2016 CAPTURE TECHNOLOGY MEETING

LAB-SCALE DEVELOPMENT OF A HYBRID CAPTURE SYSTEM WITH ADVANCED MEMBRANE, SOLVENT SYSTEM AND PROCESS INTEGRATION

DE-FE0026464

AUGUST 11, 2016

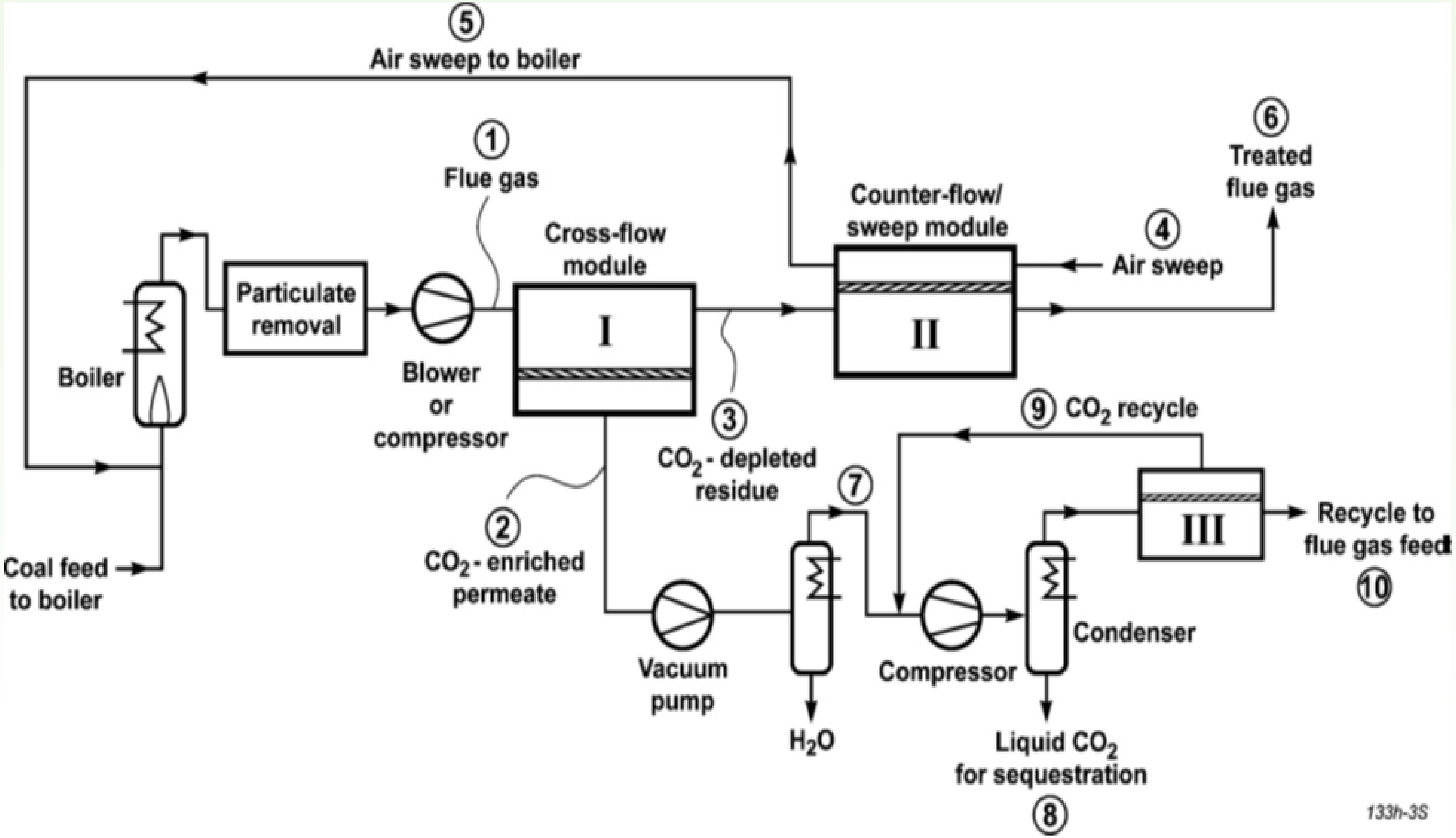
CARBON CAPTURE SCIENTIFIC LLC

