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Combined Pressure and Temperature Contrast and Surface-enhanced Separation of Carbon-dioxide for Post-combustion Carbon Capture

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DOE Project Kick-off Meeting (DE-FE0007531)

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Outline

- About Rice University
- Project Team
- Background of proposed technology
- Combined Pressure and Temperature Contrast and Surface-enhanced Separation of Carbon-dioxide
- Supporting data
- Merits of proposed technology
- Project Objectives
- Scope of project
- Project Schedule
- Budgeting

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Rice University

- Located in Houston, TX
- 295-acre, heavily wooded campus
- Ranked 17th in the US and in the top 100 in the world
- 650 full-time faculty, 3500 undergraduates and 2300 graduate students
- Chemical and Biomolecular Engineering program, 13 faculty members, 70 graduate students
- Chemistry program, 38 faculty members, 130 graduate students

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Project Team

Project Director

George Hirasaki
A J. Hartsook Professor in Chemical & Biomolecular Engineering

Co-Project Investigator

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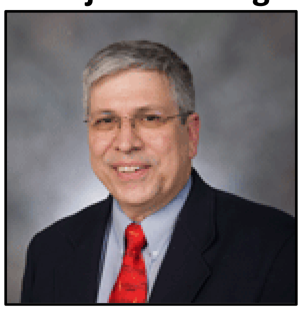
Co-Project Investigator

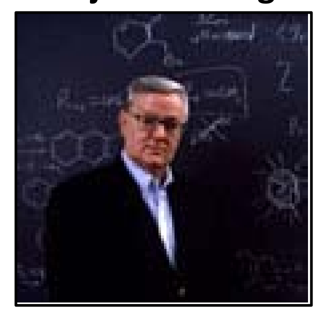


Kenneth Cox
Professor-in-practice in Chemical and Biomolecular Engineering

Graduate Student

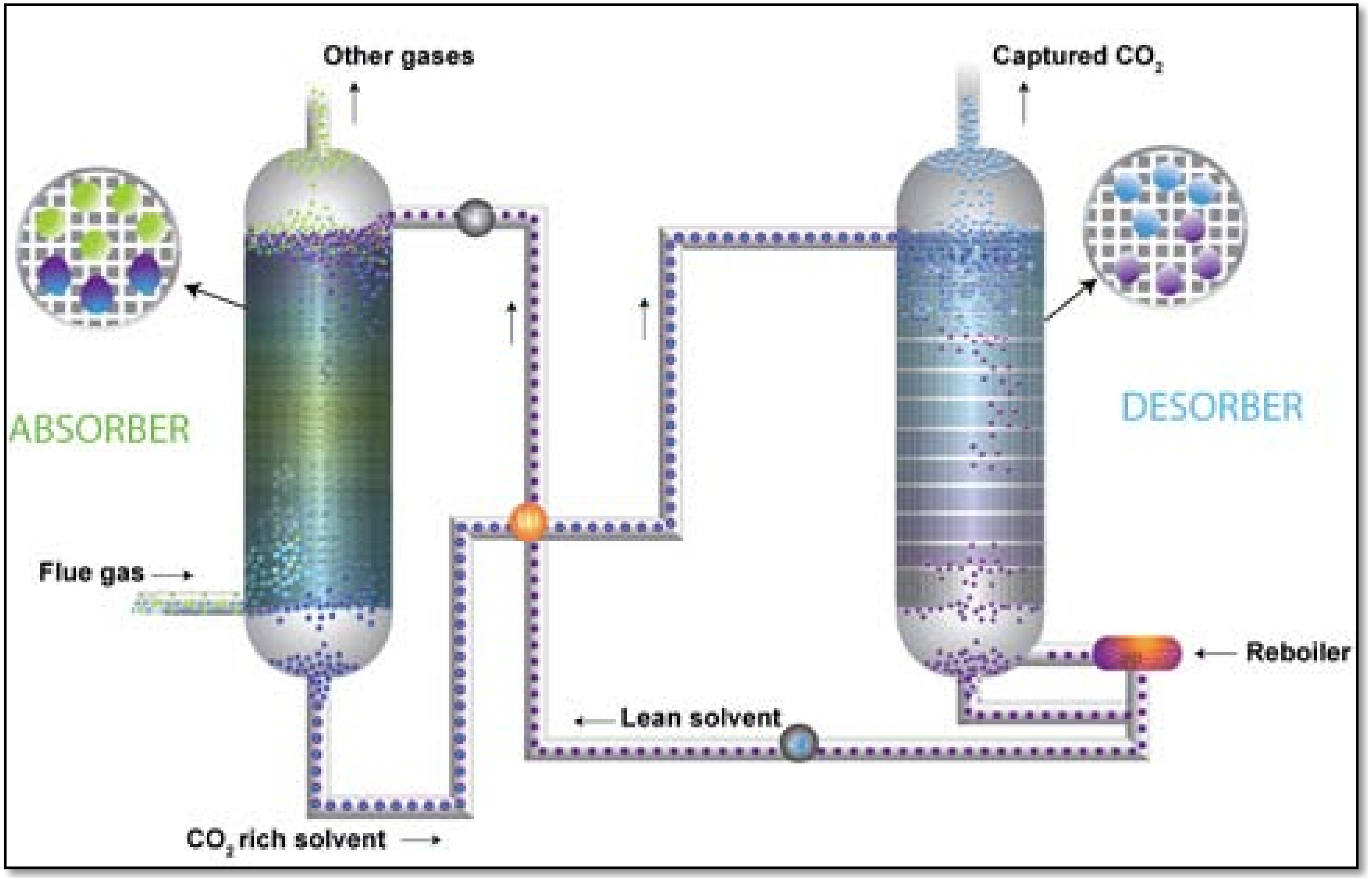
Sumedh Warudkar
PhD Candidate

Co-Project Investigator



Edward Billups
Professor in Chemistry

Conventional Amine Absorption



Absorber
Operating Pressure: ~ 1 atm
Operating Temperature: 50°C – 60°C
Amine Entry Temperature: 45°C

Desorber
Operating Pressure: ~ 1.5 atm
Operating Temperature: 120°C
Steam supply to reboiler: 60 psia, 140 °C

1: http://www.co2crc.com.au/aboutccs/cap_absorption.html

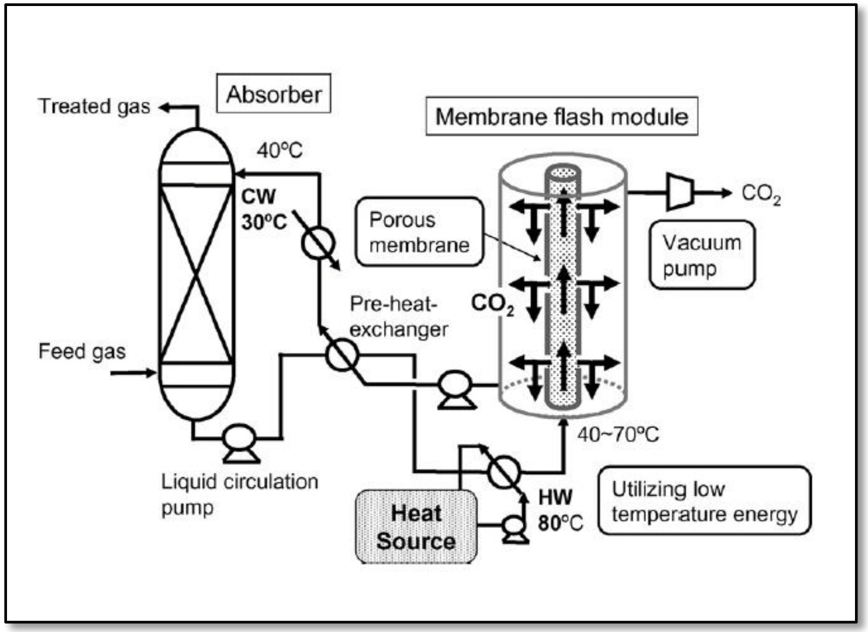
Drawbacks of Conventional Amine Absorption

- Current technology has been optimized for Natural gas sweetening not Carbon Capture
- Absorbent regeneration is very energy intensive and requires diverting low pressure steam from the LP steam turbine at coal-fired utilities
- Parasitic load due to Carbon capture can be in excess of 50% of rated capacity of power plant
- Commonly used amines like MEA and DEA are very corrosive at high CO_2 loadings
- Corrosion problems are worse at higher operating temperatures which correspond to higher stripper pressure
- Requires space for a separate absorber and desorber column which can be a problem while retrofitting existing coal-fired utilities

Proposed Combined Approach

- Based on reactive solvent
- Membrane to separate absorber and desorber in same unit
- Functionalization of high surface area substrate is similar to adsorption

Similarity to Membrane Separation



Schematic of membrane flash process for separation of CO_2 with utilization of waste heat*

Process description

- Feed gas (CO_2/N_2) and absorbent are contacted in a bubble column at slightly higher than 1 atm.
- Rich absorbent is pre-heated to 70°C using waste heat and is introduced on the lumen side of the hollow fiber at 1 atm.
- Pressure on the shell side of the hollow fiber is maintained between 4.5 and 6.5 psi absolute.
- Energy consumption is estimated at 0.30 kWh/kg-CO_2 which is less than 0.33 and 0.47 kWh/kg-CO_2 for hindered amine (KS-1) and MEA respectively.

