Award: DE-FE0026422

AIR LIQUIDE

Project Review: Bench Scale Testing of Next Generation Hollow Fiber Membrane Modules

August 11, 2016

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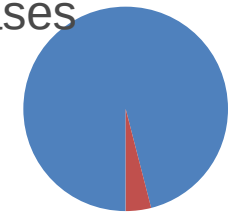
J.-M. Gauthier | MEDAL

Air Liquide & MEDAL

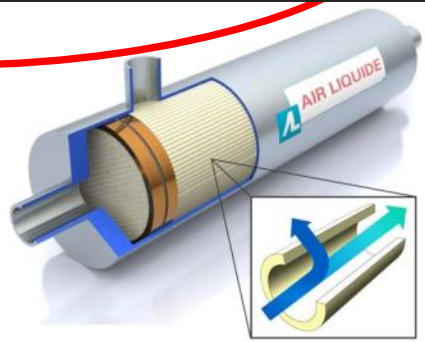
Air Liquide: world leader in industrial and medical gases

68,000 employees

$18.1 billion sales (2015)



Air Liquide Advanced Separations, MEDAL



N_2 applications / markets

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

H_2 applications / markets

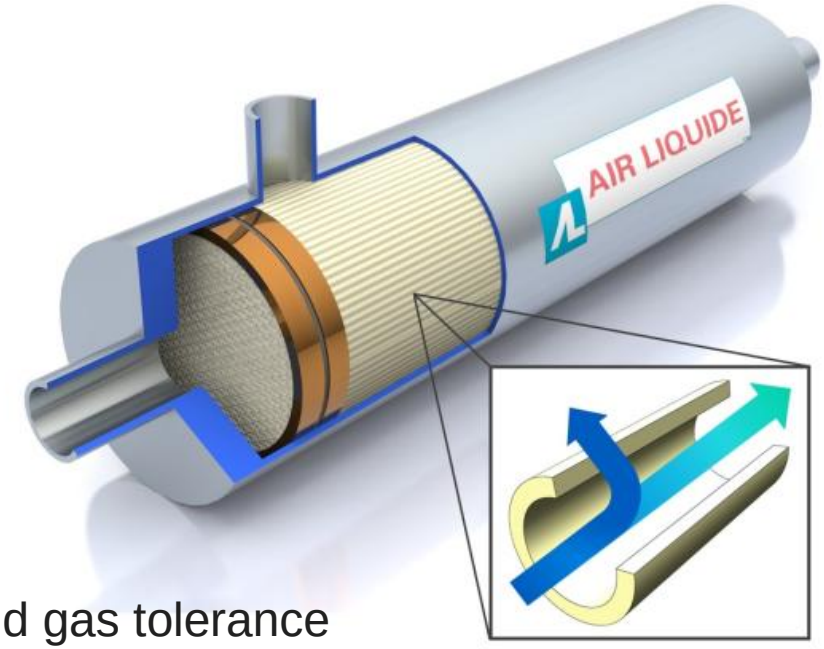
HDT | HCR/ RDS | CR | CCR | OPAL (C2 cracker) | GTL (CO/H2 adj) | MeOH | Syngas (CO/H2 adj) | CO (coldbox) | NH_3

CO_2 applications / markets

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

Outline

- Project Overview
- Technology Background
  - Process design
  - PI-2 novel material
- Project Details / Progress
  - Equipment set-up
  - Formulation development
  - Manufacturing development
  - Acid gas tolerance
  - Hybrid process analysis
- Conclusions & Future Work



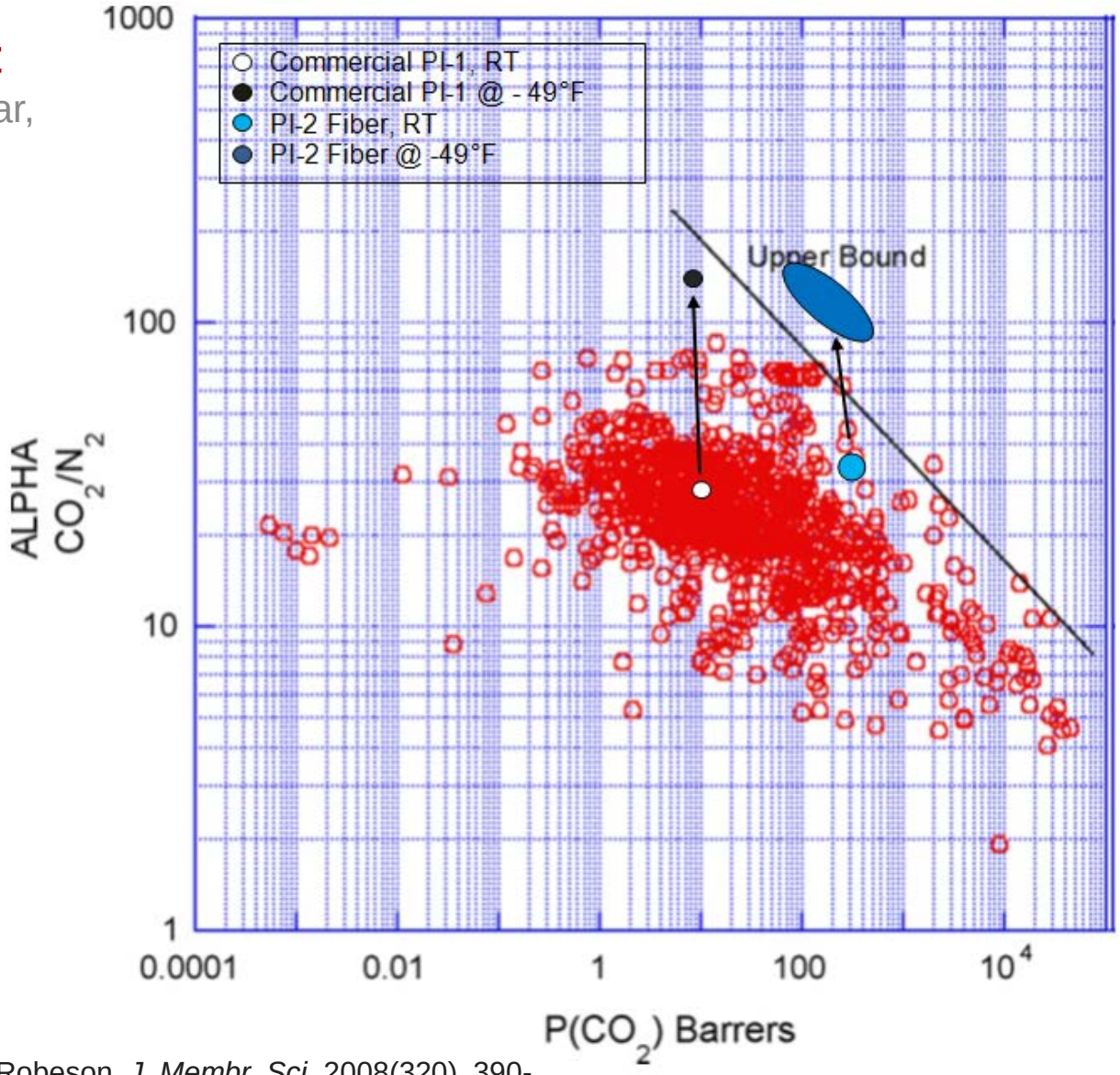
Motivation: Increase Membrane Productivity

