RICE

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

DOE Project # DE0007531

Project Manager: Ms. Elaine Everitt

Dr. George Hirasaki

A J. Hartsook Chair Professor in Chemical Engineering, Rice University

NETL CO_2 Capture Technology Meeting

July 9th, 2012

Outline

- About Rice University
- Project Team
- Project Overview
- Combined Pressure and Temperature Contrast and Surface-enhanced Separation of Carbon-dioxide
- Supporting experimental and simulation results
- Merits of proposed technology
- Project Objectives
- Project Budget

Rice University

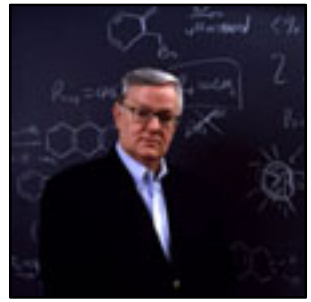
- Located in Houston, TX
- 295-acre, heavily wooded campus
- Ranked 17th in the US and in the top 100 in the world
- 650 full-time faculty, 3500 undergraduates and 2300 graduate students
- Chemical and Biomolecular Engineering program, 13 faculty members, 70 graduate students
- Chemistry program, 38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

Project Team

Project Director

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

Co-Project Investigator



Edward Billups
Professor in Chemistry

Co-Project Investigator

Michael Wong
Professor in Chemical & Biomolecular Engineering & Chemistry

Co-Project Investigator

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

Graduate Student

Sumedh Warudkar
PhD Candidate

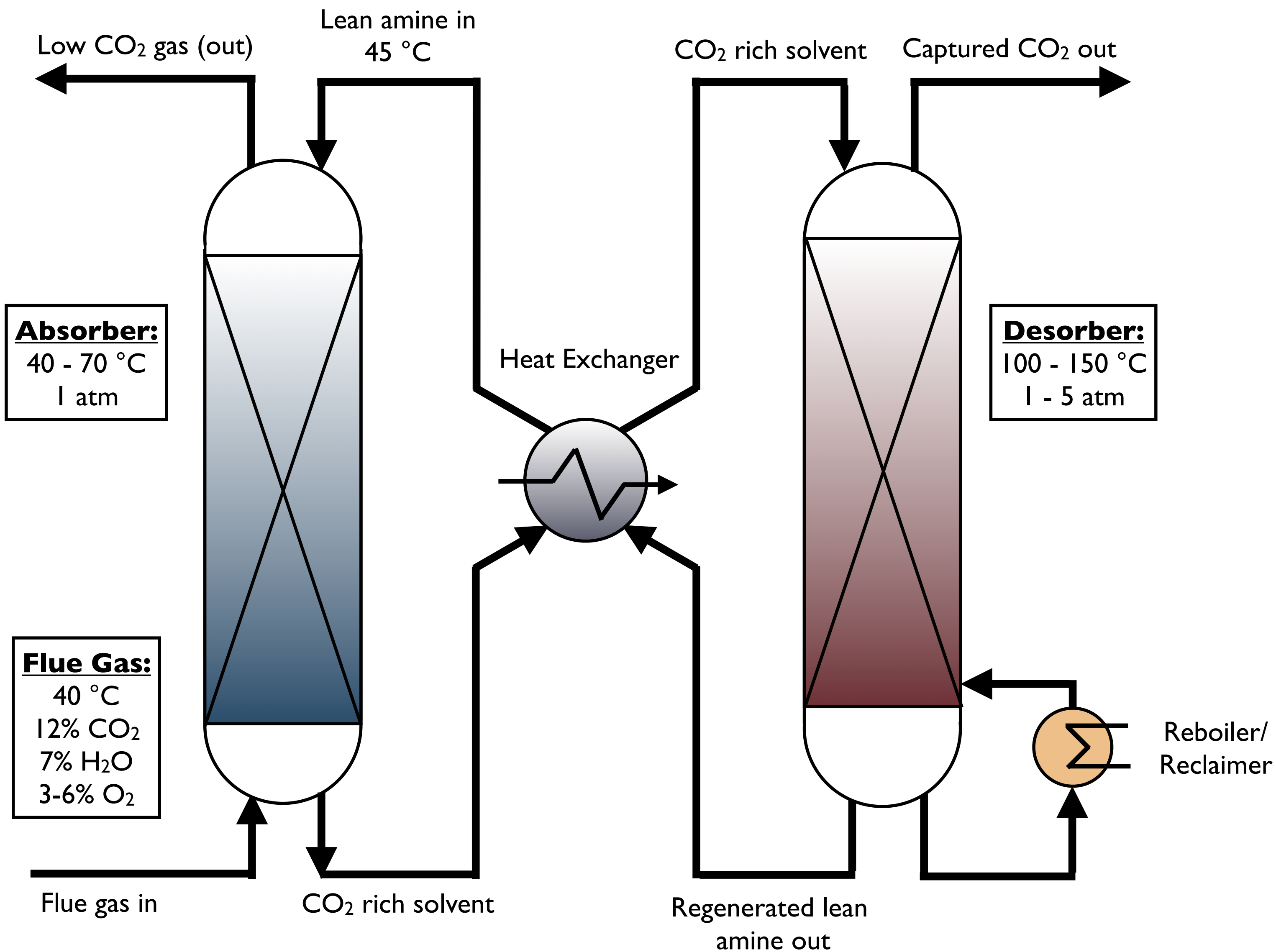
Postdoctoral Associate

Jerimiah Forsythe
PhD, Chemistry (LSU, 2011)

Project Overview

- Project funding under DOE agreement – DE-FE0007531
- Total project cost - $960,811 over three years with 20% cost-share agreement
- Contract awarded executed October 2011
- Project objective - Performance of bench-scale R&D to demonstrate and develop Rice University's "*combined pressure and temperature contrast and surface-enhanced separation of CO_2 for post-combustion carbon capture to meet DOE's goal of at least 90% CO_2 removal at no more than 35% increase in the cost of electricity*"

