Project Kickoff Meeting

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

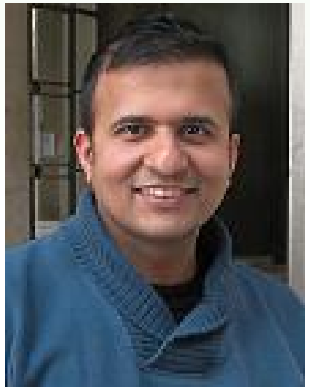
DE-FE0026464
10/29/2015

CARBON CAPTURE SCIENTIFIC LLC

Liquid Ion Solutions

PennState

LIS Team



Professor Hunaid Nulwala – Principal Investigator

- Experienced Chemist with Experience in Industry, Government, and Academia
- Strong background in Polymers, Ionic Liquids, Gas Separations
- Founder of Two Technology Companies
- 40+ Publications and 16+ Patents and applications in Material Development

Dr. David Luebke

- Chemical Engineer Specializing in Carbon Capture
- Former ORD Carbon Capture Technical Coordinator
- Membrane Scientist with Experience Designing, Constructing and Operating Performance Systems

CCS Team

Dr. Scott Chen

- Experienced Chemical Engineer
- Strong background in separation processes and thermodynamics
- Founder of Carbon Capture Scientific, LLC

Dr. John Pan

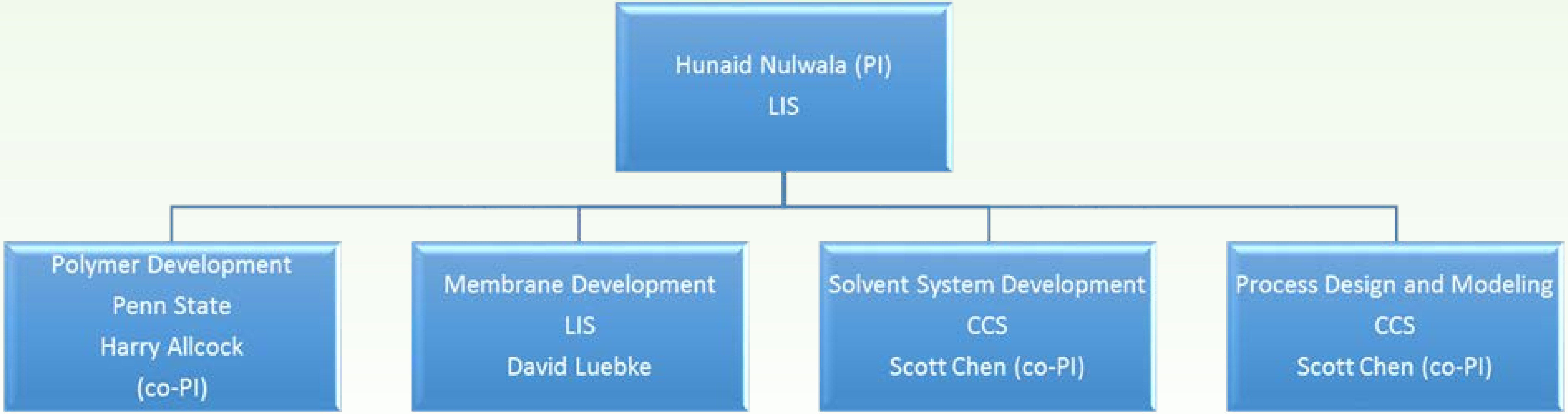
- Experienced Chemical Engineer
- Strong background in separation processes
- Founder of two technical companies

