2018 CAPTURE TECHNOLOGY MEETING

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

DE-FE0026464

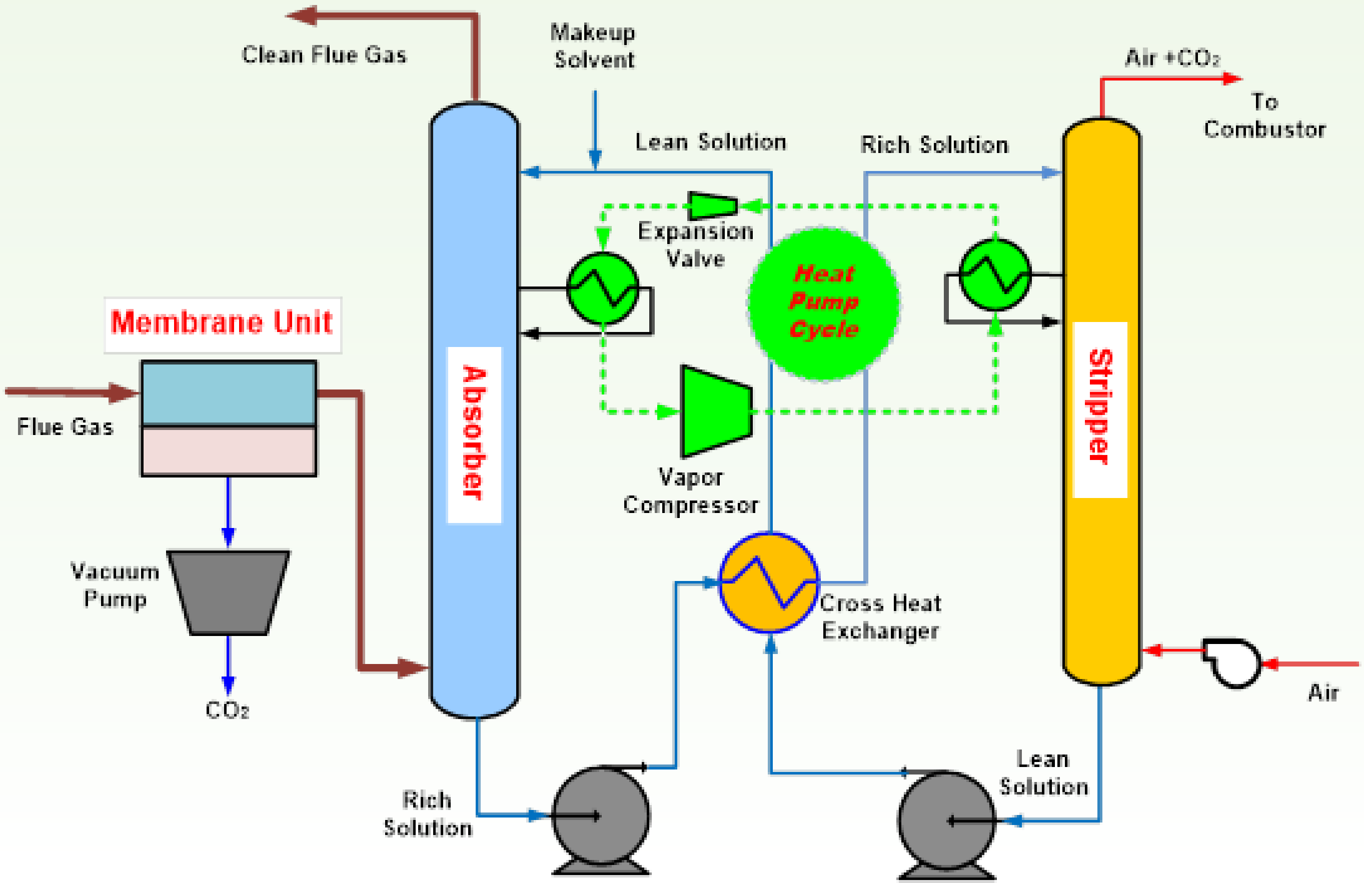
AUGUST 15, 2017

CARBON CAPTURE SCIENTIFIC LLC

Liquid Ion Solutions

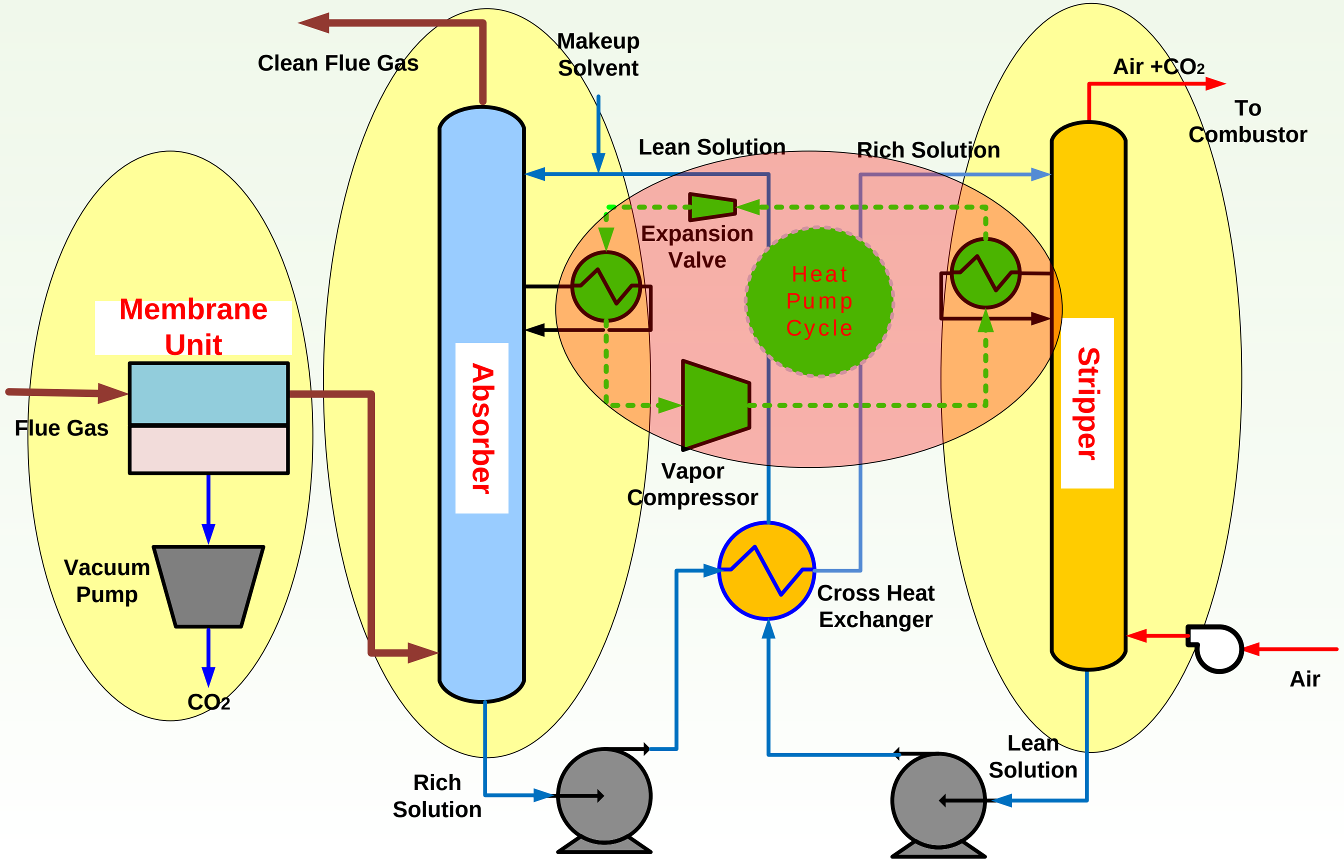
PennState

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



CCS Team

Dr. Scott Chen and Dr. John Pan

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

LIS Team

Prof. Hunaid Nulwala and Dr. Dave Luebke

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

PSU Team

Prof. Harry Allcock and Dr. Chen Chen

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

Project Outline