Advantages

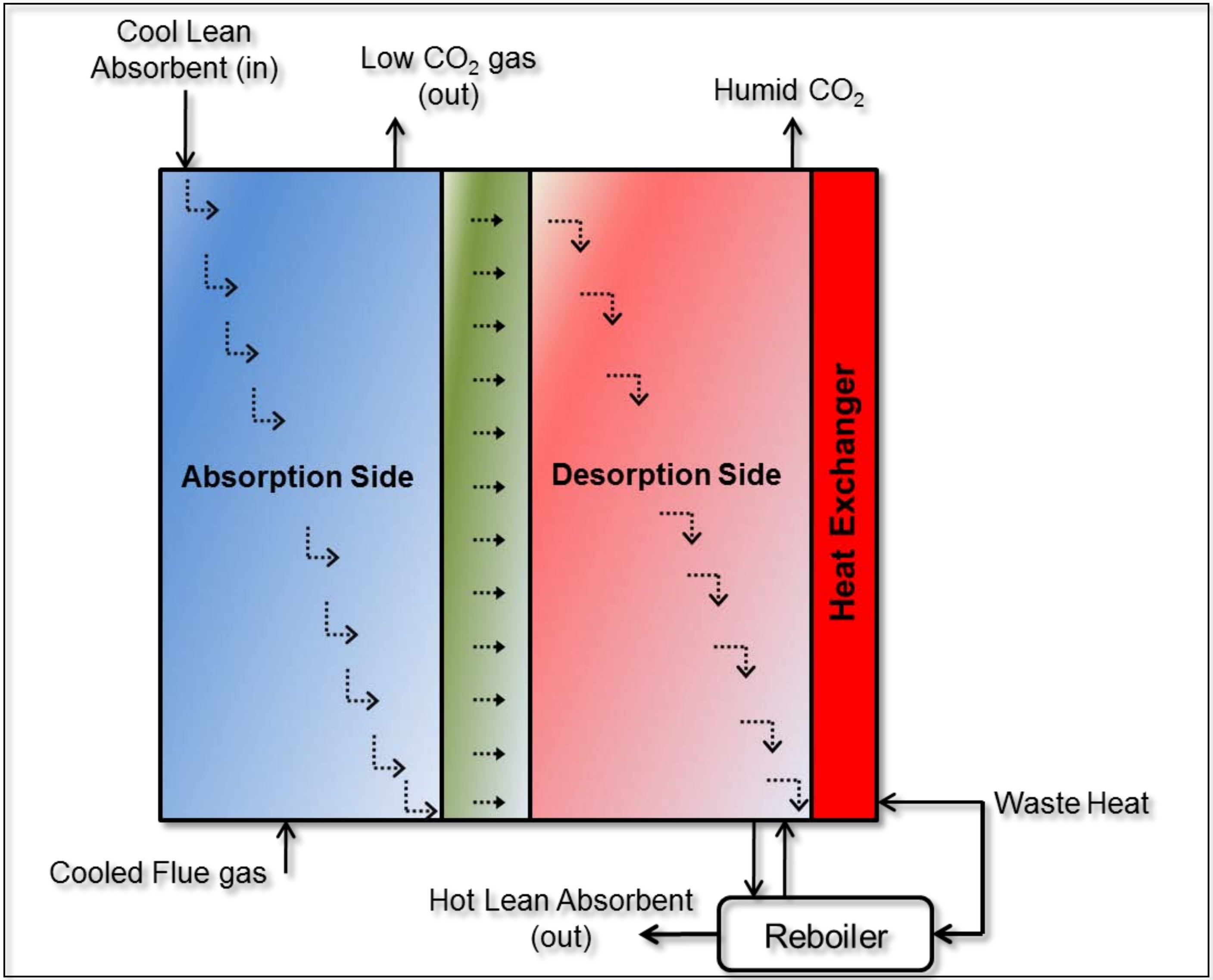
- Waste heat (low cost) is used instead of low pressure steam which will limit the increase in cost of electricity.

Disadvantages

- Scalability of process
- Lack of a process model to simulate and optimize process.
- Essentially the conventional absorption process but with a vacuum stripper.

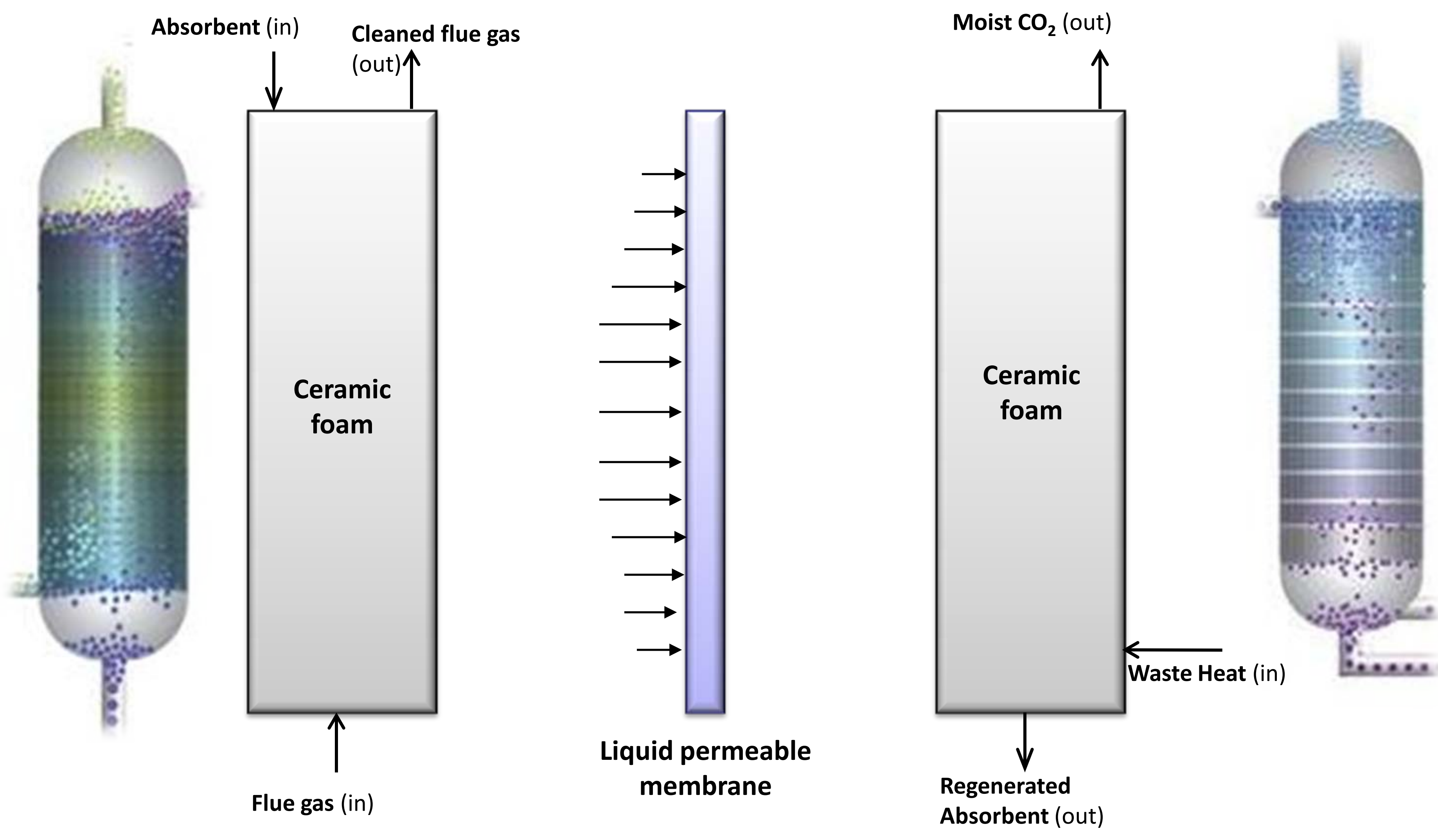
*Okabe, et al., Separation and recovery of carbon dioxide by a membrane flash process utilizing waste thermal energy, Energy Procedia (2009)

Combined Pressure and Temperature Contrast and Surface-enhanced separation of CO_2



Schematic of Combined Pressure and Temperature Contrast and Surface-enhanced separation of CO_2