PI-1 commercial product

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

PI-2 novel material

- Thin film properties near Robeson* upper bound
- Spinnable
- Performance at lab-scale over 500+ hours



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

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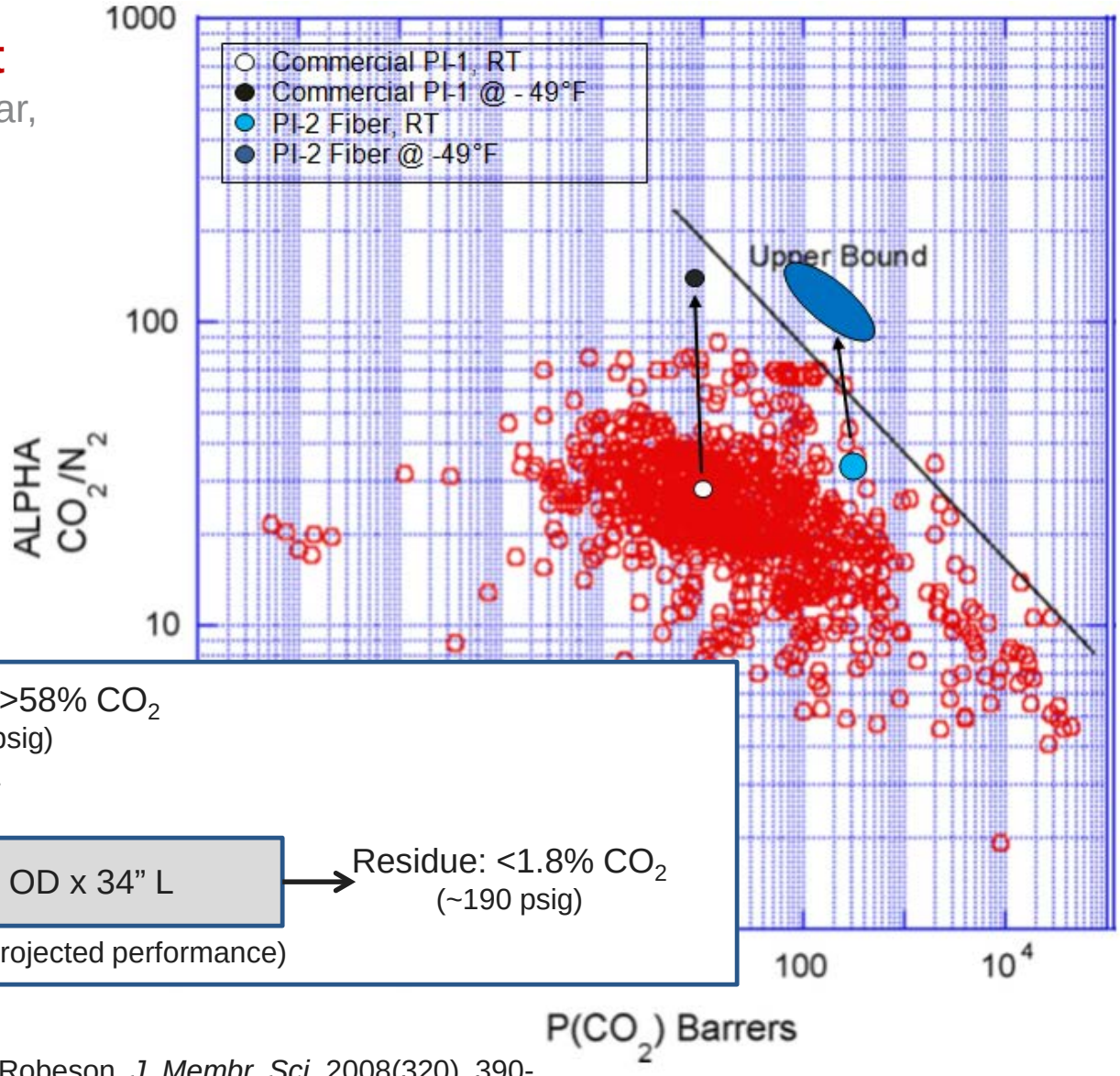

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Project Objectives

- 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 Nm3/h feed @ 90% CO2 recovery, >58% CO2 purity
    - Manufacture at least one 12” bundle
  - Field-test 6” bundles at 0.3 MWe scale with real flue gas at NCCC
  - Techno-economic analysis achieving >90% CO_2 capture at a cost of electricity 30% less than DOE baseline