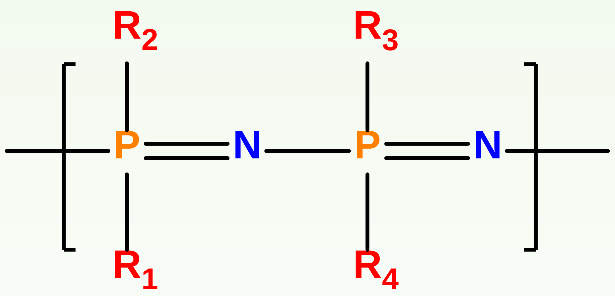
- Task 1: Project Management
- Task 2: Computer Simulation of Hybrid Process
- Task 3: Generation 0 ICE Membrane Development
- Task 4: Modification, Installation, and Testing of Absorption Column
- Task 5: Generation 1 ICE Membrane Development
- Task 6: Modification, Installation, and Testing of Air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

Year 1 Year 2 Year 3

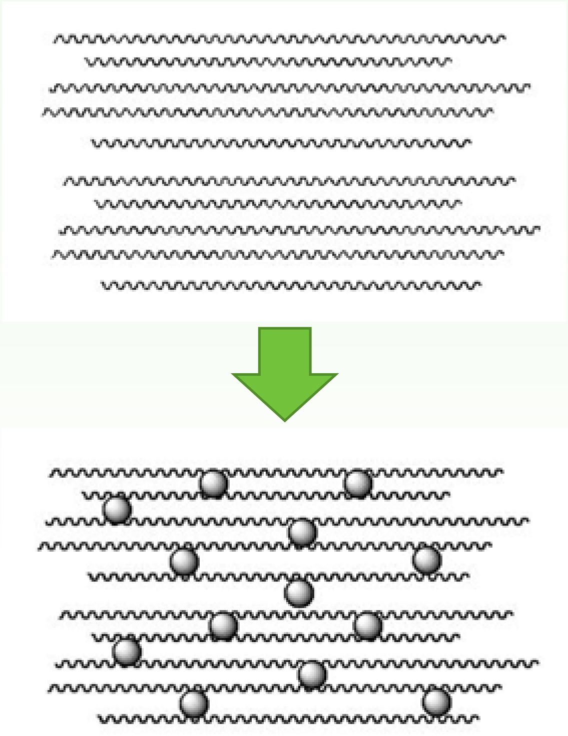
Membrane Performance

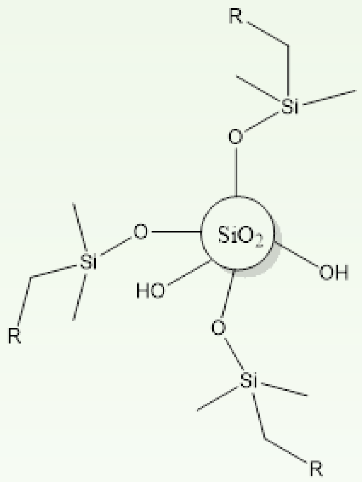
Mixed Matrix Membrane Optimization

23
Polymers



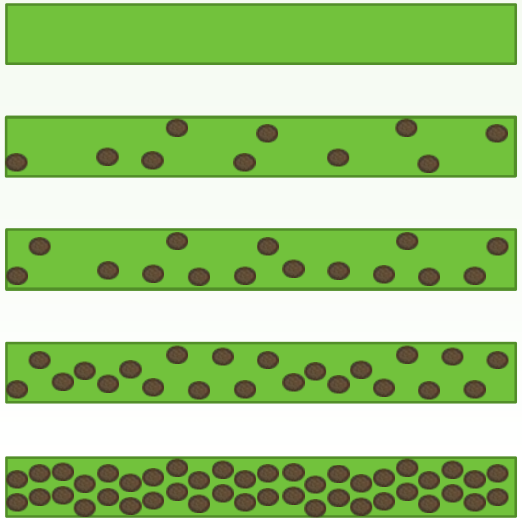
2
X-linker
Conc.