Conventional Amine Absorption
Adapted for Carbon Capture

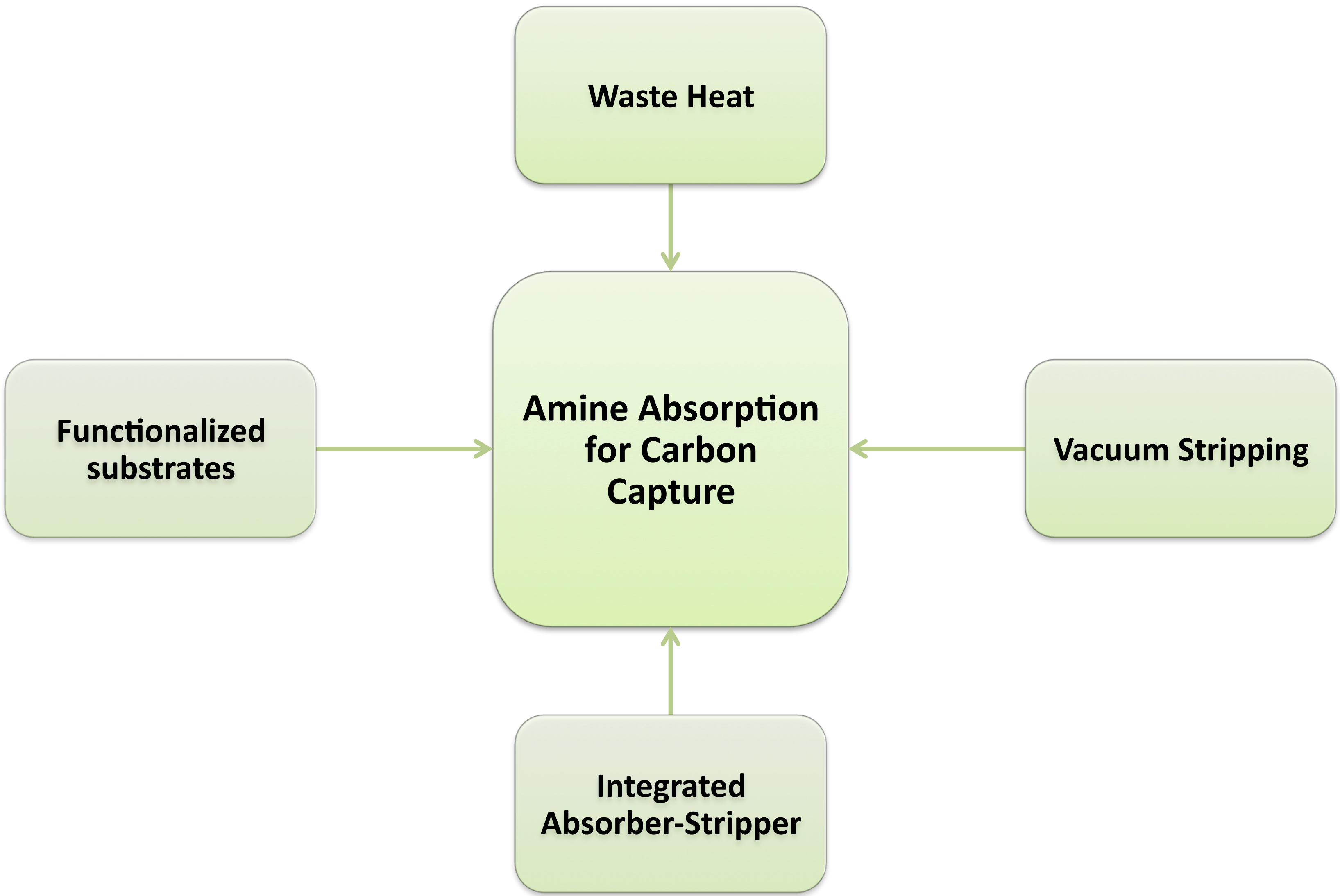


Drawbacks of Conventional Amine Absorption

- Amine absorption was developed and 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

