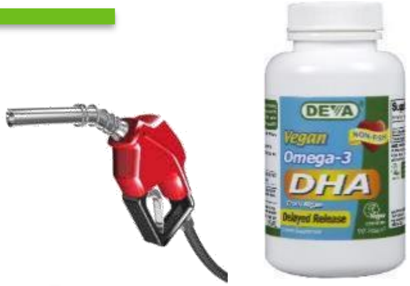
ASU LightWorks
ARIZONA STATE UNIVERSITY

Atmospheric CO_2 Capture and Membrane Delivery

CO_2

Large-scale algae cultivation (courtesy of Joule®)



Bruce Rittmann, Ph.D.
Principal Investigator

DOE Peer Review 2017

Goal Statement

- Goal: Design, build, and demonstrate outdoors a system for capturing and concentrating CO_2 from ambient air and delivering the CO_2 to microalgae.
- Outcomes:
  - Capture and concentrate CO_2 from ambient air
  - Store CO_2 in a carbonate brine
  - Extract, concentrate, and pressurize CO_2
  - Efficiently deliver CO_2 to grow microalgae
  - Outdoor algal cultivation for 1 month in 75L PBR and 1500L pond with CO_2 captured from ambient air.
- Relevance: Provide a renewable, clean, and concentrated CO_2 stream to microalgae grown far from concentrated CO_2 sources.

Quad Chart Overview

Timeline

- **Start:** 10/1/15 (Validation), 3/1/16 (Research)
- **End:** 2/28/18
- **Status:** ~50% complete

Budget

	FY 15 Costs	FY 16 Costs	Total Planned Funding (FY 17-Project End Date)
DOE Funded	0	$224,782	$775,218
Project Cost Share (Comp.)*	0	$89,279	$162,715

Barriers

- **Technical Barriers**
  - Atmospheric **CO_2 Capture** and Concentration
  - **CO_2 Storage** and Extraction
  - Efficient **CO_2 delivery** and utilization
- **MYPP Technical Targets**
  - **Productivity:** 25 g/m^2-d (2022)
  - **CO_2 Utilization:** 90%
  - **CO_2 + Nutrient Cost:** $120 / ton AFDW (2022)

Partners

- **None, ASU Only**

1 – Project Overview

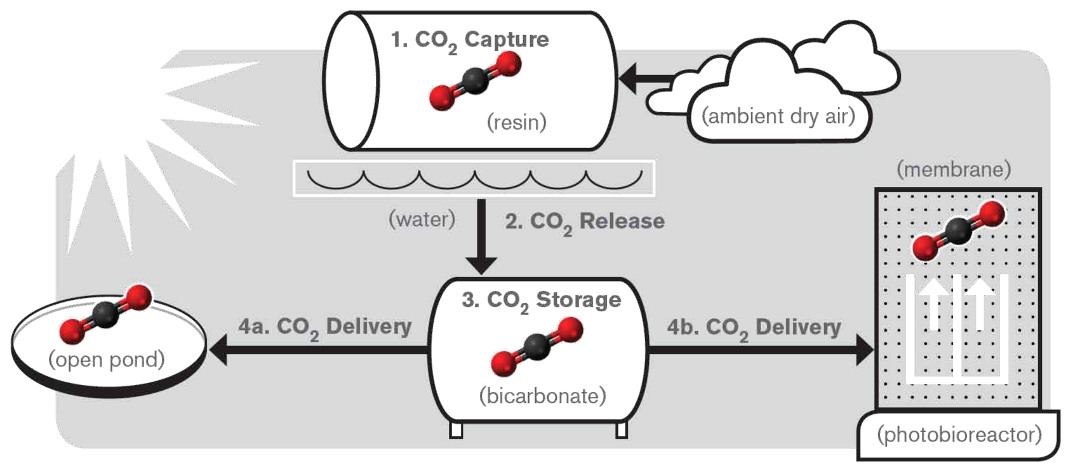
- History
  - Bruce Rittmann patented technology using membranes to deliver H_2 to treat wastewater and adapted it for PBR carbonation in 2011
  - Klaus Lackner joined ASU in Fall 2014, bringing technology to capture and concentrate CO_2 from ambient air

- Objectives

  Build a system that:

  1. Captures and concentrate atmospheric CO_2
  2. Stores CO_2 in a buffer to ensure adequate supply at any time and further concentrate CO_2 for delivery

Atmospheric CO_2 Enrichment and Delivery Concept



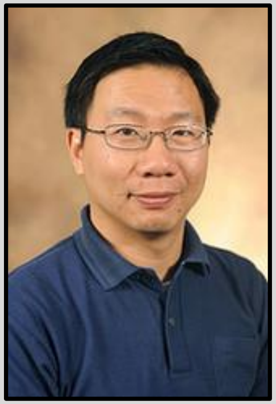
  3. Uses bubble-less CO_2 delivery: >90% into media, >70% into biomass

2 – Approach (Management)

Membrane Carbonation (MC) | Key Personnel

Bruce Rittmann

Principal Investigator



Yen-jung Lai

Research Scientist

Everett Eustance

Postdoc

Justin Flory

Technical Project Manager

Robert Stirling

Techno-Economic Analyst

Moisture Swing Sorption (MSS)

Klaus Lackner

Co-Principal Investigator

Allen Wright

Lead Engineer

Steve Atkins

Senior Engineer

Jason Kmon

Engineer

Yun Ge

Software Engineer

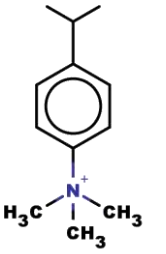
William Barr

Postdoc

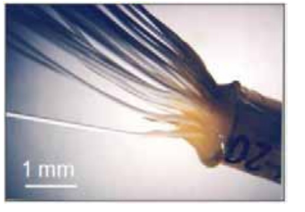
2 – Approach (Technical)

- Technical Approach
  - Anionic resin sheets capture CO_2 when dry and release when wet
  - CO_2 is transferred to sodium carbonate/bicarbonate brines to buffer capture and demand rates; thermally extracted and pressurized
  - ~100% CO_2 is delivered on demand into PBR using membrane fibers
  - Integrated system is tested ≥1 mo outdoors in a 75L PBR and 1500L pond
- Go / No Go [Mar 2017]:
  - Capture/storage system delivers CO_2 partial pressure that meets or exceeds the demand of membrane carbonation / microalgae system
- Challenges
  - Capture: Support structure cost, resin density, and dead space
  - Storage: CO_2 transfer rate and efficiency into and out of brine
  - Delivery: Accumulation of non-CO_2 gases in fibers
- Success Factors
  - Capture: kg CO_2 / kg resin; kg structure / kg resin
  - Storage: transfer rates; heat recovery; storage cost / kg CO_2
  - Delivery: CO_2 transfer efficiency and flux stability over time

