Summary of the Small Scale and Modular Carbon Capture Workshop

Joshuah Stolaroff, Lawrence Livermore National Laboratory

Motivation

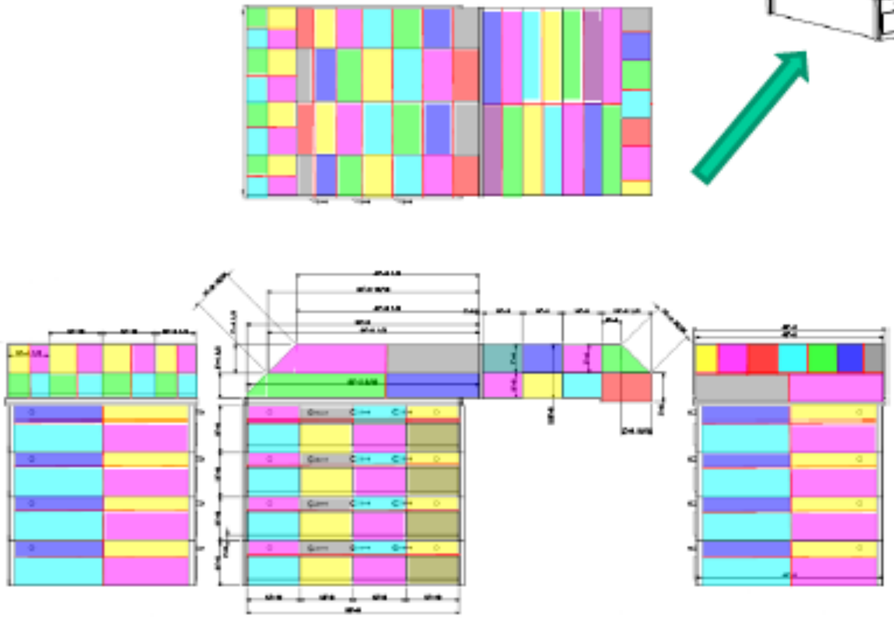
- Carbon capture could start more easily in high value, niche markets. Do we have appropriate capture technology?
- We want to lower capital costs, accelerate deployment. Can small scale/modular capture systems help?
- CCS needs to address industrial CO_2 sources, which are often in remote areas and have a wide range of scales in size.
- Regulatory environment may impose gradually ratcheting emissions standards on a given facility.

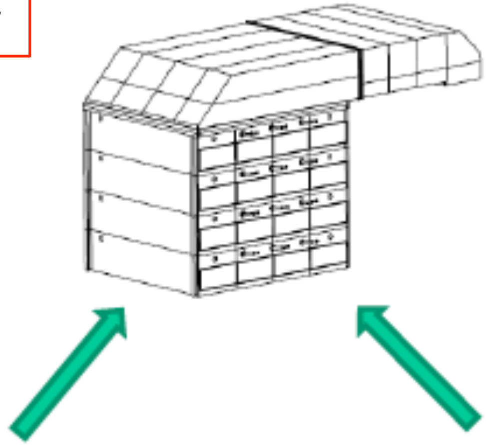
“Modular” may refer to:

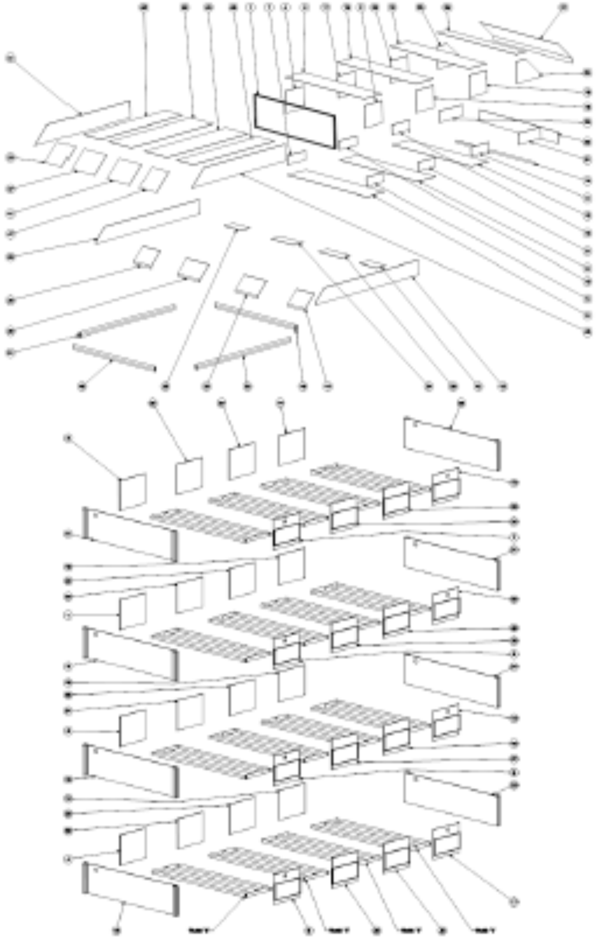
- A system or component that is self-contained and repeatable (build 10 units of capture capacity and later add 10 more).
- A process unit consisting of many repeated elements.
- A large system built from distinct, pre-assembled modules.

“Modular” VS “Knock-Down”

Presented by
Diego Mier, Riley Power







Containerized
(201 flat panels + internals)

Both options to deliver 36 modules to site.