Liquid Ion Solutions

PennState

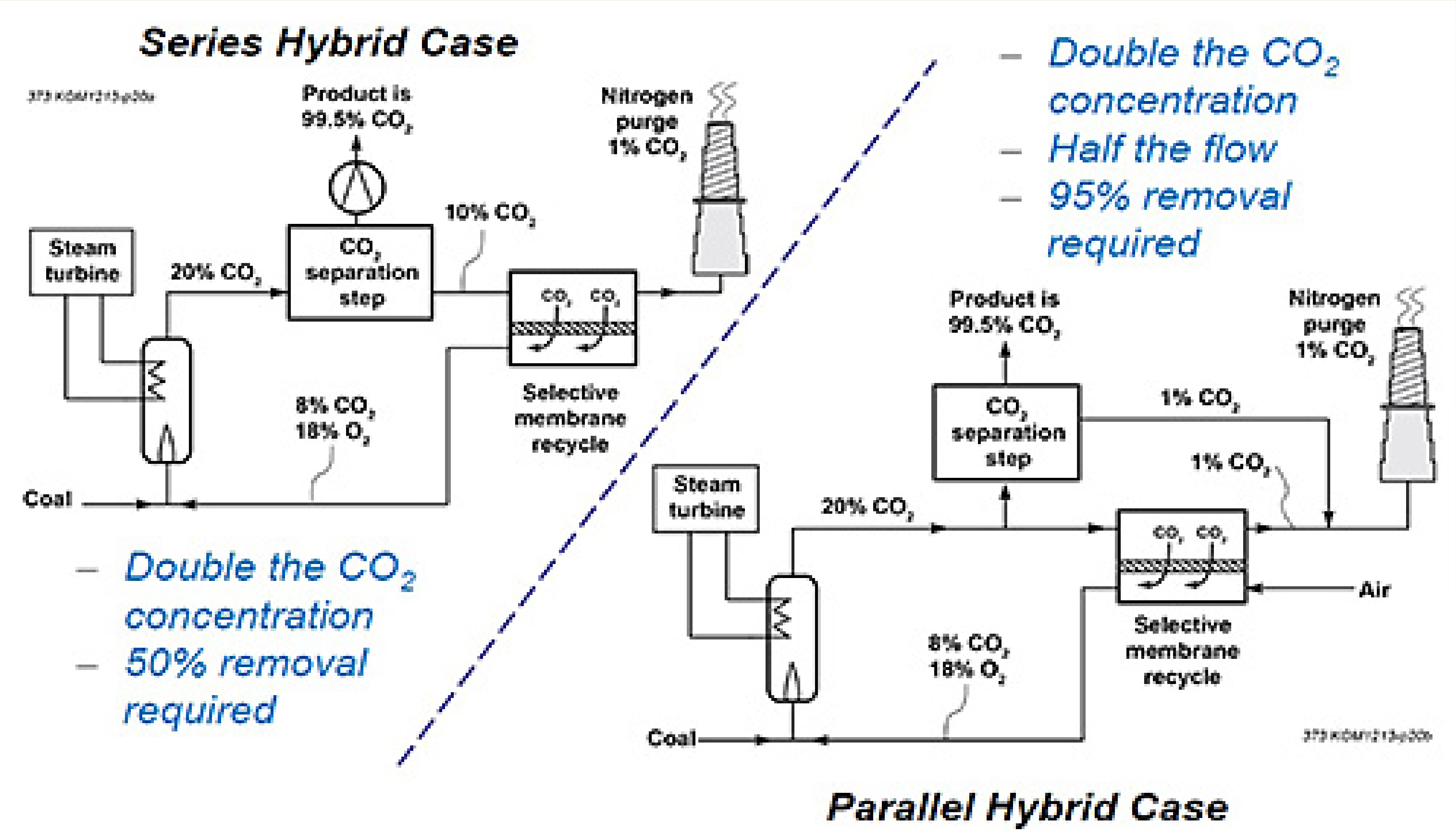
The System

Membrane Process Innovation (MTR)



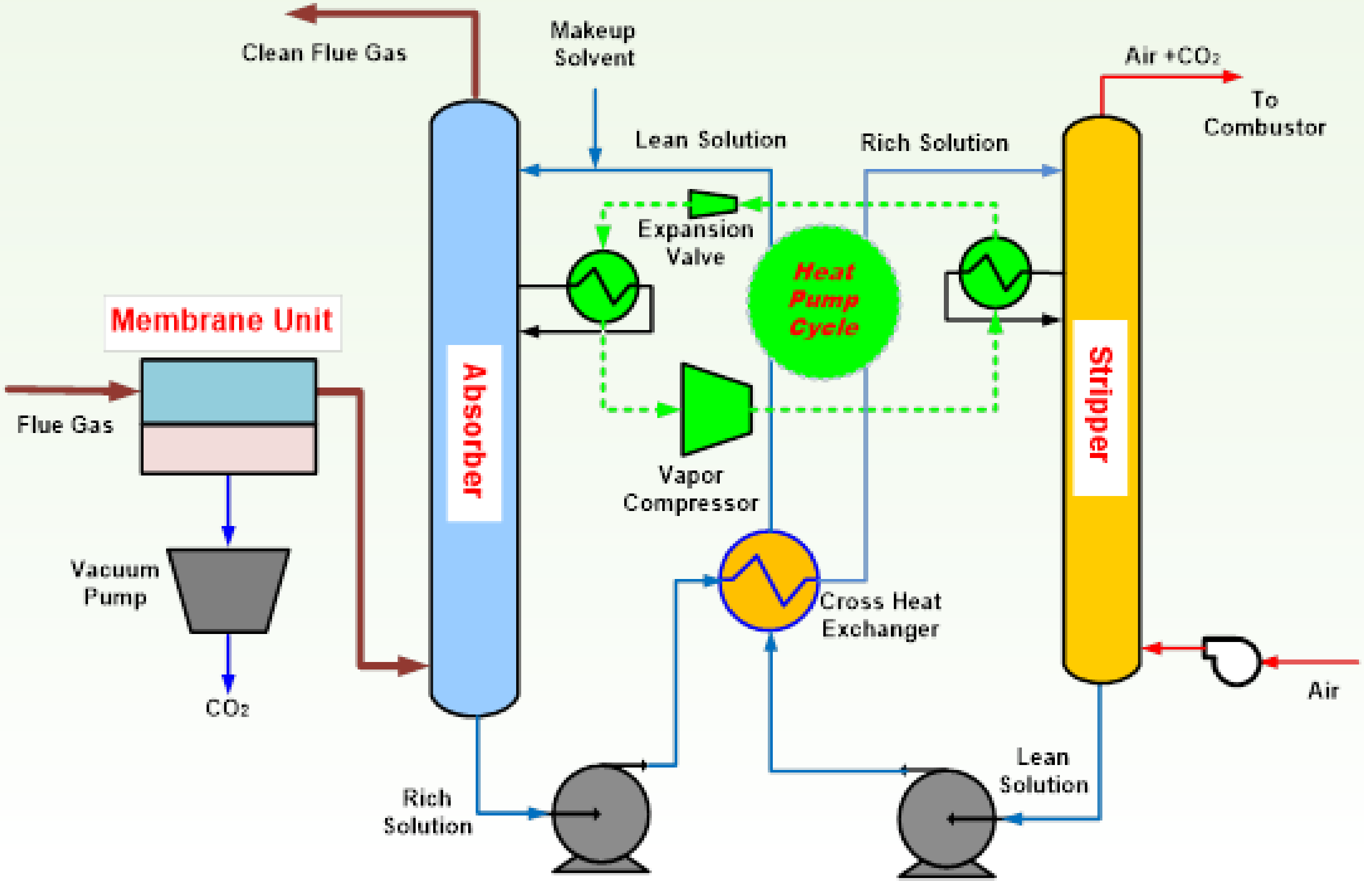
Merkel, T., Lin, H., Wei, X., Baker, R., J. Memb. Sci. 359, 126–139 (2010).