PSU Team

Professor Harry Allcock

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

Project Organization



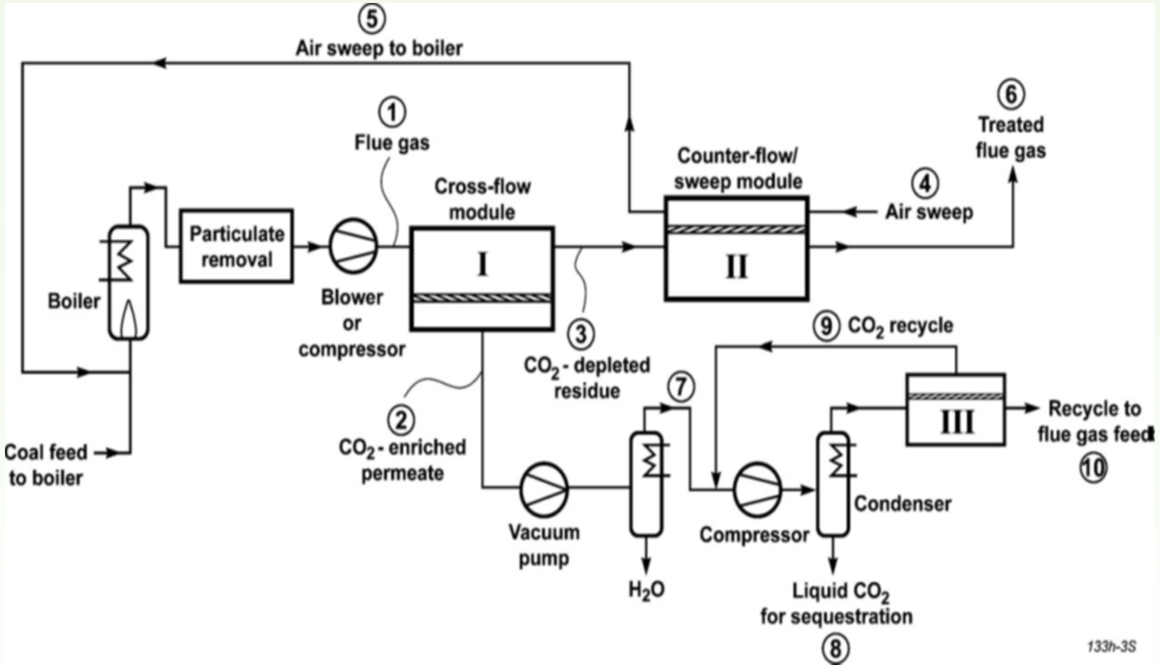
Project Objectives

- Simulation of Membrane and Solvent Subsystems
- Synthesis and Characterization of Tailored Polyphosphazenes
- Fabrication of Interfacially-Controlled Envelope (ICE) Membranes
- Optimization of Polymer, Nano-filler, and Fabrication Process
- Design and Construction of Membrane Test Systems
- Modification of Absorber and Stripper Units of Solvent System
- Optimization of Solvent System for Operation in Hybrid System
- Demonstration of All Subsystems with Simulated Flue Gas
- Completion of Preliminary Economic Analysis

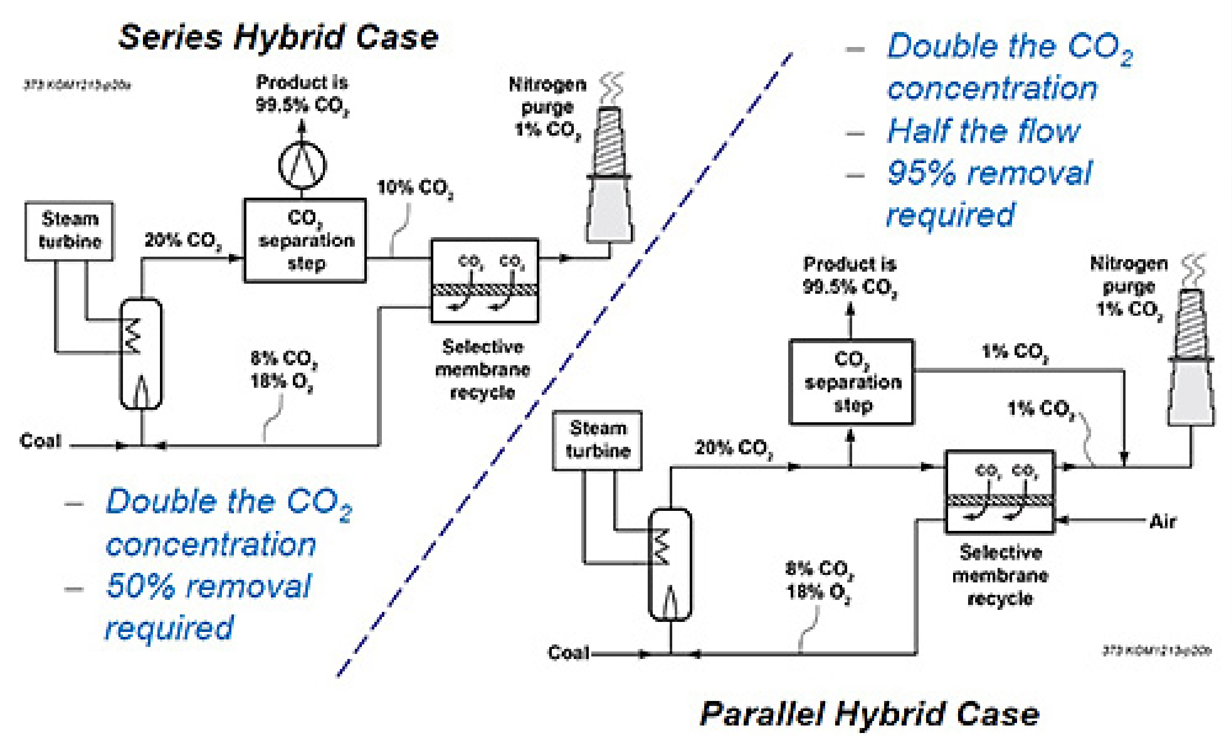
Technical Approach

Previous Membrane Process Innovation (MTR)