Oct ’15 → Mar ‘17

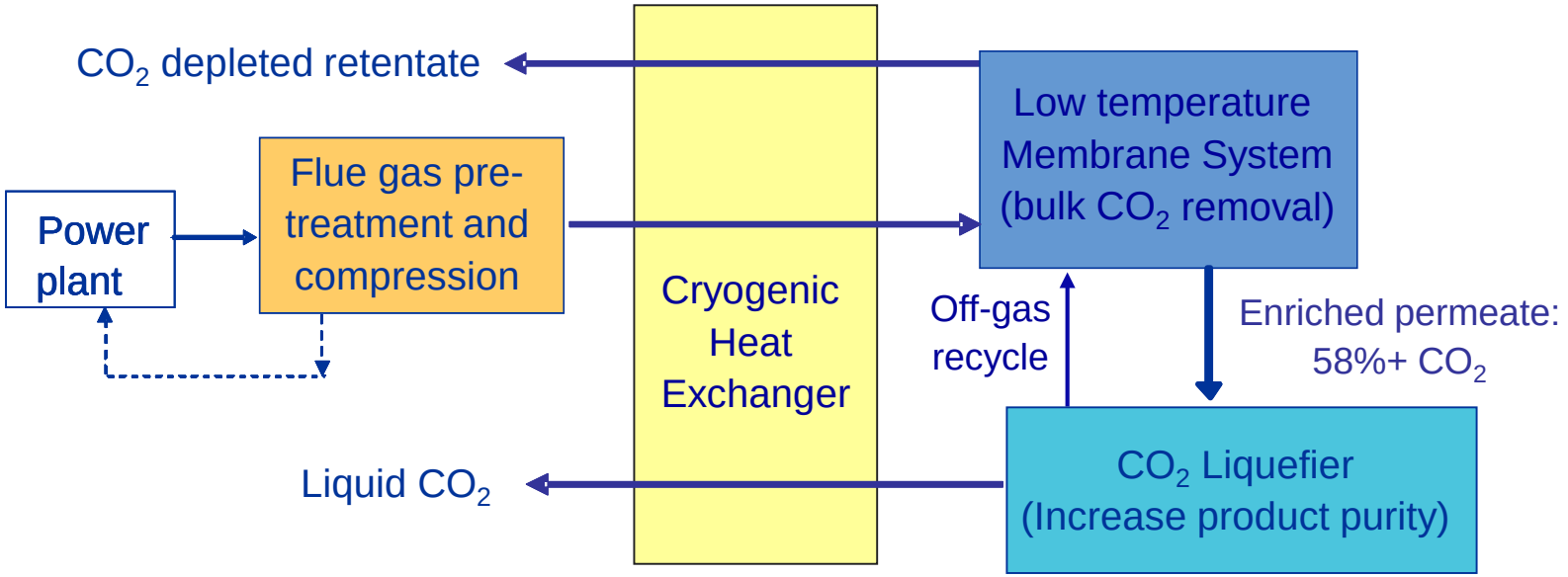
Apr ’17 → Sept ‘18

Total Budget - $3.98 MM (25% cost share), 9.4 man-years total
Partners – DRTC, MEDAL, and Parsons

Technology Background: Process Concept

- 2010 – 2012 DOE: DE-FE0004278
  - Cold membrane hybrid process
  - PI-1: synthetic flue gas (TRL 4)
  - Techno-economic analysis

- Energy recovery by turbo-expansion and cold production
- Energy integration
- BFW generation
- Pumping liquid CO_2



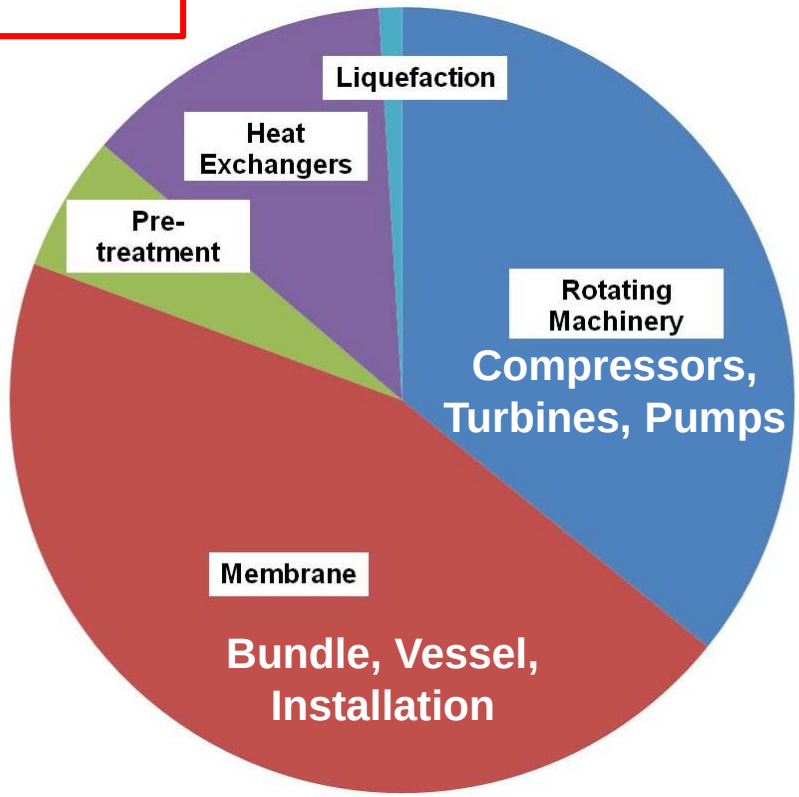
Technology Background: Capture Cost

- 2013 – 2016 DOE: DE-FE0013163
  - 2x12” PI-1 bundles, real flue gas
  - TRL 5 (PI-1)
  - Techno-economic analysis

Projected CO_2 capture cost 42 - 48$/tonne
(DOE Target – 40$/tonne of CO_2)

Areas of improvement:

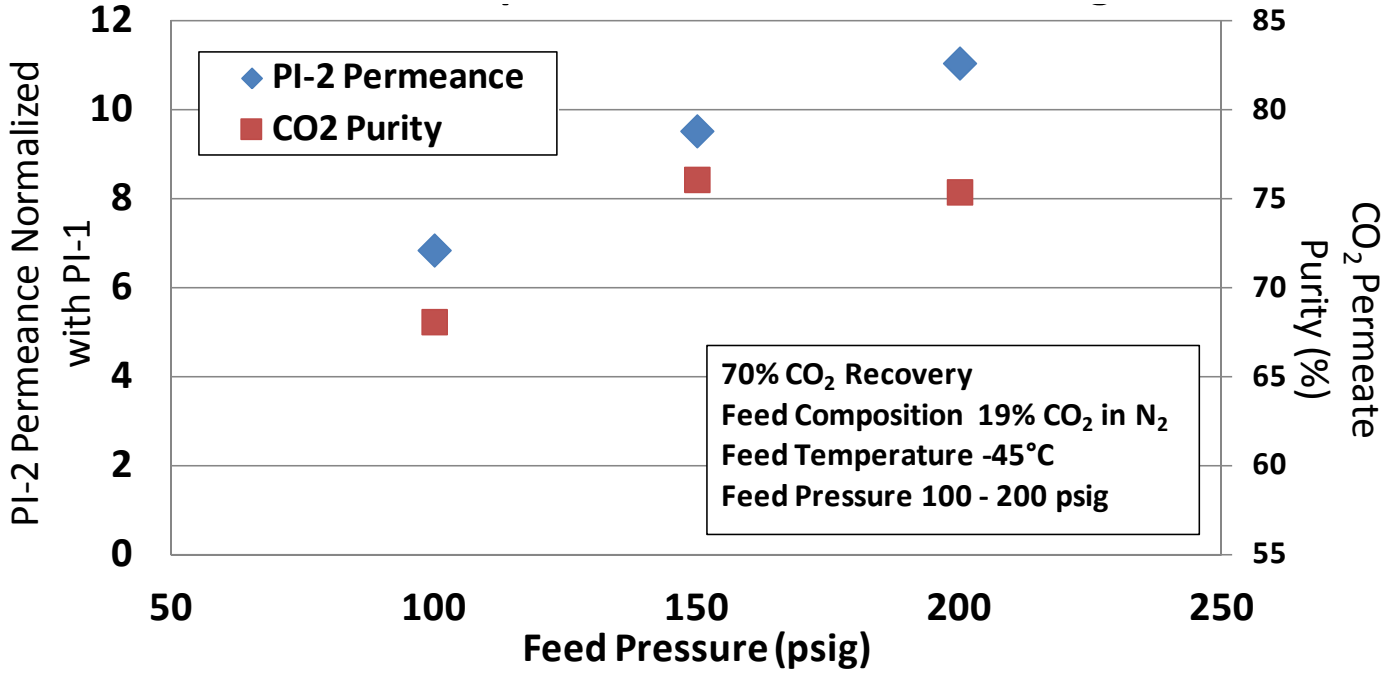
- Reduce membrane cost – **improve membrane performance**
- Reduce pre-treatment / compression costs, **lower operating pressure**