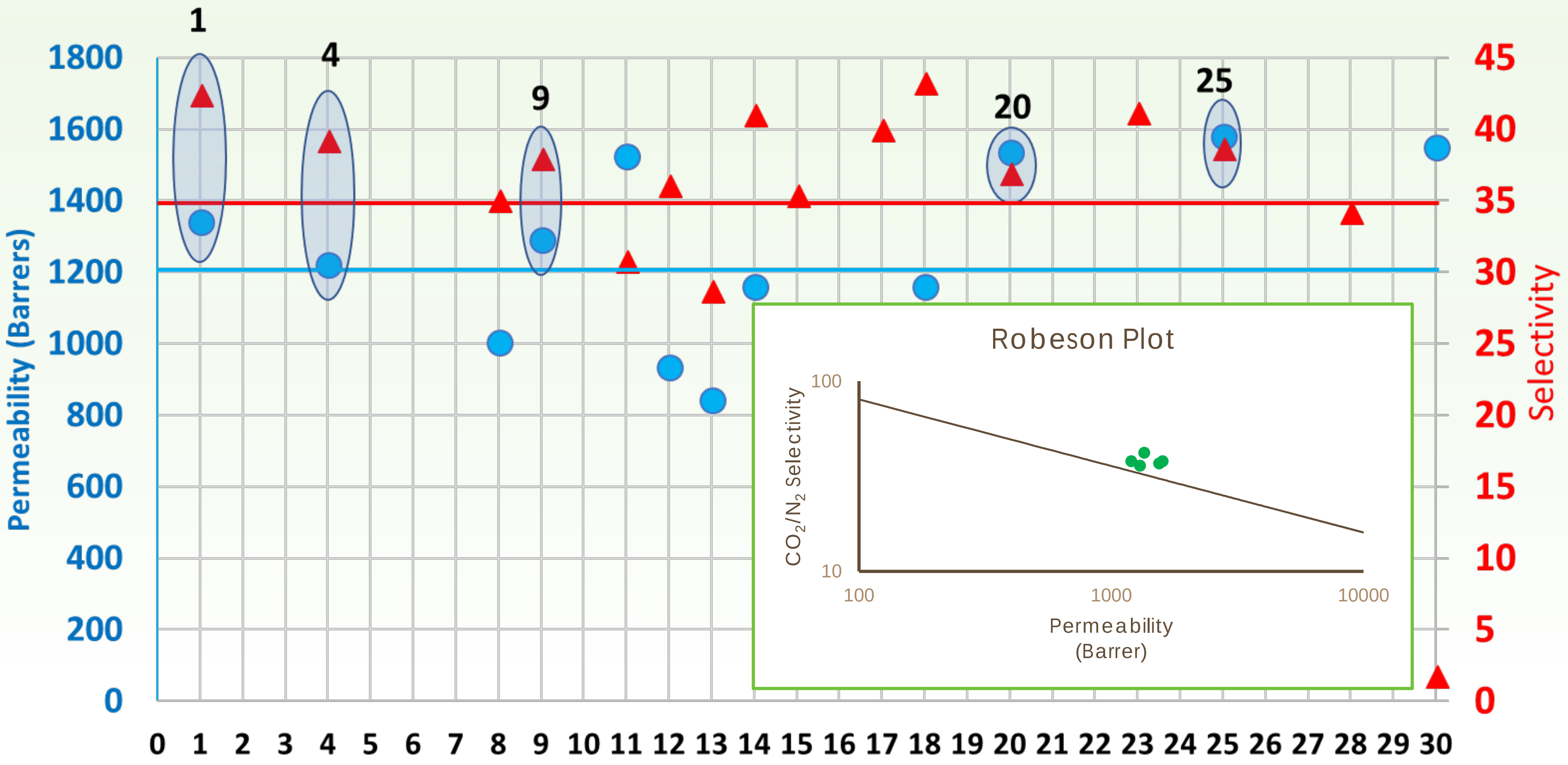


3
Surface
Modification
Ratios

5
Particle
Loadings



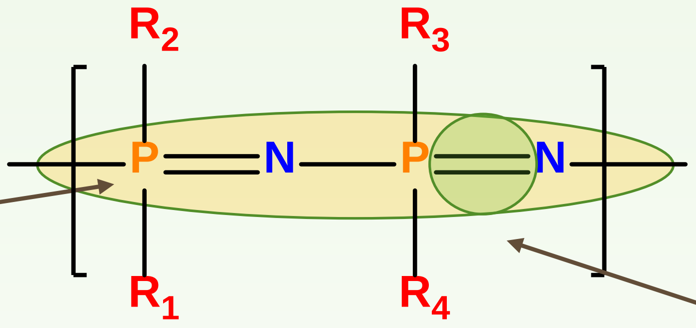
Design of Experiments Optimization



Polymer Scale-up

Polymer of Choice

Macromolecular Substitution



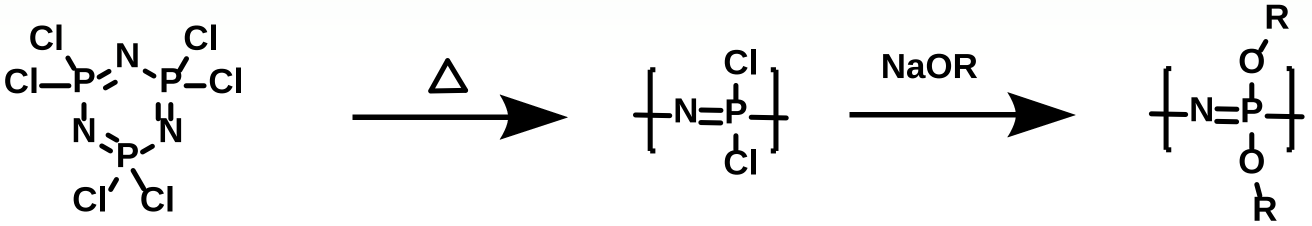
Ultra Flexible Chains

- High chain mobility
- Improved gas solubility and diffusion

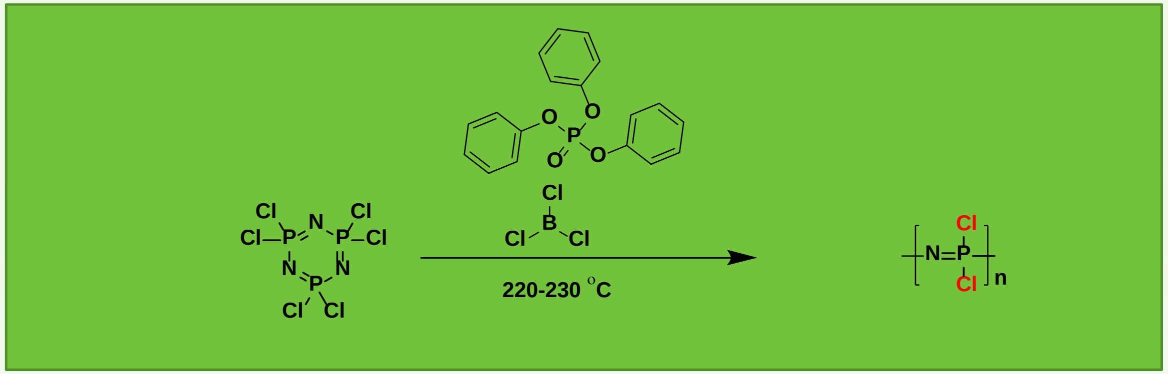
Excellent Chemical and Thermal Stability

C-C =607ΔHf kJ/mol vs.