Process Description



Simplified schematic of proposed CO_2 separation process

Application of Proposed Technology at Power Plant

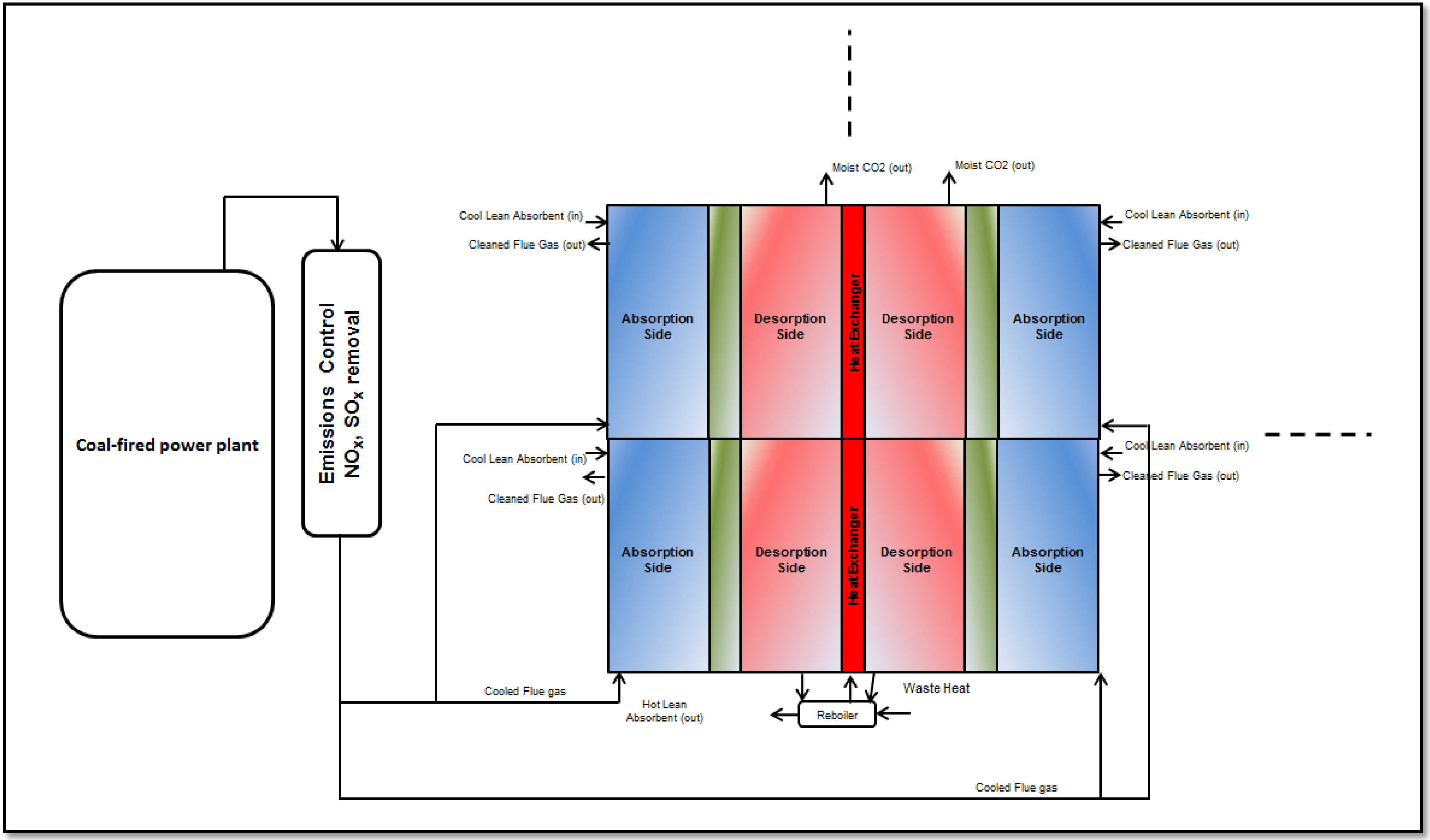
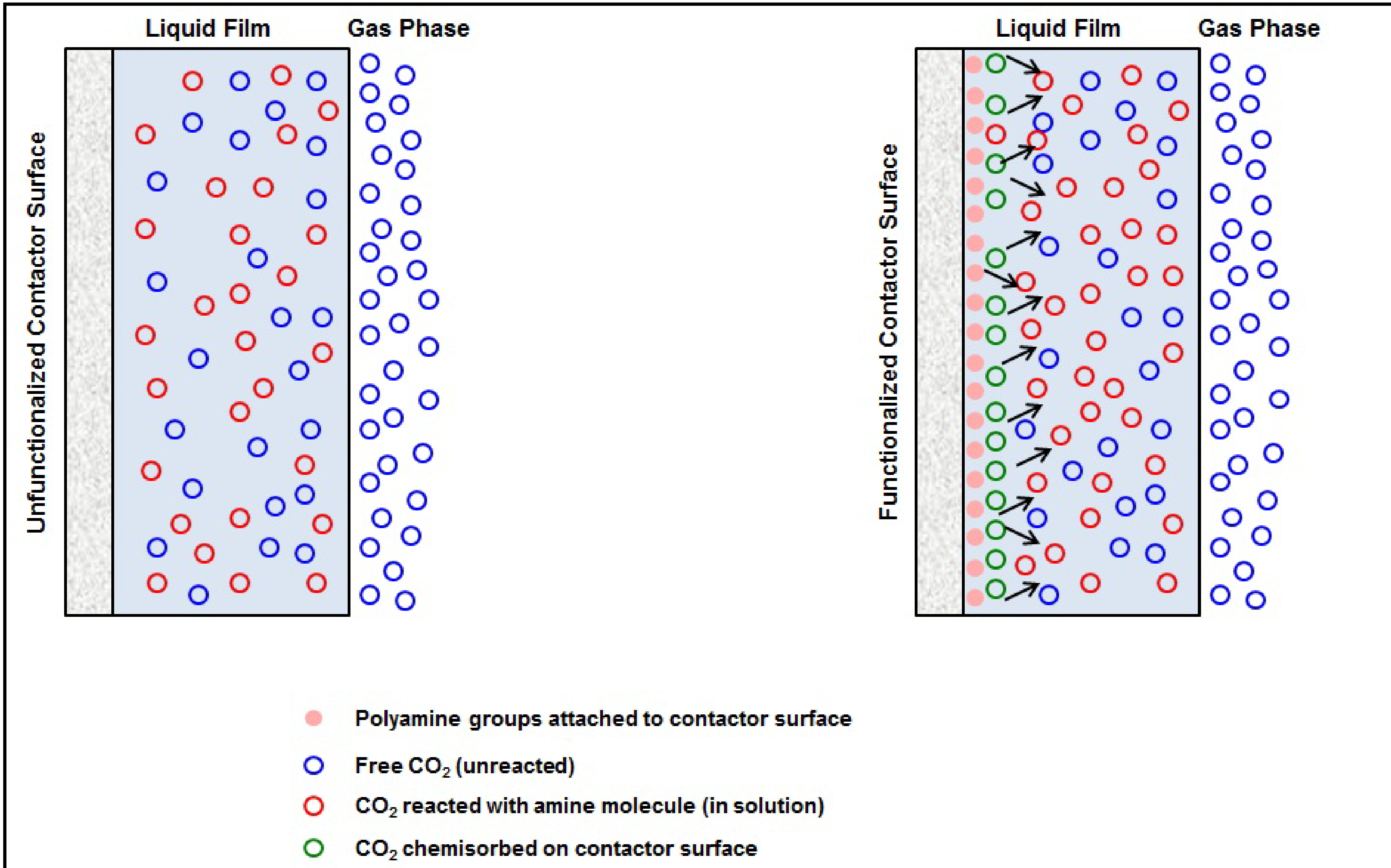


Illustration of use of proposed process for capturing CO_2 from a pulverized coal fired power plant

Optimize Absorber

- Higher pressure favors absorption capacity and kinetics but costs for compressing flue gas are high
- Lower temperature increases absorption capacity but slows kinetics
- Can the substrate have a role in kinetics?
  - Alkali enhances adsorption
  - Acid inhibits adsorption
- Functionalize substrate
  - Amine on absorber
  - Carboxylate on desorber