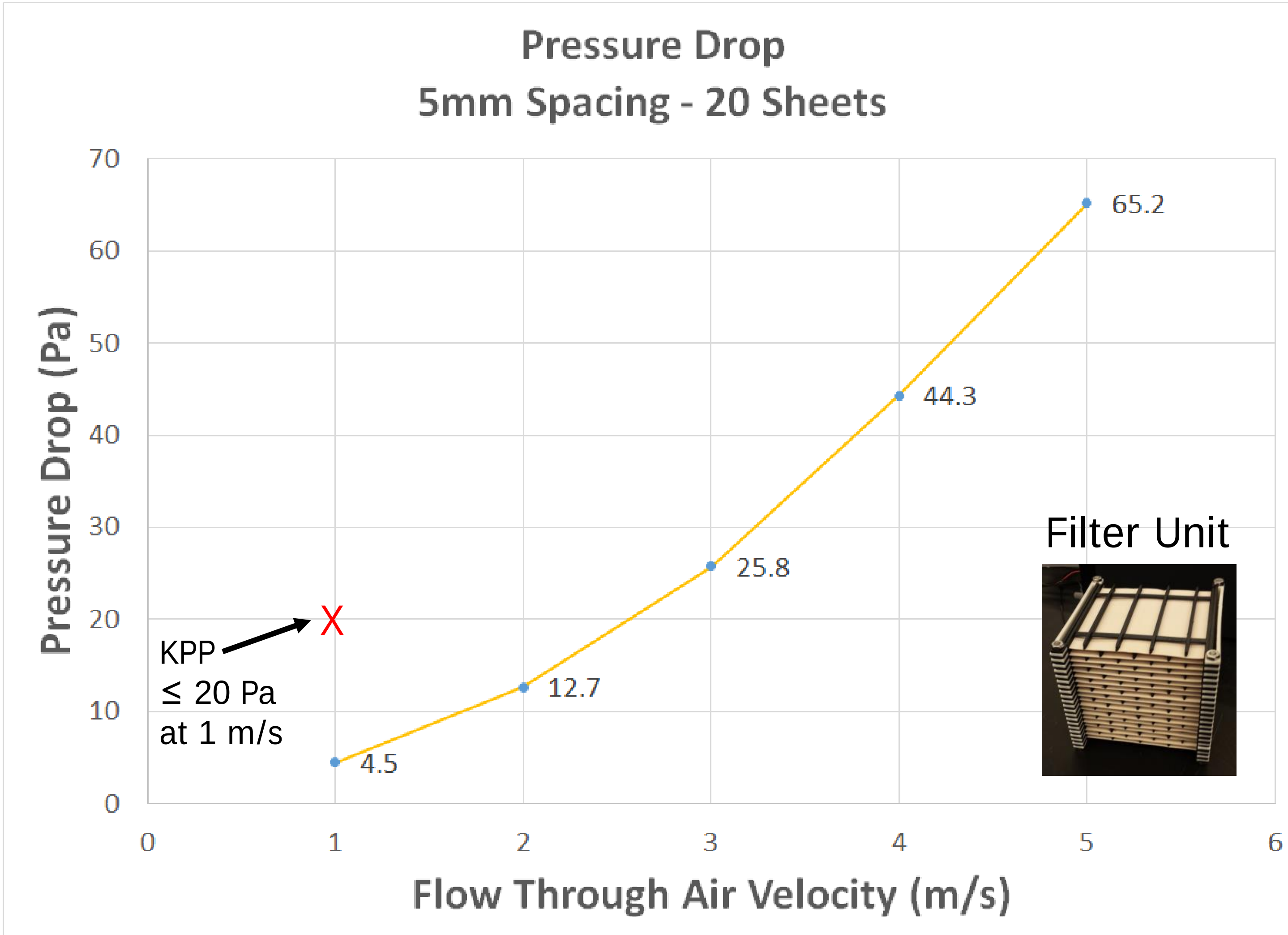
Resin



Hollow Fiber Membranes

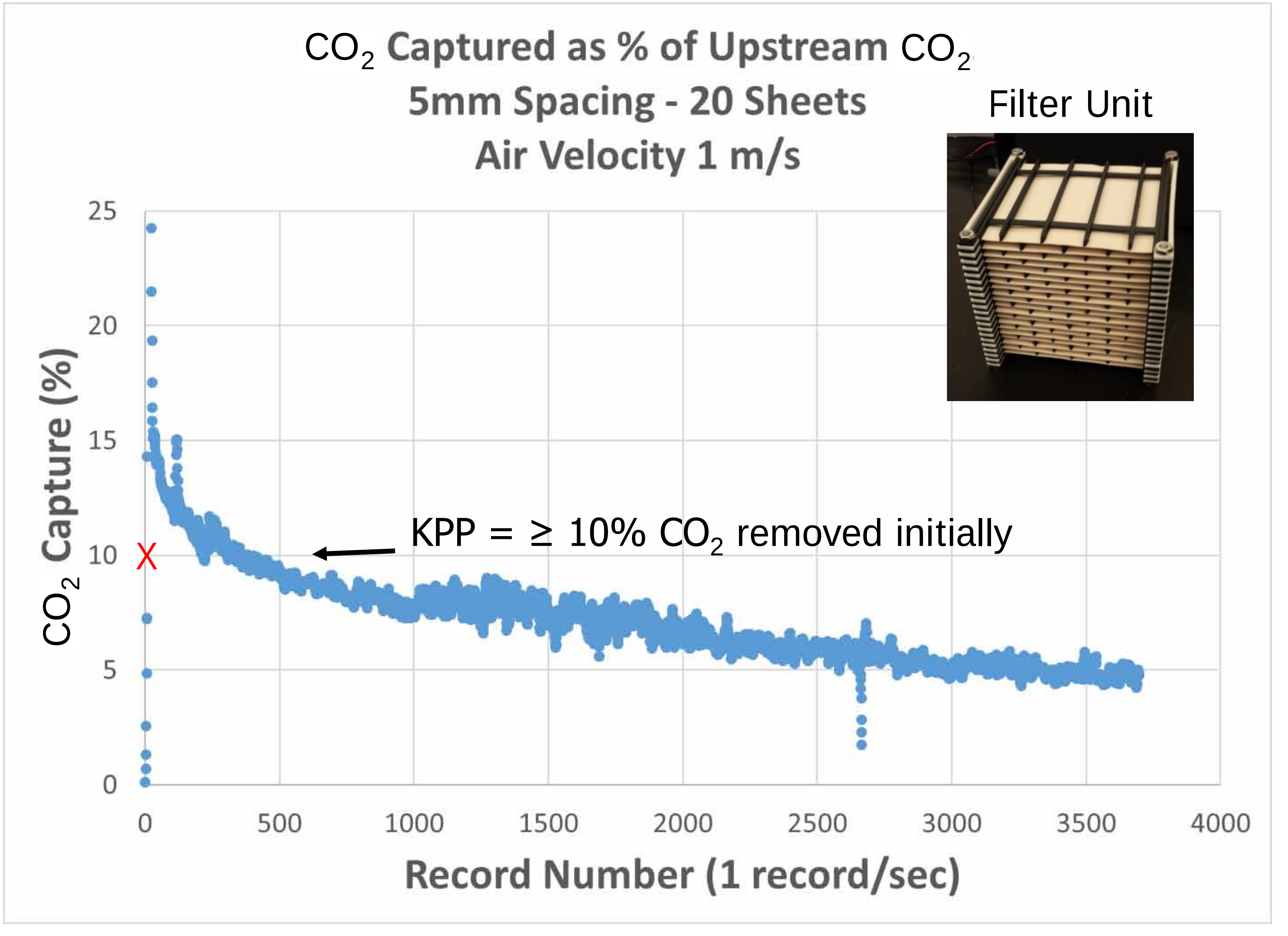


Filter Unit Built & Tested: Pressure Drop



- Low pressure drop ensures sufficient air flow at low wind speed

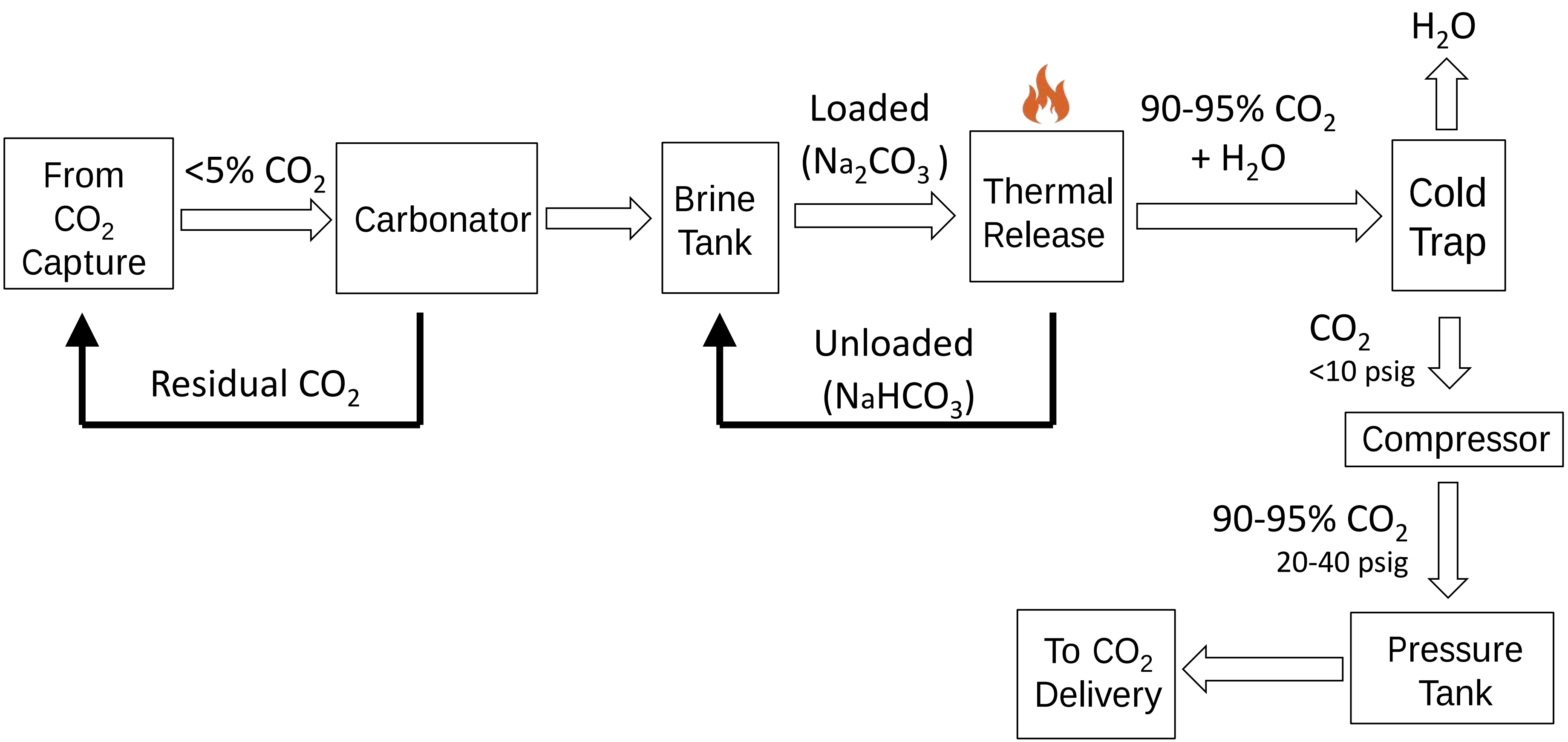
Filter Unit: Atmospheric CO_2 Captured