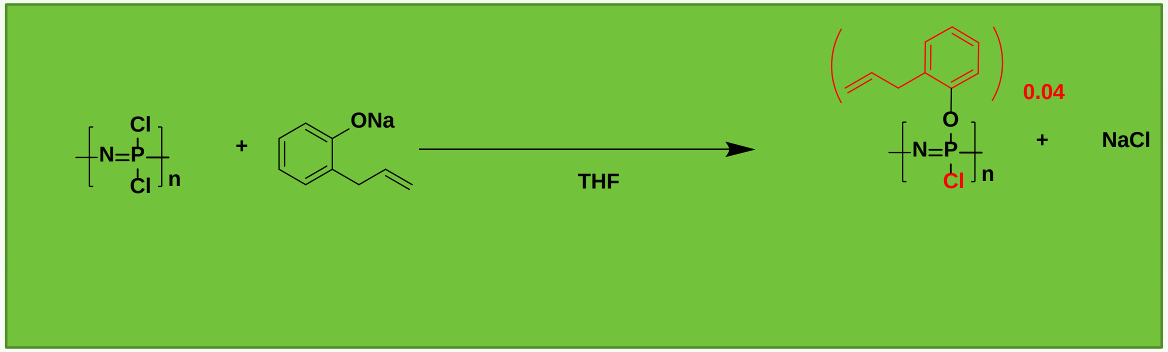
P-N =617 ΔHf kJ/mol



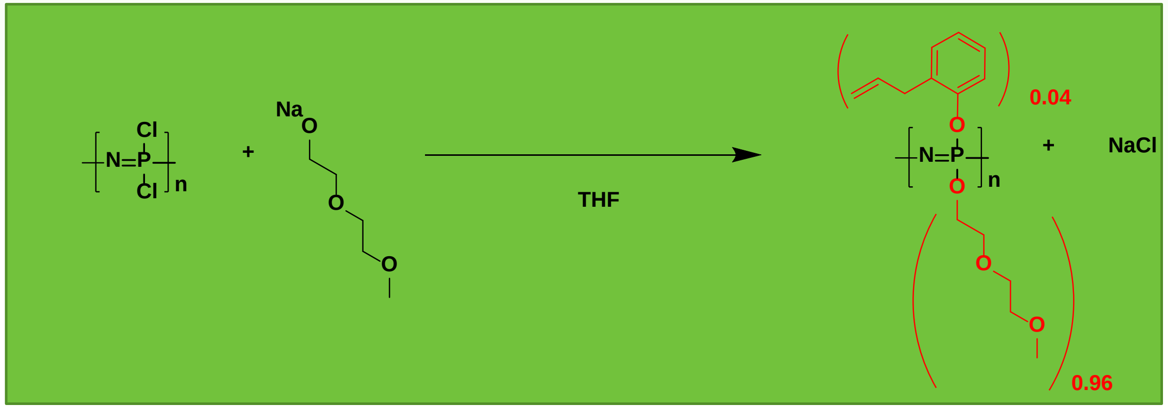
Polymer Synthesis



Ring Opening



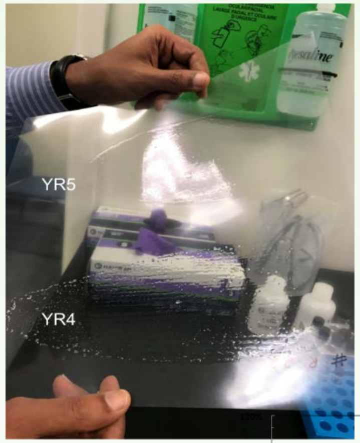
Post Modification Opening

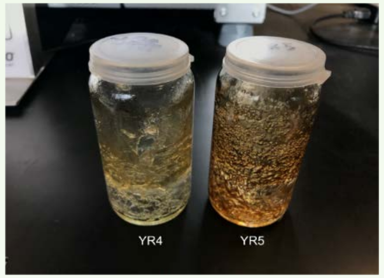


Post Modification Opening

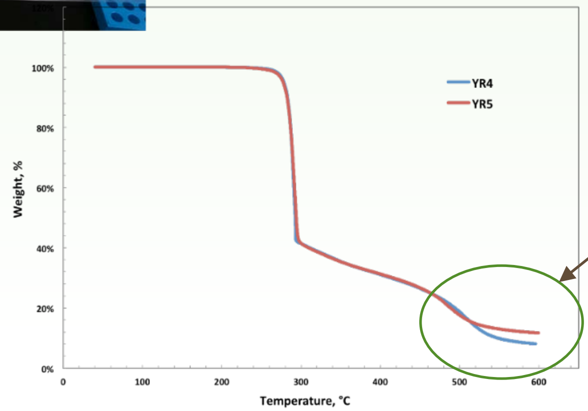
Polymer Purification

- At smaller scale, dialysis works extremely well to remove NaCl and excess reactants from the polymer.
- Dialysis does not work on larger scales (>20g).
- Consistency of the polymer is a problem on larger scales when purified via dialysis.