Substrate Functionalization
Absorber side

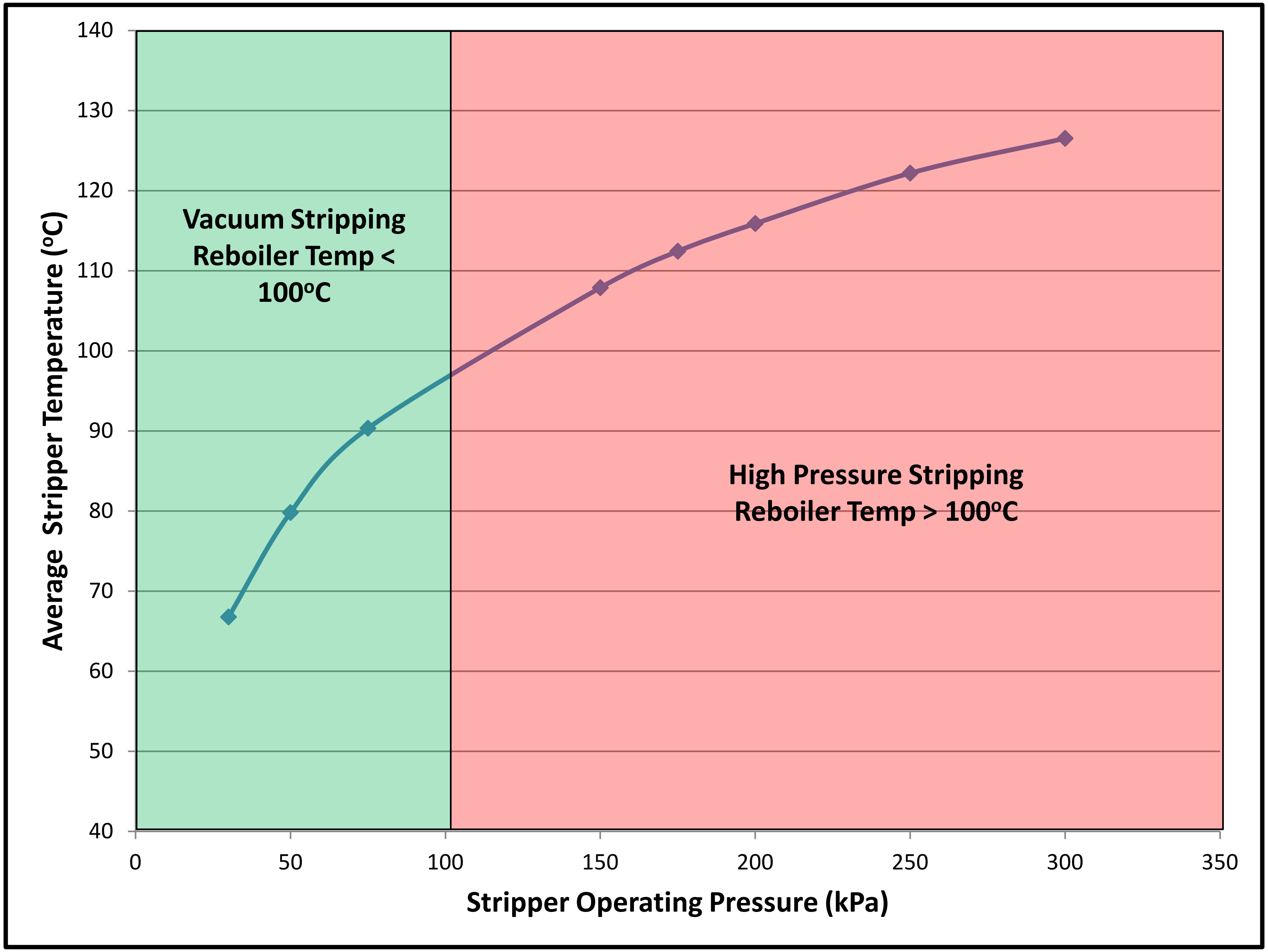


Schematic Representation of Substrate functionalization concept

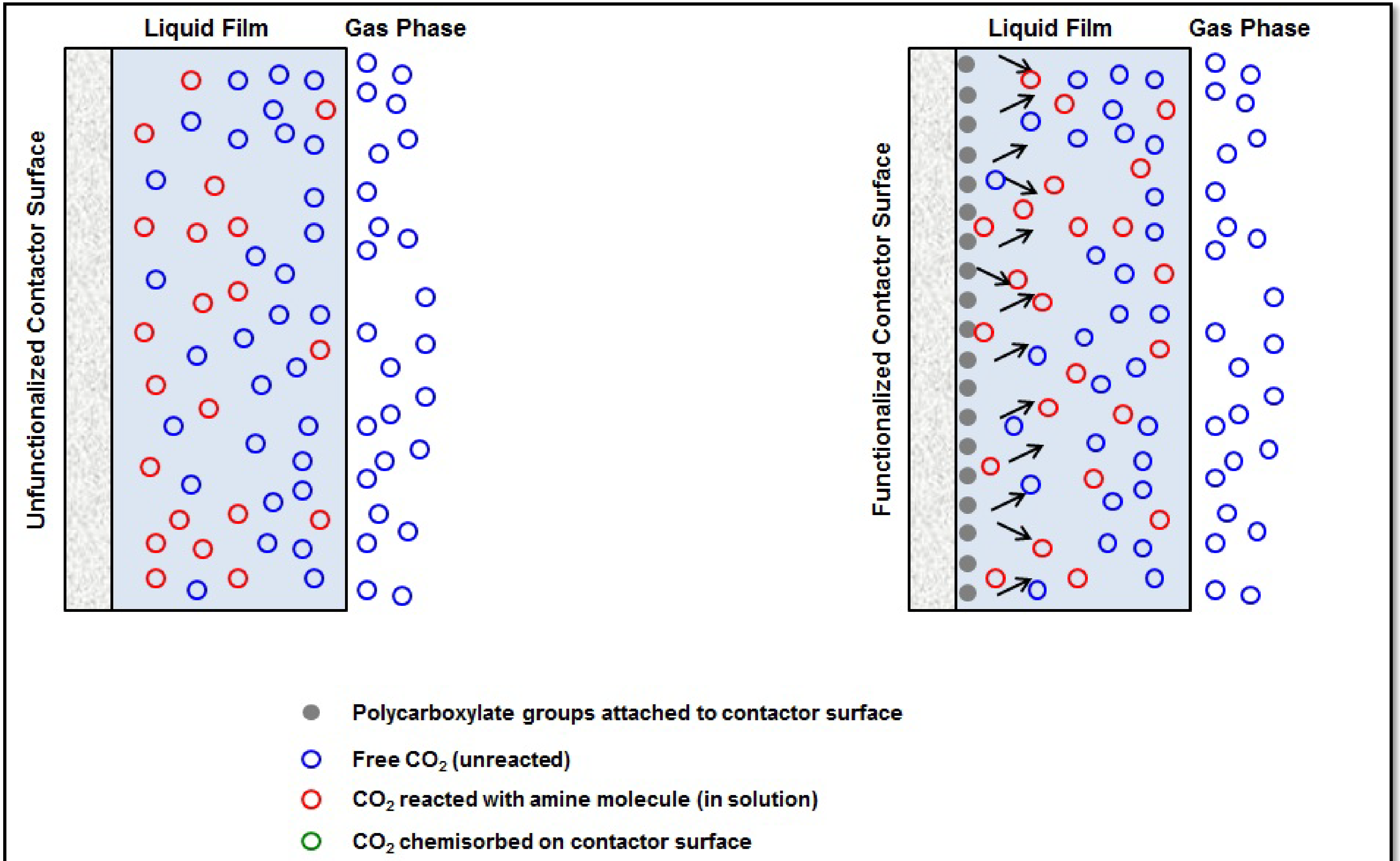
Optimize Desorber

- Lower pressure favors desorbing but costs for steam injector
- Lower pressure also allows use of lower temperature, possibly waste heat
- Carboxylate substrate functionalization may help desorption kinetics

Correlation of Stripper Operating Conditions



Substrate Functionalization
Desorber side



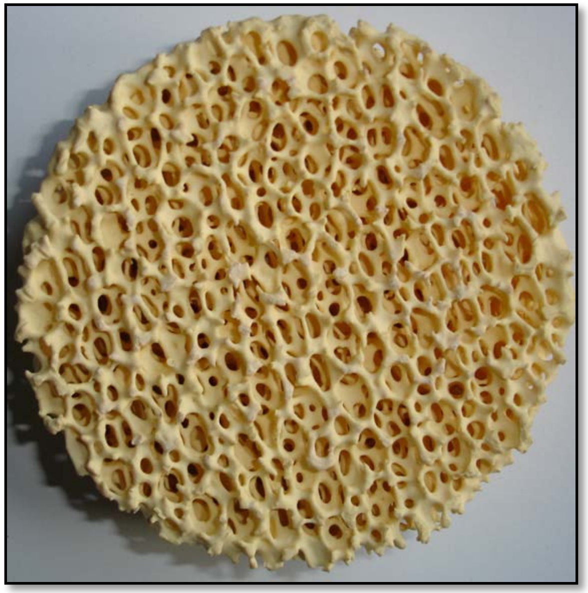
Schematic Representation of Substrate functionalization concept

Gas-liquid contactor – Ceramic Foam

Ceramic Foam

- Low bulk density
- Very high macro-porosity (80%-90%)
- Very high geometric surface area
- Regulated pore-size
- Low pressure drop
- High structural uniformity
- Ease of reproducibility of structure

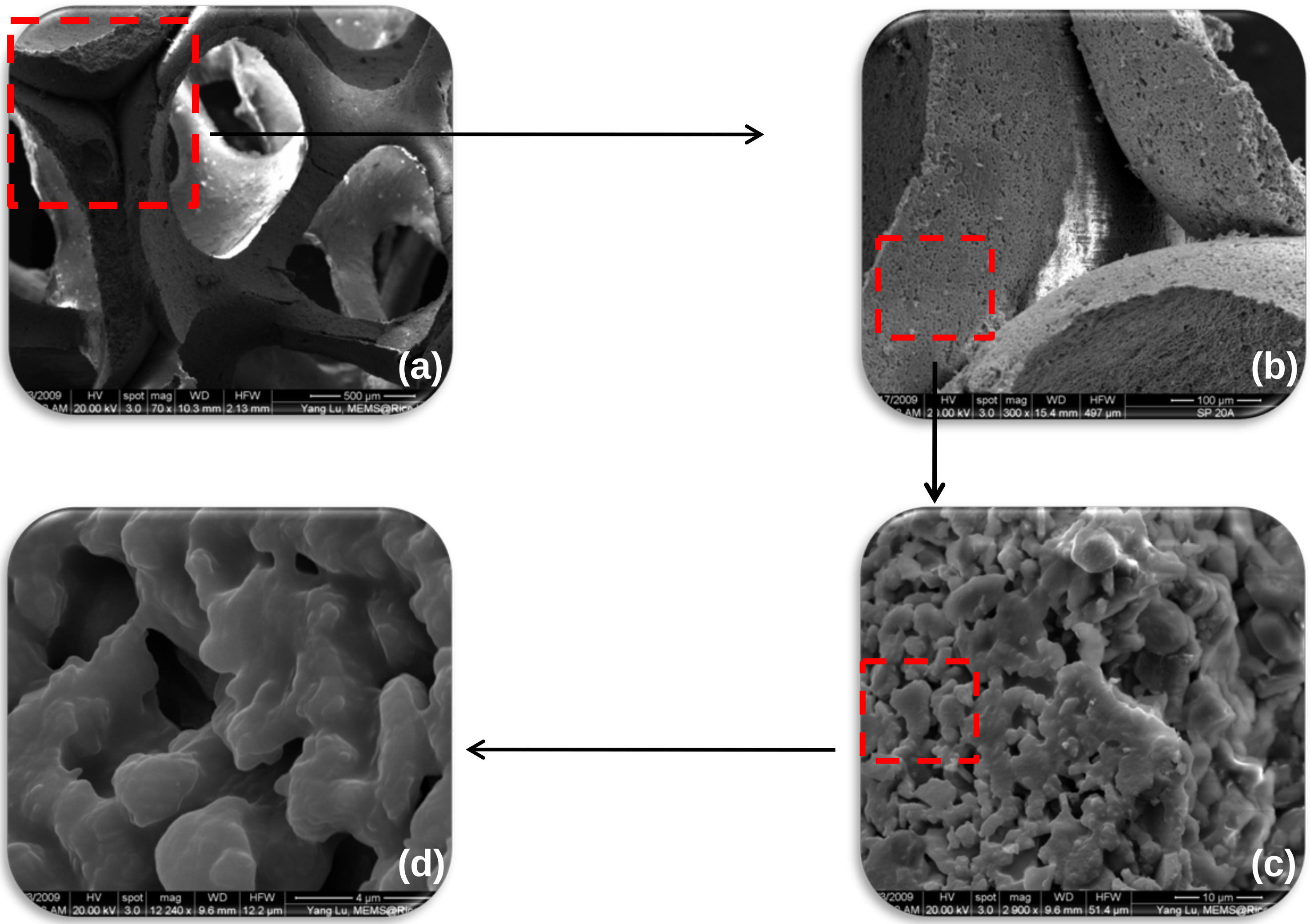
Structure	S (m^2/m^3)	Porosity (ε)
5 mm packing spheres	600	0.392
Raschig ceramic rings, 25 mm	200[1]	0.646
Corrugated metal structured packing (AceChemPack) – 500 x/y	500[3]	0.93
30-PPI -Al_2O_3 foam, no washcoat	3360[2]	0.83