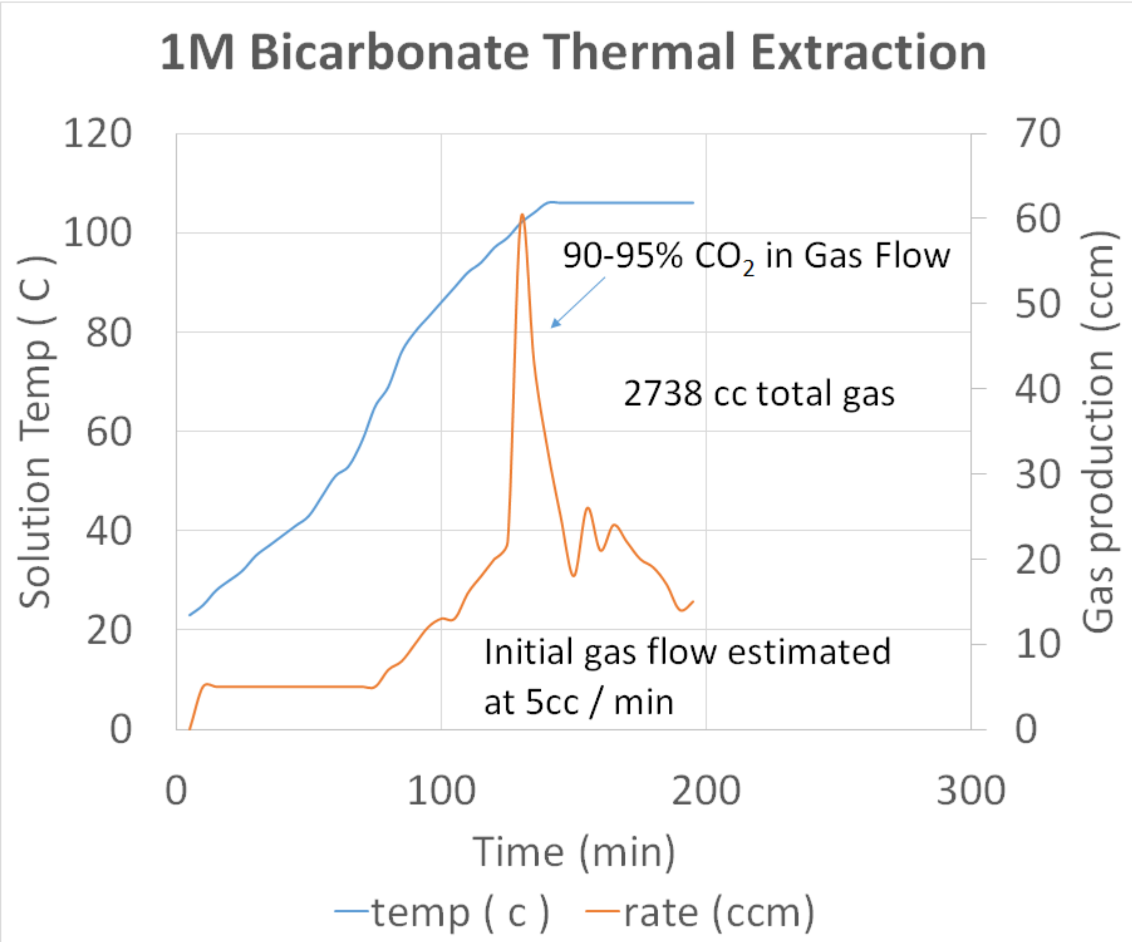
Design: CO_2 Storage Brine

- Captured CO_2 stored in sodium a (bi)carbonate brine

$$Na_2CO_3 + CO_2 + H_2O \Longleftrightarrow 2\ NaHCO_3$$

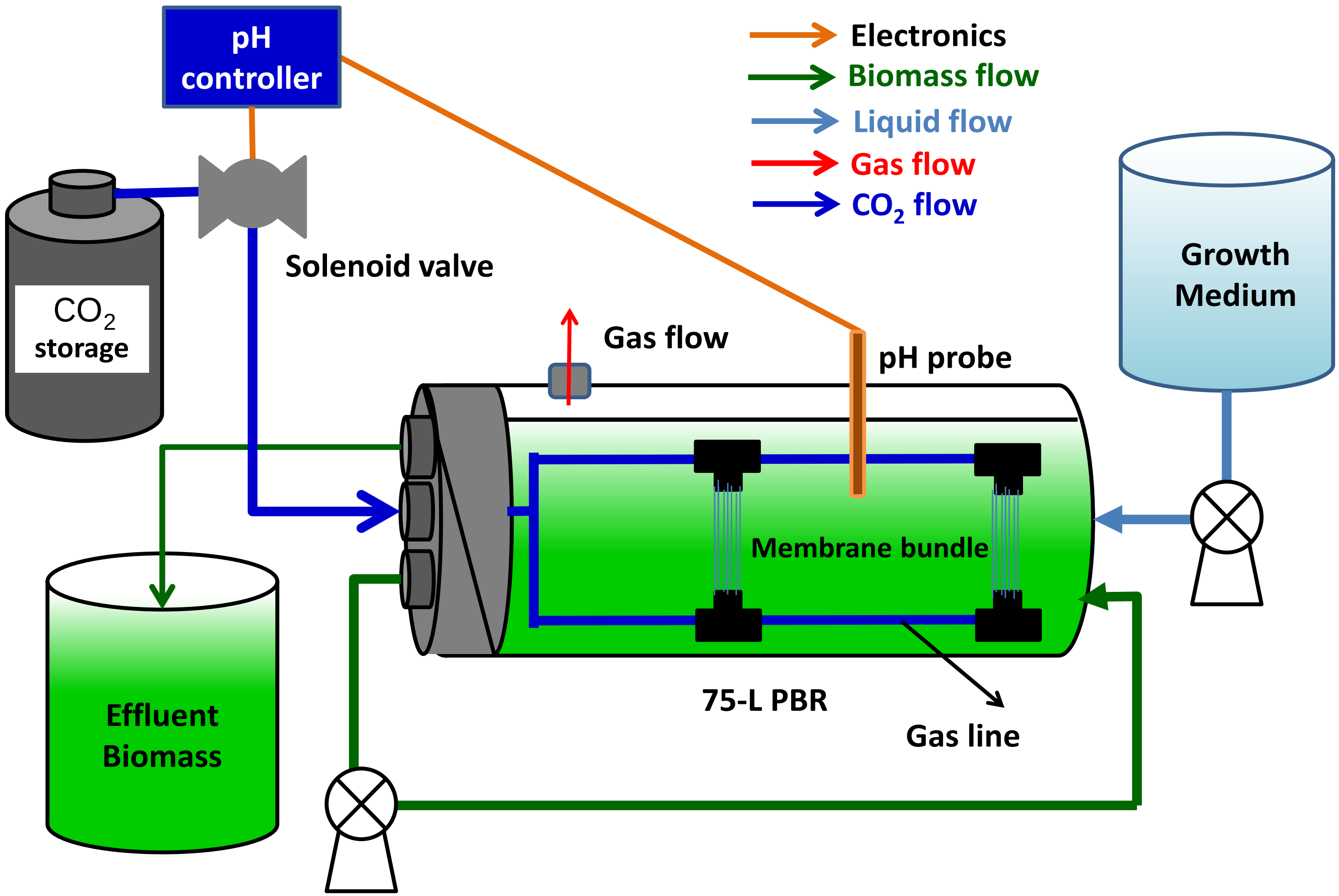


Design Validated: Thermal CO_2 Extraction

