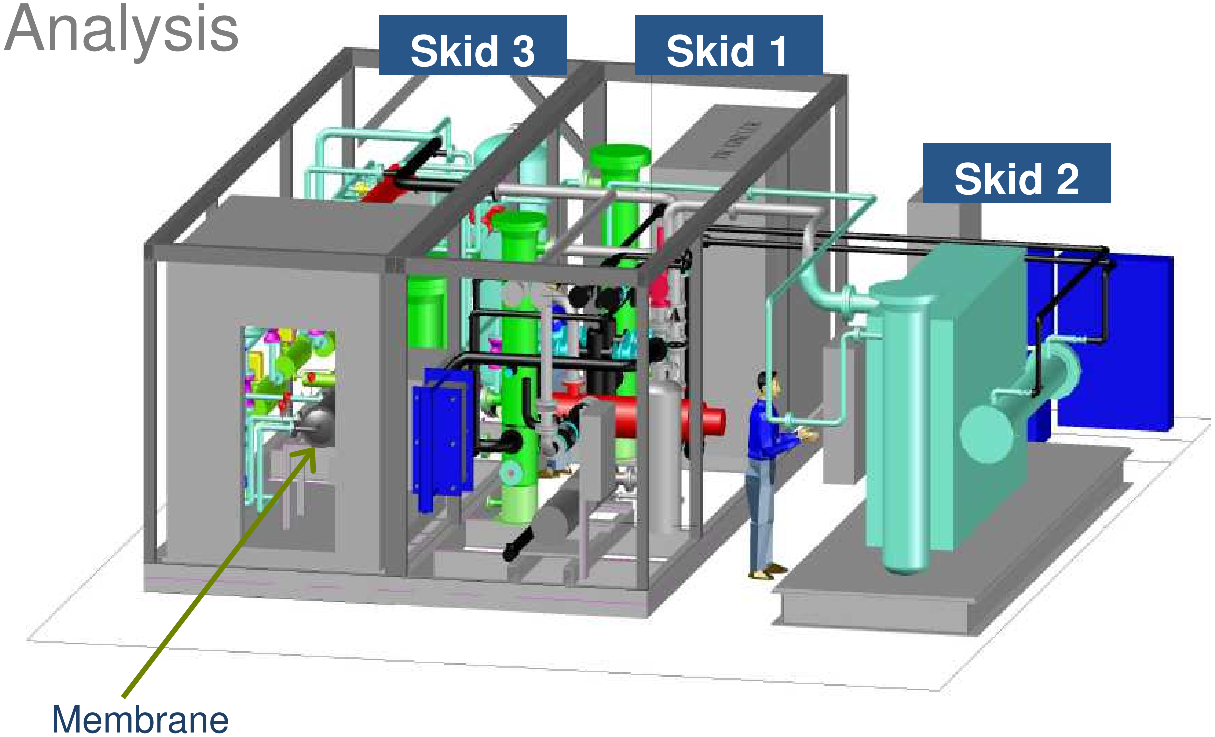
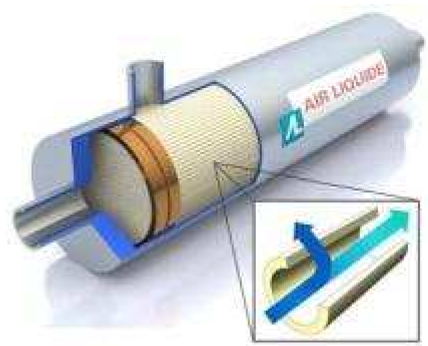


Conclusions

- PI-2 manufacturing scale-up
  - Fiber synthesized on full manufacturing line
  - Formed into seven commercial size bundles
  - Consistent performance on testing



- Field-test at NCCC, 0.3 MWe scale
  - Two bundles tested for 150 hours each
  - Excellent performance – both exceeded success criteria at 90% CO_2 recovery

- Techno-economic analysis underway
  - First pass estimates show significant reduction in COE

Next Steps

Seeking CO_2 utilization partner for additional testing!

- Timeframe: early/mid 2019
- Utilities: electricity, cooling water, instrument air

	Coal Flue gas	Cement/SMR Flue gas	Natural gas flue gas
CO_2 Content	15%	20%	10%
CO_2 Product	6 tpd	10 tpd	4 tpd
Operating Cost*	$125-135 /tonne	$70-80 /tonne	$185-195 /tonne

*Operating cost is for 0.3 MWe skid and is not representative of larger on-site CO_2 solution

- Cost sharing: negotiable

0.3 MWe Field-Test Unit at NCCC, Pilot Bay 3 (DE-FE0013163 & FE0026422)

Acknowledgments / Disclaimer

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- Air Liquide: Rob Gagliano, Shilu Fu, Sudhir Kulkarni, Dave Hasse, Mike Bennett, Andrew Hamilton, Dean Kratzer, Trapti Chaubey, Jean-Marie Gauthier, Tim Poludniak

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Research & Development

Opening new ways

THANK YOU FOR YOUR ATTENTION