Commercial Sample of Ceramic foam

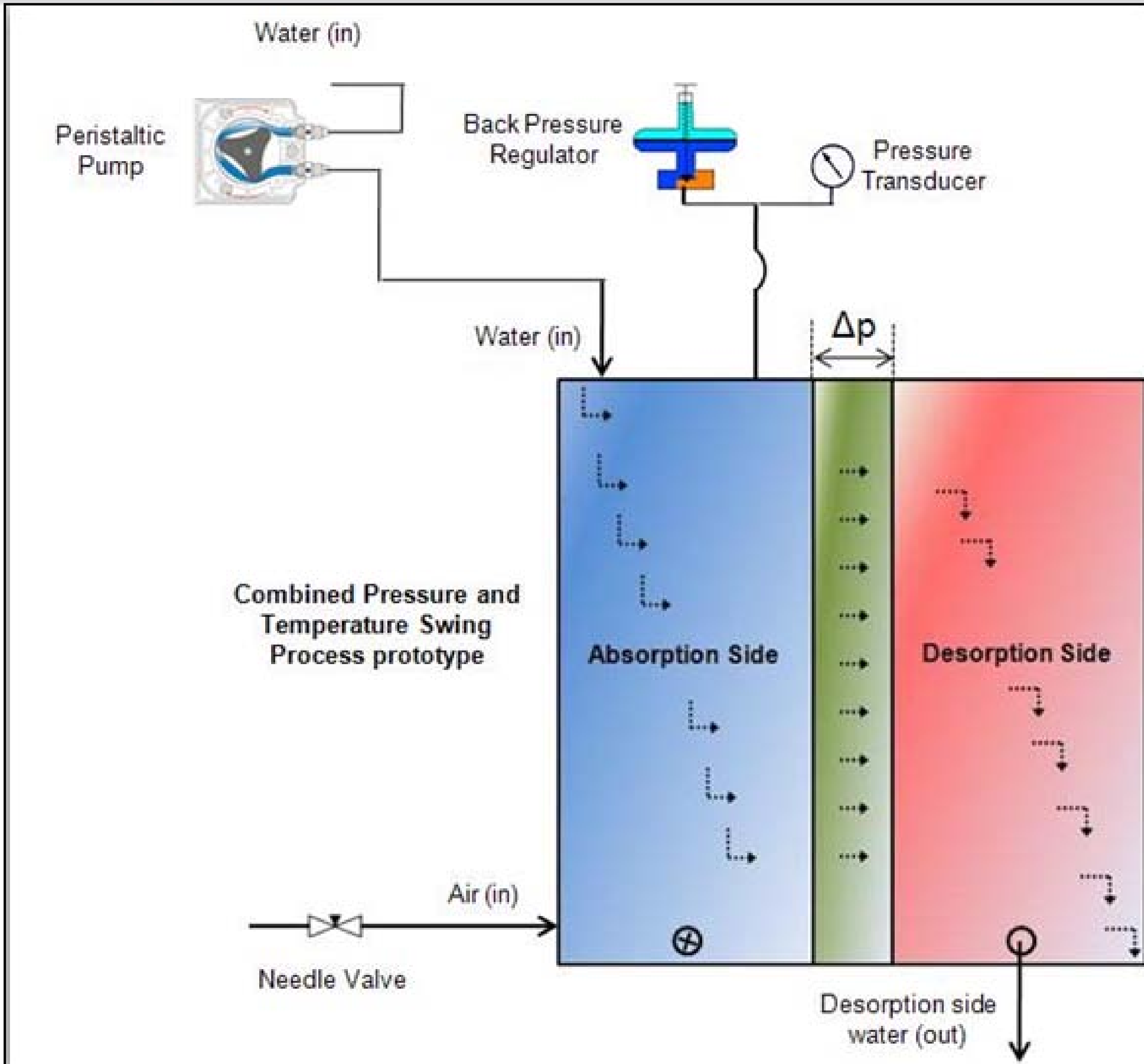
1: DOI: 10.1021/ie00027a023, **2:** DOI:10.1205/026387602753501906; **3:** http://www.tower-packing.com

Ceramic Foam - Micrographs

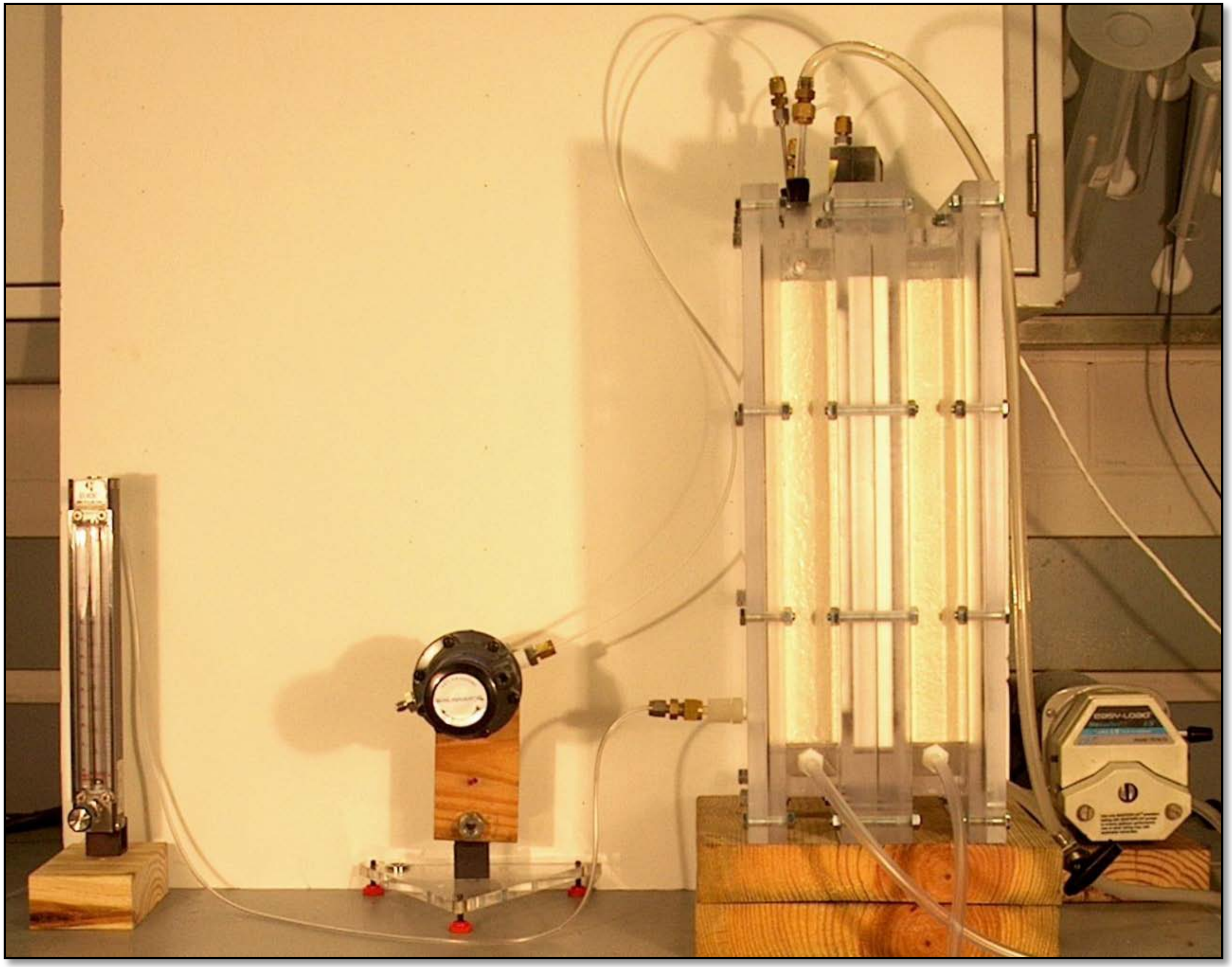


SEM images of commercial 40 ppi ceramic foam (a) 70x (b) 300x (c) 2900x (d) 12240x