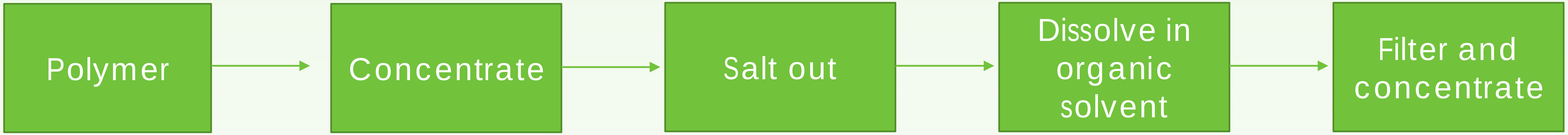
Color Variations



Inconsistent Char Values

Polymer Purification

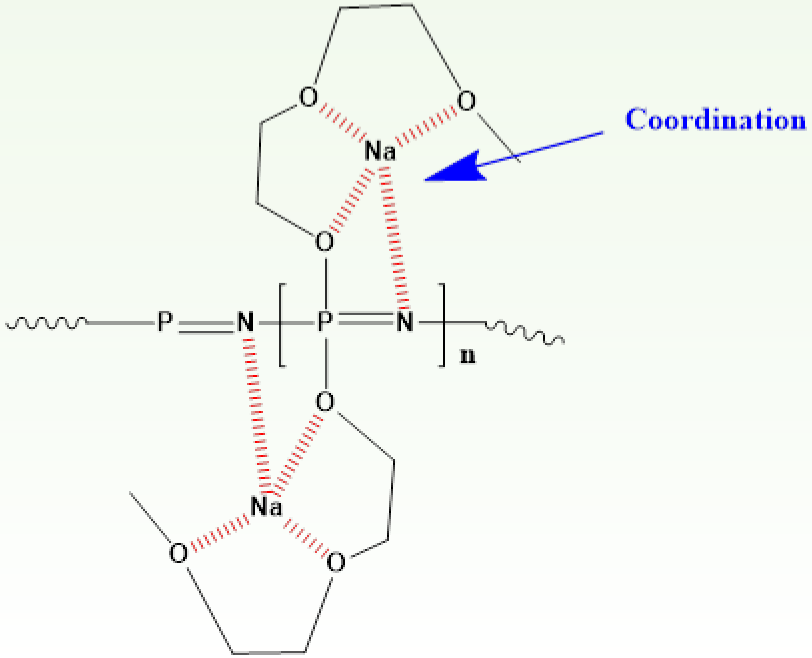
Generalized Purification Methodology



- New purification methodologies were developed using precipitation routes.
- Obtained consistent results on DSC and TGA
- Consistent color and viscosity
- Scale-up materials failed in performance testing

Sodium Metal Coordination

- Only small scale dialysis seems to give polymer with the desired properties
- Likely the polymeric sites are taken up by Na ions. This results in significant reduced performance.
- Dialysis is not an option for scaling up these materials.
- Likely, ammonium based cation is needed for the synthesis and scale-up.