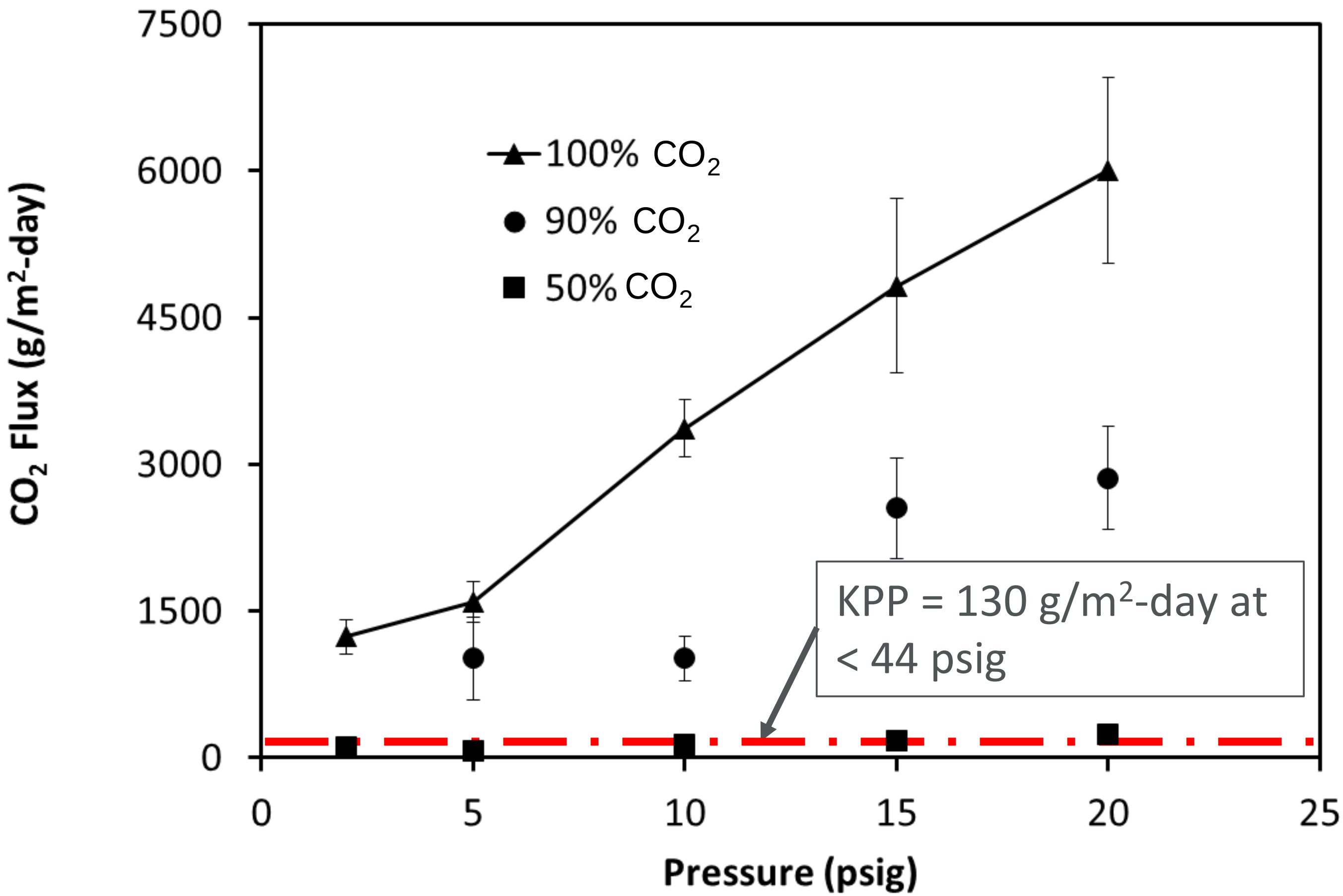


- Most CO_2 released near 100 °C
- Multi-tray design underway to recycle heat

Design: CO_2 Delivery



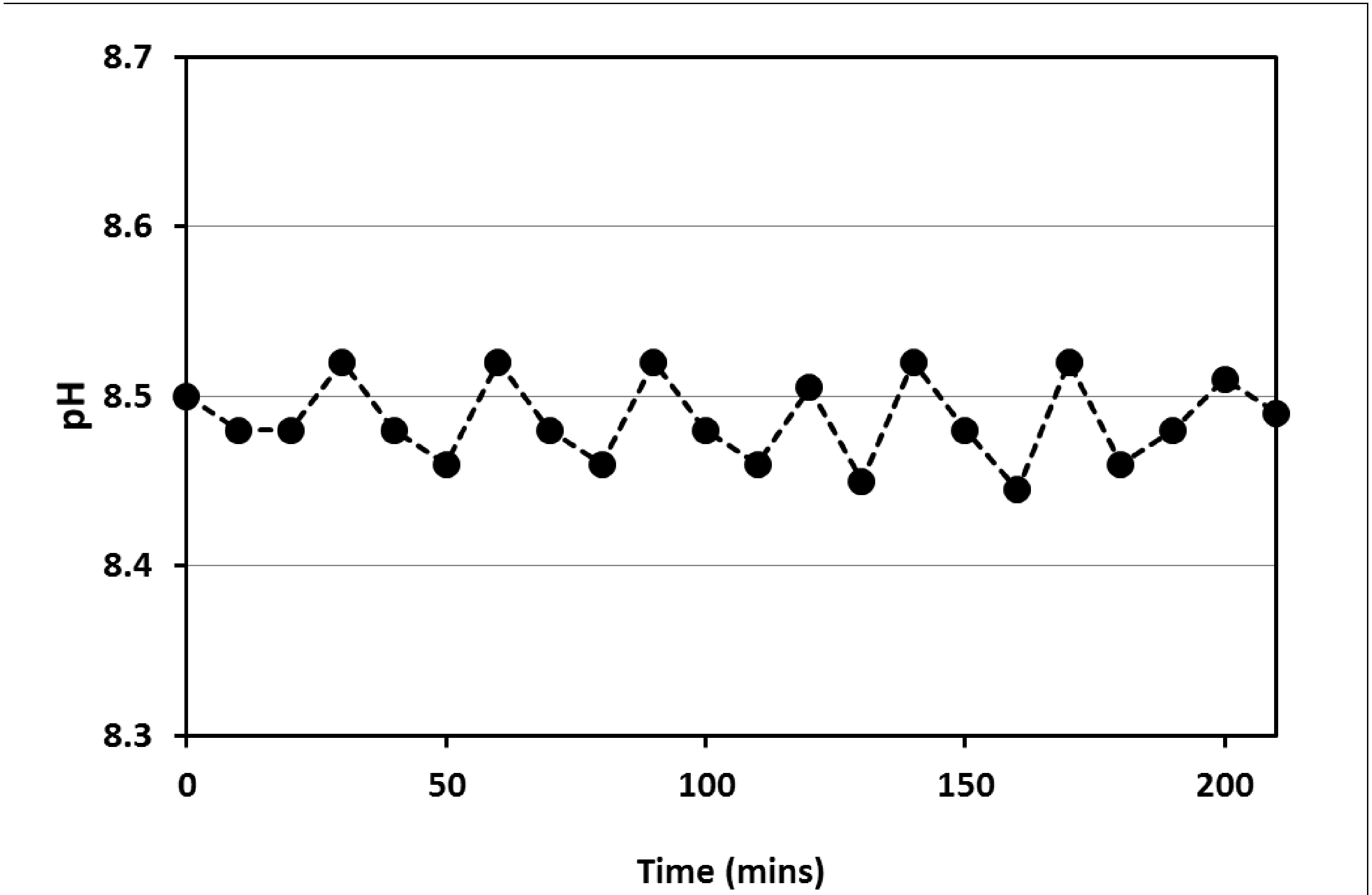
Lab Scale: CO_2 Flux Evaluated



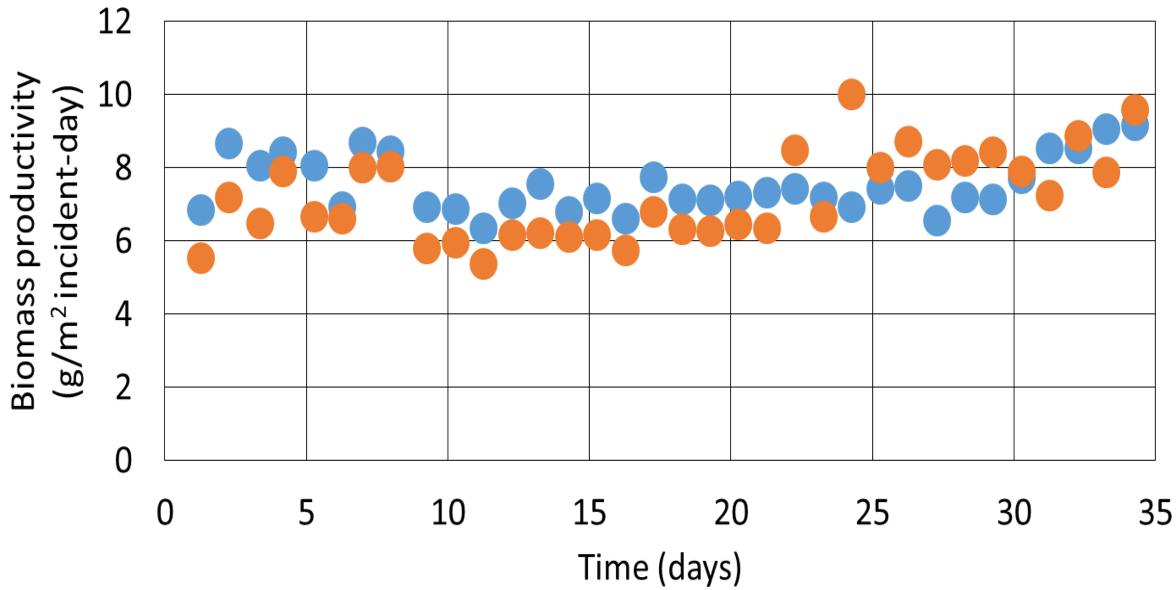
- Substantially exceed KPP criterion for >50% CO_2.