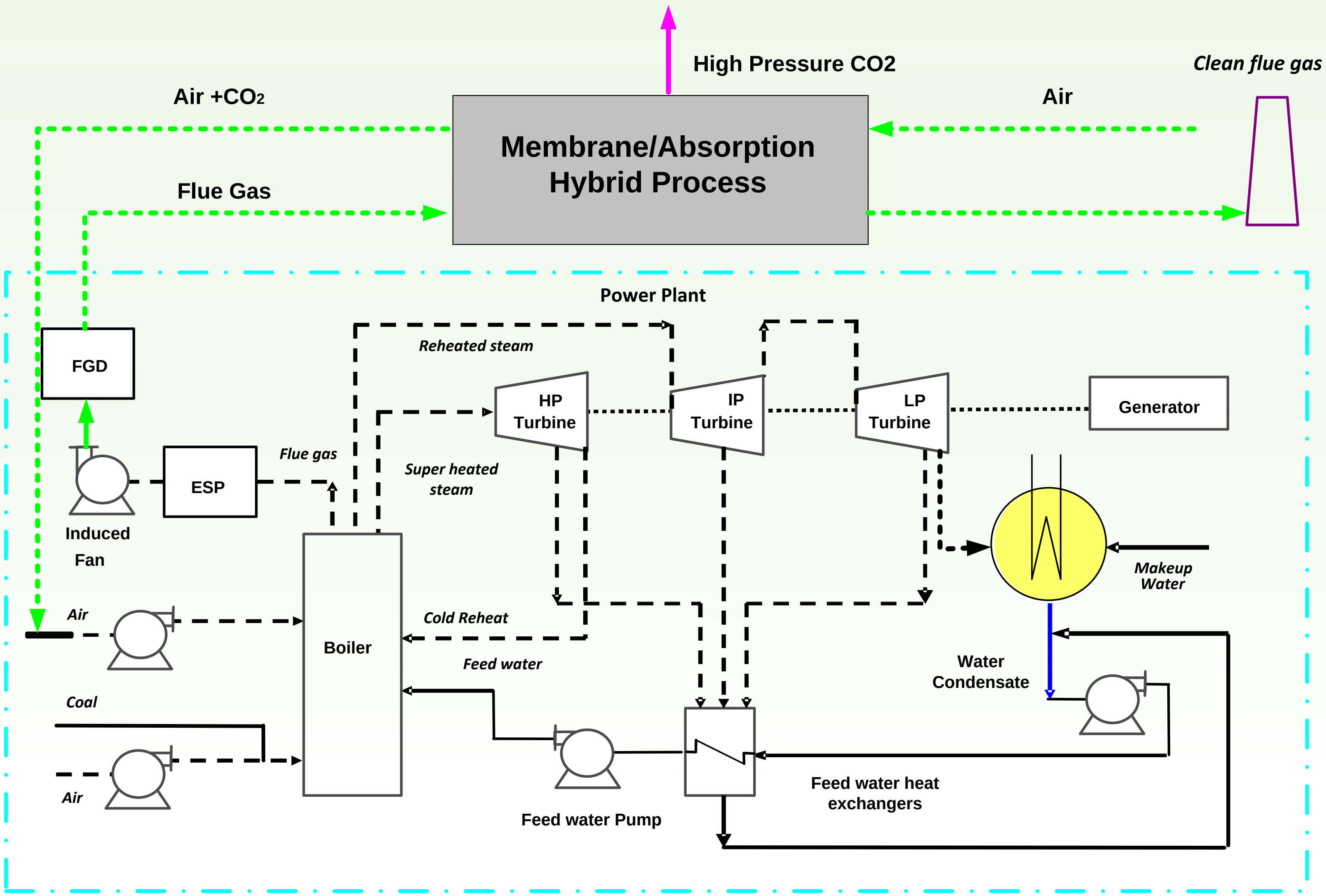
Pure Membrane



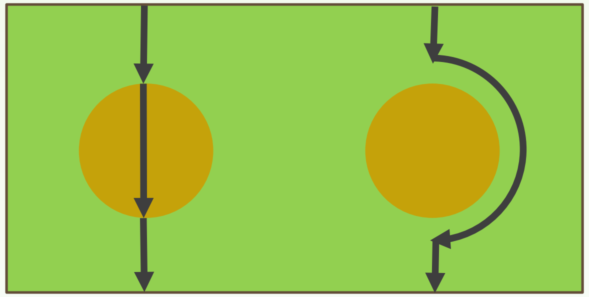
Hybrid Membrane



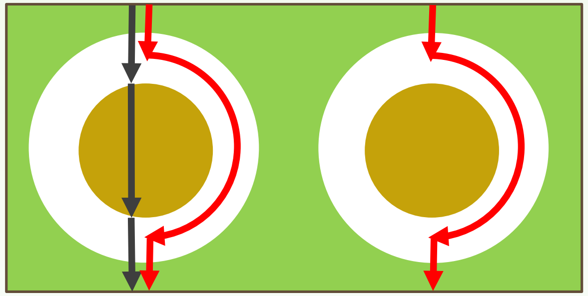
Straightforward Plant Integration



The Trouble with Mixed Matrix Membranes



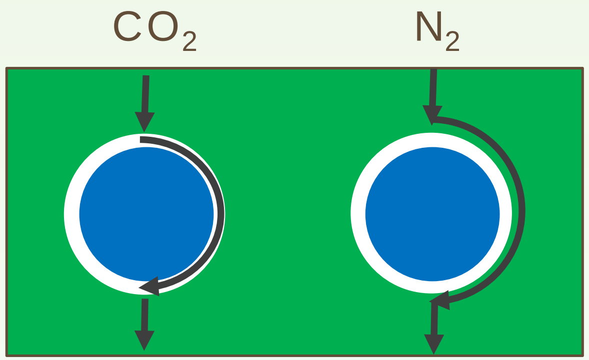
“True” MMM
Transport



Particle
Bypass

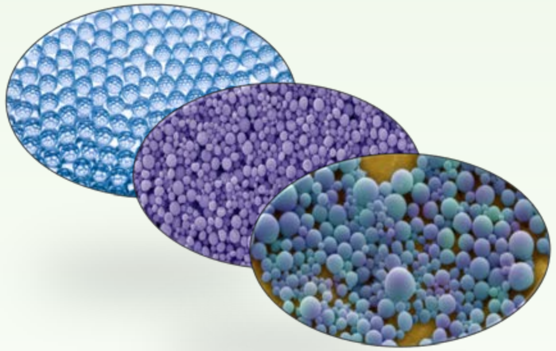
Interfacially-Controlled Envelope (ICE) Membranes

If you can't beat 'em, join 'em!