Hybrid Membrane Process Innovation



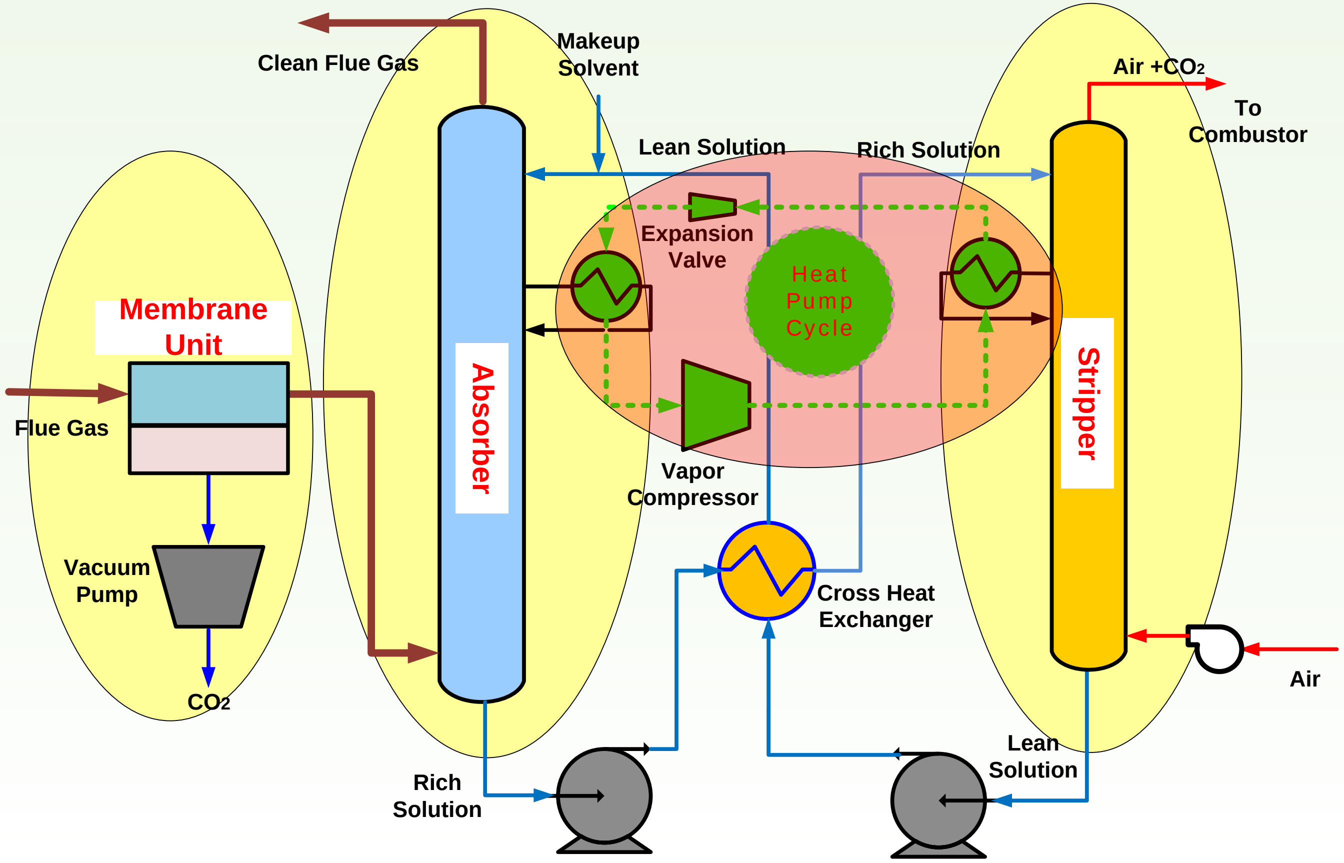
Freeman, B., Kniep, J., Baker, R., Merkel, T., Hao, P., Rochelle, G., Chen, E., Zhang, Y., Ding, J., Sherman., B., NETL CO_2 Capture Technology Meeting (2014).