Technology Background: PI-2 Fiber Development

- 2013 – 2016 DOE: DE-FE0013163
  - 1” PI-2 modules (500+ fibers)
  - TRL 4 (PI-2)

- PI-2 lab-scale spinning methodology
- 1” OD modules (500 fibers) achieved good performance in real flue gas



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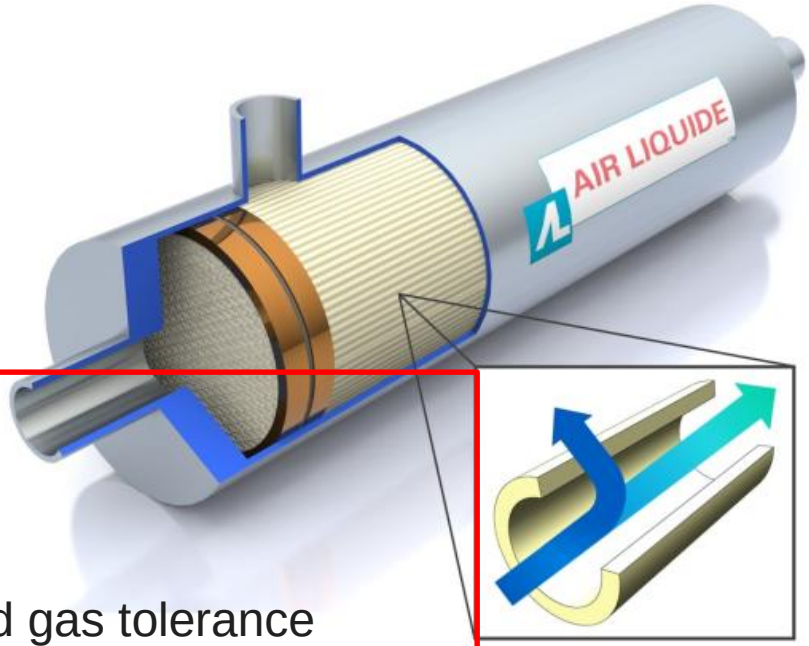
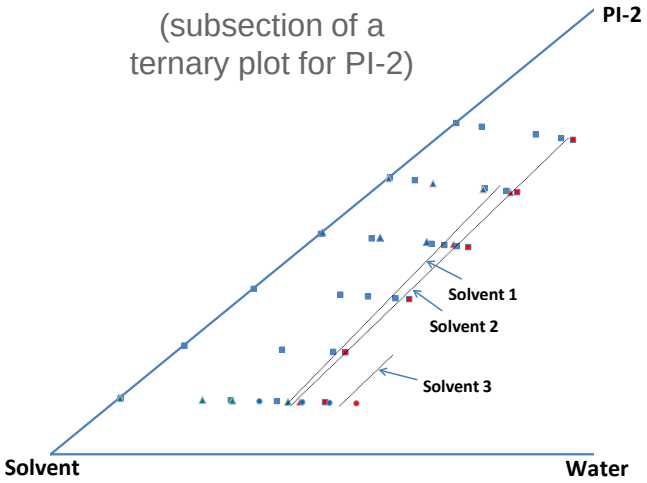


Project Milestones & Dates

BP #	Expected	Milestone
BP1	03-31-2016	Complete prototype manufacturing setup and initiate 4” bundle fabrication
	12-31-2016	Complete prototype bundle testing: >90 Nm^3/hr productivity @ 18%CO_2, 16 bar, 90% CO_2 recovery, and >58% CO_2 permeate composition
	03-31-2017	Complete verification of PI-2 flue gas contaminant testing
	03-31-2017	Complete hybrid process analysis comparing different applicable process schemes
GO/NO-GO Decision		
BP2	03-31-2018	Complete PI-2 commercial bundle fabrication and testing: >400 Nm^3/h productivity @18%CO_2, 16 bar, 90% CO_2 recovery, and >58% CO_2 permeate composition
	01-31-2018*	Complete installation and commissioning of the 0.3 MWe field-test unit at NCCC
	09-30-2018*	Complete 0.3 MWe field-testing including parametric testing and at least 500 hours for one membrane
	09-30-2018*	Techno-economic analysis of CO_2 capture at 550 MWe net AFPC plant using cold membrane technology
	09-30-2018*	Environmental, Health, and Safety analysis of cold membrane technology at full scale

Polymer Formulation Development

(subsection of a ternary plot for PI-2)



Baseline

Normalized Permeance	5
α-CO_2/N_2	>70

Alternate Formulations

Normalized Permeance	**5 - 15**
α-CO_2/N_2	**40 - 85**

Performance Improvement

Cost Reduction

Alternate Formulations

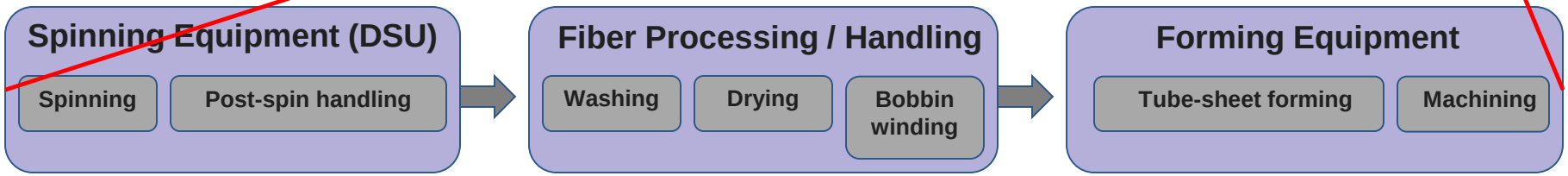
Normalized Permeance	**0.5 – 1.5**

	Blend A	Blend B	Blend C	Blend D	Blend E	Blend F	Blend G
Dope 1	Neg	Neg					
Dope 2			Neg	Pos			
Dope 3				Pos			
Dope 4					Neg		
Dope 5						Neg	
Dope 6							Neg
Dope 7				Pos			

(polymer blending attempts)