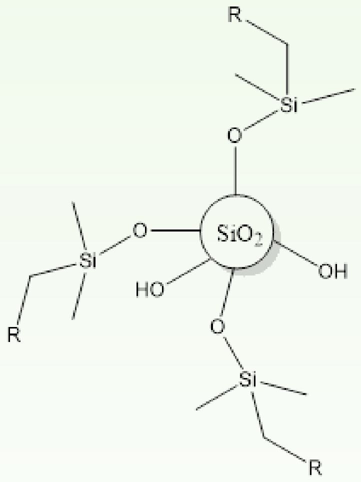


- Makes use of envelopment effects
- Diffusion phenomena determined by interactions with the particle and polymer surface
- Advanced polymers allow an excellent starting point

Membrane Fabrication and Optimization



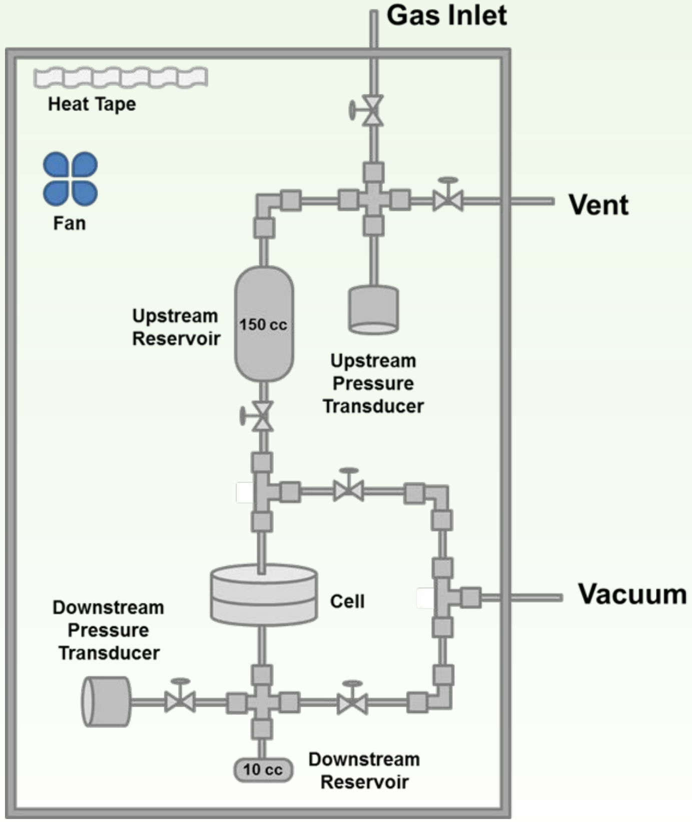