A New Kind of Membrane Integration



Membrane/Solvent Integrated Process

- Advantages
  - Tail-end technology which is easily used in retrofits
  - No steam extraction is required
  - Heat pump is seamlessly integrated into the cooling and heating of absorption/stripping process
  - Operating pressure of the stripper will be very flexible depending on the low quality heat
- Disadvantage
  - Capital cost could be intensive



Project Outline

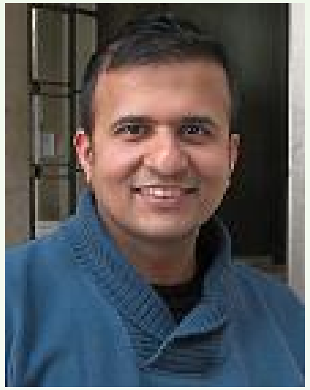
- Task 1: Project Management
- Task 2: Computer Simulation of Hybrid Process
- Task 3: Generation 0 ICE Membrane Development
- Task 4: Modification, Installation, and Testing of Absorption Column
- Task 5: Generation 1 ICE Membrane Development
- Task 6: Modification, Installation, and Testing of Air Stripper
- Task 7: Membrane Scale-up and Simulated Flue Gas Testing
- Task 8: Preliminary Techno-economic Analysis

CCS Team

Dr. Scott Chen and Dr. Fei Yi

- Experienced Chemical Engineer
- Strong Background in Separation Processes and Thermodynamics
- Founder of Carbon Capture Scientific, LLC

LIS Team



Professor Hunaid Nulwala

- Experienced Chemist with Experience in Industry, Government, and Academia
- 40+ Publications and 16+ Patents and Applications in Material Development

PSU Team

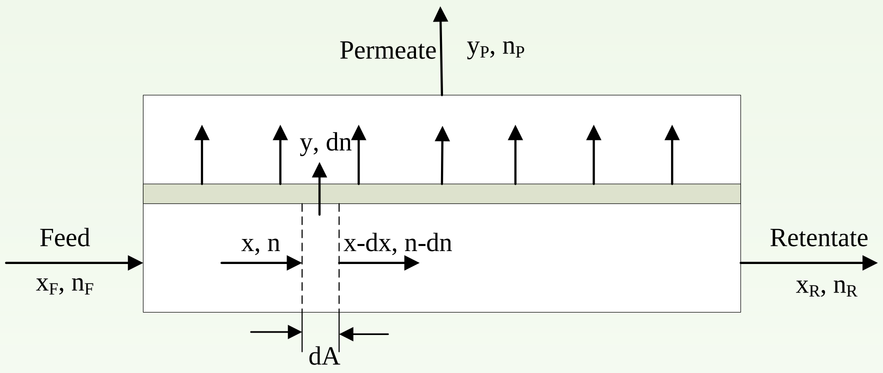
Professor Harry Allcock and Dr. Zhongjing Li

- Leading Investigator of Phosphazene Polymers (>630 Articles in the Area)
- Renowned Chemist with Experience in Industry, Government and Academia

Hybrid Process Simulation

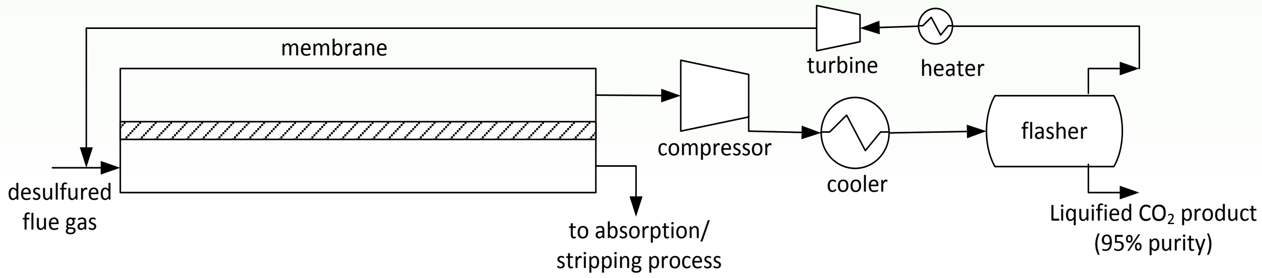
Simulation inputs for CO_2 separation

Inlet molar flow rate (mol/hr)	1000
Pressure of retentate side (bar)	1.1
Pressure of permeate side (bar)	0.22
Inlet composition (mol%)	CO_2: 24 N_2: 61 H_2O: 15
Permeance of CO_2 (GPU)	5000
Permeance of H_2O (GPU)	1000



Simulation of membrane separation performance

Case	N_2 permeance (GPU)	CO_2/N_2 Selectivity	Accumulated CO_2 mol% (dry basis)
1	167	30	74.6%
2	83.5	60	82.8%
3	41.75	120	89.1%
4	20.875	240	93.3%
5	10.4375	480	96.1%