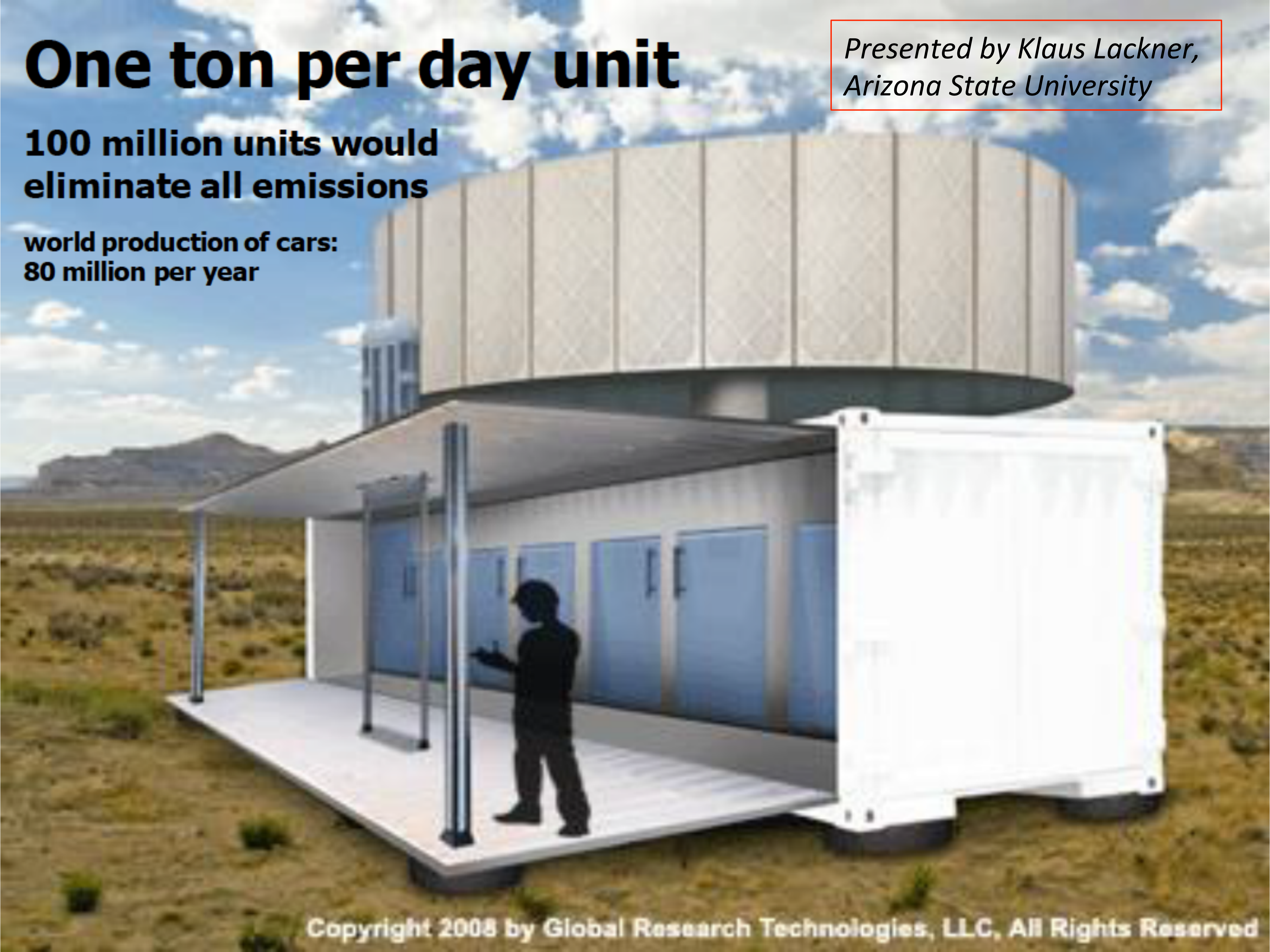
Break Bulk
(90 flat panels + internals)

One ton per day unit

Presented by Klaus Lackner,
Arizona State University

100 million units would eliminate all emissions

world production of cars:
80 million per year



The meaning of small scale varied.

Capture at Multiple Scales

- Small plants
  - Less than 100 t/d CO_2
  - Absorbers up to 2.0 m
- Mid-size plants
  - 100 to 1,000 t/d CO_2
  - 2.0 to 6.0 m Absorbers
- Large plants
  - Over 1,000 t/d
  - Absorbers exceeding 6.0 meters

Presented by Satish Reddy, Fluor

The capital cost of a collection of small, identical units, and of a single, large unit, scales similarly with total size.

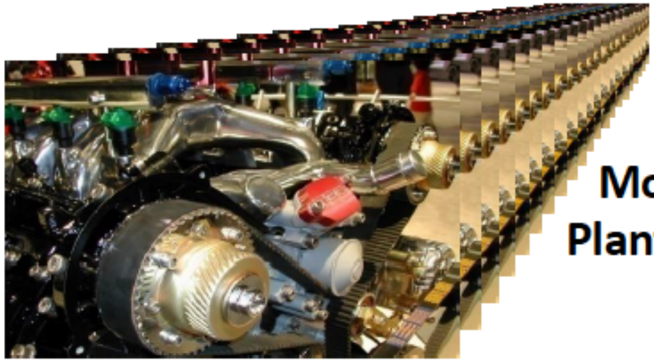
Economies of Scale

$$\text{Cost} = C_0 \cdot (\text{size})^{\alpha}, \quad \alpha < 1$$

Economies of Mass Manufacturing

Unit cost drops with production: $\frac{c_{2n}}{c_n} = \varepsilon$

Cost of n-th unit: $c_n = c_1 \varepsilon^{\log_2 n} = c_1 n^{\log_2 \varepsilon}$



Modular Plant

Cost of N units $= \frac{c_1}{1+\log_2 \varepsilon} \cdot N^{1+\log_2 \varepsilon}$

Empirically: $\alpha \cong 1 + \log_2 \varepsilon$

Presented by Klaus Lackner, Arizona State University

Labor cost favors large units

- Images from Wikipedia

Presented by
Tim Merkel, MTR

Cost Reduction through Volume Manufacturing

Year	Cost (Normalized to 1980 U.S.$)	Productivity (Normalized to 1980)	Reciprocal Salt Passage (Normalized to 1980)	Figure of Merit
1980	1.00	1.00	1.00	1.0
1985	0.65	1.10	1.56	2.6
1990	0.34	1.32	2.01	7.9
1995	0.19	1.66	3.52	30.8
1999	0.14	1.94	7.04	99.3