Nano-particle Selection



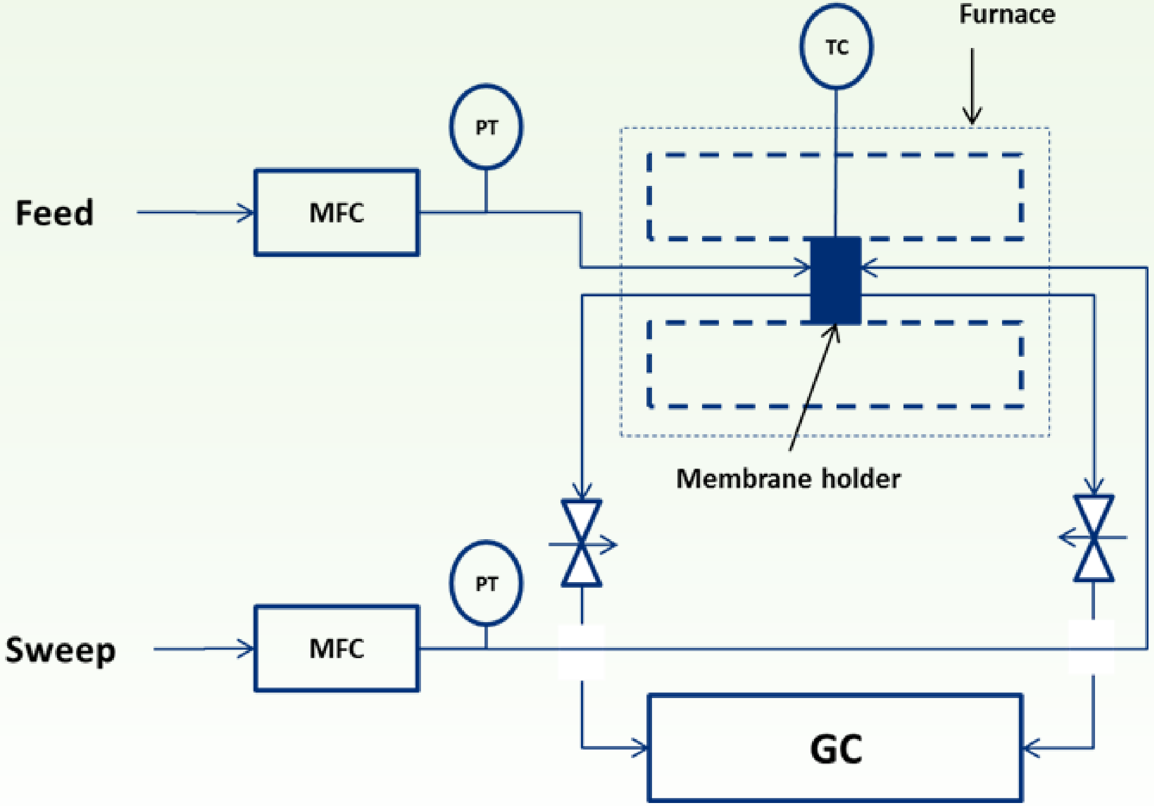
Nano-particle Modification

Membrane Film Fabrication

Performance Testing



Isochoric System

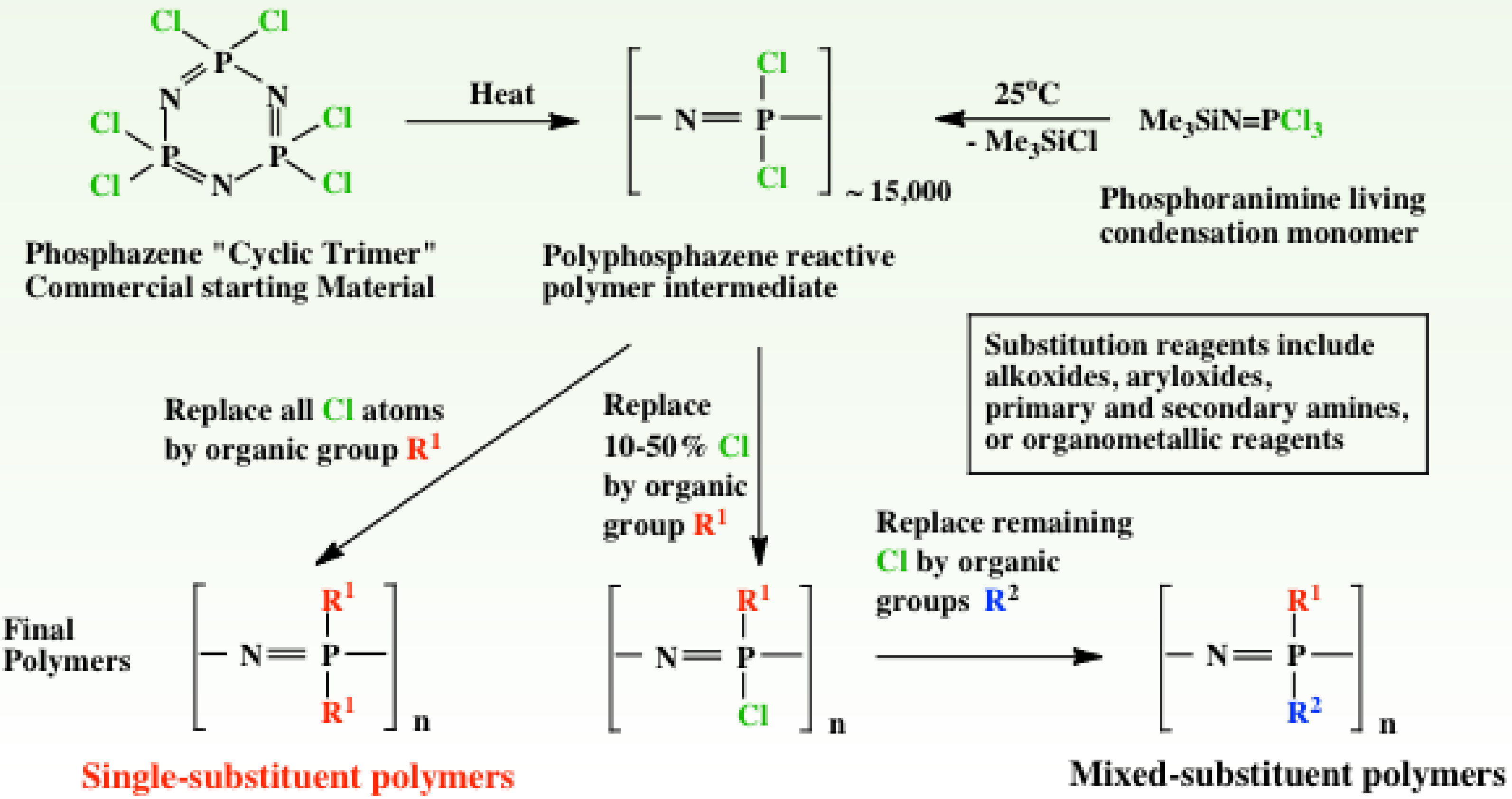


Isobaric System

What is great about polyphosphazenes?