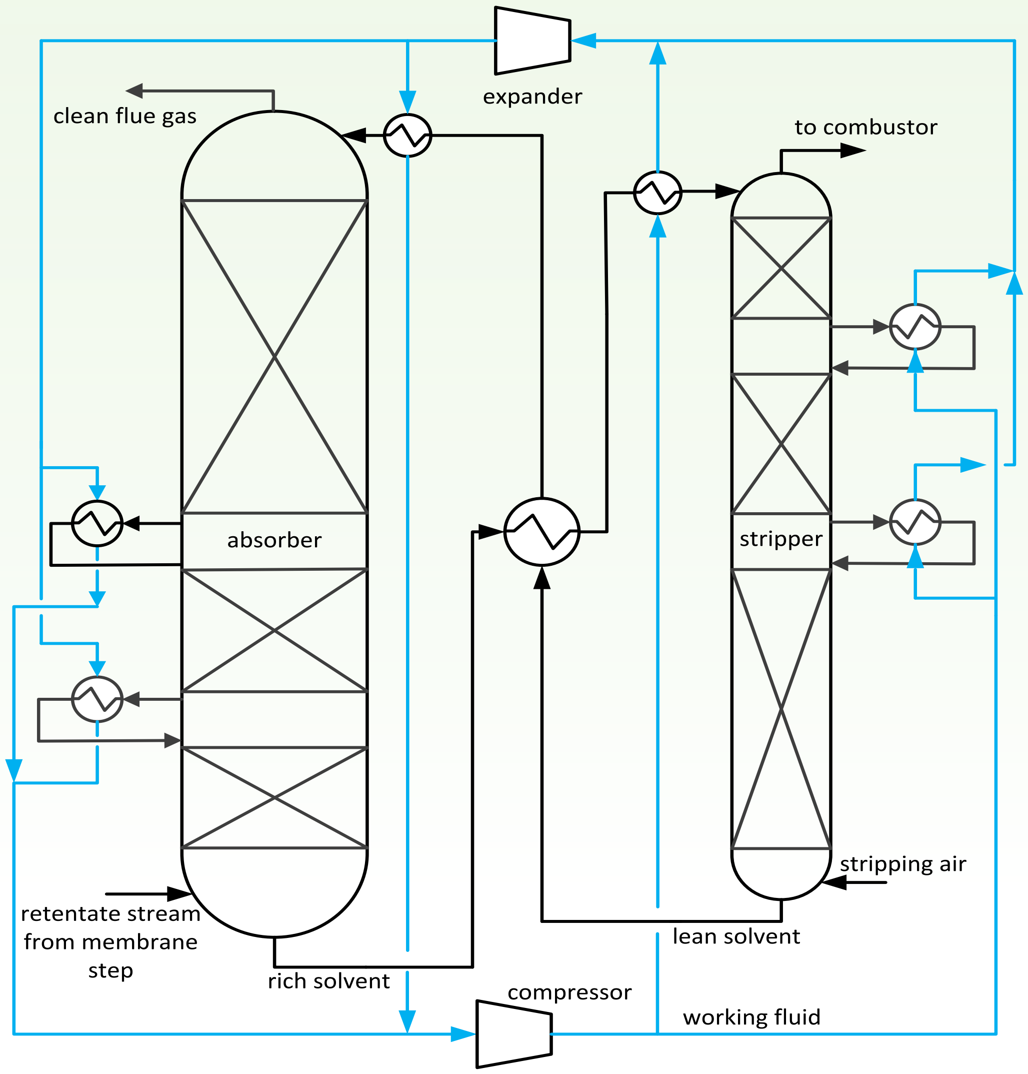
Hybrid Process Simulation

Heat duties (MW) for the absorption/stripping process

	Absorber	Stripper
top	-71.85	24.54
1st inter-stage	-50.71	60.68
2nd inter-stage	38.14	32.00
3rd inter-stage		22.95
total	-160.7	140.17

Energy Performance of the Hybrid Process

Power Item (in MWe)	Baseline Case 12	Hybrid Process
Compression	44.8	87.48
Steam Usage	139.19	0
Heat Pump Cycle	0	18.5
Membrane Unit	0	15.7
Others	20.6	20.6
total	204.6	142.28

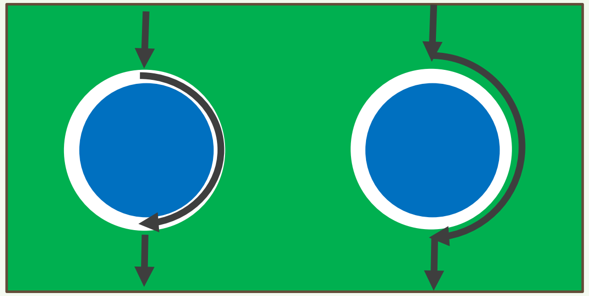


The Membrane

Building a Better Membrane

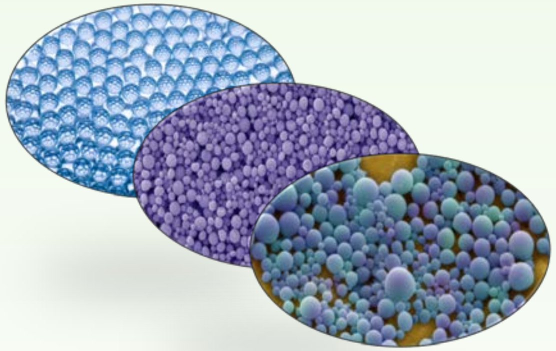
- Current commercialized membranes are pretty good.
  - CO_2 Permeance: ~2000 GPU
  - CO_2/N_2 Selectivity: ~30
- Less conventional membrane needed to make substantial improvements
  - Supported Liquids
  - Mixed Matrix Membranes
- Mixed matrix membranes
  - Better particles
  - Improved polymers
  - Controlled interaction of polymer with particles