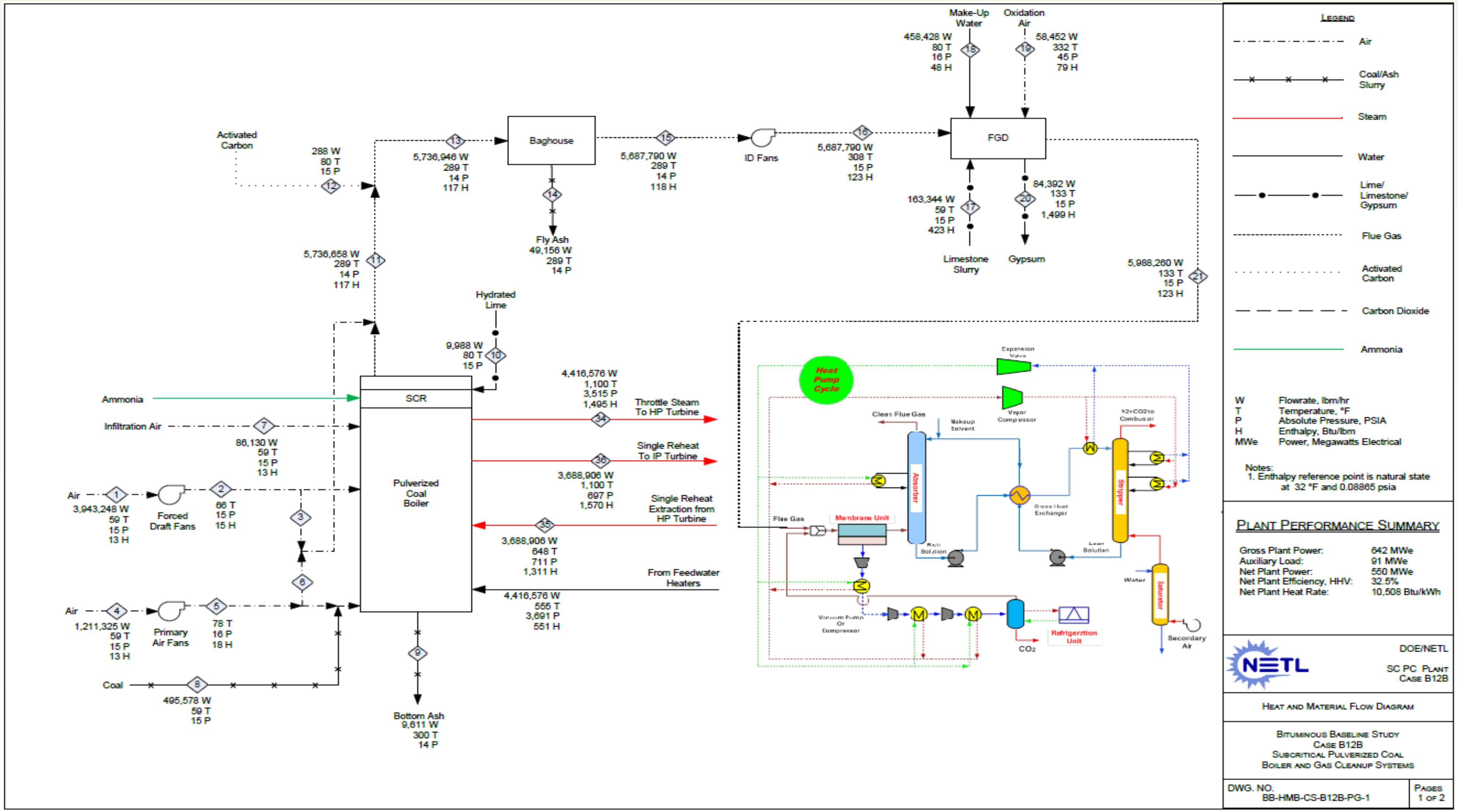


Techno-Economic Analysis

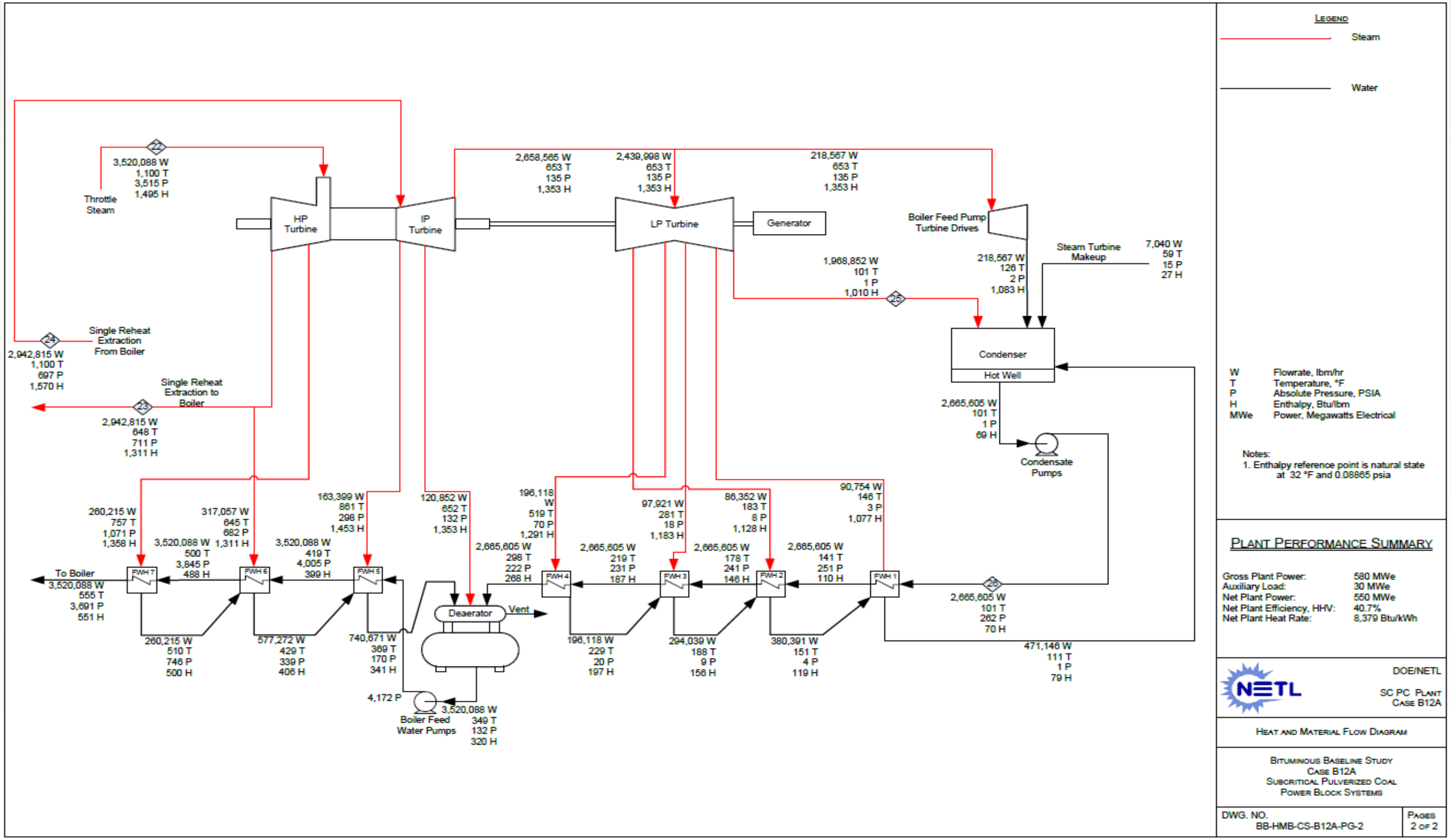
Reference Reports Used in the TEA Analysis

1. *Techno-Economic Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3", DOE/NETL-2015/1723, July 6, 2015*.
2. *Analysis of GPS-based Technology for CO_2 Capture Topical Report by Nexant Inc. and Carbon Capture Scientific, LLC, 2015.*