- Suspect non-CO_2 gas accumulating in the fiber.
- Investigating a bleed valve
- No significant change in flux vs pH (6.5–10.5) or alkalinity (5–20 mg/L)

Flux units are m^2 of fiber surface area

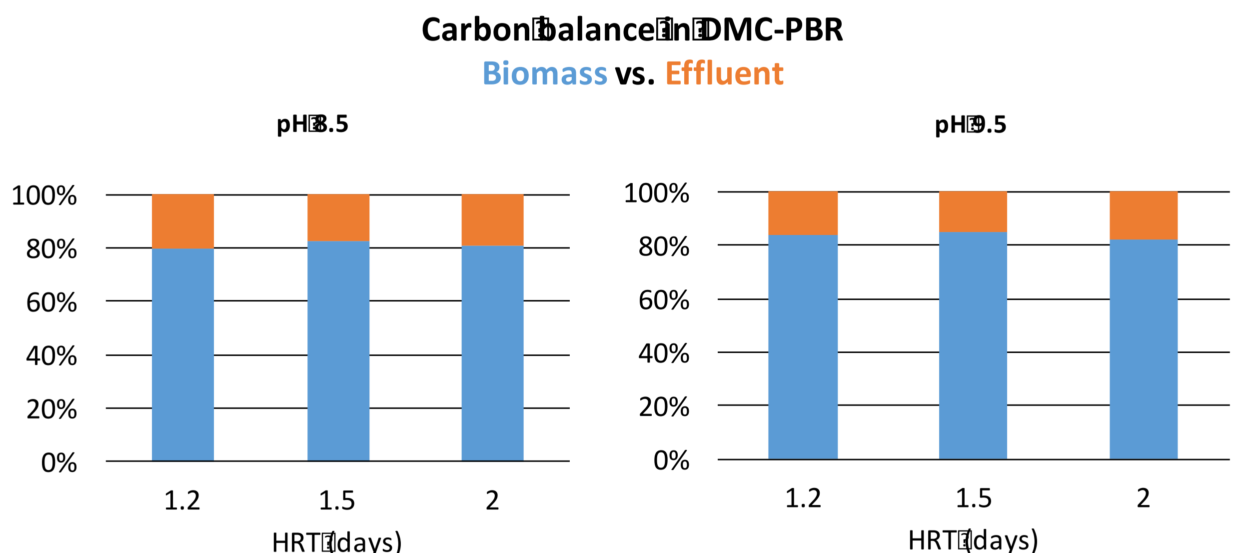
Lab Scale: pH Controlled by Membrane Carbonation