Plan of Attack for Mixed Matrix Membranes

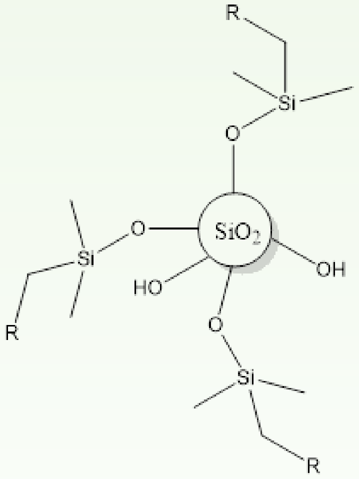


- Use simple nanoparticle fillers
- Surface modify the particles to improve interactions with CO_2 and the polymer
- Employ an advanced polymer with good compatibility and CO_2 transport properties
- Create a membrane in which diffusion phenomena are determined by interactions with the particle and polymer surface

Membrane Fabrication and Optimization



Nano-particle
Selection

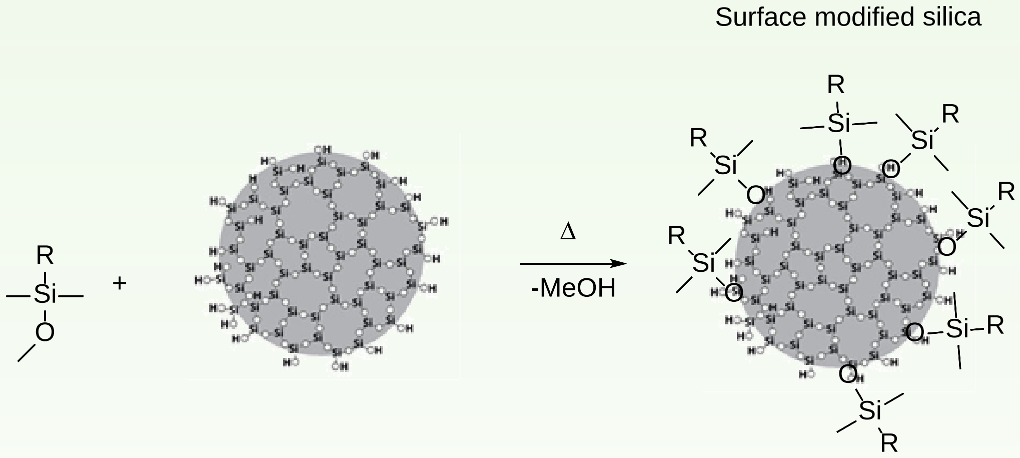


Nano-particle
Modification

Membrane Film
Fabrication

The Particle

Nano-filler Particle Selection

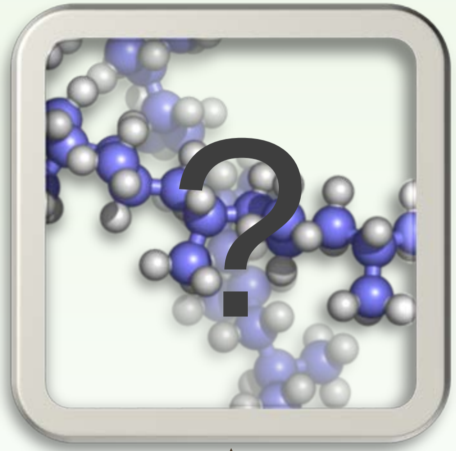


- Synthesis methodology developed
- Obtained starting nanomaterials from Nissan Chemicals and Crystalplex Corporation

The Polymer

The Ideal Polymer?

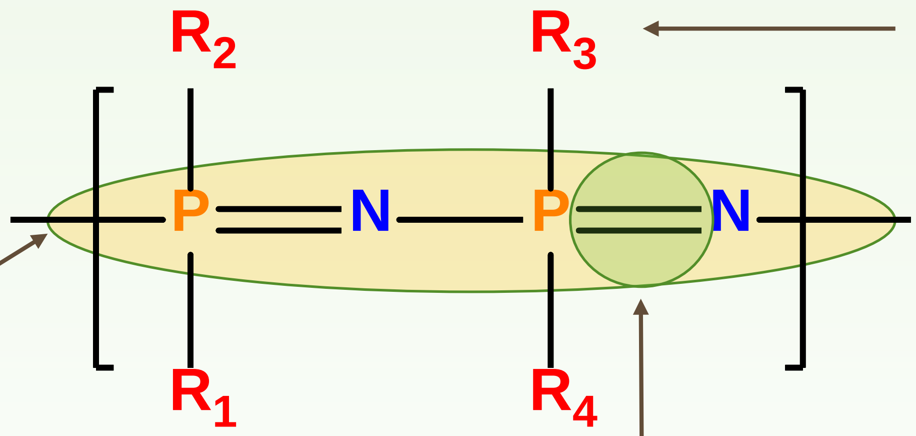
Processability/
Mechanical Properties



Chemical and
Environmental
Stability

Gas Separation Performance

What's so great about polyphosphazenes?