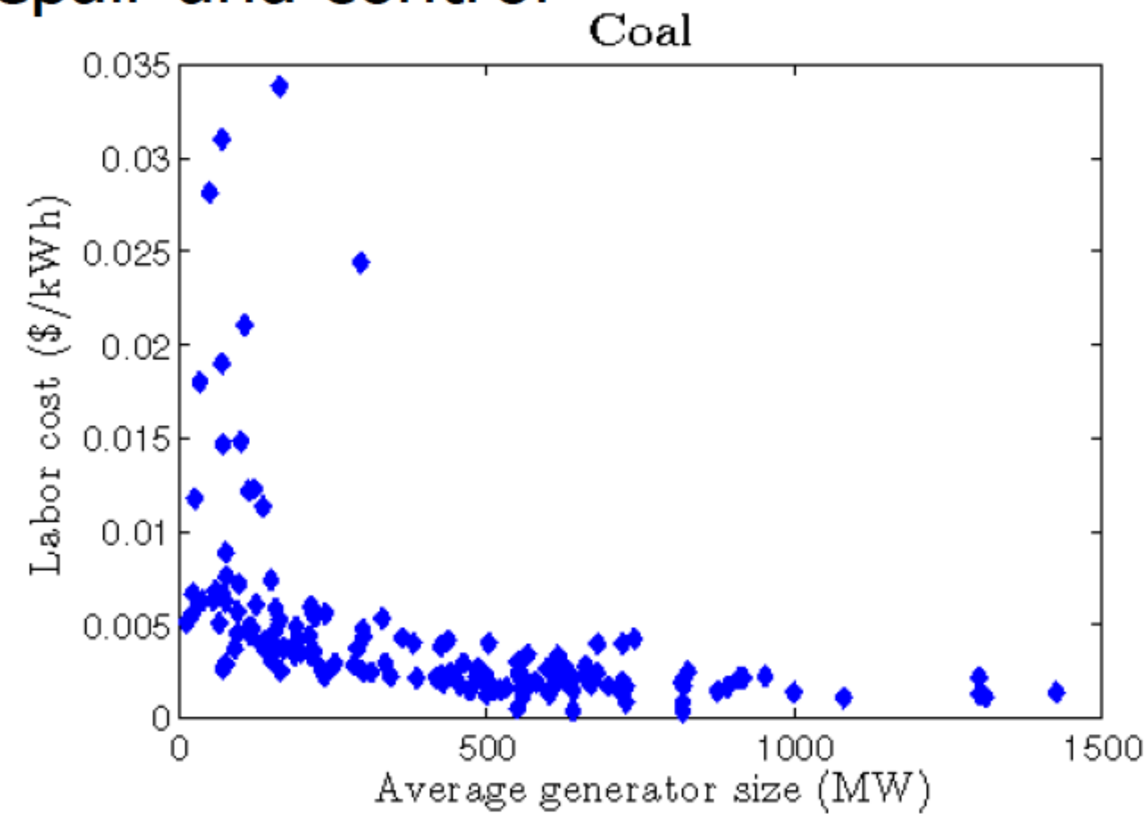
Dave Furukawa (1999)

- Over ~20 years, production improvements reduced the cost of membrane modules for RO by 7-fold, while water permeance doubled
- Today's large RO systems use 10s of thousands of modules
- Similar improvements are likely for carbon capture membranes if there is a market for small scale learning

But other factors encourage large scale.

Personnel costs drive scale

- Fixed and variable cost – pilots and attendants
- Large fraction of cost scales with number of units
- Maintenance, repair and control



Presented by Klaus Lackner, Arizona State University

Different technologies have different optimum sizes.

Efficiency scaling is complex

large units are better

- **Heat retention**
  - Insulation gets cheaper
- **Wall losses (evap, etc.)**
  - Turbines need to be large
  - Wall corrosion
  - Contamination from walls
- **Wall friction**
  - Pistons etc.
- **Control systems**
  - Less coordination required

small units are better

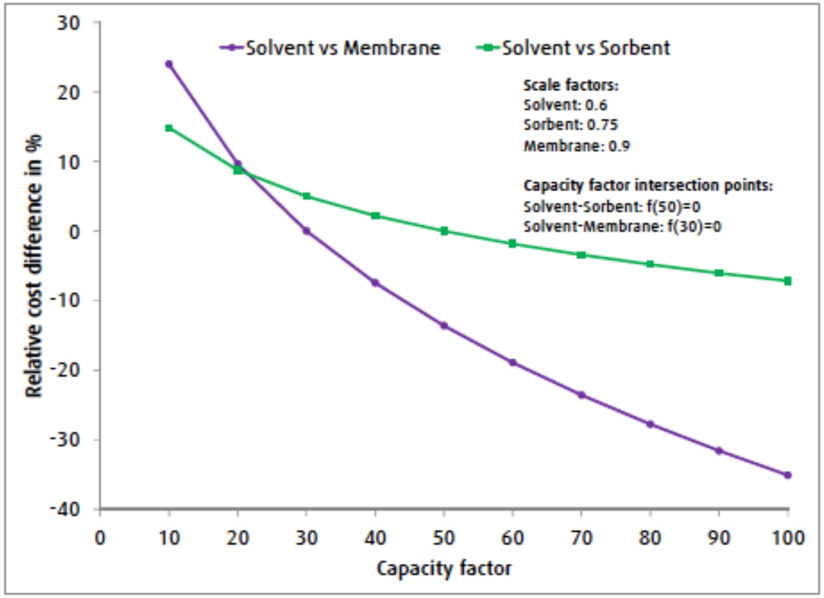
- **Heat transfer**
  - Diffusion is helped
- **Transport and diffusion**
  - Take advantage of fast reactions
- **Mixing**
  - Faster and more uniform
- **Accurate control**
  - Temperature, pressure, etc.
- **Redundancy**
  - Parallel systems