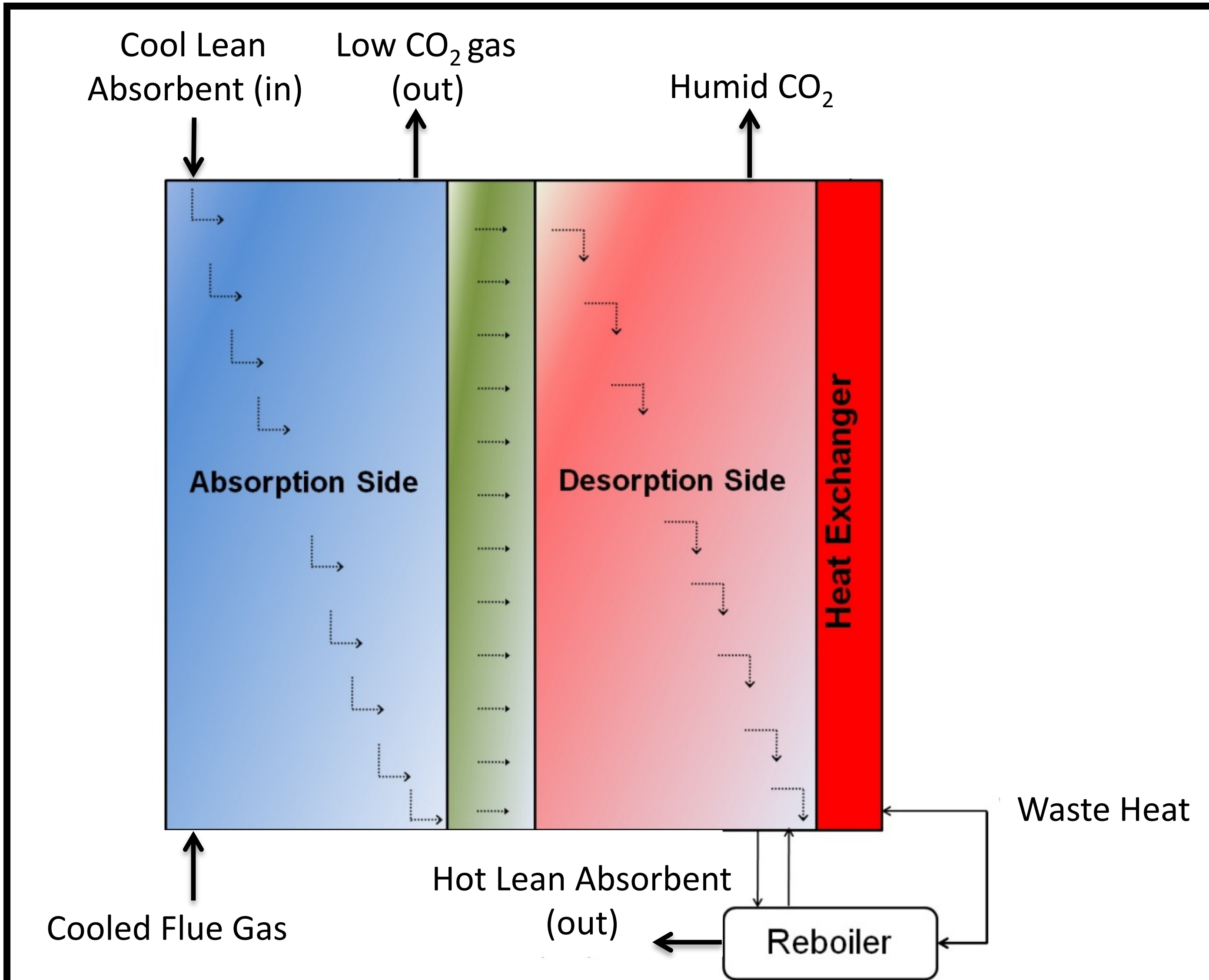
Our Approach

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

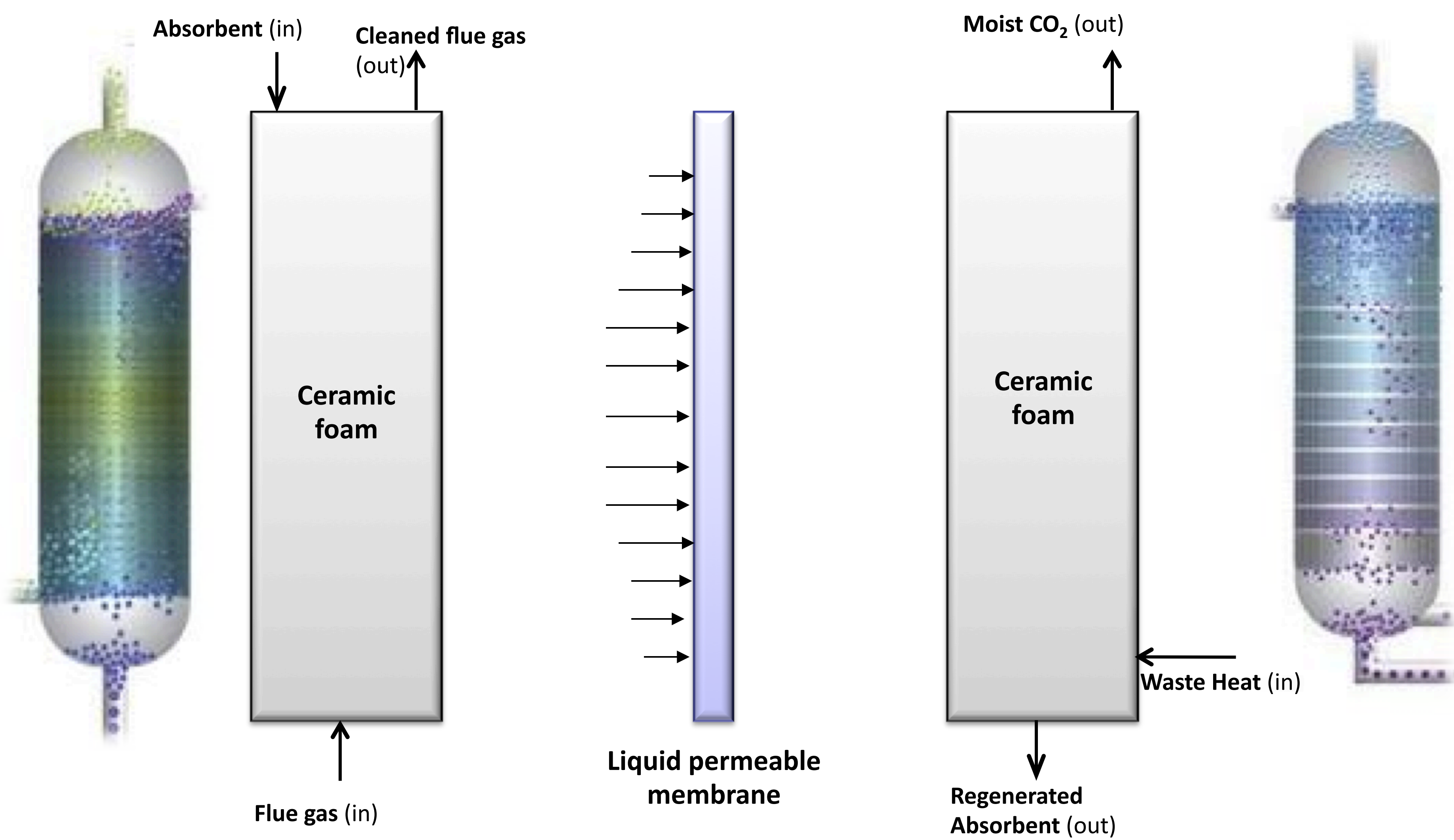


Process Schematic

Integrated Absorber-Stripper



Process Description

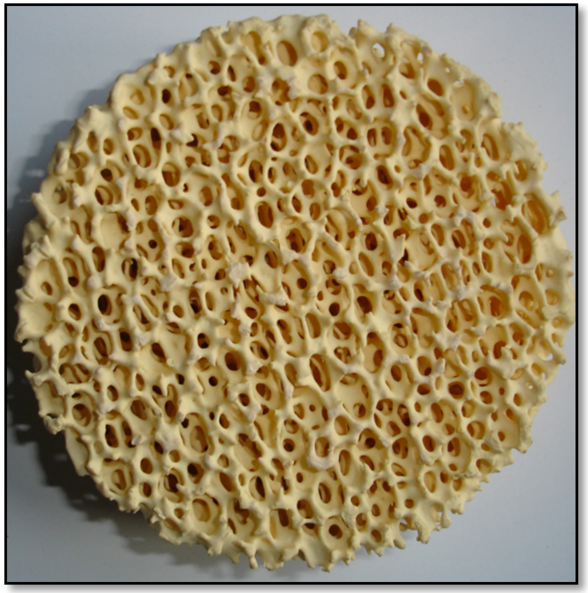


Gas-liquid contactor – Ceramic Foam

Ceramic Foam

- Low bulk density
- Very high macro-porosity (80%-90%)
- Very high geometric surface area (upto 4756 m^2/m^3 (solid))
- Regulated pore-size
- Low pressure drop
- High structural uniformity
- Ease of reproducibility of structure

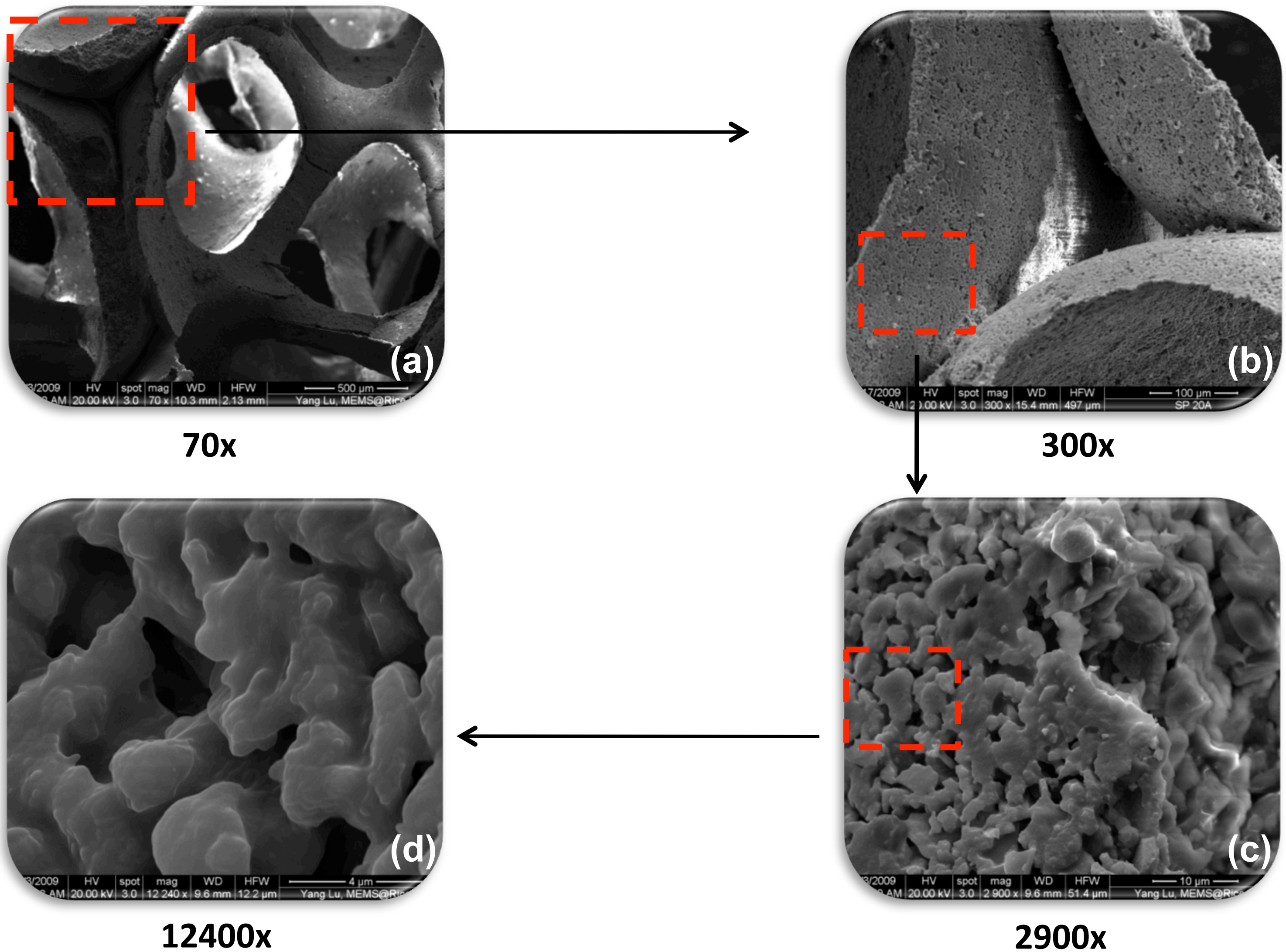
Structure	S (m^2/m^3)	Porosity (ε)
5 mm packing spheres	600	0.392
Raschig ceramic rings, 25 mm	200[1]	0.646
Corrugated metal structured packing (AceChemPack) – 500 x/y	500[3]	0.93
30-PPI -Al_2O_3 foam, no washcoat	3360[2]	0.83