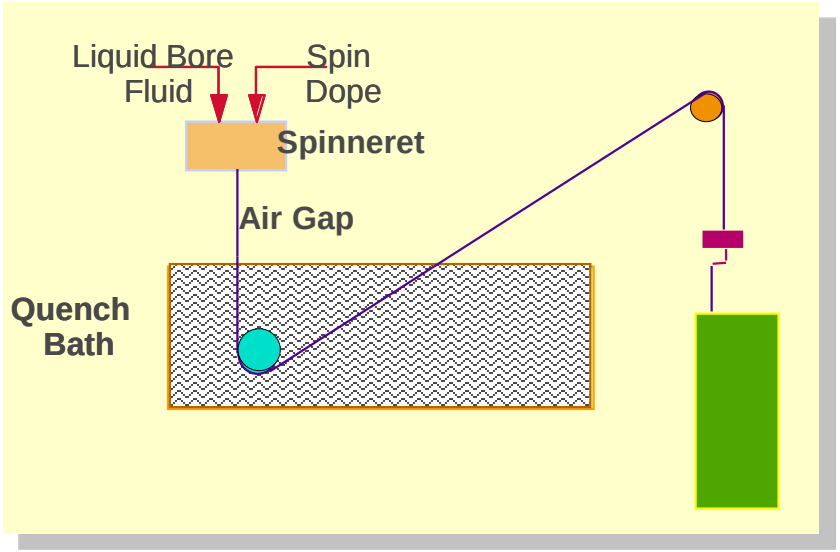
Manufacturing Development

	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		



Demonstration Scale Fiber Synthesis Equipment

Dry jet wet quench fiber spinning



12-filament Development Spin Unit

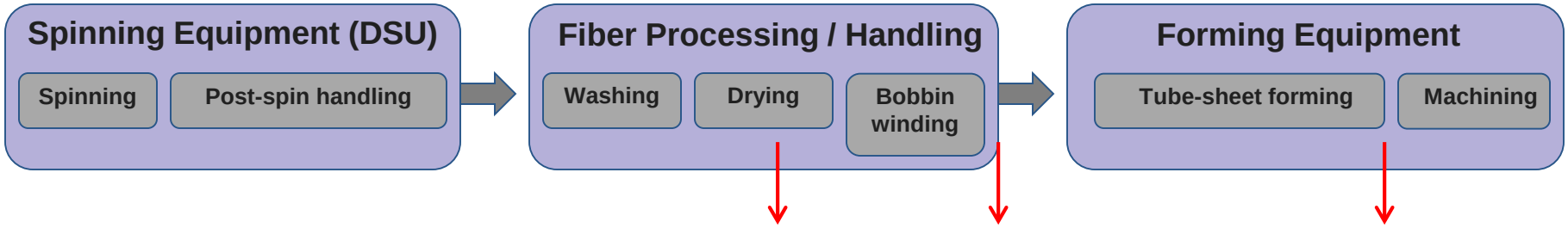
2-gallon mixer

15-gallon mixer

Batches of fiber

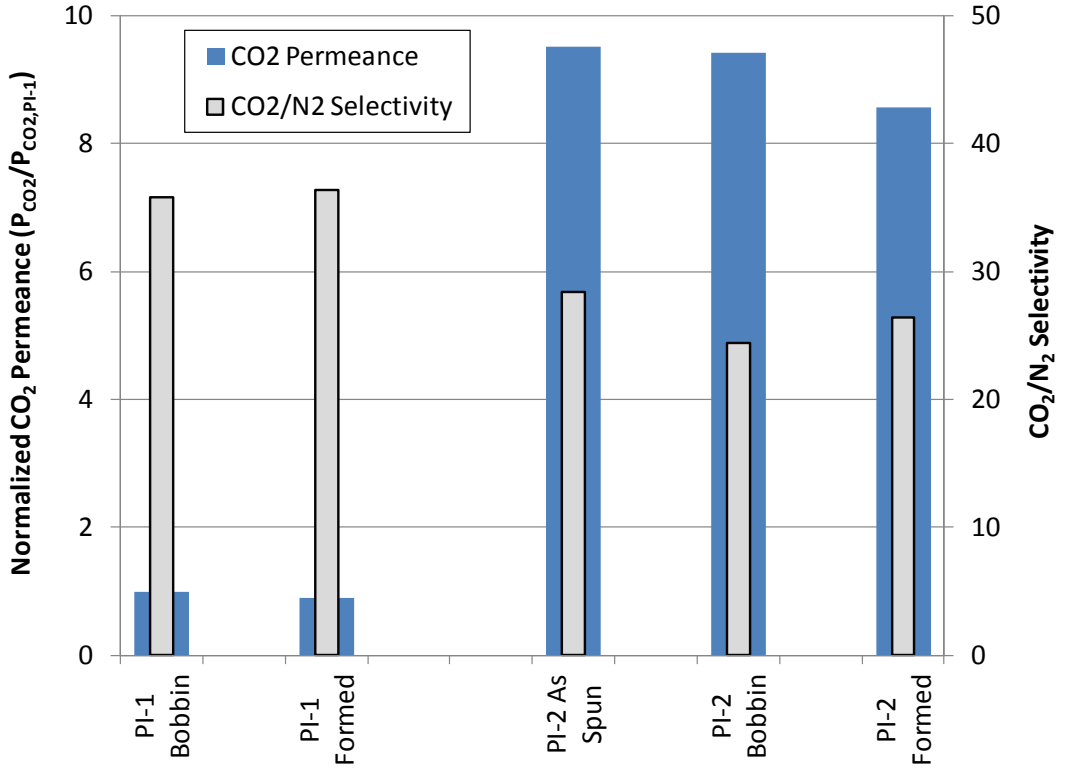
MEDAL manufacturing equipment for processing

Fiber Synthesis & Handling Damage



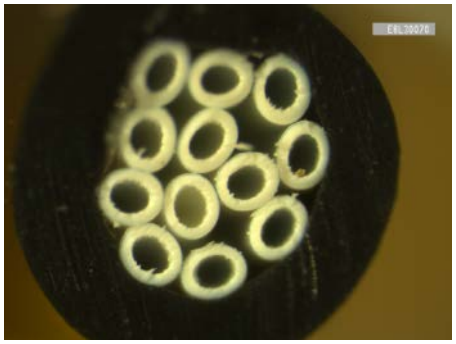
Samples taken and quality tested at ambient temperature

- Minor selectivity loss due to bobbin winding: minor handling damage
- No selectivity loss due to forming: little or no further handling damage



Fiber Synthesis & Bundle Forming

1.9 lbs of PI-2 fiber synthesized on the DSU over 3 hours



Periodic samples for quality control:

Sample #	Normalized CO_2 Perm	CO_2/N_2 Selectivity	Fiber ID
1	13.1	27.8	*Proprietary
2	11.7	31	
3	14.3	28	
4	11.0	26	
5	13.2	35	
6	9.4	27	
Average	**12.1**	**29.1**	
Std Dev	**11.6%**	**14.7%**	**3.6%**