- Compared to classical organic polymers, the inorganic backbone provides stability to oxidation and photolysis, and resistance to many reagents that would decompose petrochemical-based polymers. The backbone also gives rise to polymers with low glass transition temperatures.
- The macromolecular substitution approach allows the synthesis of hundreds of different polymers with a wide range of properties many of which cannot be generated from conventional polymers.
- These special properties include control of membrane characteristics, such as high transmission of gases such as CO_2, controlled glass transition and melting temperatures, and stability to many chemicals.
- Property tuning is accomplished by changing any of 250 different side groups and their ratios within the polymer.
- Further changes are possible by surface reactions, and via composites such as interpenetrating polymer networks. Also block copolymers are accessible.

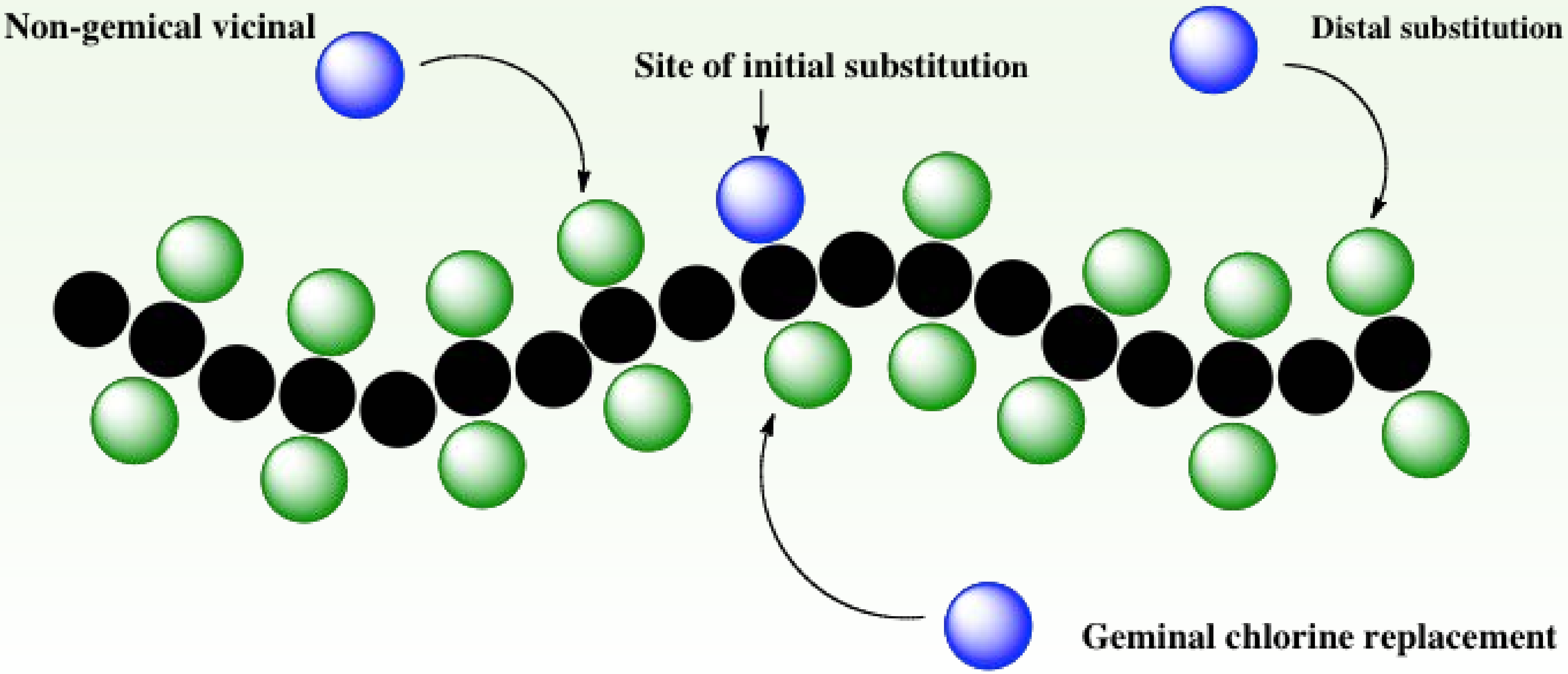
The Macromolecular Substitution Method



More than 250 different side groups used either alone or in combinations to give several hundred different polymers made by this method at Penn State.

Each Different Side group arrangements gives a polymer with different properties and potential uses.

Carrying Out Reactions on a High Molecular Weight Polymer Presents Some Unique Challenges and Opportunities



Does the substituent that enters first direct the next one to a nearby or a distant site? Is substitution cis- or trans-, gem- or non-gem? All these factors affect the structure and properties of the final polymer.

Different types of polymers formed from different side groups

Macromolecular substitution

- Elastomers (alkoxy and fluoroalkoxy groups)
- Hydrogels (alkyl ether or arylcarboxylate groups)
- Bioerodible polymers (amino acid esters, glucosyl, glyceryl
- Polymer electrolytes (alkyl ether groups)
- Non-flammable polymers (nearly all side groups)
- Optical and photonic polymers (organic dyes, polyaromatic, liquid crystalline groups)
- Controlled surface materials (fluorinated alkoxy or aryloxy groups)
- Hybrid systems (phosphazene polymers with organic or organosilicon block, graft, or IPN systems)

Examples of Polyphosphazene Membranes

$[NP(OCH_2CF_3)_2]_n$ $[NP(OCH_2CF_2CF_2CF_2CF_2H)_2]_n$

Tasks for Budget Period 1 (2016)