Lab Scale: Cultivation & Carbon Balance

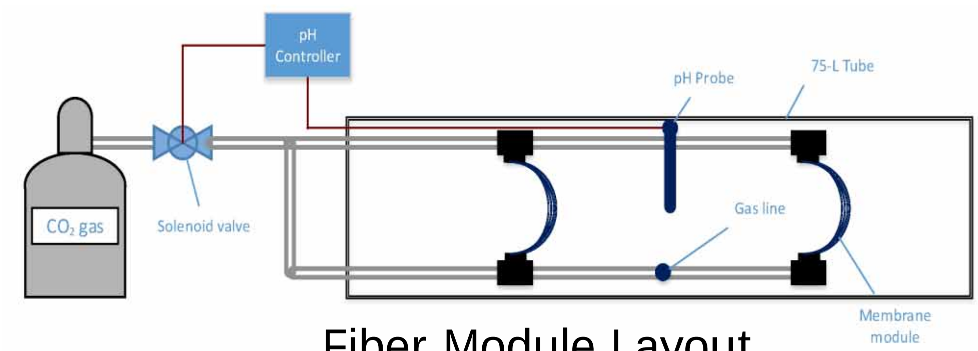


- Expected productivity for Scenedesmus is 5-10 g/m²-day

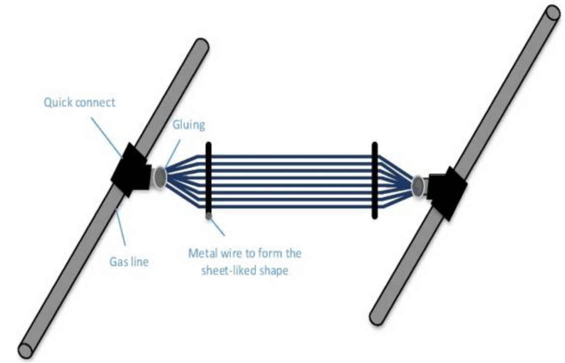


- On target to exceed 90% CO_2 utilization MYPP target

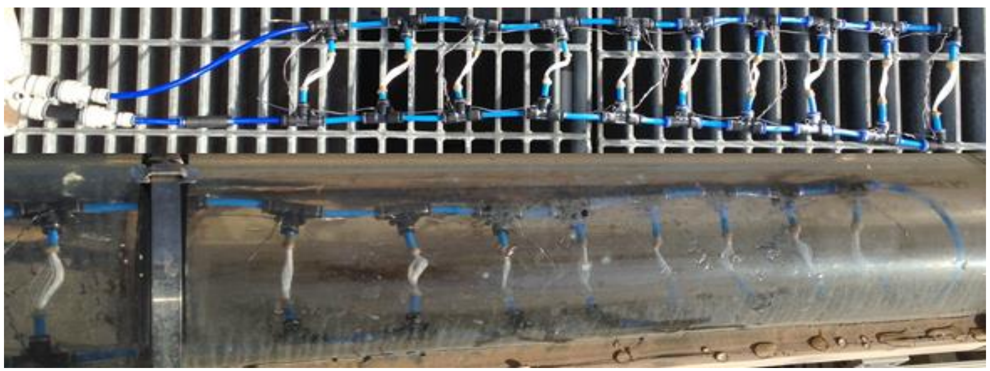
Design: Scaling up Fibers to 75L



Fiber Module Layout



Fiber Module

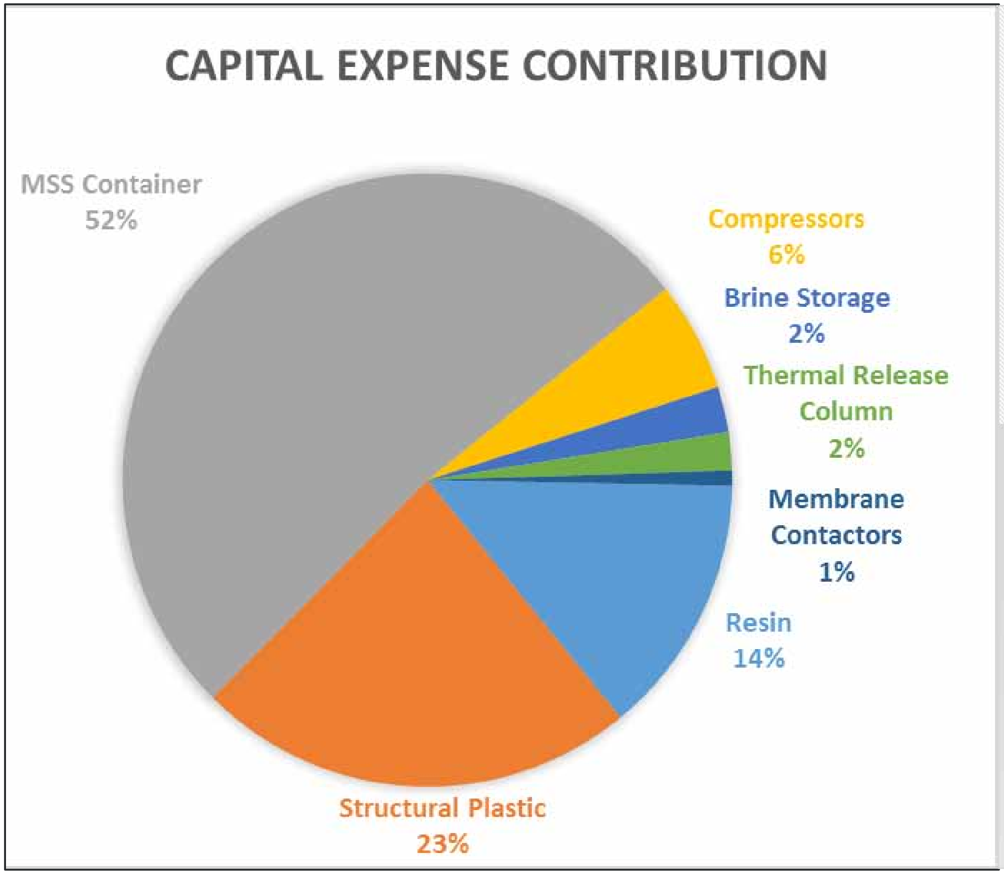


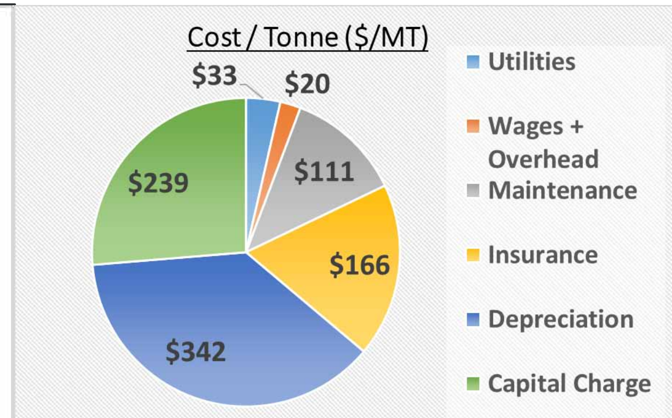
Assembled Fiber Modules

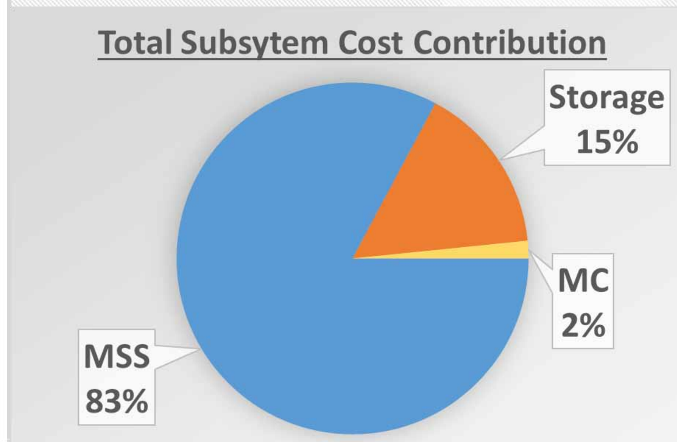
75-L PBR (x4)