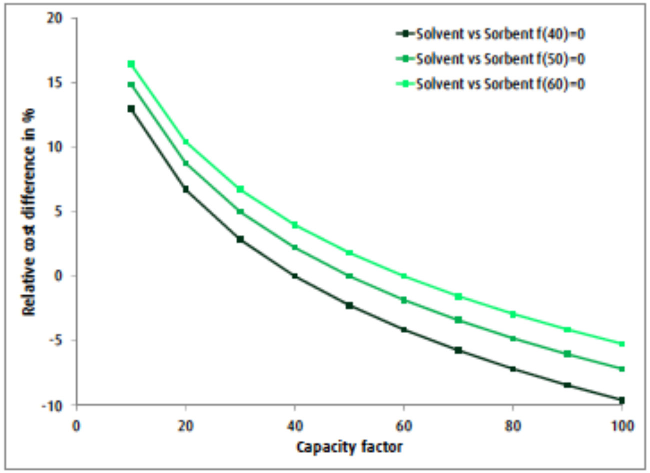
Case by case analysis required

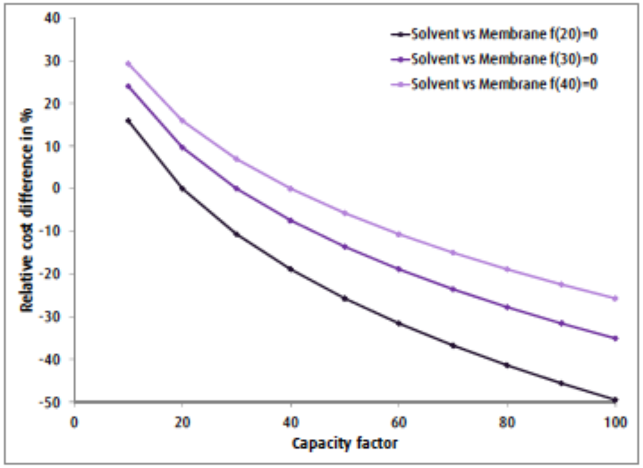
Each process has its intrinsic scale

Presented by Klaus Lackner, Arizona State University

Technology sweet-spots and effect of scale







- Past experience shows that solvent based processes offers the best capex benefit at the largest scale, sorbent based processes is best at intermediate scale and membranes are best at smaller scales.
- Breakeven points and sweet spot ranges can vary by application for each technology and further be affected by modularization based cost reduction concepts.

Presented by Krish R. Krishnamurthy, Linde LLC

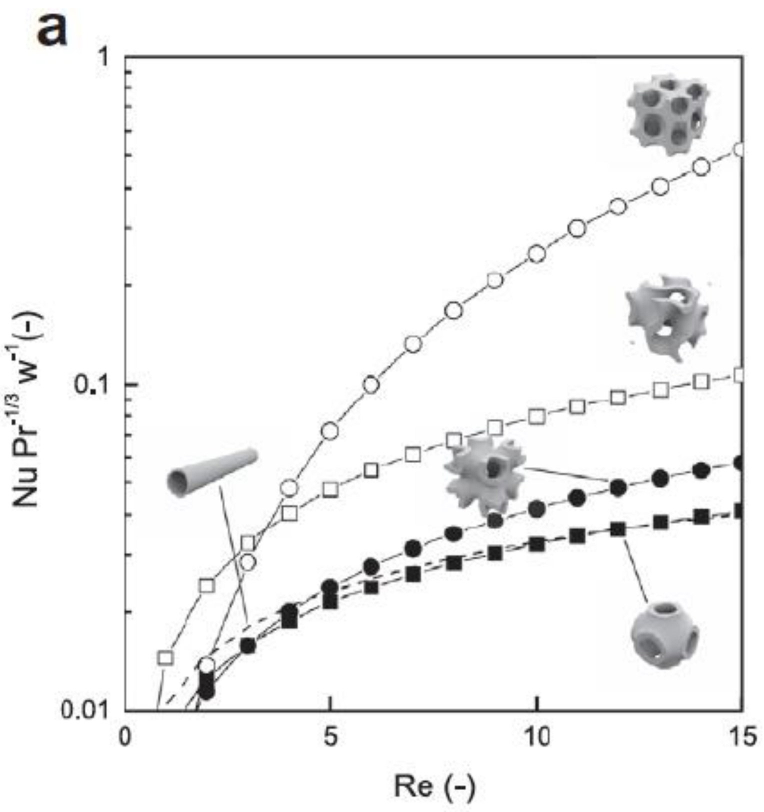
Advanced manufacturing can enable new types of intensified reactors, and is inherently (for now) modular and small scale.

How to Reduce Capital Costs?

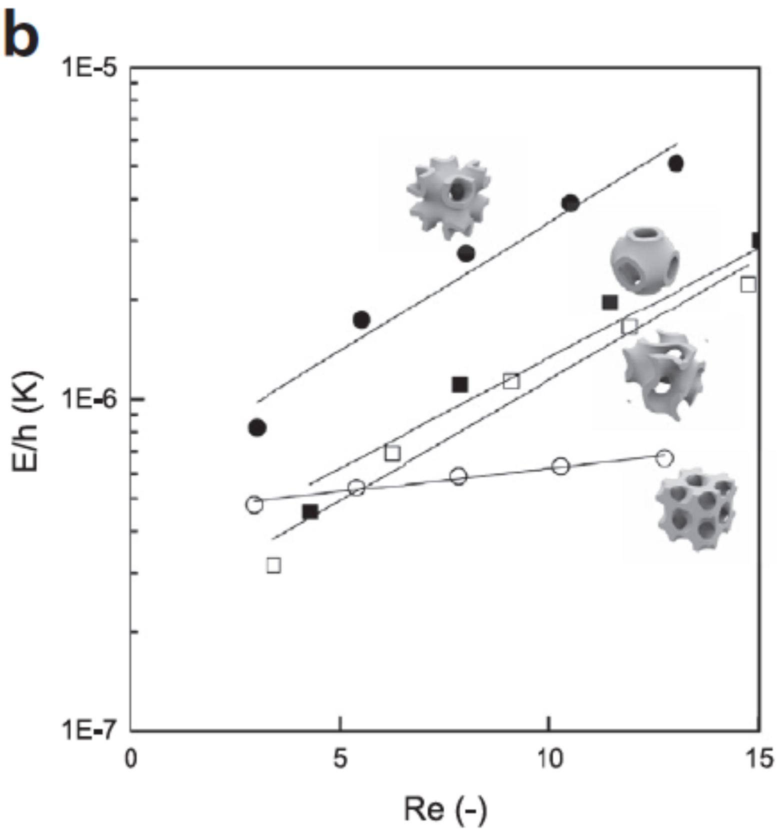
- For most heat and mass transfer devices, capital costs are proportional to size$^{\text{exponent}}$
- Hence, need to reduce size, without decreasing area for heat and mass transfer
- Equivalent to increasing heat and mass transfer area per unit size (volume often assumed)
- Does modularization provide an answer?

Presented by Abhoyjit Bhown, Electric Power Research Institute

Order-of-magnitude improvement in heat transfer performance over tubes and flat plates.