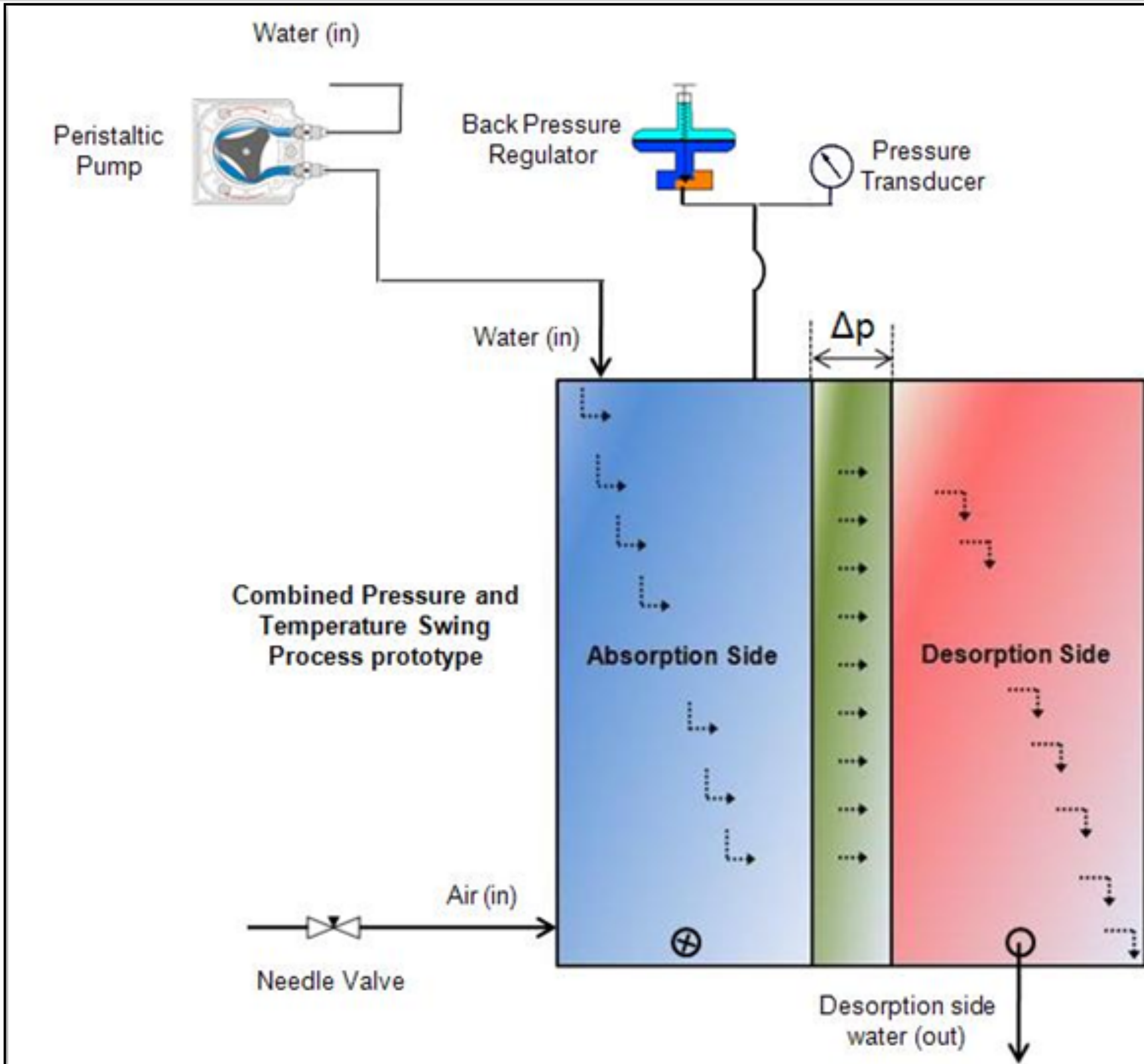
Commercial Sample of Ceramic foam

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

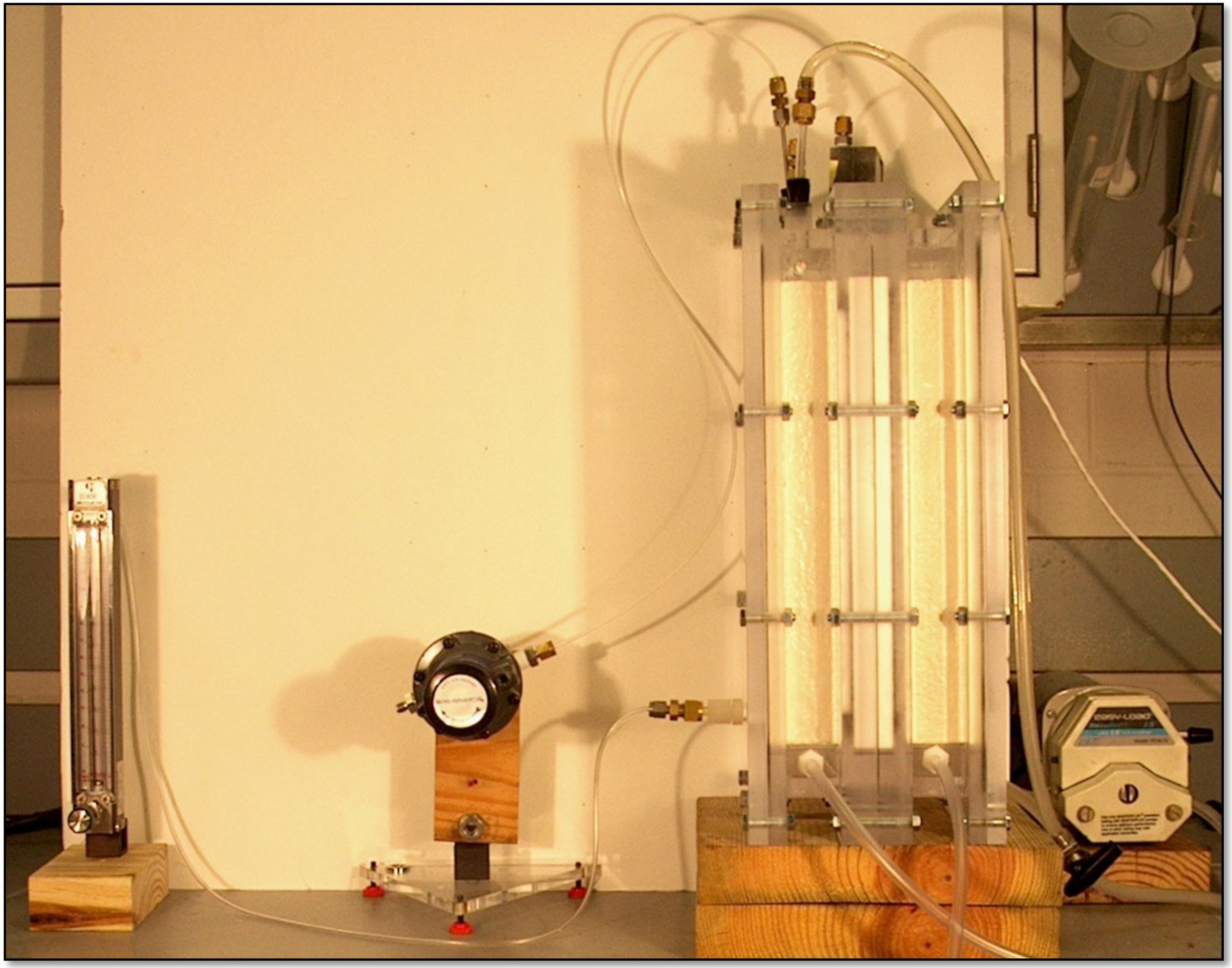
Ceramic Foam – SEM Micrographs