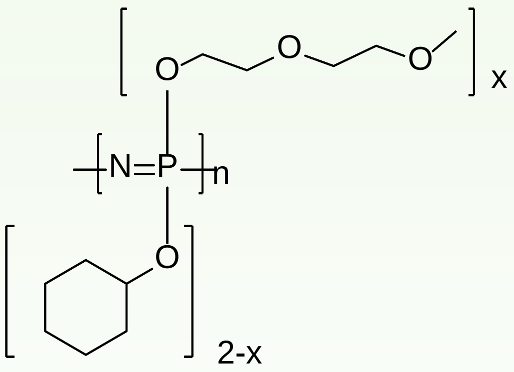


Macromolecular substitution

<u>Ultra Flexible chains</u>
High chain mobility
Improved gas solubility and diffusion

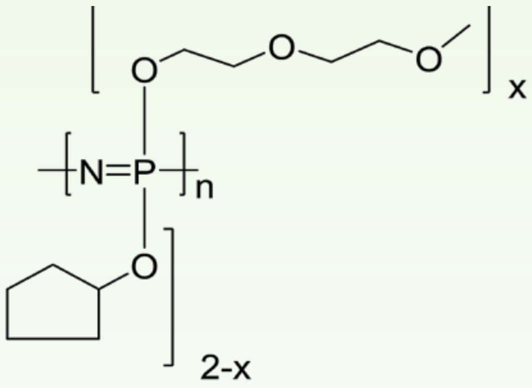
<u>Excellent chemical and thermal stability</u>
C-C =607Δ*Hf* kJ/mol vs. P-N =617 Δ*Hf* kJ/mol

Polyphosphazene Synthesis
(Lots of Possibilities)

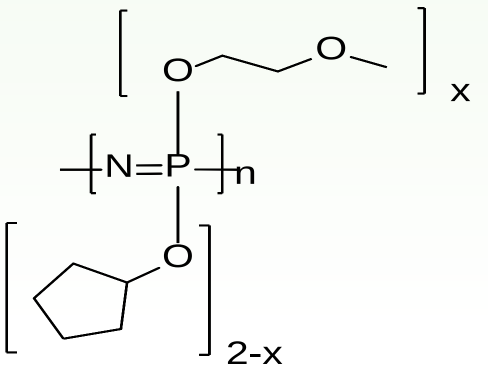


x	2-x
0.25	1.75
0.74	1.26
1	1
1.5	0.5
0.89	1.11

Polymers in red do not form good films

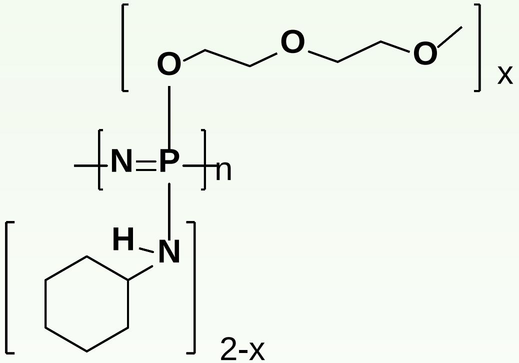


X	2-x
1	1

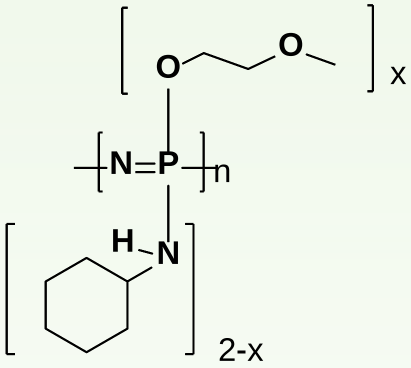


x	2-x
0.6	1.4

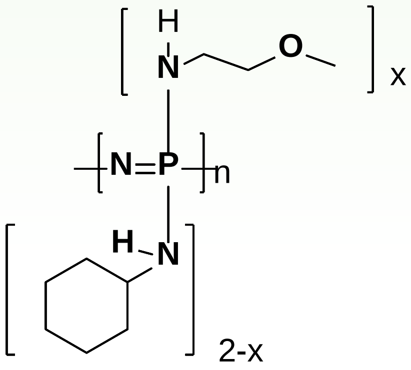
Polyphosphazene Synthesis
(Lots of Possibilities)