3. *MTR CO2 CAPTURE PROCESS FOR A SUPERCRITICAL COAL-FIRED PLANT--Technical and Cost Evaluation, Final Report, by WorleyParsons Group, Inc.,2015.*
4. *Process Equipment Cost Estimation, Final Report, Loh, H. P., Lyons, Jennifer, White, Charles W., DOE/NETL-2002/1169, 2002.*

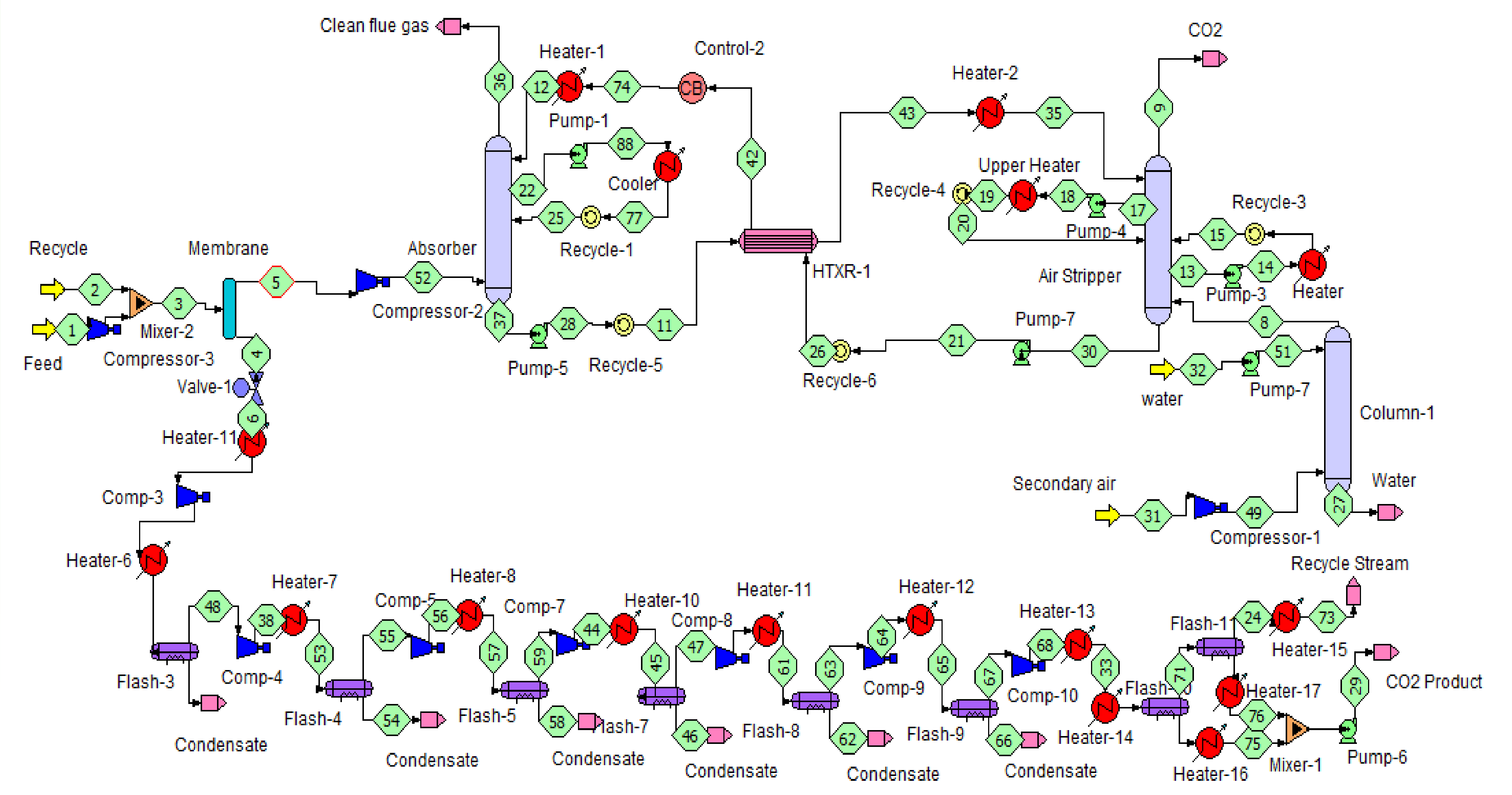
Integration of Power Plant and the Hybrid Process