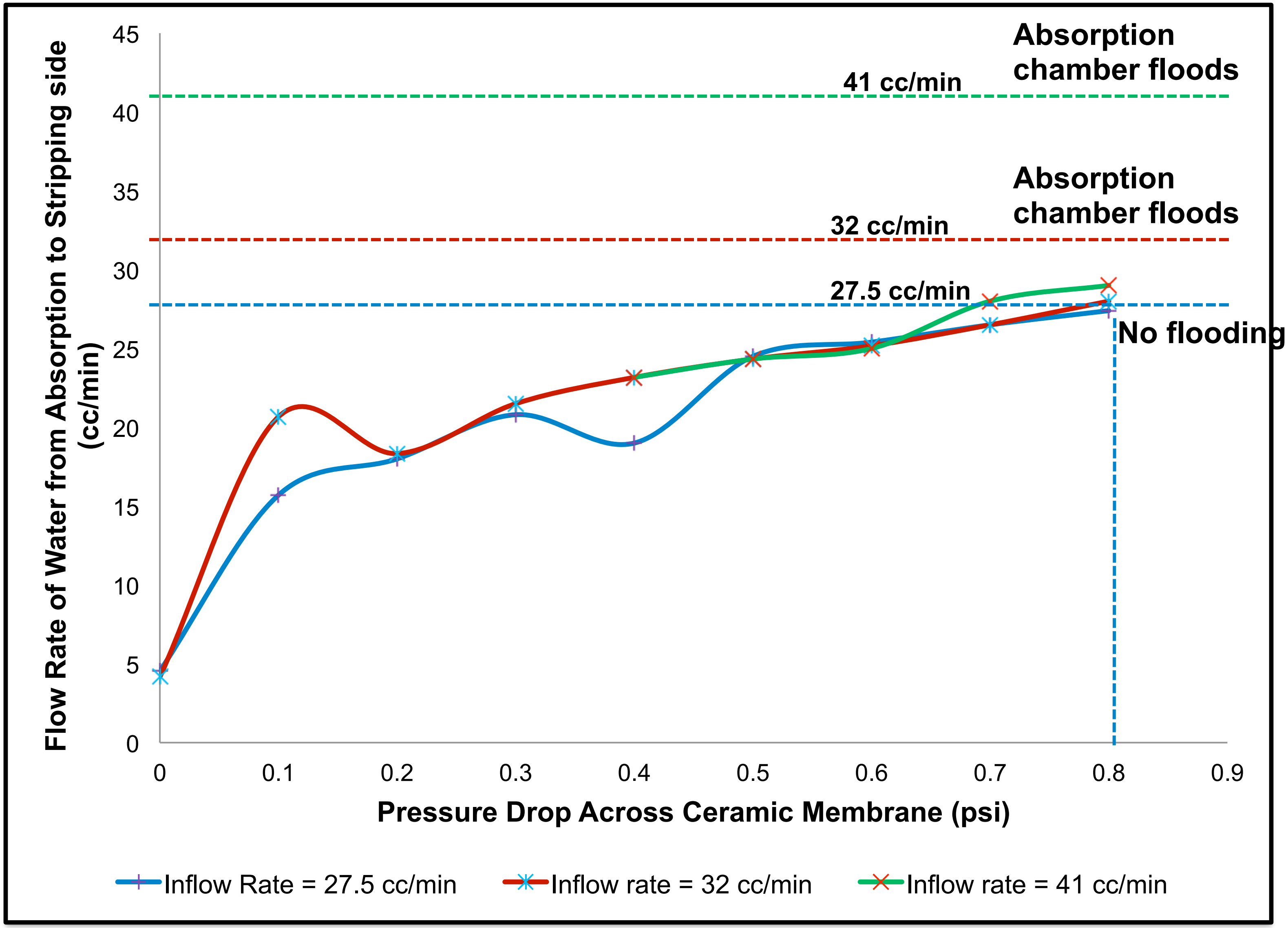
Schematic of Plexiglas Setup



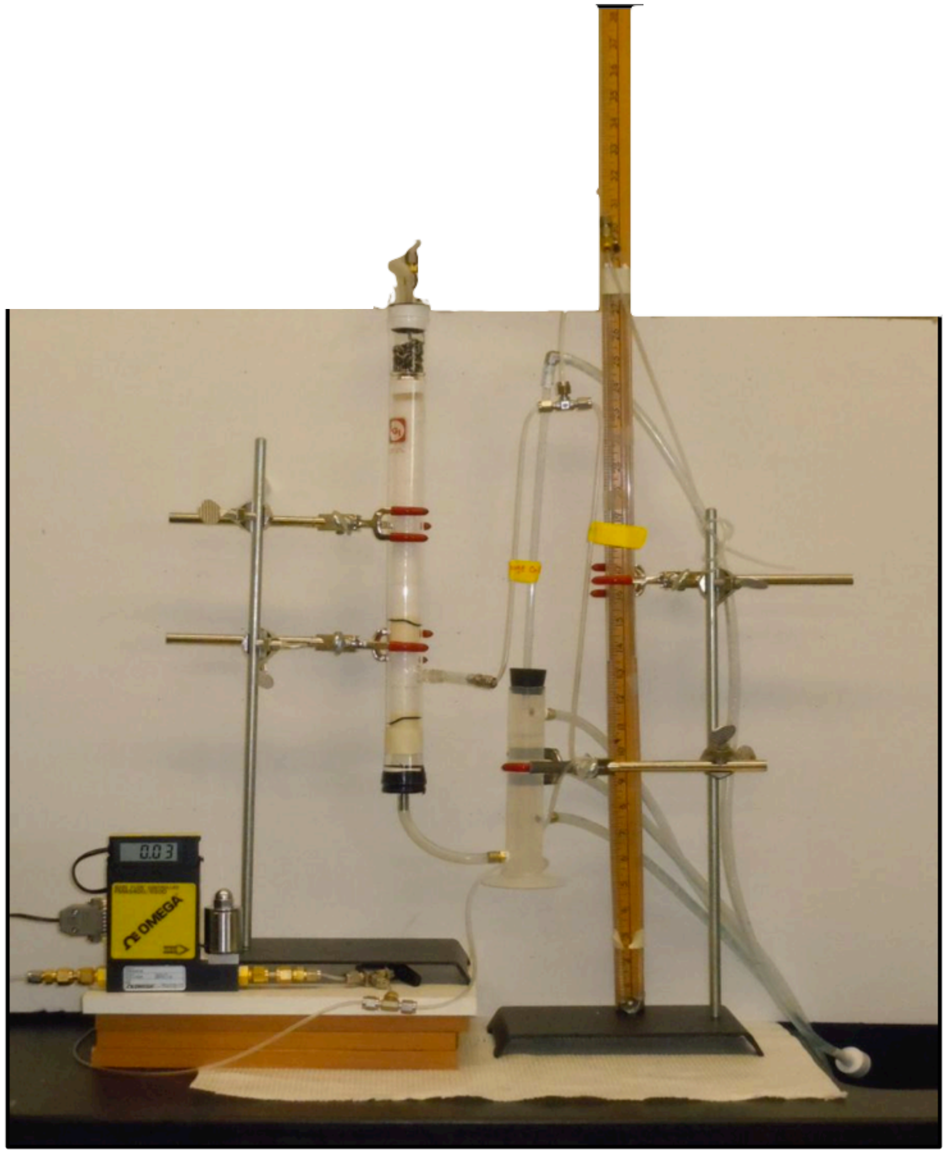
Plexiglas Experimental Prototype



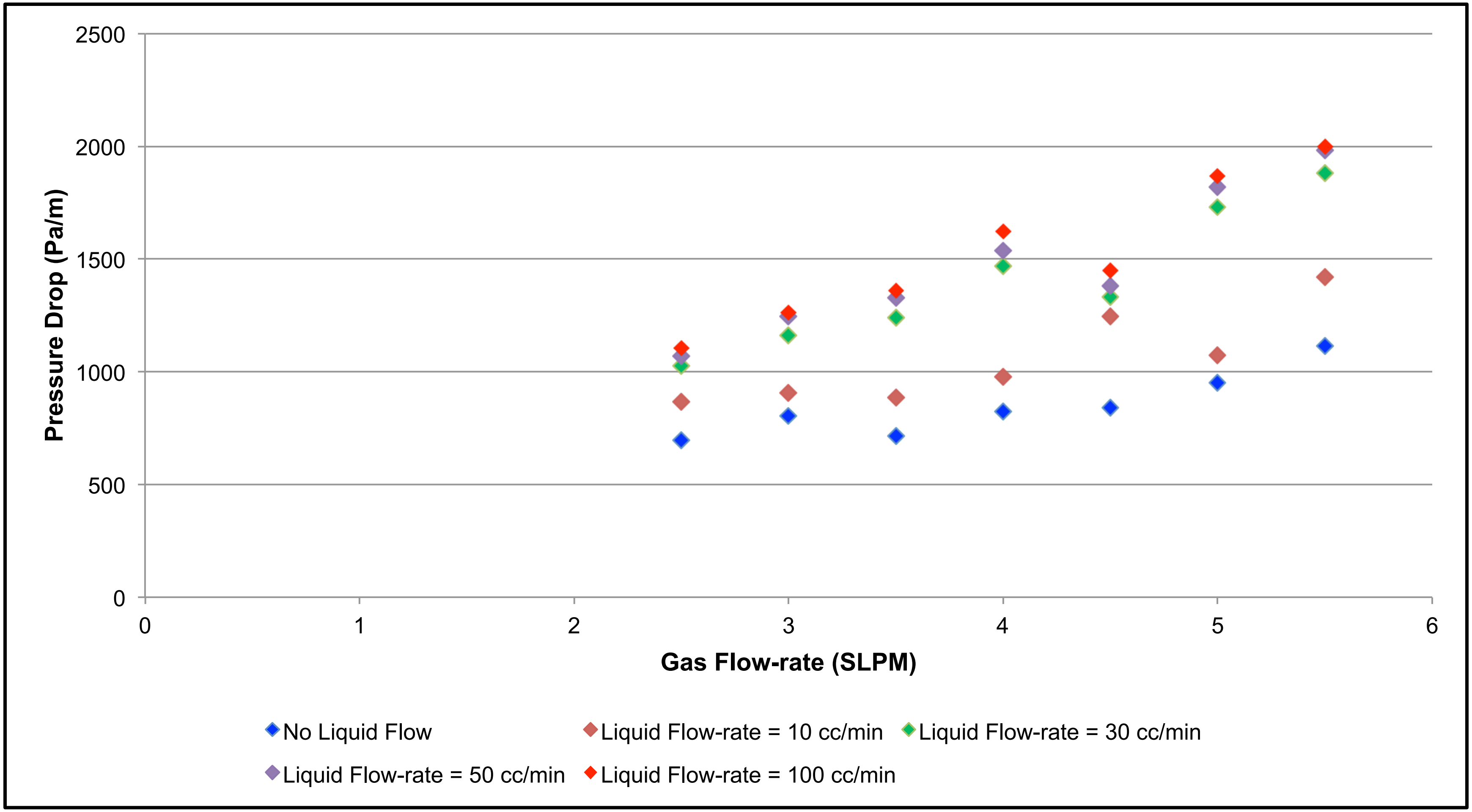
Result of Flow Experiments