Schematic of Plexiglas Setup

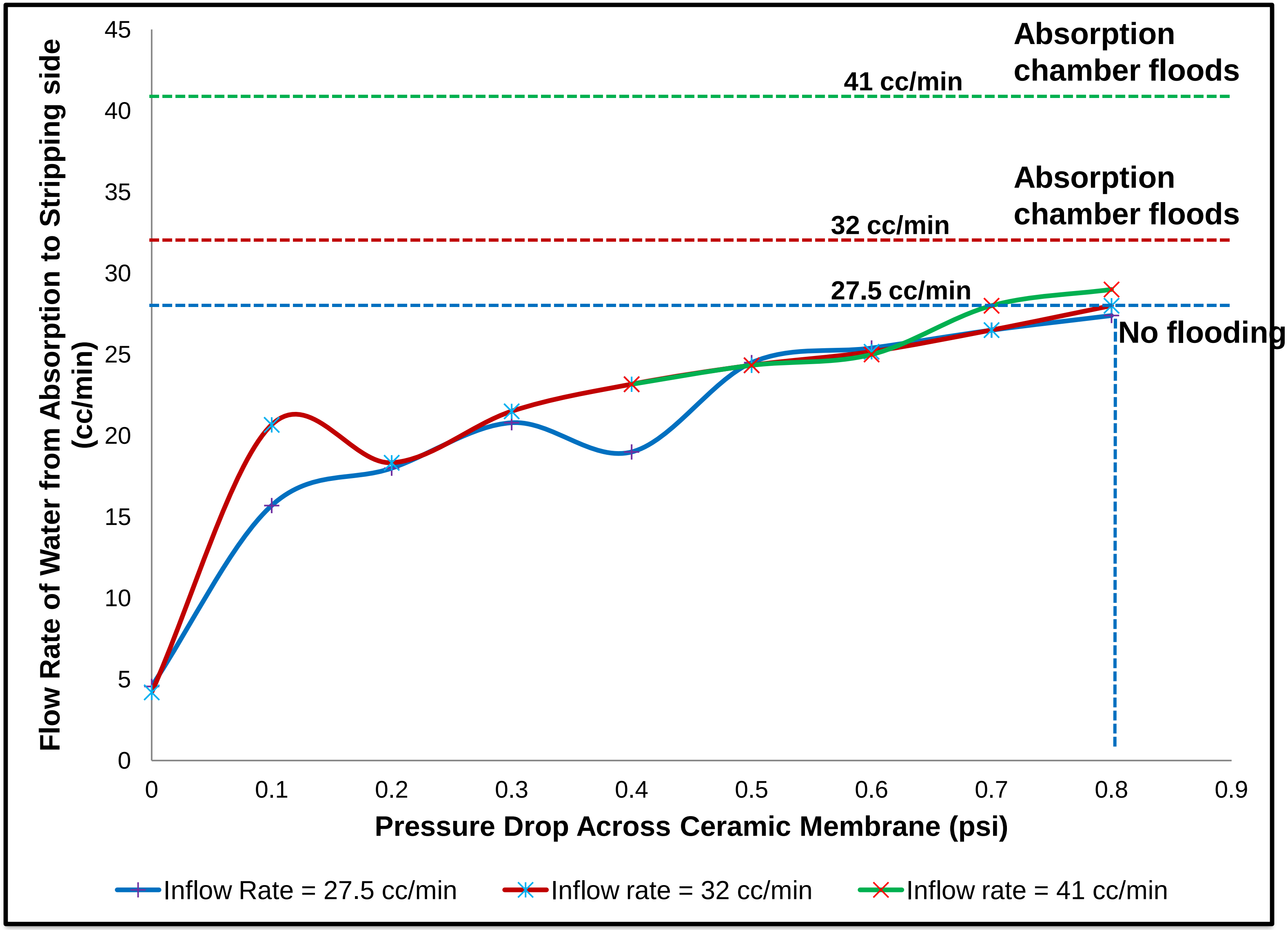


Plexiglas Experimental Prototype



2^{nd} Generation Plexiglas prototype for flow experiments

Result of Flow Experiments



Amine Absorbents
Comparison

Monoethanolamine (MEA)

Advantage
- Primary amine with very high reaction rate with CO_2
- Low amine circulation rate
- Low molecular weight

Drawbacks
- High heat of reaction
- MEA concentrations above 30-35% (wt) are corrosive
- Highly corrosive at CO_2 loadings above 0.35-0.4
- Highly volatile

Diglycolamine (DGA)

Advantage
- High DGA concentrations around 50-70% (wt) can be used due to low volatility
- High reaction rate with CO_2
- Low amine circulation rate

Drawbacks
- High heat of reaction
- Highly corrosive at CO_2 loadings above 0.35-0.4

Diethanolamine (DEA)

Advantage
- Low volatility
- Low heat of reaction

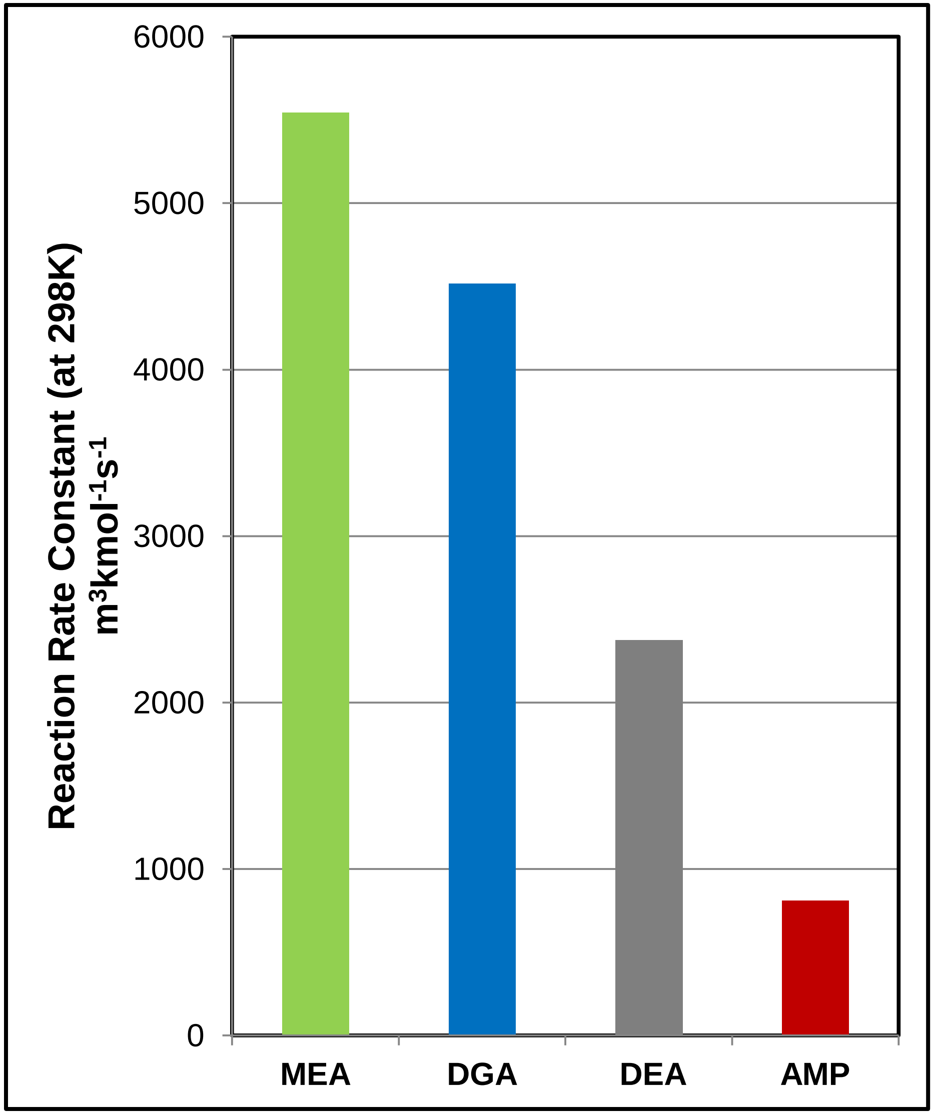
Drawbacks
- High amine circulation rate
- Secondary amine, low reaction rate
- DEA concentrations above 30-35% (wt) are corrosive
- Forms highly corrosive at CO_2 loadings above 0.35-0.4. Reacts irreversibly with O_2 in flue gas.

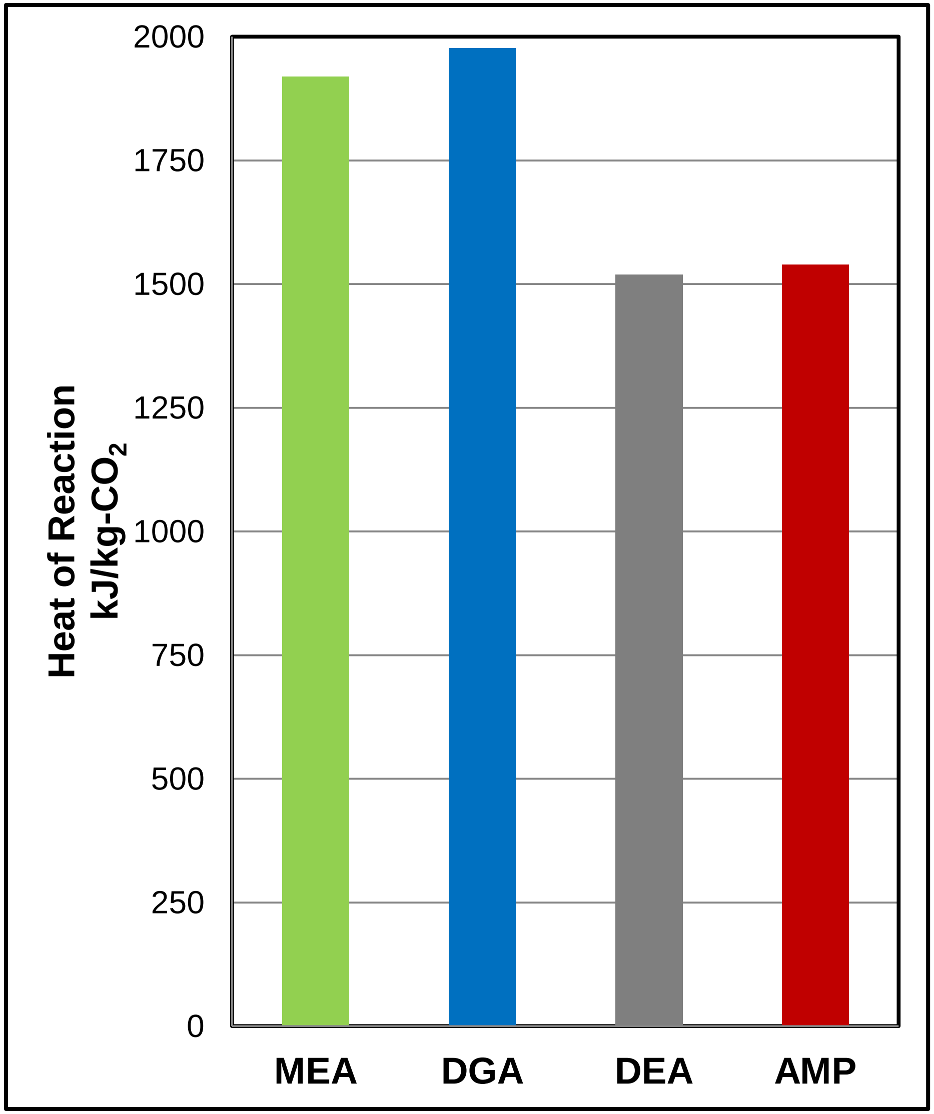
2-amino-2-methyl-1-propanol (AMP)

Advantage
- High theoretical CO2 loading capacity
- Low volatility and few corrosion problems
- Low heat of reaction

Drawbacks
- Very low reaction rate
- High amine circulation rate
- High steam consumption to heat amine solution in stripper