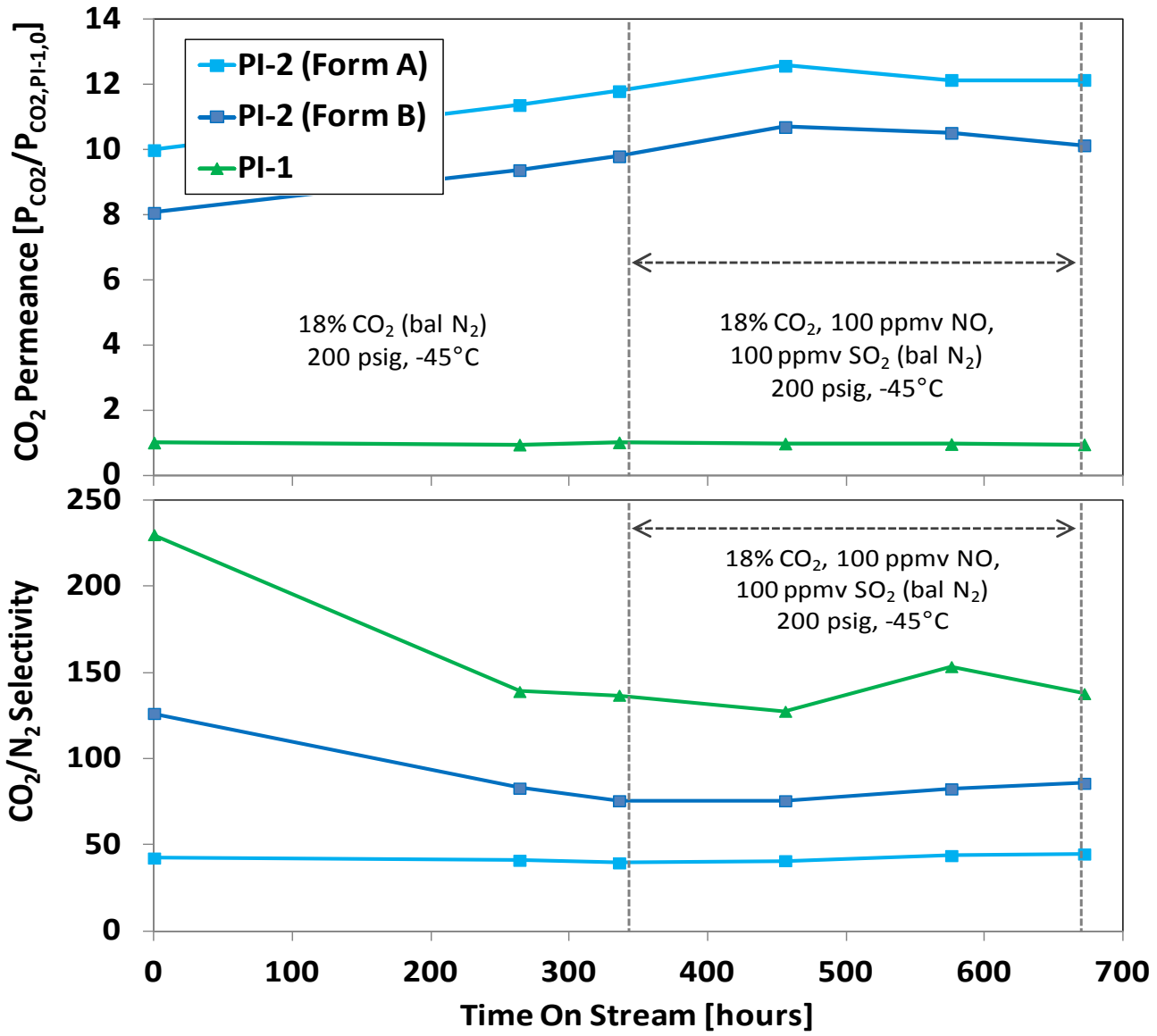
- Fiber performance was consistent and agreed with previous lab-scale results

- Fiber “formed” into two prototype bundles (to be tested at 0.1 MWe skid at DRTC)

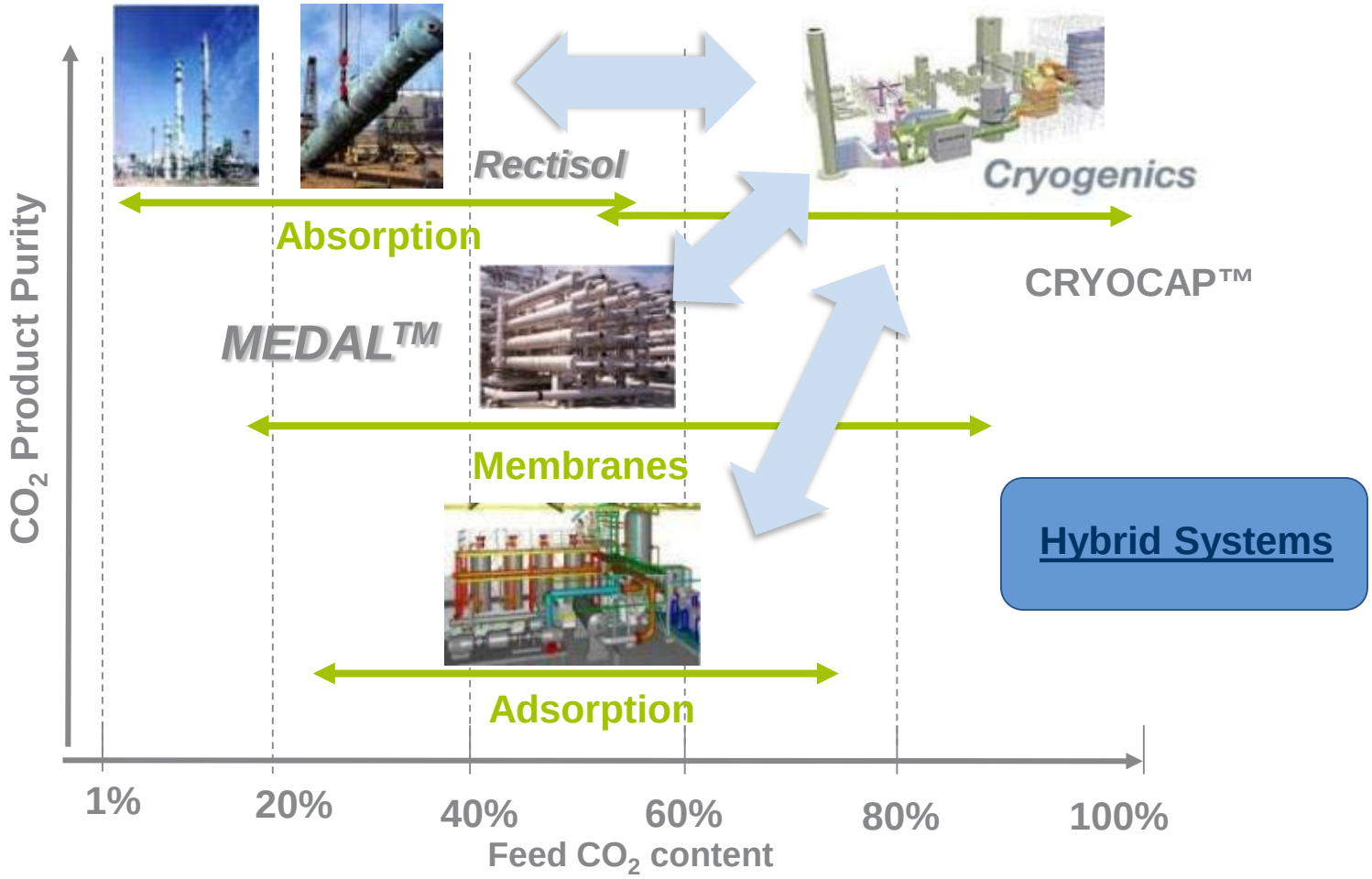
Acid Gas Contaminant Testing

Fiber samples in three mini-permeators simultaneously exposed to 100 ppmv NO and SO_2 over two weeks