A Proof-of-concept



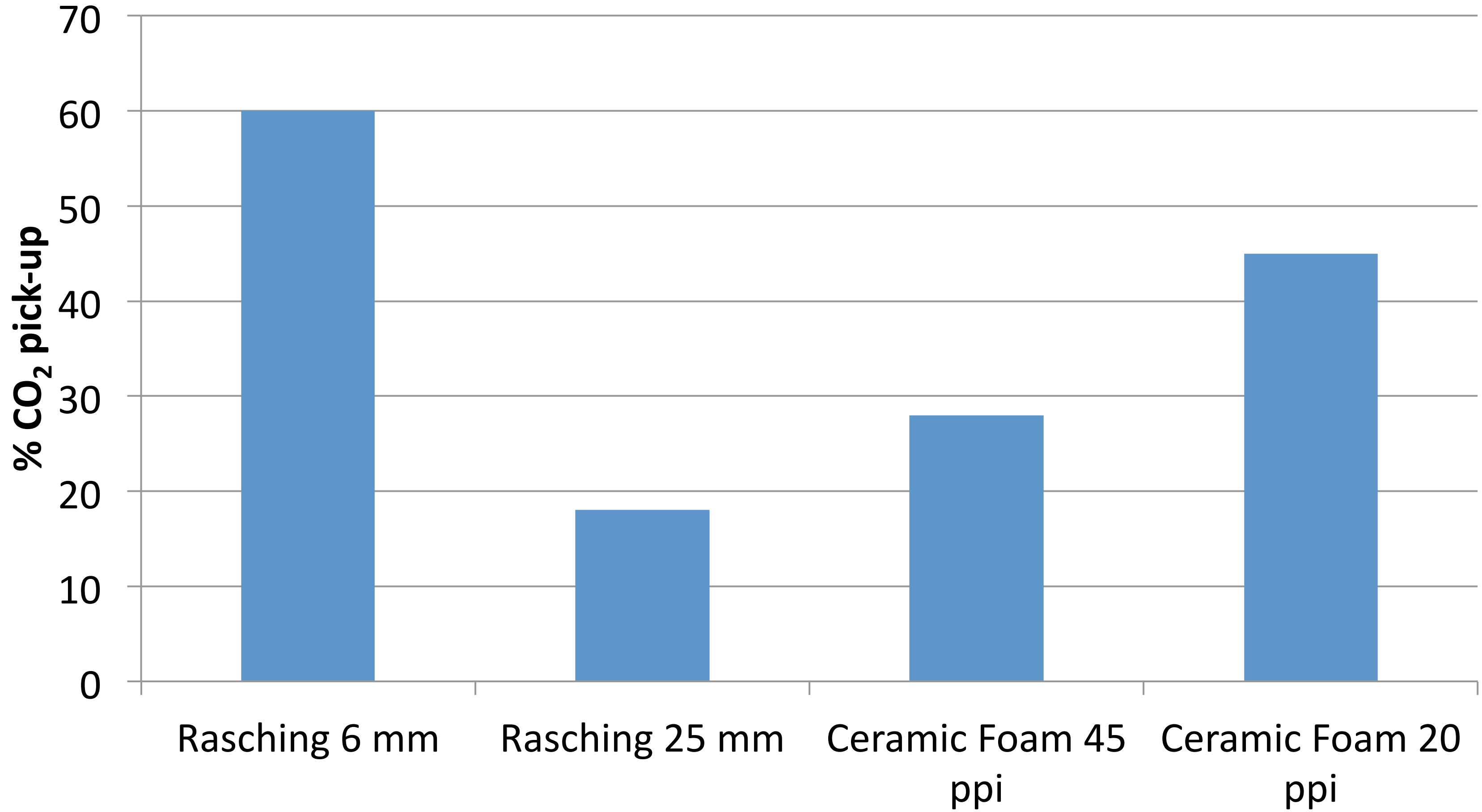
1-D Column for Mass Transfer Evaluation



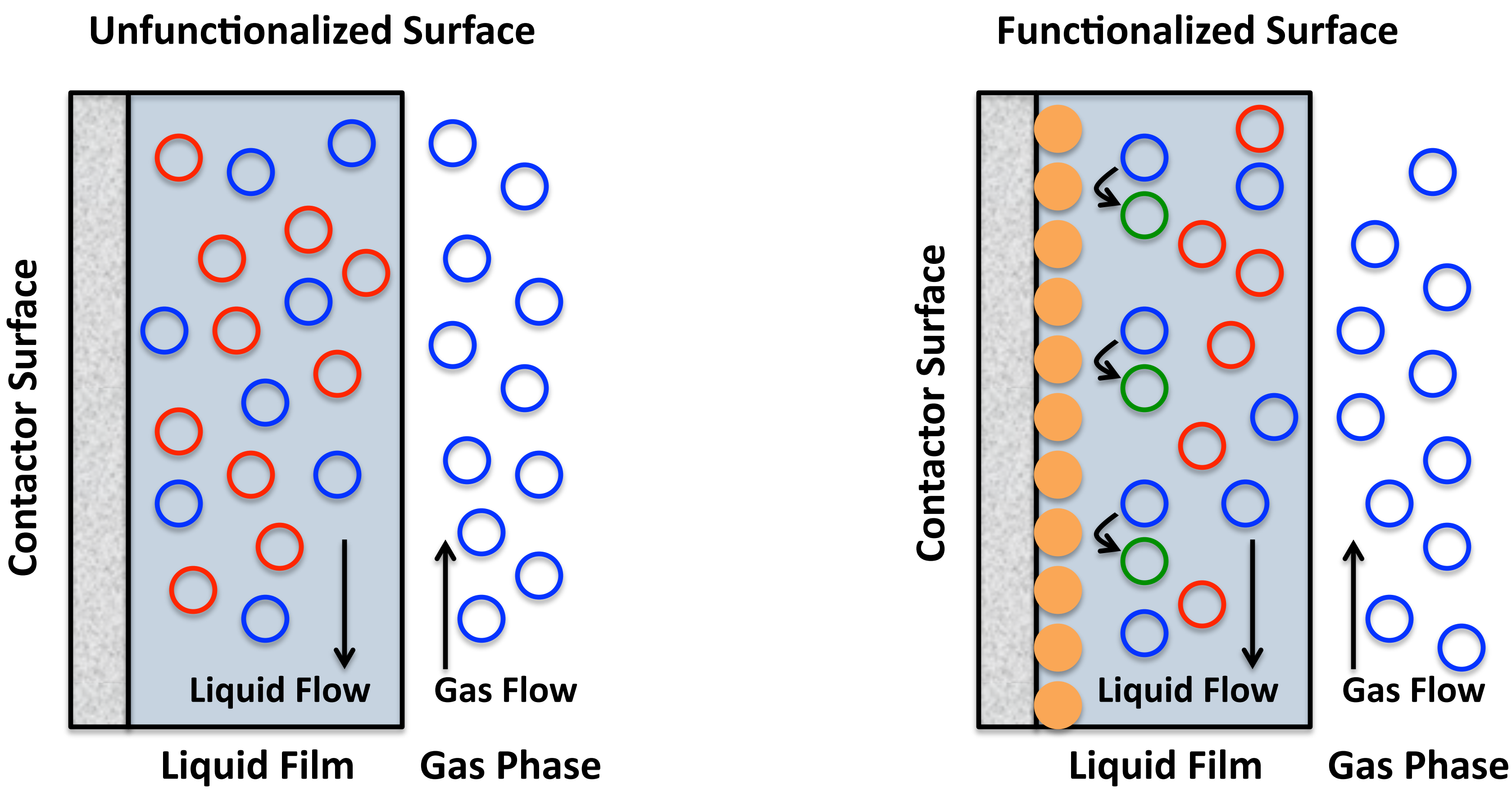
Pressure drop in 30-ppi ceramic foam at varying gas and liquid flow-rates