- Task 2: Computer Simulation of Hybrid Process
  - 2.1: Simulation of Membrane System
  - 2.2: Simulation of Absorption/Air Stripping System
  - 2.3: Simulation of Heat Pump Cycle
  - 2.4: Optimization of Hybrid Process
- Task 3: Generation 0 ICE Membrane Development
  - 3.1: Polyphosphazene Synthesis and Characterization
  - 3.2: Design and Construction of Isochoric Membrane System
  - 3.3: Generation 0 ICE Membrane Performance Testing
  - 3.4: Nano-filler Particle Selection
- Task 4: Modification, Installation, and Testing of Absorption Column
  - 4.1: Modification of Absorption Column
  - 4.2: Installation of Absorption Column
  - 4.3: Parametric Testing of Absorption Column

Tasks for Budget Period 2 (2017)

- Task 5: Generation 1 ICE Membrane Development
  - 5.1: Polyphosphazene Optimization and Characterization
  - 5.2: Fabrication of Generation 1 ICE Membrane
  - 5.3: Generation 1 ICE Membrane Performance Testing
  - 5.4: Design and Construction of Mixed Gas Membrane Testing System
- Task 6: Modification, Installation, and Testing of Air Stripper
  - 6.1: Modification of Air Stripper
  - 6.2: Installation of Air Stripper
  - 6.3: Parametric Testing of Air Stripper

Tasks for Budget Period 3 (2018)

- Task 7: ICE Membrane Scale-up and Simulated Flue Gas Testing
  - 7.1: Polyphosphazene Scale-up and Characterization
  - 7.2: Fabrication of Optimized1 ICE Membrane
  - 5.3: Simulated Flue Gas Testing
- Task 8: Initial Technical and Economic Feasibility Study
  - 8.1: System Performance Modeling
  - 8.2: Economic Analysis
  - 8.3: Sensitivity Analysis

Schedule

	Start Date	End Date	Cost	Budget Period 1 10/1/2015 - 9/30/2016				Budget Period 2 10/1/2016 - 9/30/2017				Budget Period 3 10/1/2017 - 9/30/2018			
				Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1.0 - Project Management and Planning	10/1/2015	9/30/2018	$111,197.00												
Subtask 1.1 - Project Management and Planning	10/1/2015	9/30/2018													
Subtask 1.2 - Briefings and Reports	10/1/2015	9/30/2018													
Milestones															
- Milestone A - Update Project Management Plan				Δ											
- Milestone B - Kickoff Meeting				Δ											
Task 2.0 - Computer Simulation of Hybrid Process	10/1/2015	9/30/2016	$130,520.00												
Subtask 2.1 - Simulation of Membrane System	10/1/2015	3/31/2016													
Subtask 2.2 - Simulation of Absorption/Air Stripping System	1/1/2016	6/30/2016													
Subtask 2.3 - Simulation of Heat Pump Cycle	1/1/2016	6/30/2016													
Subtask 2.4 - Optimization of the Hybrid Process	4/1/2016	9/30/2016													
Milestones															
- Milestone C - Complete Optimized Hybrid Process Design							Δ								
Task 3.0 - Generation 0 ICE Membrane Development	10/1/2015	9/30/2016	$585,160.00												
Subtask 3.1 - Polyphosphazene Synthesis and Characterization	10/1/2015	9/30/2016													
Subtask 3.2 - Design and Contruction of Isochoric Membrane System	10/1/2015	3/31/2016													
Subtask 3.3 - Generation 0 (Neat Polymer) ICE Membrane Performance Testing	4/1/2016	9/30/2016													
Subtask 3.4 - Nano-filler Particle Selection	4/1/2016	9/30/2016													
Milestones															
- Milestone D - Down-select to Three or Fewer Polyphosphazene Candidates							Δ								
Task 4.0 - Modification, Installation, and Testing of Absorption Column	10/1/2015	9/30/2016	$200,137.00												
Subtask 4.1 - Modification of Absorption Column	10/1/2015	3/31/2016													
Subtask 4.2 - Installation of Absorption Column	1/1/2016	6/30/2016													
Subtask 4.3 - Parametric Testing of Absorption Column	4/1/2016	9/30/2016													
Task 5.0 - Generation 1 ICE Membrane Development	10/1/2016	9/30/2017	$576,420.00												
Subtask 5.1 - Polyphosphazene Optimization and Characterization	10/1/2016	9/30/2017													
Subtask 5.2 - Fabrication of Generation 1 ICE Membranes	10/1/2016	3/31/2017													
Subtask 5.3 - Generation 1 ICE Membrane Performance Testing	4/1/2017	9/30/2017													
Subtask 5.4 - Design and Construction of Mixed Gas Membrane Testing System	4/1/2017	9/30/2017													
Milestones															
- Milestone E - Complete Fabrication of Gen 1 ICE Membrane									Δ						
- Milestone F - Down-select of Optimizal Polymer/Particle Composition											Δ				
- Milestone G - Complete Construction and Shakedown of Iso-baric System											Δ				
Task 6.0 - Modification, Installation, and Testing of Air Stripper	10/1/2016	9/30/2017	$215,171.00												
Subtask 6.1 - Modification of Air Stripper	10/1/2016	3/31/2017													
Subtask 6.2 - Installation of Air Stripper	1/1/2017	6/30/2017													
Subtask 6.3 - Parametric Testing of Air Stripper	4/1/2017	9/30/2017													
Milestones															
- Milestone H - Complete Modification of Stripper									Δ						
Task 7.0 - ICE Membrane Scale-up and Simulated Flue Gas Testing	10/1/2017	9/30/2018	$498,365.00												
Subtask 7.1 - Polyphosphazene Scale-up and Characterization	10/1/2017	9/30/2018													
Subtask 7.2 - Fabrication of Optimized ICE Membranes	1/1/2018	6/30/2018													
Subtask 7.3 - Simulated Flue Gas Testing	4/1/2018	9/30/2018													
Milestones															
- Milestone I - Complete Fabrication of Optimized Membrane														Δ	
- Milestone J - Complete Simulated Flue Gas Testing															Δ
Task 8.0 - Preliminary Techno-Economic Analysis	10/1/2017	9/30/2018	$180,630.00												
Subtask 8.1 - System Performance Modeling	10/1/2017	3/31/2018													
Subtask 8.2 - Economic Analysis	1/1/2018	6/30/2018													
Subtask 8.3 - Sensitivity Analysis	4/1/2018	9/30/2018													
Milestones															
- Milestone K - Complete System Performance Model													Δ		
- Milestone L - Complete Preliminary Techno-Economic Analysis															Δ