Heat transfer per unit surface area

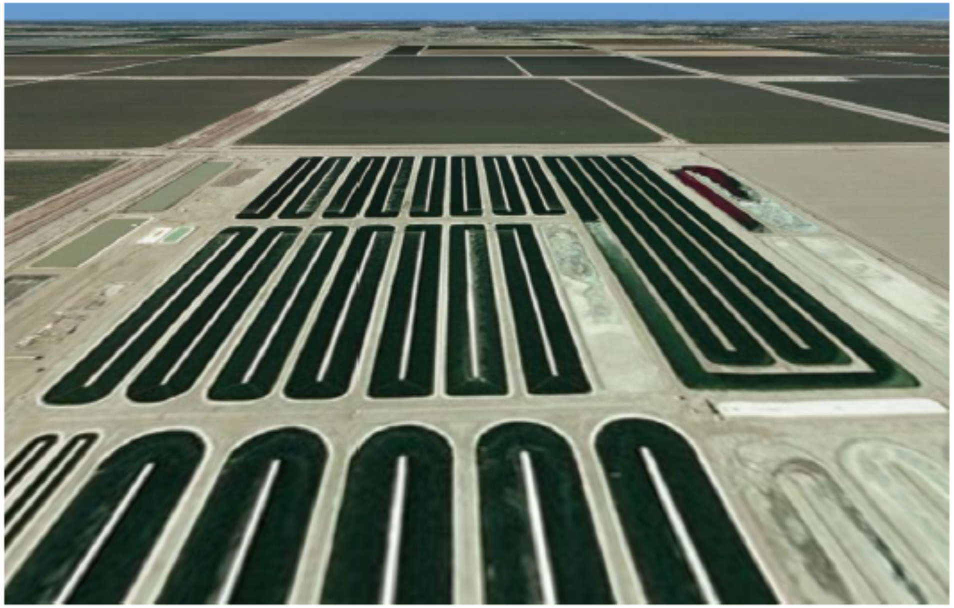


Friction loss per unit heat transferred at ΔT=1◦C

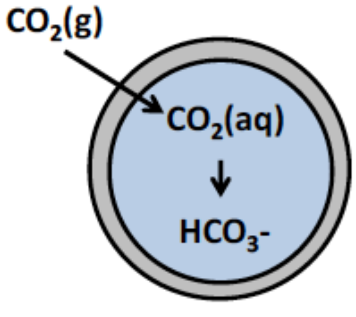
Presented by Joshuah Stolaroff, Lawrence Livermore National Laboratory

From: T. Femmer et al. *Chemical Engineering Journal* 273 (2015) 438–445.

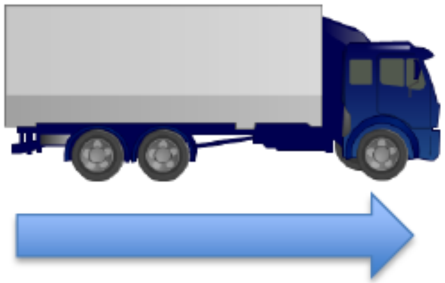
Microcapsules can be used for algae production

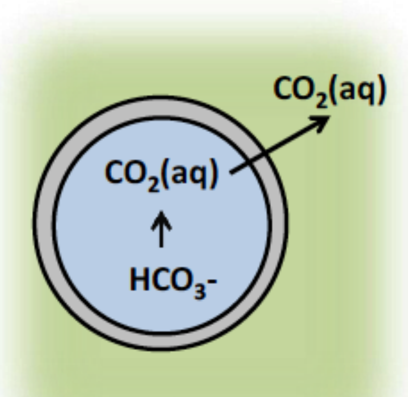


- CO_2 is at least 20% of costs of algae cultivation
- CO_2 can be delivered by capsule more efficiently
- Save 75% of cost of capture

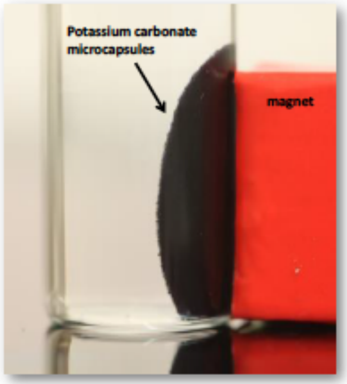


Absorption





Release (Algae Pond)



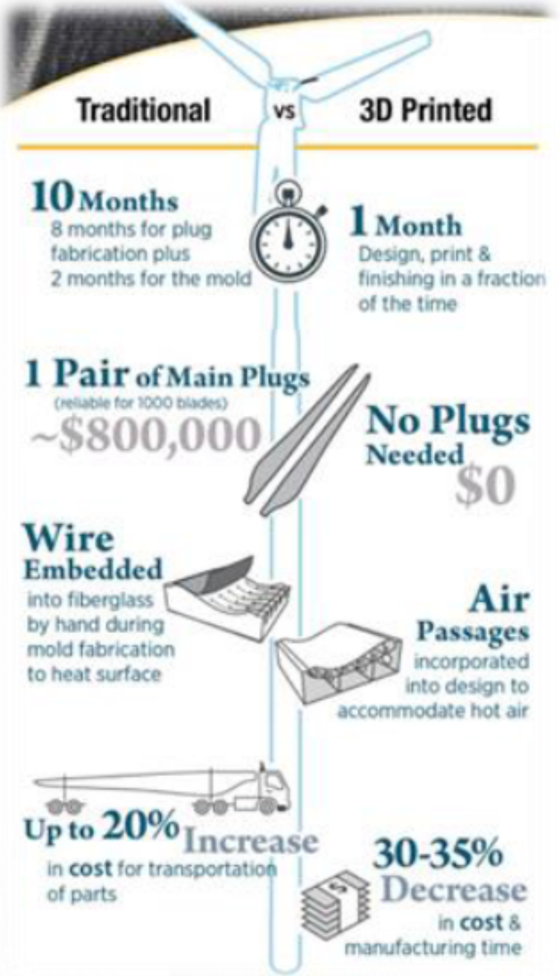
Magnetic separation

Presented by Joshuah Stolaroff, Lawrence Livermore National Laboratory

Additive manufacturing can be achieved in increasingly large sizes, but capital scaling law is unkown.