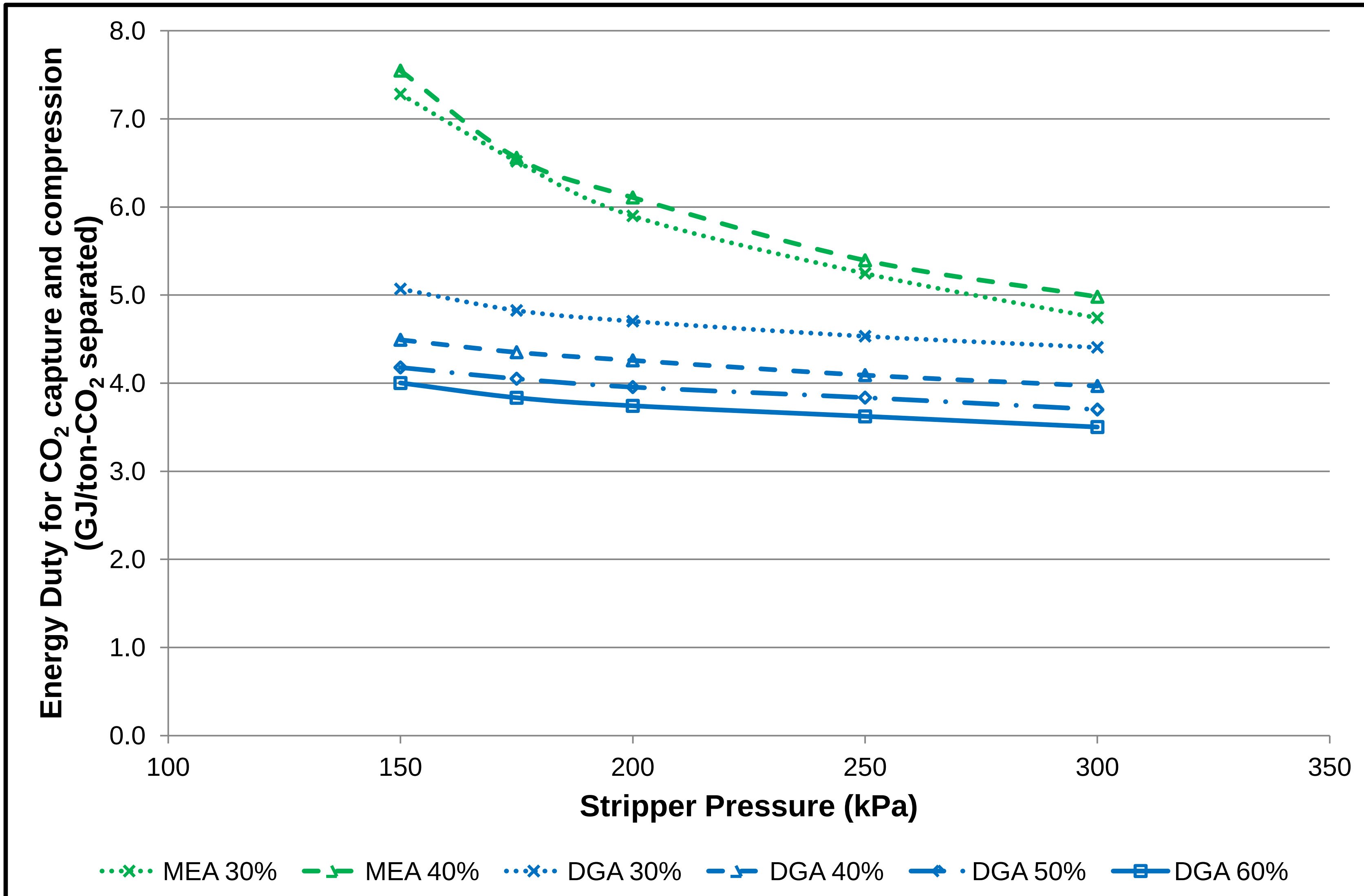
Reaction Rate Constant and Heat of Reaction





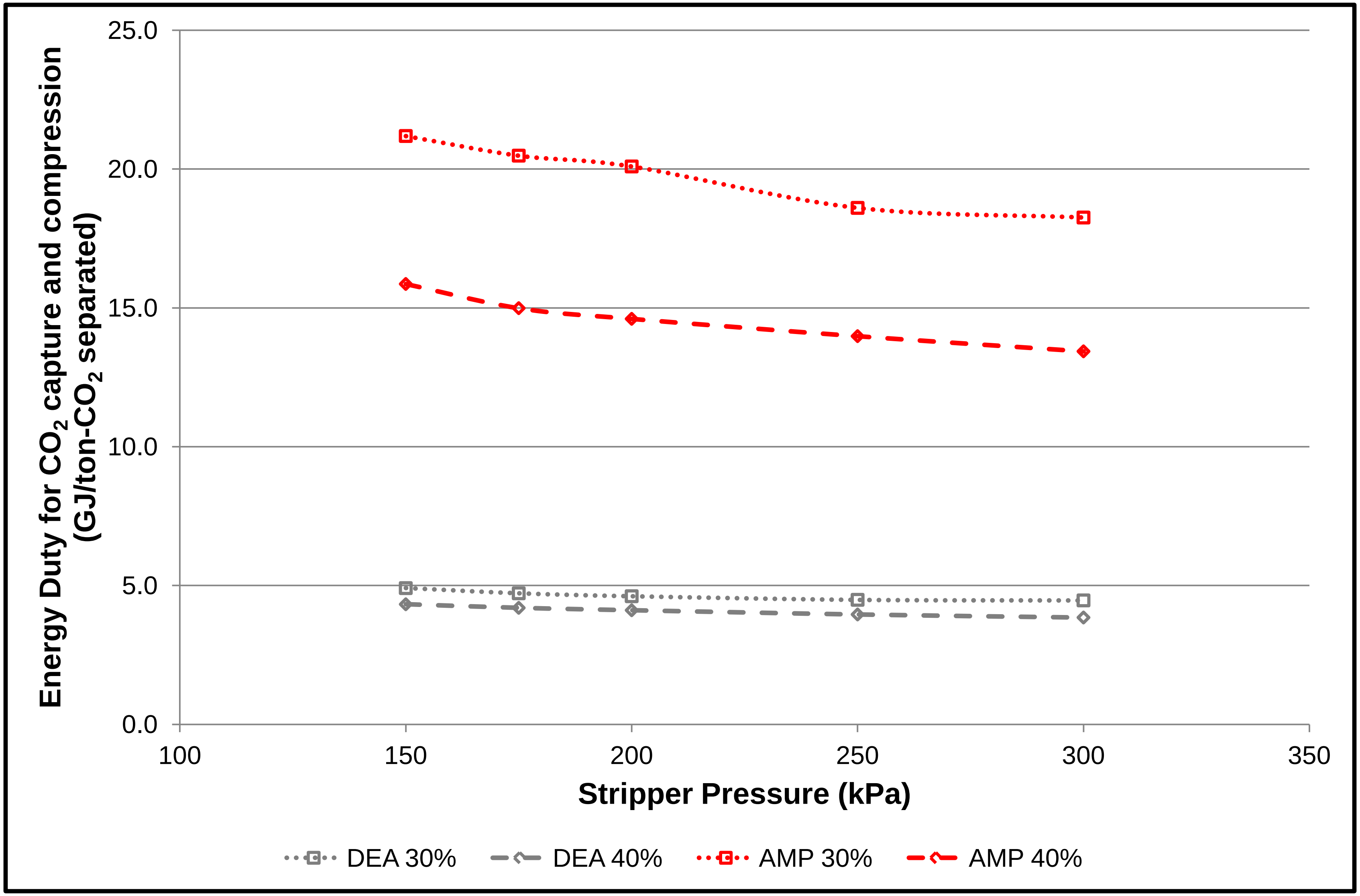
Energy Required for CO_2 capture

Effect of Stripper Pressure on MEA & DGA



Energy Required for CO_2 capture

Effect of Stripper Pressure on DEA & AMP



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Merits of Proposed Technology

- **Ceramic foam has a geometric surface area up to 10x that of conventional packing.**
- **Functionalized packing may increase the rate of CO_2 absorption into absorbent solution thus making it attractive to use slow reacting amines which also have low heat of regeneration.**
- **High geometric surface area packing, along with surface enhancement by functionalization can reduce the size of contacting towers.**
- **Integrated absorber – desorber arrangement reduces space requirements. This will be an important factor when retrofitting existing coal-fired power plant with CO_2 capture technology.**
- **Waste heat usage for absorbent regeneration can significantly reduce parasitic duty for power plant and thus, limit the increase in cost of electricity.**
- **Operating the desorber at lower temperatures decreases amine losses and equipment corrosion problems.**

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Project Tasks

1. Project Initiation – Technical and Economic Feasibility Study
   - At project initiation, a technical and economic feasibility study will be performed on this project to determine the possibilities of scaling up this process to pilot scale and beyond.
   - As a part of the feasibility study, an environmental risk assessment will also be performed to evaluate the potential environmental impacts of the proposed technology.
2. Design of stainless steel prototype
   - A stainless steel prototype will be designed and fabricated for demonstrating absorption and stripping of CO_2 in the combined absorber/desorber arrangement. In addition, absorbent regeneration will be carried out under vacuum.
3. Demonstrate absorption and stripping using stainless steel prototype
   - Once the stainless steel prototype is designed and fabricated, the complete CO_2 capture process will be implemented and demonstrated
   - Various factors affect CO2 absorption and desorption. Some of these are (i) Absorbent and gas flow-rate (ii) Macro-pore sizing in ceramic foam (iii) Vacuum on stripping side
4. Heat and Mass Transfer Studies
   - Once CO_2 absorption and desorption is demonstrated; we will conduct studies to measure the heat and mass transfer coefficients for ceramic foam.
   - Several factors affect the heat and mass transfer coefficient. Some of these are (i) Temperature (ii) Pressure (iii) Gas superficial velocity (iv) Gas and liquid physical properties

Project Tasks

5. Substrate functionalization

- Polyamine and polycarboxylate functionalization on absorption and desorption side substrate
- Basic and acidic functionalities influence local pH conditions and increase forward and reverse reactions between amine and CO_2 respectively
- Effectiveness of substrate functionalization will be evaluated by measuring changes in the mass transfer coefficients.

6. Process modeling

- Both horizontal and vertical mass and heat transport are significant.
- Develop a 2-D model to capture the influence of reaction kinetics, gas-liquid mass and heat transfer properties, operating pressure and temperature.