Budget

	Budget Period 1 10/01/15-09/30/16		Budget Period 2 10/01/16-09/30/17		Budget Period 3 10/01/17-09/30/18		Total Project	
	NETL Share	Cost Share	NETL Share	Cost Share	NETL Share	Cost Share	NETL Share	Cost Share
LIS	$337,781	$84,445	$330,789	$82,697	$268,345	$67,086	$936,914	$234,228
Penn State	$160,000	$40,000	$160,000	$40,000	$160,000	$40,000	$480,000	$120,000
CCS	$276,646	$69,162	$166,051	$41,513	$138,418	$34,605	$581,116	$145,280
Total	$774,427	$193,607	$656,840	$164,210	$566,763	$141,691	$1,998,030	$499,508
Cost Share	**80%**	**20%**	**80%**	**20%**	**80%**	**20%**	**80%**	**20%**

Technical Risks

- Polyphosphazene Performance Insufficient
- Insufficient Control of Interfacial Envelope
- Lack of Reproducibility of Membrane Results Because of Minor Differences in Fabrication Procedure
- Energy Consumption in Heat Pump System Too High
- Capital Cost for Solvent System Too High

Resource Risks

- Inability to Locate Qualified Staff
- Loss of Senior Team Member
- Lack of Analytical Resources

Management Risks

- Problems with Initiating Work Processes for New Company
- Collaboration Problems Among Organizations

IP Risks

- IP Agreements Not Reached with Subcontractors
- Others Make Use of Process Innovations Because of Lack of IP Protection
- Patents Not Issued for Polymers
- ICE Membrane Fabrication Methods Not Patentable

Milestones: BP 1

- Update PMP – 10/31/2015
- Kickoff Meeting – 12/31/2015
- Synthesize and Characterize 10 Polyphosphazenes – 3/31/2016
- Construct Isochoric Performance System – 3/31/2016
- Optimize Hybrid Process – 9/30/2016
- Down-select to 3 Polyphosphazenes – 9/30/2016
- Down-select to 3 Nano-fillers – 9/30/2016
- Complete Parametric Testing of CO_2 Absorption Column – 9/30/2016

Success Criteria: BP 1

- Completion of All Work Proposed
- Best Polyphosphazene Achieves 150 Barrer Permeability and 25 CO_2/N_2 Selectivity
- 90% Removal Achieved in Absorber Testing
- 30% Decrease in Parasitic Power Demonstrated Compared to Case 12
- Submission of Continuation Application

Milestones: BP 2

- Fabricate 3 Gen 1 ICE Membranes – 3/31/2017
- Modify Air Stripping Column – 3/31/2017
- Select Up to Two Best Gen 1 Membranes – 9/30/2017
- Construct Isobaric Performance System – 9/30/2017
- Complete Parametric Testing of Air Stripping Column – 9/30/2017

Success Criteria: BP 2

- Completion of All Work Proposed
- Best Gen 1 ICE Membrane Achieves 2500 GPU Permeance and 25 CO_2/N_2 Selectivity
- Successful Test of Air Stripping Column with Difference in Absorption and Stripping Temperatures of No More than 50^{o}C
- Submission of Continuation Application

Milestones: BP 3

- Model Performance and Conduct Mass and Energy Balances for Hybrid Process – 3/31/2018
- Scale-up Optimal Polyphosphazene to 1 kg – 6/30/2018
- Conduct Simulated Flue Gas Testing of Gen 1 ICE Membrane – 9/30/2018
- Complete Technical and Economic Feasibility Study and Sensitivity Analysis – 9/30/2018

Success Criteria: BP 3

- Completion of All Work Proposed
- Scale-up Polymer Synthesis to 1 kg
- Best Gen 1 ICE Membrane Achieves 5000 GPU Permeance and 30 CO_2/N_2 Selectivity
- Economic Analysis Shows Significant Progress toward Achieving a 30% Reduction in Cost of Electricity
- Submission of State Point Data Tables
- Submission of Final Report

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?