ORNL’s Integrated 3D Printed Home and Vehicle

Example of AMO-Wind Demonstration



Traditional	3D Printed
10 Months 8 months for plug fabrication plus 2 months for the mold	**1 Month** Design, print & finishing in a fraction of the time
1 Pair of Main Plugs (reliable for 1000 blades) ~$800,000	**No Plugs Needed** $0
Wire Embedded into fiberglass by hand during mold fabrication to heat surface	**Air Passages** incorporated into design to accommodate hot air
Up to 20% Increase in cost for transportation of parts	**30-35% Decrease** in cost & manufacturing time

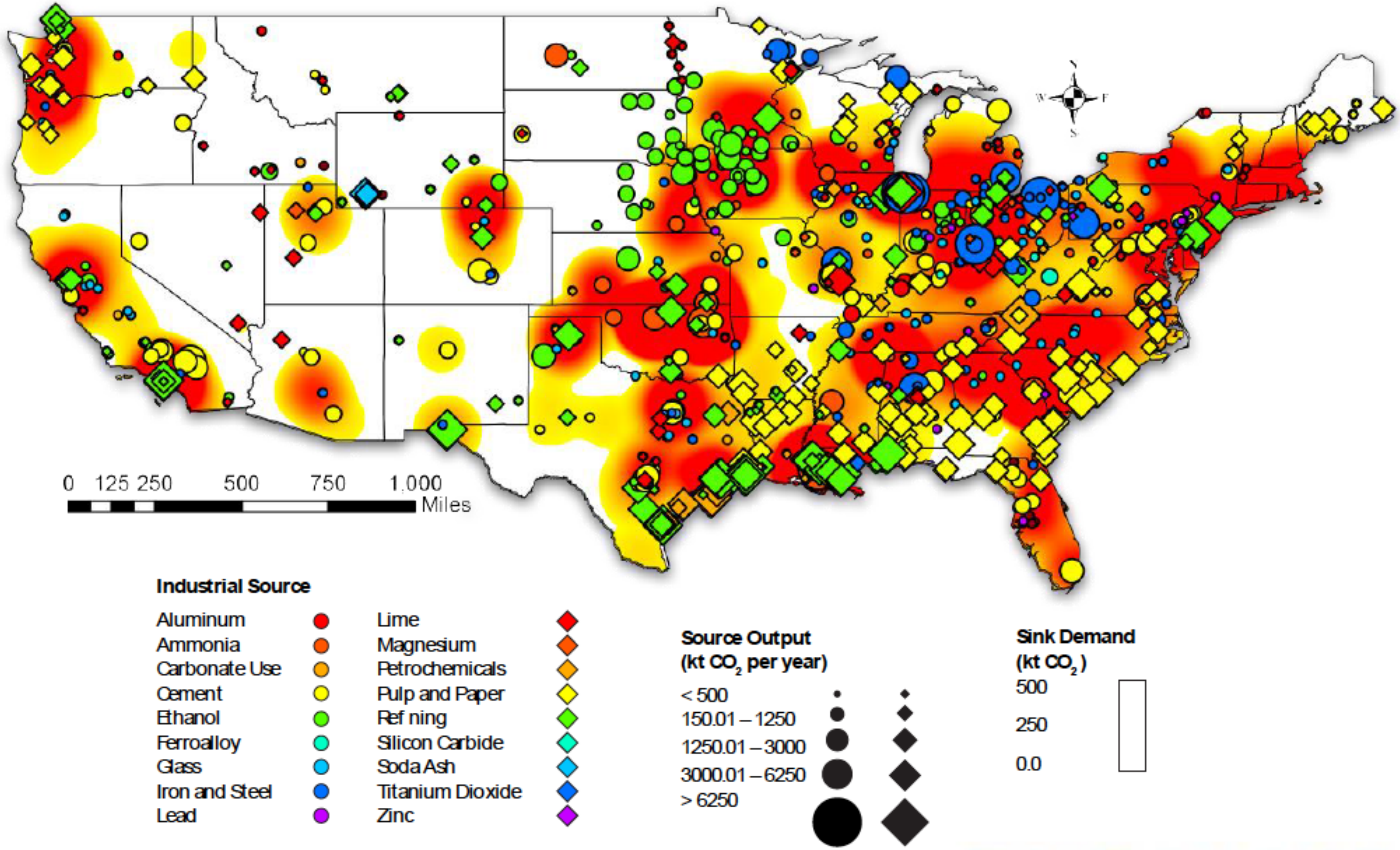
- **Large Scale Printers**
  - Cincinnati System 8'x20'x6' build volume
- **Fast Deposition Rates**
  - Up to 100 lbs/hr (or 1,000 ci/hr)
- **Cheaper Feedstocks: Pellet-to-Part**
  - Pelletized feed replaces filament with up to 50x reduction in material cost
- **Better Materials**
  - Higher temperature materials
  - Bio-derived materials
  - Composites Hybrids

OAK RIDGE
National Laboratory

Industrial sources lend themselves to small scale capture and utilization.