7. Sensitivity analysis and process optimization

- Large number of degrees of freedom like properties of ceramic foam and porous slab, operating pressure and temperature, gas and liquid flow rate, choice of absorbent
- Overall process optimization to reduce the energy requirement and costs

8. Project Completion – Feasibility and Economics Analysis

- The Feasibility and Economics analysis performed at project initiation will be updated based on information generated as a part of this project.
- This feasibility and economic analysis will indicate the possibility of scaling up the project to a pilot demonstration.

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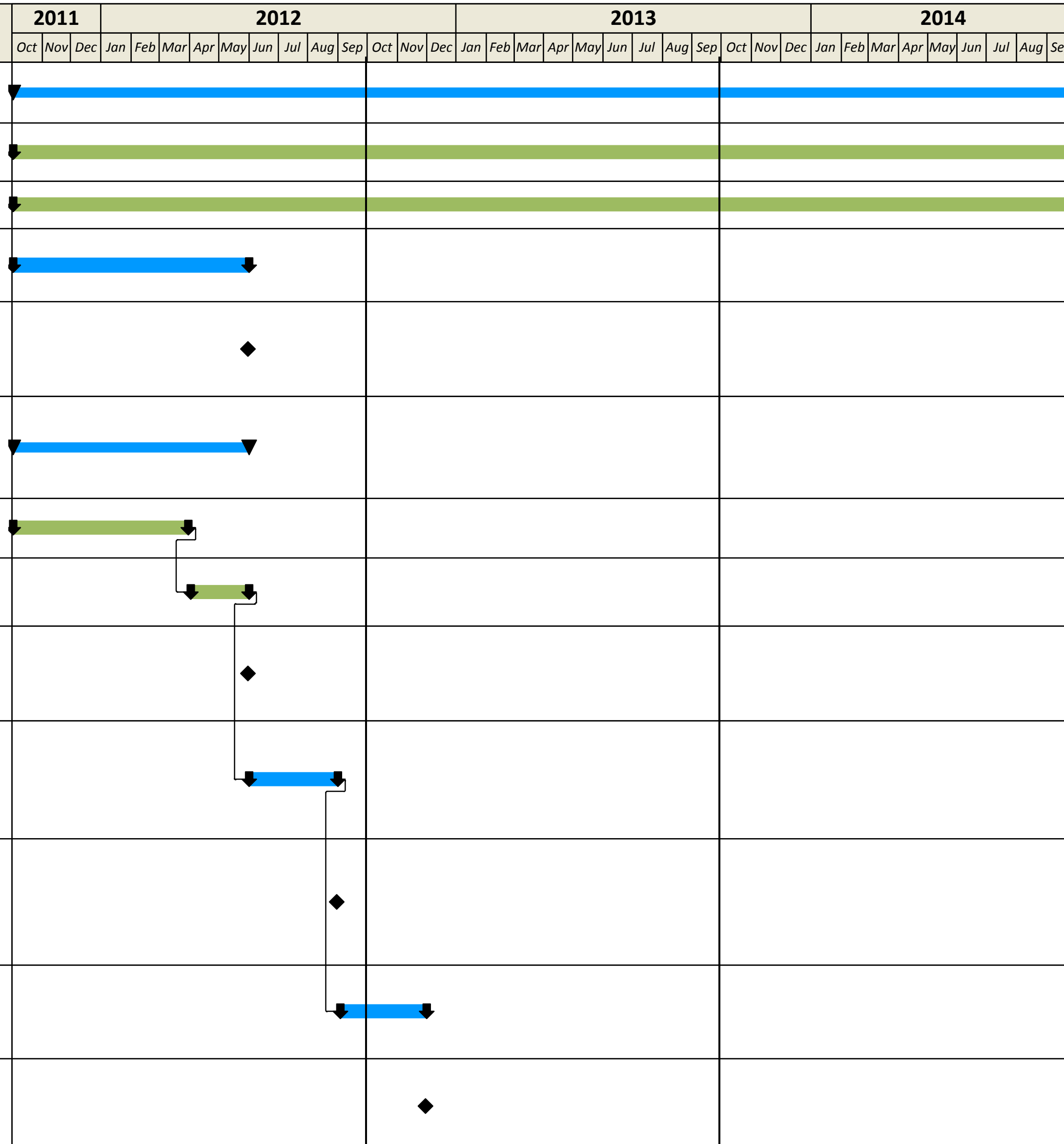
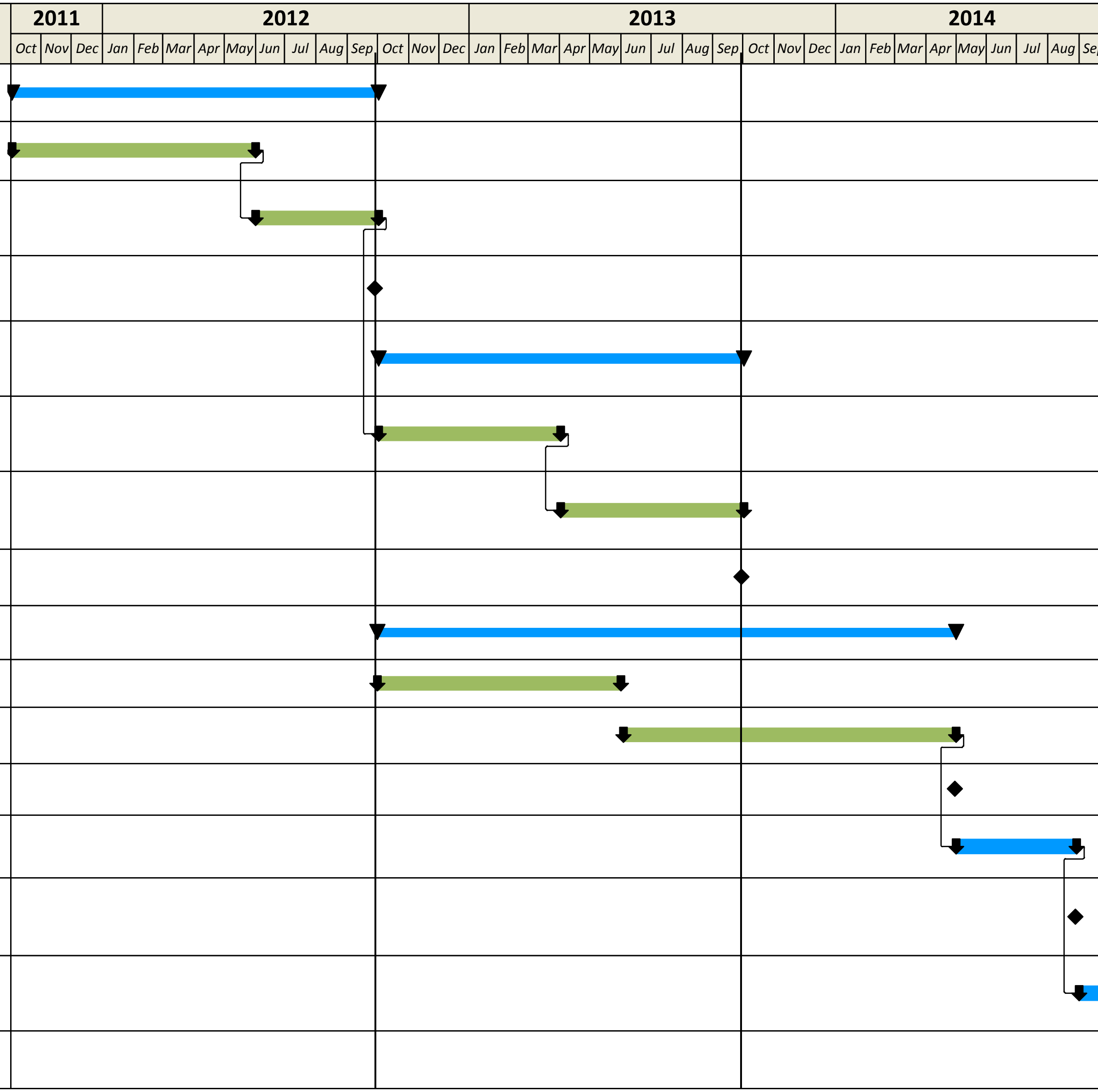
Detailed Project Schedule -I

ID	Task Name
1	1: Project Management Planning
2	1.1: Project Management and Planning
3	1.2: Briefings and Reports
4	2: Project Initiation: Technical and Economic Feasibility Study
5	Milestone: Submission of Project Initiation: Technical and Economic Feasibility Study
6	3: Develop stainless steel prototype for heat and mass transfer studies
7	3.1: Design and Fabricate stainless steel prototype
8	3.2: Setup of stainless steel prototype
9	Milestone: Assembled stainless-steel experimental prototype
10	4: Demonstration of CO_2 capture process (with Unfunctionalized ceramic foam)
11	Milestone: CO_2 capture process demonstration (with Unfunctionalized ceramic foam)
12	5: Mass and heat transfer studies on unfunctionalized ceramic foam
13	Milestone: Completion of mass and heat transfer studies on unfunctionalized ceramic foam



Detailed Project Schedule - II

ID	Task Name
1	6: Functionalization of Ceramic foam
2	6.1: Preliminary experiments to functionalize ceramic foam
3	6.2: Preparation of functionalized ceramic foam for mass transfer studies
4	Milestone: Completion of functionalization of ceramic foam
5	7: Characterization of functionalized ceramic foam
6	7.1: Quantifying amount of acidic or basic moieties on ceramic foam
7	7.2: Conduct mass transfer studies on functionalized ceramic foam
8	Milestone: Characterization of Functionalized Ceramic Foam
9	8: Process Modeling and Simulation
10	8.1: Development of 1-D flow model
11	8.2: Development of 2-D flow model
12	Milestone: Completion of Process Modeling and Simulation
13	9: Project Completion: Technical and Economic Feasibility Study
14	Milestone: Completion of Project Completion Technical and Economic Feasibility Study
15	10: Technology EH&S Risk Assessment
16	Milestone: Completion of Technology EH&S Risk Assessment



Questions