x	2-x
1.5	0.5
1.25	0.75
1	1
0.75	1.25



x	2-x
1.5	0.5
1	1
0.4	1.6



x	2-x
1	1
1.5	0.5
1.25	0.75

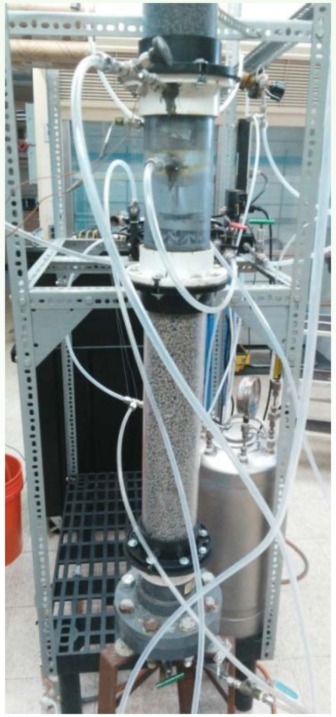
Polymers in red do not form good films

The Absorber

Absorber Testing

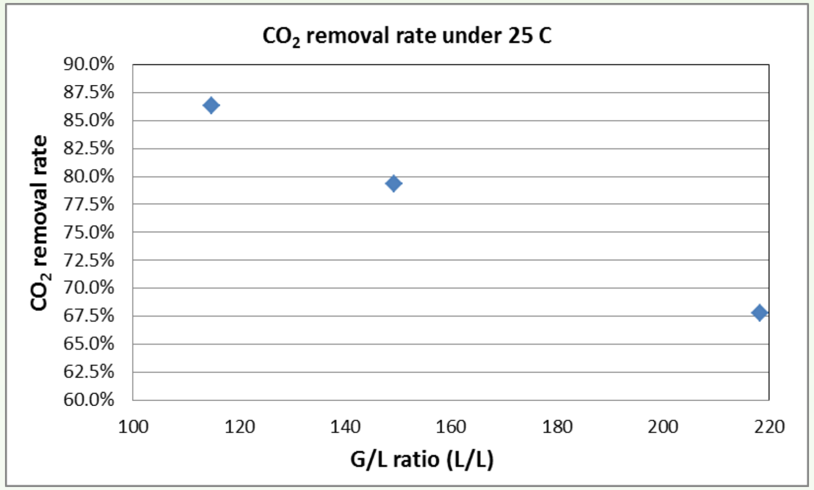
Based on computer simulation results, the absorption column has:

- 4 inch ID
- 4 mm θ ring random packing
- Total packing height of 96 inch
- Three packing sections with each height of 46, 29 and 21 inches respectively
- Two inter-stage cooling loops between first/second and second/third packing section

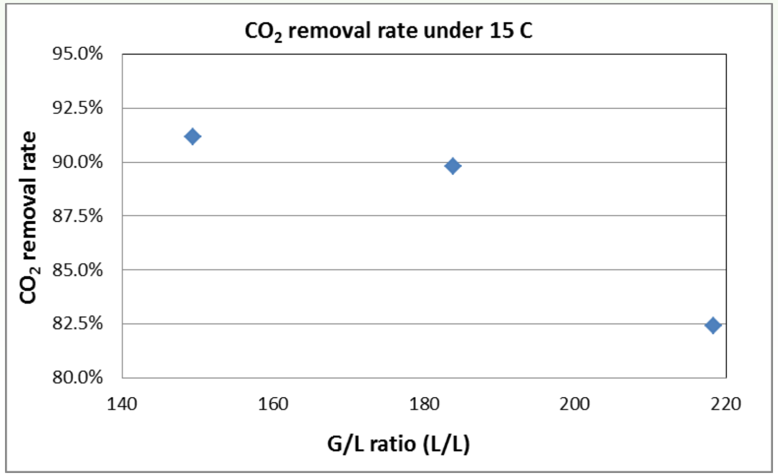


Absorber Testing

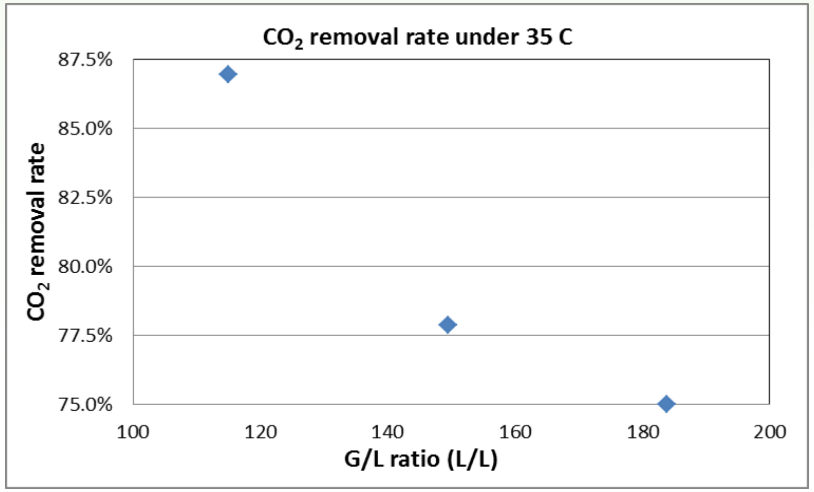
- Completed the parametric tests on CO_2 removal rate:
  - Gas/liquid ratio
  - Operating temperature



Lean loading: 6.4 wt%



Lean loading: 6.4 wt%



Lean loading: 5.8 wt%

Acknowledgement

Liquid Ion Solutions, Carbon Capture Scientific and Penn State University gratefully acknowledge the support of the United States Department of Energy's National Energy Technology Laboratory under agreement DE-FE0026464, which is responsible for funding the work presented.

Questions?