Mass transfer characteristics of various tower packing materials



Substrate Functionalization



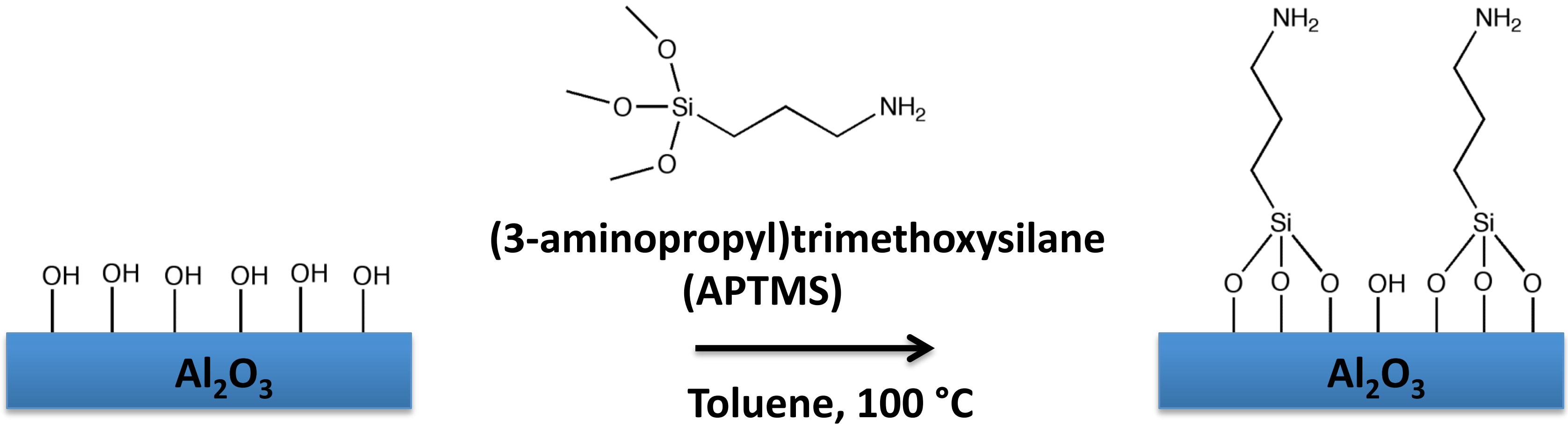
CO_2 (unreacted)

CO_2 + amine intermediate (in solution)

Surface generated CO_2 + amine (reacted, intermediate)

Immobilized basic groups on surface

Substrate Functionalization
Silanization Chemistry Approach



Surface Modifier	Grafting Density (ρ, molecules nm^{-2}) S(BET) = 250 $m^2\ g^{-1}$	Grafting Density (ρ , molecules nm^{-2}) S(BET) = 155 $m^2\ g^{-1}$
APTMS	1.00	1.60
APTMS (Post-Bubbler #1)	0.90	1.50
APTMS (Post-Bubbler #2)	0.80	1.35

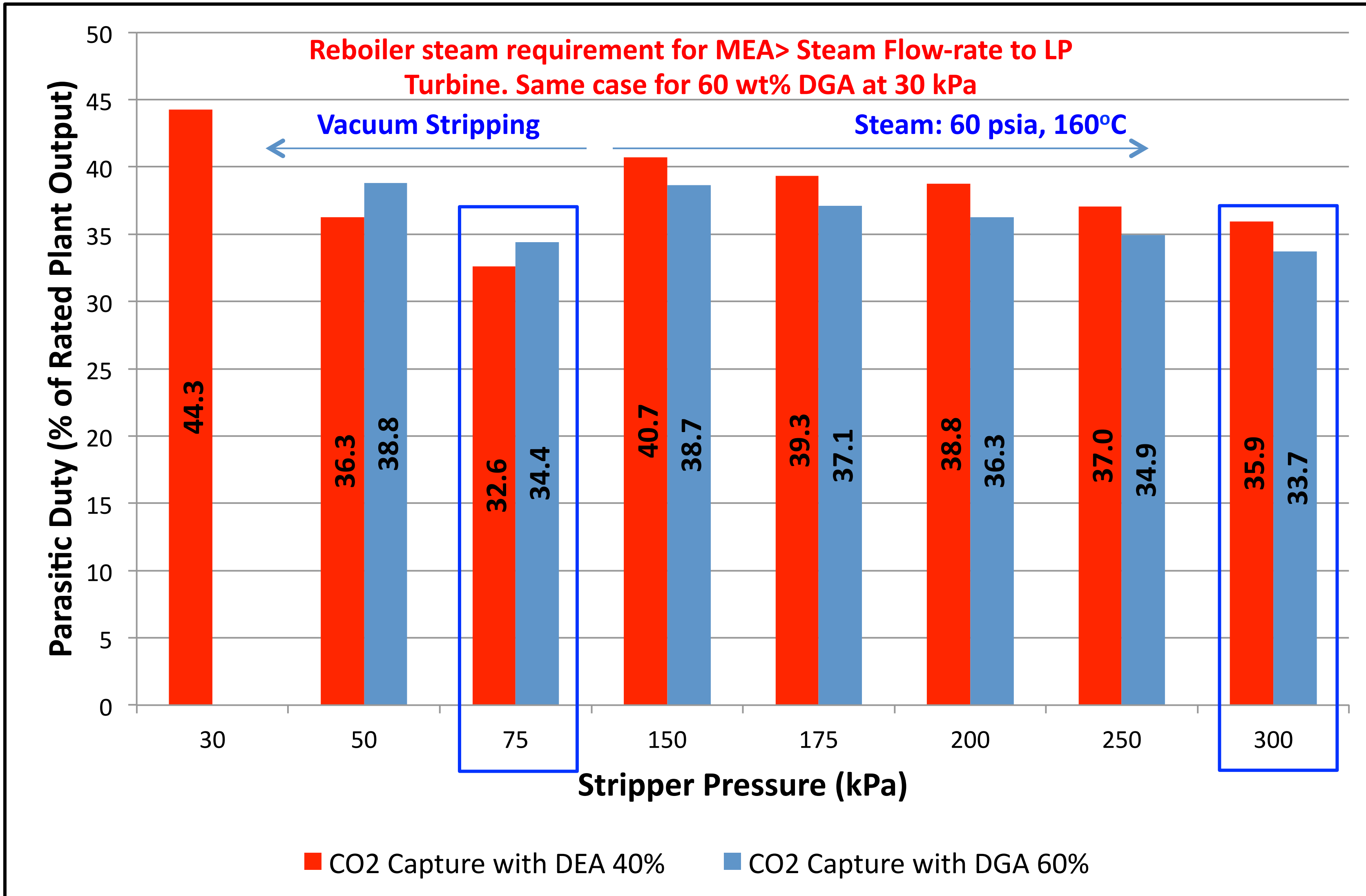
100 to 325 mesh α-alumina substrate
Grafting density determined by thermogravimetric analysis (TGA)
10 wt% diglycolamine (DGA)/water with 1 hour contact time