- Stable / slightly increasing permeance for all samples
- Stable selectivity for all samples
- No apparent effect of NO or SO_2 on the PI-2 fiber
- Still to do: 100 ppmv NO_2 (not stable in combination with NO & SO_2)

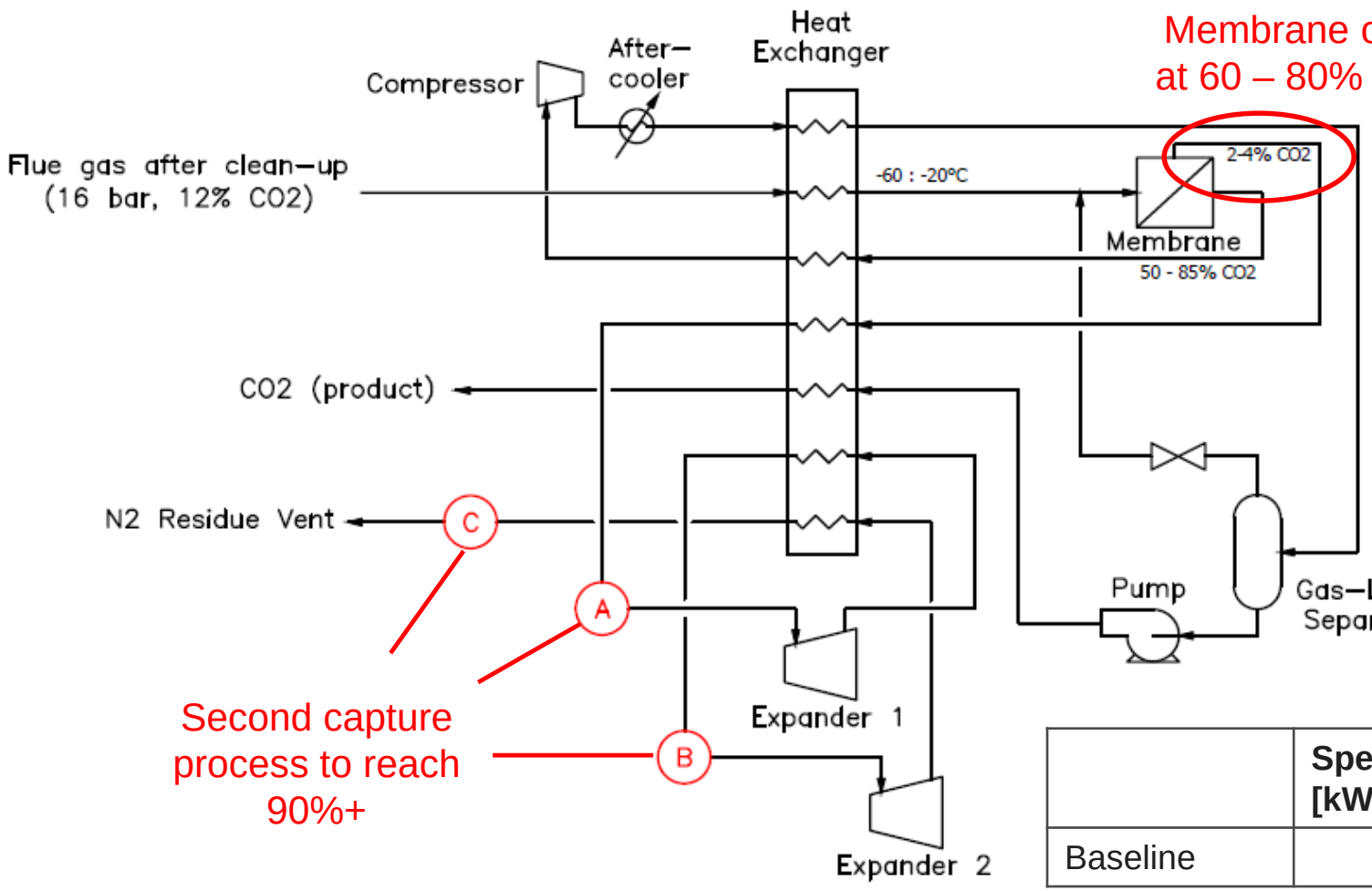


Air Liquide's Unique Position on CO_2



Technology for the whole range of CO_2 feed and product purities from any CO_2 source