- Go / No Go
  - Integration requirements met
  - Expected CO_2 composition from storage delivered at required rate

Techno-Economic Analysis of Prototype

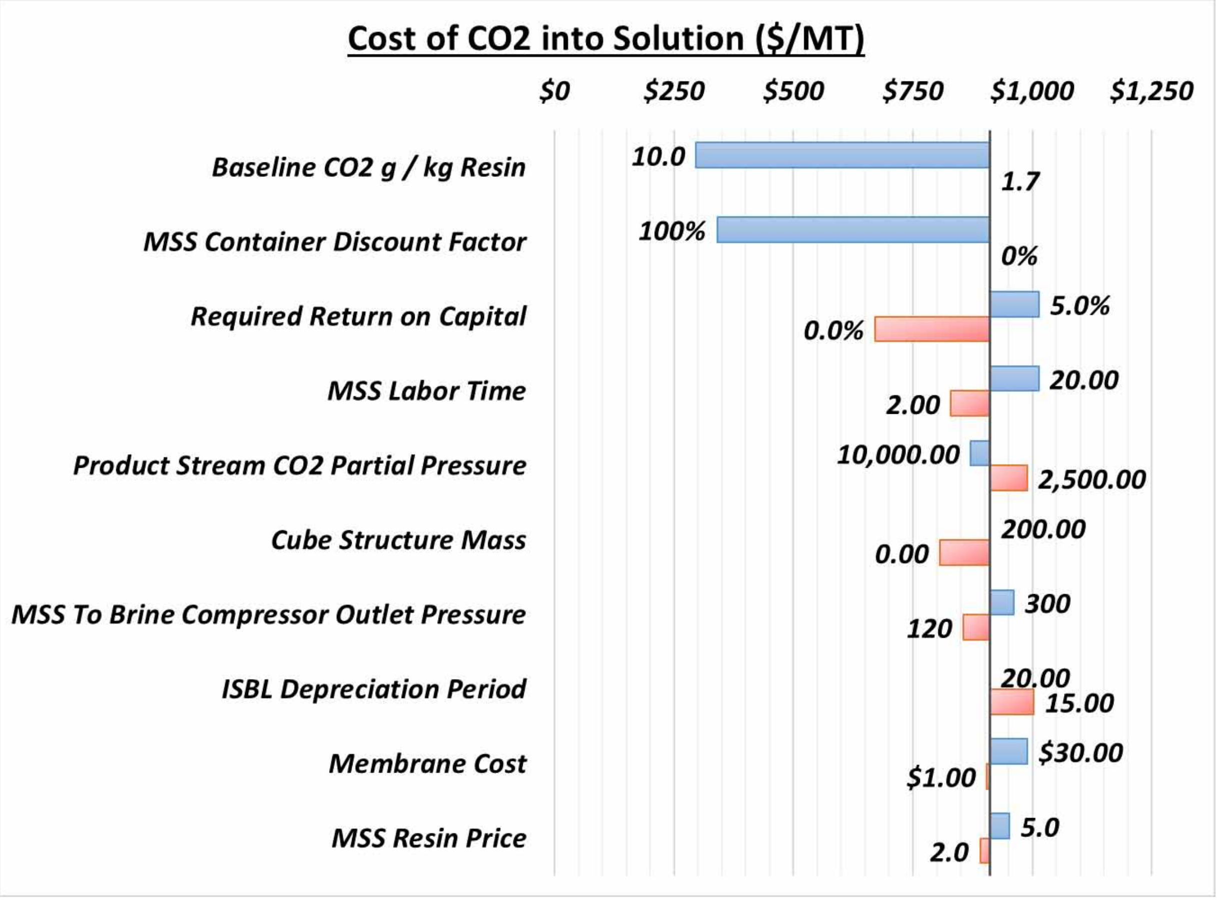






- Extrapolating the Prototype housing design to large scale leads to an estimated cost of dissolved, bioavailable CO_2 of ~**$900 per metric ton**.
- The majority of the cost comes from the CapEx required to enclosed, wet, and dry the functional resin.

TEA: Tornado Chart



Baseline Values

1.7 g / kg-hr

0%

3.5%

10 hr

5,000 Pa (5%)

200 g

200 kPa

20 yr

$3 / m^2$

$3 / kg

Observations & Recommendations:

1. Maximize resin productivity
2. Minimize MSS container cost
3. Sparging captured CO_2 into storage brine is costly (P_{CO2}; compressor)

Blue = Assumption Increases
Red = Assumption Decreases

Relevance

- Goal: Design, build, and demonstrate outdoors a system for capturing and concentrating CO_2 from ambient air and delivering the CO_2 to microalgae.
- Demonstrated ~100% CO_2 delivery into PBR
- Industry Relevance
  - Provide clean, sustainable, concentrated CO_2 in sunny locales far from concentrated sources
  - Deliver valuable CO_2 into PBR with ~100% efficiency
- Project Impact
  - Enable high productivities of microalgae from sustainable CO_2 sources

- Marketability
  - CO_2 Capture & Storage: algae, greenhouses, solar fuels, sequestration
  - Membrane Carbonation: air capture, bottled CO_2, flue gas

Future Work

- Integrate Systems
  - Build, integrate and test system for 75L PBR and 1500L pond
  - Operate ACED system for 1 month in 75L PBR and 1500L pond
  - Milestones 9.1 (75L), 10.1 and 10.2 (1500L)
- Techno-economic Model and Validation
  - Milestone 11.1
- Improve Performance and Reduce Cost
  - CO_2 Capture and Storage
    - Carbonator: Replace sparging with low pressure contactor
    - Engineer lower costs scaffolding materials (acrylic, fiberglass)
    - Investigate faster sorbent materials
  - CO_2 Delivery
    - Assess impact of humidity on CO_2 flux through membrane
    - Optimize flow of CO_2 into PBR while venting other accumulating gases
    - Optimize placement of fiber module and density of fibers for efficient CO_2 transfer

Raceway Pond at ASU

Summary

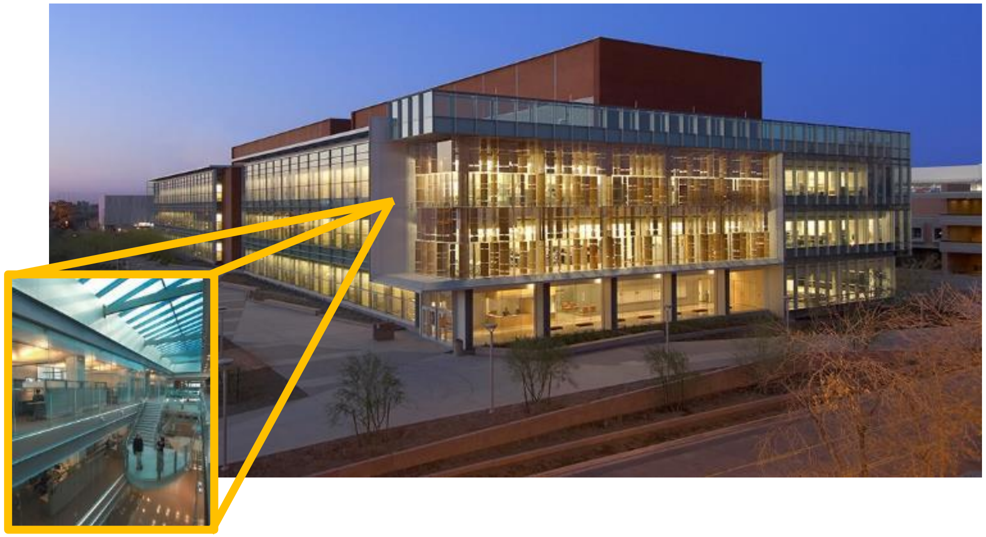
- Overview
  - Outdoor demonstration of the ACED system for delivering concentrated CO_2 to microalgae captured directly from ambient air.
- Approach
  - Moisture swing sorption CO_2 capture, carbonate brine storage, and membrane carbonation CO_2 delivery.
- Technical Accomplishments / Progress / Results
  - Subsystem designs validated: CO_2 captured, delivered into brine, extracted from brine, delivered into PBR.
- Relevance
  - Provide clean, sustainable, concentrated CO_2 in sunny locales far from concentrated sources and delivered into PBRs with ~100% efficiency.
- Future Work
  - Integration, 1 mo. outdoor operation (75L & 1500L), TEA, optimization

Questions?