Silane functionalization not stable in amine solutions

Other directions:
- Phosphonates
- Other organic linkages (e.g. carboxyl)
- Protecting polymer layer
- Other surface coating to increase bond strength

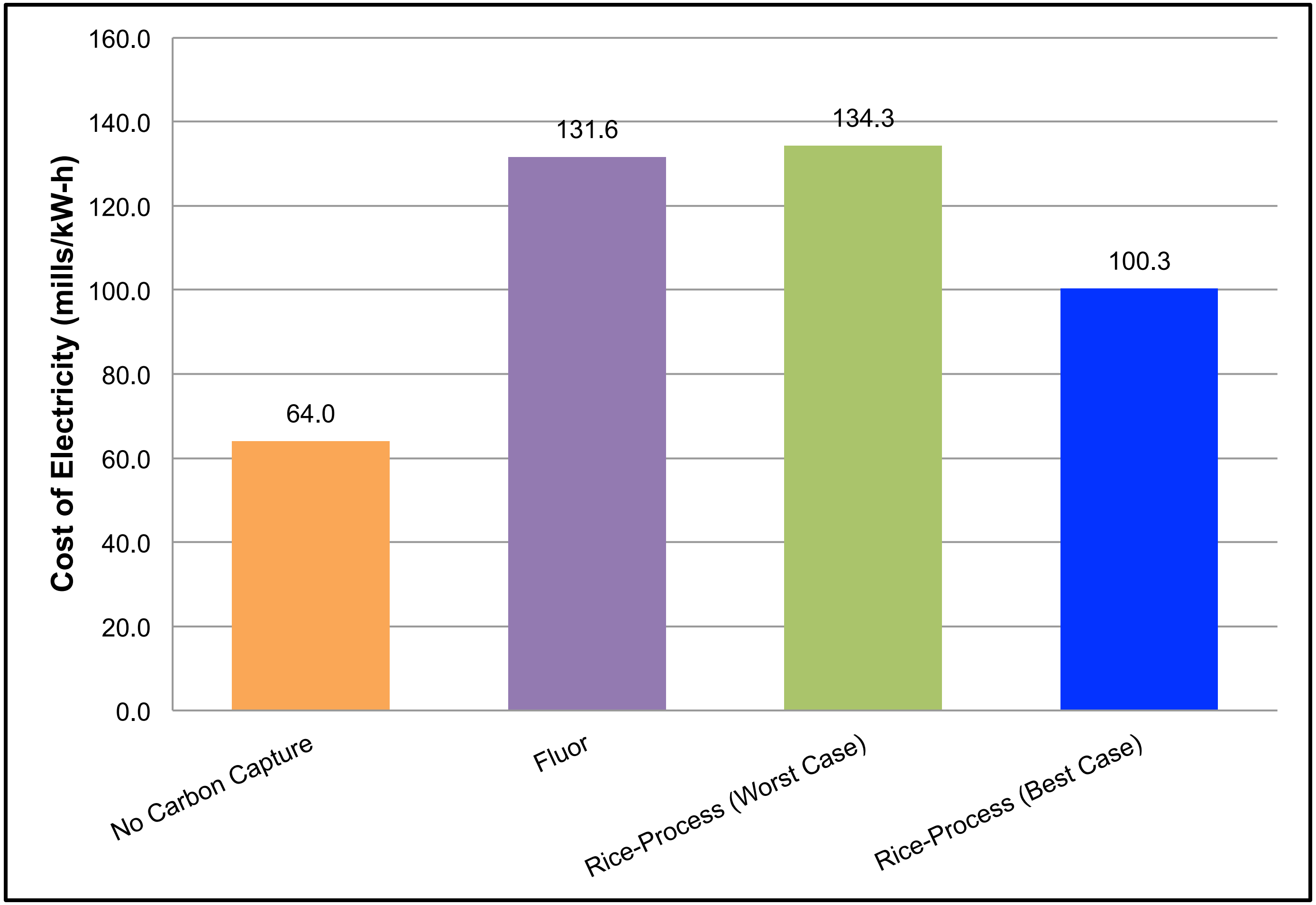
Parasitic Power Losses

Vacuum *vs*. Conventional stripping



Technical & Economic Feasibility

Comparison of cost of electricity for various processes



Merits of Proposed Technology

- Ceramic foam has a geometric surface area up to 10x that of conventional packing (e.g. Raschig rings).
- Functionalized packing can 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 height of tower packing.
- 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 significantly reduces 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.

Project Objectives

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. **Hydrodynamics and Mass Transfer Studies**
   - We will conduct studies to measure the hydrodynamic properties of the ceramic foam.
   - We will conduct studies to measure the mass transfer properties for ceramic foam as compared to a standard tower packing material like ceramic Raschig rings. ✓
3. **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.
4. **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

Project Objectives (Contd..)

5. **Substrate functionalization**
   - Amine 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 heat and 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.

Requested Personnel

Budget Period Personnel	Role	Budget Period 1 (10.01.11 – 09.30.12)	Budget Period 2 (10.01.12 – 09.30.13)	Budget Period 3 (10.01.12 – 09.30.13)
Prof. George Hirasaki	Project Director, Lead Investigator	✓ 1 month summer salary	✓ 1 month summer salary	✓ 1 month summer salary
Prof. Michael Wong	Co-Project Investigator	✓ 1 month summer salary	✓ 1 month summer salary	✓ 1 month summer salary
Prof. Kenneth Cox	Co-Project Investigator	✓ 1 month summer salary	✓ 1 month summer salary	✓ 1 month summer salary
Prof. Ed Billups	Co-Project Investigator	✓	✓	✓
Mr. Sumedh Warudkar	Graduate Student	✓ Graduate Student Salary	✓ Graduate Student Salary	
Dr. Jerimiah Forsythe	Postdoc (Substrate functionalization)	✓ Postdoctoral Salary	✓ Postdoctoral Salary	
TBD	Postdoc (Modeling)		✓ Postdoctoral Salary	✓ Postdoctoral Salary
TBD	Undergraduate researcher(s)	✓	✓	✓

Project Budget

Budget Period Object Class Category	Budget Period 1 (10.01.11 – 09.30.12)	Budget Period 2 (10.01.12 – 09.30.13)	Budget Period 3 (10.01.12 – 09.30.13)	Total
Personnel	$134,079	$180,738	$113,637	$428,454
Fringe Benefits	$28, 586	$40,953	$29,811	$99,350
Travel	$4,700	$4,700	$4100	$13,500
Equipment	$27,035	$0	$0	$27,035
Supplies	$25,000	$15,000	$15,000	$55,000
Contractual	$0	$0	$0	$0
Construction	$0	$0	$0	$0
Other	$11,600	$10,480	$600	$22,680
Total Direct Charges	$231,000	$251,871	$163,148	$646,019
Indirect Charges	$102,094	$127,045	$85,653	$314,792
Federal Share	$243,621	$327,568	$197,458	$768,647
Non-Federal Share	$89,473	$51,348	$51,343	$192,164
Total	$333,094	$378,916	$248,801	$960,811

Acknowledgements

Personnel

- Dr. Joe Powell, Chief Scientist at Shell Oil Company
- Dr. TS Ramakrishnan, Scientific Advisor at Schlumberger-Doll Research Center
- Hirasaki Group & Wong Group members

Funding Support

- Energy and Environmental Systems Institute (EESI) at Rice University
- Rice Consortium on Processes in Porous Media
- Schlumberger
- US DOE DE0007531

Questions