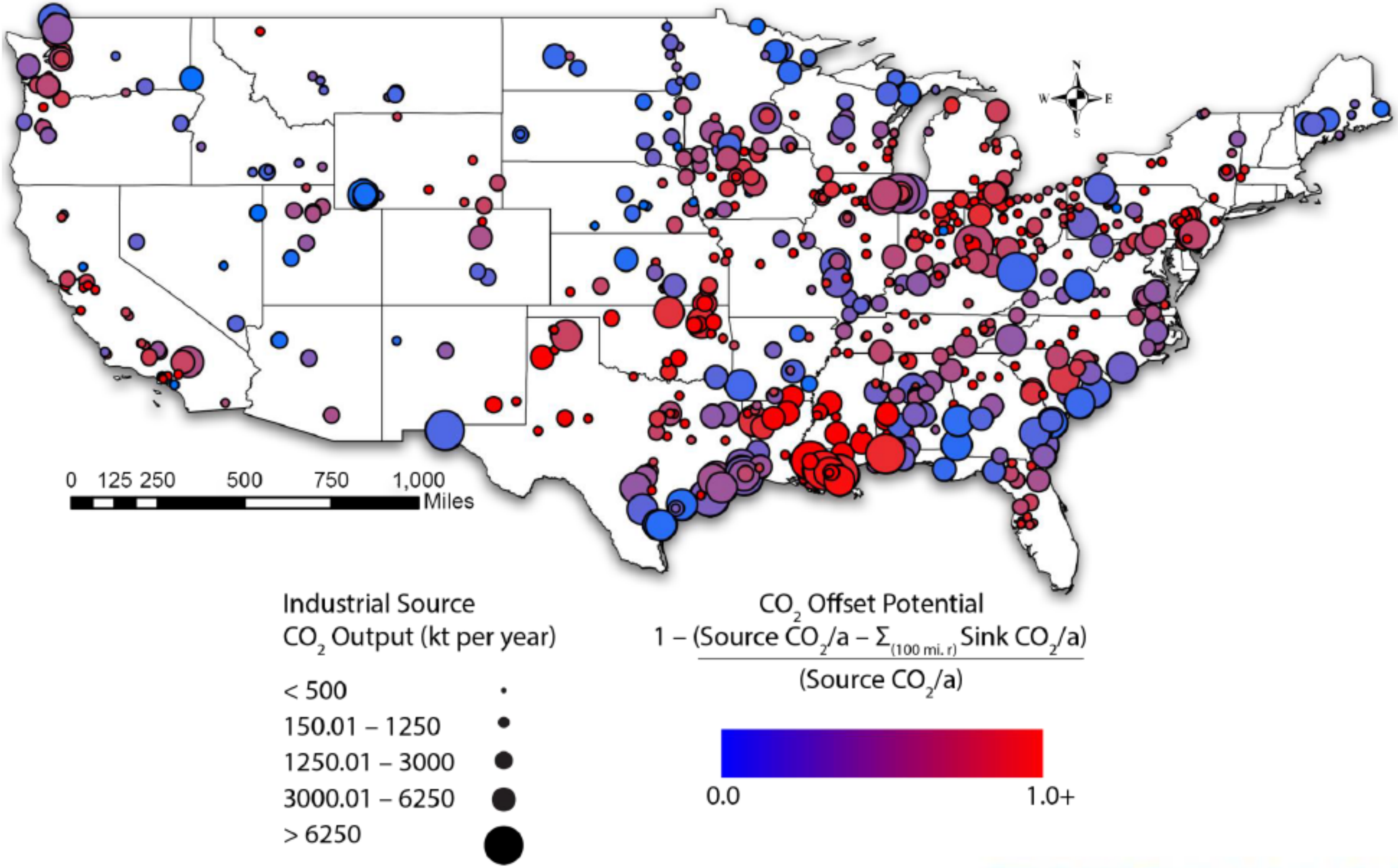
Presented by Peter Campbell Psarras, Colorado School of Mines

National Essential Industry Distribution



Psarras et. al, *A Pathway Toward Removing CO_2 Emissions from the Industrial Sector*, in review

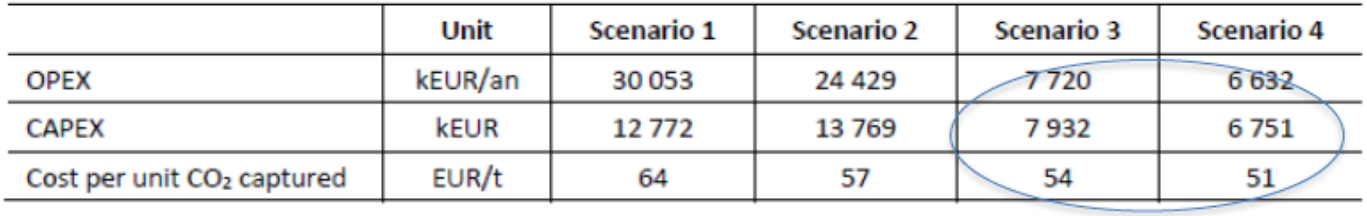
National Level – CO_2 Offset Potential



Psarras et. al, *A Pathway Toward Removing CO_2 Emissions from the Industrial Sector*, in review

Presented by Ragnhild Skagestad, Tel-Tek

Economic results



	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4
OPEX	kEUR/an	30 053	24 429	7 720	6 632
CAPEX	kEUR	12 772	13 769	7 932	6 751
Cost per unit CO_2 captured	EUR/t	64	57	54	51

The lowest capture cost per unit of CO2 is found to be Scenario 4. Here, the capture plant is reduced in size, allowing 90% capture of part of the total flue gas. Comparison of Scenario 3 and 4, shows that it is slightly more beneficial from a cost perspective to have a capture plant sized according to waste heat available.

Some modular / small scale systems have already been deployed or demonstrated.