Bruce Rittmann, Ph.D.
ACED Principal Investigator
Director, Swette Center for Environmental Biotechnology
Regents' Professor of Environmental Engineering
The Biodesign Institute
Arizona State University

Arizona State University

Biodesign Institute



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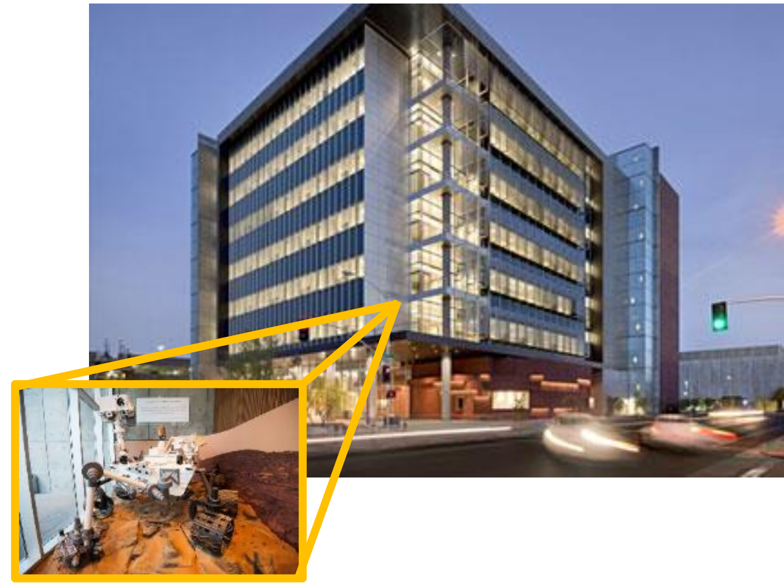

Arizona Center for Algae Technology and Innovation (AzCATI)

Supporting Slides

Responses to Previous Reviewers' Comments

- First review, no prior comments
- Go / No Go review will occur after this presentation

Publications, Patents, Presentations, Awards, and Commercialization

- Publications
  - Kim, H.-W., J. Cheng, and B. E. Rittmann (2016). Direct membrane-carbonation photobioreactor producing photoautotrophic biomass via carbon dioxide transfer and nutrient removal. Bioresource Technology 204: 32 – 37
  - Wang, T., Liu, J., Lackner, K. S., Shi, X., Fang, M. and Luo, Z. (2016), Characterization of kinetic limitations to atmospheric CO_2 capture by solid sorbent. Greenhouse Gas Sci Technol, 6: 138–149.
  - Shi, Xiaoyang, et al. "Capture CO2 from Ambient Air Using Nanoconfined Ion Hydration." *Angewandte Chemie* (2016).
  - Shi, Xiaoyang, et al. "The Effect of Moisture on the Hydrolysis of Basic Salts." *Chemistry-A European Journal* 22.51 (2016): 18326-18330
  - Lackner, Klaus S. "The promise of negative emissions." *Science* 354.6313 (2016): 714
- Awards
  - Bruce Rittmann, Gordon Maskew Fair Award, American Academy of Environmental Engineers and Scientists, April 14, 2016, Washington, DC
  - Bruce Rittmann, Perry L. McCarty/AEESP Founders' Award, August 2016
- Patents: Nothing to report
- Commercialization: Nothing to report

Publications, Patents, Presentations, Awards, and Commercialization

- Presentations
    - Klaus Lackner, "Air Capture Technology" *Oxford Greenhouse Gas Removal Conference,* Oxford, England. October 5, 2015
    - Klaus Lackner, "Progress in Direct Air Capture" *Gary C. Comer Climate Change Conference,* Soldier Grove, WI. November 18, 2015
    - Klaus Lackner, "The State of Direct Air Capture" *Carbon Management Technology Conference*, Sugarland, TX. November 18, 2015
    - Klaus Lackner, "Climate 3.0 Engineering" *ASU Climate 3.0 Conference,* Tempe, AZ. January 12, 2016
    - Klaus Lackner, "Negative Carbon Emissions" *The Ohio State University, Department of Chemical and Biomolecular Engineering,* Columbus, OH. February 18, 2016
    - Klaus Lackner, "The Needs and Opportunities for Capturing Carbon Dioxide from the Atmosphere" *ARPA-E Energy Innovation Summit, Washington DC.* February 29, 2016
    - Klaus Lackner, "Air Capture of CO2 as a Core Technology for Sustainable Development" *Google X Talk/Visit, Mountain View, CA.* April 25, 2016
    - Klaus Lackner, "Air Capture Carbon Negative: A Technology For The Future" *AREDay*, Aspen, CO. June 21, 2016
    - Klaus Lackner, "Balancing the World's Carbon Budget with Direct Air Capture" *ASME Power and Energy Conference*, Charlotte, NC. June 29, 2016
    - Klaus Lackner, "Direct Air Capture" *Aspen Global Change Institute Workshop,* Aspen, CO. August 4, 2016
    - Klaus Lackner, "Balancing Carbon Budgets with Direct Air Capture" *Wyoming Global Technology Summit,* Jackson Hole, WY. September 9, 2016

Publications, Patents, Presentations, Awards, and Commercialization

- Presentations (cont)
  - Klaus Lackner, "Balancing Carbon Budgets with Direct Air Capture" *Meeting with BASF, Ludwigshafen, Germany.* September 9, 2016
  - Klaus Lackner, "Carbon Management: Moving to a Waste Paradigm" *Meeting with Siemans, Munich, Germany.* September 9, 2016
  - Klaus Lackner, "Direct Air Capture, Advances and Context" *Closing the Carbon Cycle: Fuels from Air,* Tempe, AZ. September 28, 2016
  - Klaus Lackner, "Direct Air Capture Managing CO2 as a Waste" *Comer Climate Conference, Soldier Grove, WI*. October 3, 2016
  - Klaus Lackner, "Direct Air Capture as a Tool for Carbon Management" *Beyond Carbon Neutral Seminar Series University of Michigan,* Ann Arbor, MI. October 7, 2016
  - Klaus Lackner, "Direct Air Capture as a Tool for Carbon Management" *ARPA-E Talk/Visit, Washington DC.* December 7, 2016
  - Klaus Lackner, "Industrial and Carbon Capture Storage" *Deep Carbonization Initiative Workshop, National Renewable Energy Laboratory (NREL), Golden, CO.* December 8, 2016
  - Klaus Lackner, "Mineral Carbonation Retrospective: Non-Starter, or Technology Whose Time Has Come?" *Workshop on Mineral Carbonation for Carbon Capture & Storage, San Francisco, CA.* December 16, 2016
  - Klaus Lackner, "Massively Parallel Infrastructures" *Small Scale and Modular Carbon Capture Workshop, Lawrence Livermore National Laboratory, Livermore, CA.* January 18, 2017