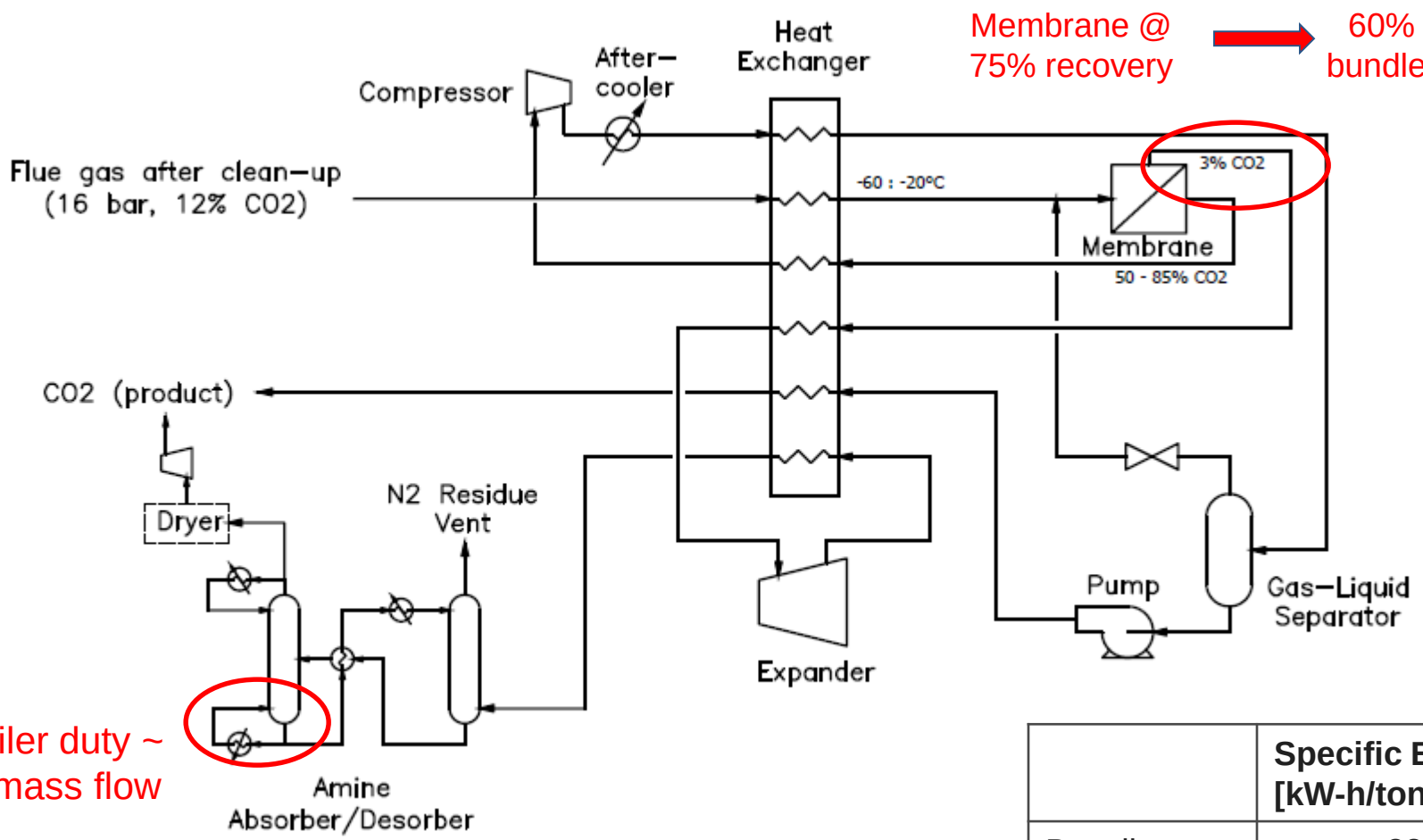
Hybrid Process Schemes



	Specific Energy* [kW-h/tonne]
Baseline	284

*CO_2 capture only

Hybrid Process Schemes (Cold Membrane + Amines)

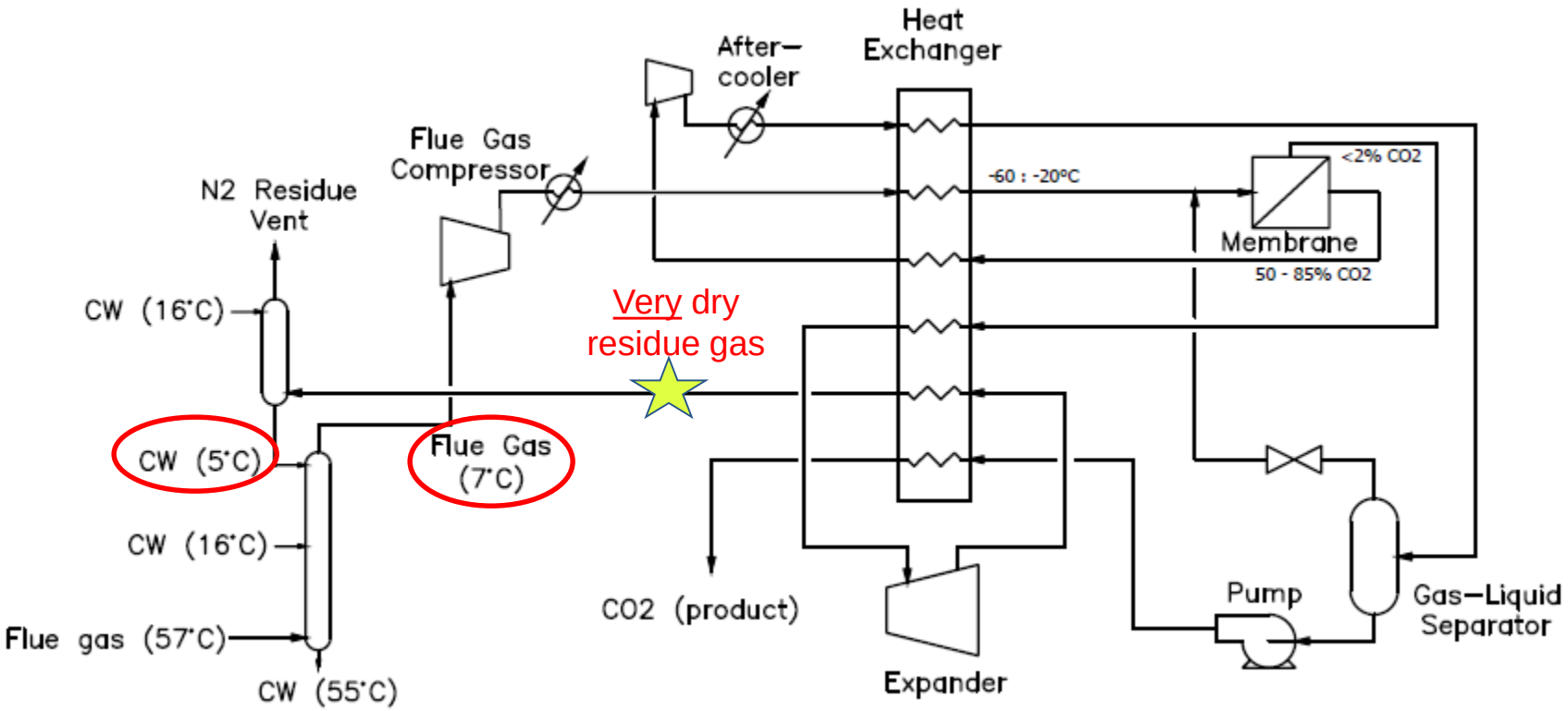


Amine system for 90%+ recovery

	Specific Energy* [kW-h/tonne]
Baseline	284
With Amines	402

***CO_2 capture only**

Hybrid Process Schemes (Cold Water)



Direct contact towers for flue gas cooling

	Specific Energy* [kW-h/tonne]
Baseline	284
Cold Water	267

***CO_2 capture only**

Conclusions & Future Work

Conclusions

- Prototype bundles fabricated (awaiting testing)
- Fiber tolerance towards NO and SO_2 demonstrated
- Hybrid processes modeled

Future Work (present to Mar ‘17)

- Prototype bundle fab / test
- Hybrid process development

Budget Period 2 (Apr ‘17 to Sept ‘18)

- Manufacturing scale-up (6” and 12” bundles)
- Field-test at NCCC (0.3 MWe unit)
- Techno-economic analysis

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

Acknowledgments / Disclaimer

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- Parsons: Brad Knutson
- Air Liquide: Rob Gagliano, Shilu Fu, Sudhir Kulkarni, Dave Hasse, Dean Kratzer, Dave Edwards, Jean-Marie Gautier

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Research & Development

Opening new ways

THANK YOU FOR YOUR ATTENTION