Power Island in the TEA Analysis

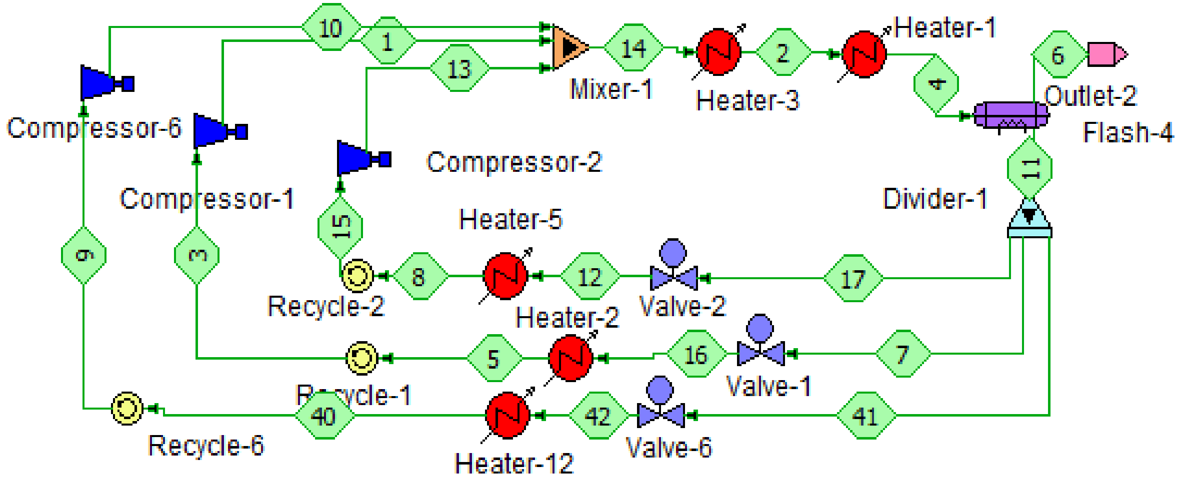


Energy and Mass Balance Calculations Process Flow

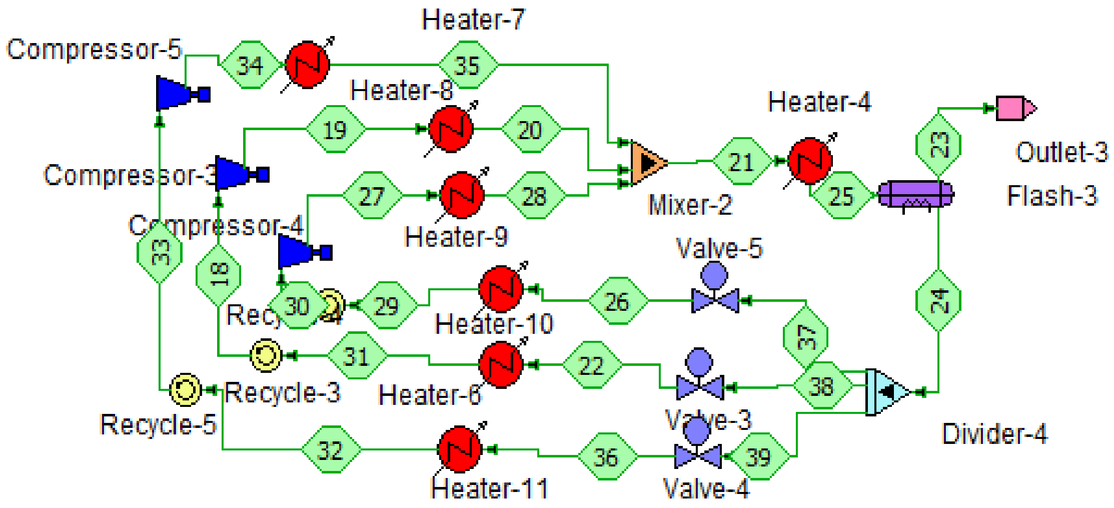


Process Flow Sheet for Heat Pump System Simulations

Compressor/Stripper Heat Pump System



Absorber/Stripper Heat Pump System



Capital Cost Estimation of Power Plant Equipped with Hybrid Process

Case:		Hybrid Process – Supercritical PC w/ CO				Estimate Type:				Conceptual	
Plant Size (MW,net):		550				Cost Base:				Jun-11	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected	Eng'g CM	Contingencies		Total Plant Cost	
				Direct	Indirect	Cost	H.O.& Fee	Process	Project	$/1,000	$/kW
1. Coal & Sorbent Handling		**$22,386**	**$5,714**	**$13,233**	**$0**	**$41,333**	**$4,133**	**$0**	**$6,820**	**$52,286**	$92.38
2. Coal & Sorbent Prep & Feed		**$15,128**	**$837**	**$3,784**	**$0**	**$19,749**	**$1,975**	**$0**	**$3,259**	**$24,983**	$44.14
3. Feed water & Miscellaneous BOP Systems		**$59,843**	**$0**	**$27,798**	**$0**	**$87,641**	**$8,764**	**$0**	**$15,745**	**$112,150**	$198.14
4. Boiler & Accessories		**$211,004**	**$0**	**$120,229**	**$0**	**$331,234**	**$33,123**	**$0**	**$36,436**	**$400,793**	$708.11
5A. Gas Cleanup & Piping		**$118,843**	**$1,034**	**$43,325**	**$0**	**$163,202**	**$16,320**	**$0**	**$17,952**	**$197,475**	$348.90
5B.1	Solvent System	$72,549	100206	162076	0	334831	43855	66966	86715	520288	919
5B.2	Membrane System	$99,880	25534	66612	0	192025	18502	7701	43646	261874	463
5B.3	Heat Pump System	$32,535	4880	10878	0	48294	4829	0	10625	63748	113
5B. CO Removal & Compression		**$ 204,964**	**$130,620**	**$239,566**	**$0**	**$575,150**	**$67,186**	**$74,667**	**$140,986**	**$845,910**	1495
7. HRSG, Ducting, & Stack		**$21,025**	**$1,088**	**$14,064**	**$0**	**$36,177**	**$3,618**	**$0**	**$5,232**	**$45,027**	$79.55
8. Steam Turbine Generator		**$129,101**	**$1,463**	**$28,909**	**$0**	**$159,471**	**$15,949**	**$0**	**$20,373**	**$195,791**	$346
9. Cooling Water System		**$16,807**	**$8,861**	**$15,664**	**$0**	**$41,332**	**$4,133**	**$0**	**$6,183**	**$51,649**	$91
10. Ash & Spent Sorbent Handling Systems		**$6,738**	**$199**	**$8,748**	**$0**	**$15,685**	**$1,569**	**$0**	**$1,774**	**$19,028**	$34
11. Accessory Electric Plant		**$30,069**	**$12,477**	**$33,082**	**$0**	**$75,628**	**$7,563**	**$0**	**$10,394**	**$93,584**	$165
12. Instrumentation & Control		**$12,233**	**$0**	**$12,269**	**$0**	**$24,502**	**$2,450**	**$1,225**	**$3,477**	**$31,654**	$56
13. Improvements to Site		**$3,680**	**$2,115**	**$7,889**	**$0**	**$13,684**	**$1,368**	**$0**	**$3,010**	**$18,063**	$32
14. Buildings & Structures		**$0**	**$29,016**	**$27,530**	**$0**	**$56,547**	**$5,655**	**$0**	**$9,330**	**$71,531**	$126
Total		**$856,131**	**$133,187**	**$505,263**	**$0**	**$1,494,582**	**$144,536**	**$63,345**	**$236,680**	**$2,159,924**	**$3,816**

Plant Performance Summary for Hybrid Process

Item	Case B12B	Hybrid Process
Total Gross Power, MWe	**642**	**728**
CO_2 Capture/Removal Auxiliaries, kWe	16,000	15,070
Membrane Unit	N/A	19,700
Heat Pump Cycle	N/A	15,340
CO_2 Compression, kWe	35,690	72,750
Balance of Plant, kWe	39,595	39,595
Total Auxiliaries, MWe	**91**	**162**
Net Power, MWe	**550**	**566**
HHV Net Plant Efficiency (%)	32.5%	33.4%
HHV Net Plant Heat Rate, kJ/kWh (Btu/kWh)	11,086 (10,508)	11388 (10795)
LHV Net Plant Efficiency (%)	33.7%	34.6%
LHV Net Plant Heat Rate, kJ/kWh (Btu/kWh)	10,693 (10,135)	10985 (10411)
HHV Boiler Efficiency, %	89.1%	89.1%
LHV Boiler Efficiency, %	92.4%	92.4%
Steam Turbine Cycle Efficiency, %	54.5%	54.5%
Steam Turbine Heat Rate, kJ/kWh (Btu/kWh)	6,608 (6,263)	6,608 (6,263)
Condenser Duty, GJ/hr (MMBtu/hr)	1,867 (1,770)	1,867 (1,770)
As-Received Coal Feed, kg/hr (lb/hr)	224,791 (495,578)	224,791 (495,578)
Limestone Sorbent Feed, kg/hr (lb/hr)	22,213 (48,970)	22,213 (48,970)
HHV Thermal Input, kWt	1,694,366	1,694,366
LHV Thermal Input, kWt	1,634,237	1,634,237
Raw Water Withdrawal, (m3/min)/MWnet (gpm/MWnet)	0.054 (14.3)	0.054 (14.3)
Raw Water Consumption, (m3/min)/MWnet (gpm/MWnet)	0.042 (11.0)	0.042 (11.0)
Excess Air, %	20.9%	20.9%

Power Summary of the Hybrid Process Equipped Power Plant

Items	Case B12B	Hybrid Process
Steam Turbine Power, MWe	642	728
Total Gross Power, MWe	**642**	**728**
Auxiliary Load Summary		
Coal Handling and Conveying, kWe	480	480
Pulverizers, kWe	3,370	3,370
Sorbent Handling & Reagent Preparation, kWe	1,070	1,070
Ash Handling, kWe	780	780
Primary Air Fans, kWe	1,670	1,670
Forced Draft Fans, kWe	2,130	2,130
Induced Draft Fans, kWe	8,350	8,350
SCR, kWe	60	60
Activated Carbon Injection, kWe	27	27
Dry sorbent Injection, kWe	108	108
Baghouse, kWe	110	110
Wet FGD, kWe	3,550	3,550
CO_2 Capture/Removal Auxiliaries, kWe	16,000	15,070
Membrane Unit	N/A	19,700
Heat Pump Cycle	N/A	15,340
CO_2Compression, kWe	35,690	72,750
Miscellaneous Balance of Plant, kWe	2,000	2,000
Steam Turbine Auxiliaries, kWe	400	400
Condensate Pumps, kWe	640	640
Circulating Water Pumps, kWe	7,750	7,750
Ground Water Pumps, kWe	710	710
Cooling Tower Fans, kWe	4,010	4,010
Transformer Losses, kWe	2,380	2,380
Total Auxiliaries, MWe	**91**	**162.0**
Net Power, MWe	**550**	**566**

COE Breakdown for Hybrid Process and Baseline Case B12B

	Case B12B		Hybrid Process	
Component	**Value, $/MWh**	**Percentage**	**Value, $/MWh**	**Percentage**
Capital	72.2	51%	78.2	53%
Fixed	15.4	11%	15.0	10%
Variable	14.7	10%	13.5	9%
Fuel	30.9	22%	30.0	21%
Total (Excluding T&S)	**133.2**	**N/A**	**136.7**	**N/A**
CO_2 T&S	9.6	7%	9.6	7%
Total (Including T&S)	**142.8**	**N/A**	**146.3**	**N/A**

Conclusions

- Trends in membrane performance were complex, but a limited optimization was possible.
- Scale-up in polymer synthesis proved challenging.
- Process efficiency gains were insufficient to offset increased capital equipment costs.

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?