Air Products CO2 Capture Demonstrations

Port Arthur, Texas

- 1MM ton/yr CO2 captured and used for EOR

Overview of Project Site, Port Arthur 2

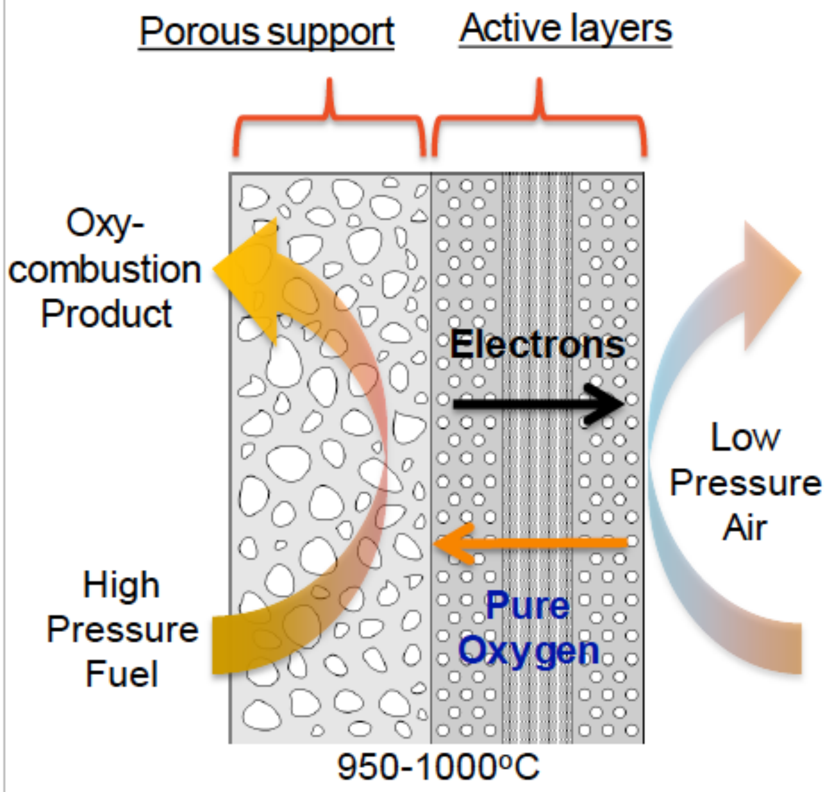
Germany

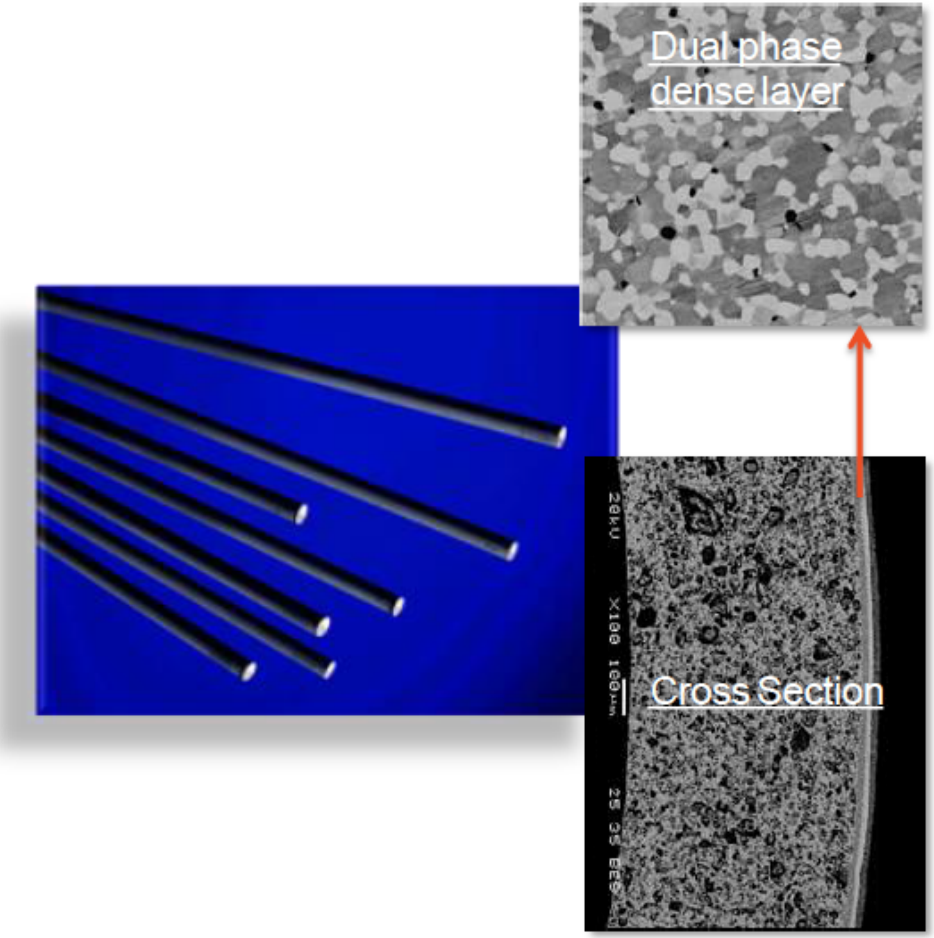
- Combination of technologies
- Low temperature separation
- Sour compression for removal of SOx and Nox
- Membrane to recover CO2 and O2 from low temp vent gas

Norway

- Containerized membrane system for CO2 capture from cement plant flue gas

OTM – How it works:





Solid-state air separation at high pressure without ASU and air compression

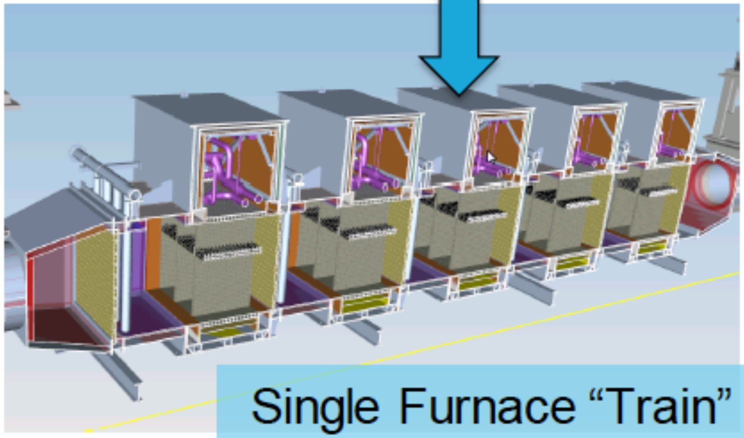
Presented by Sean Kelly, Praxair

Modular System Scale-Up

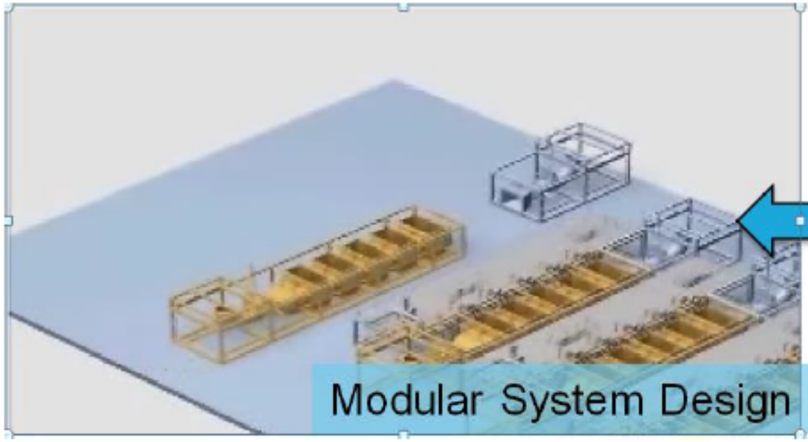
Ceramic and Reformer

Panel Array

Furnace “Pack”



Single Furnace “Train”



Modular System Design

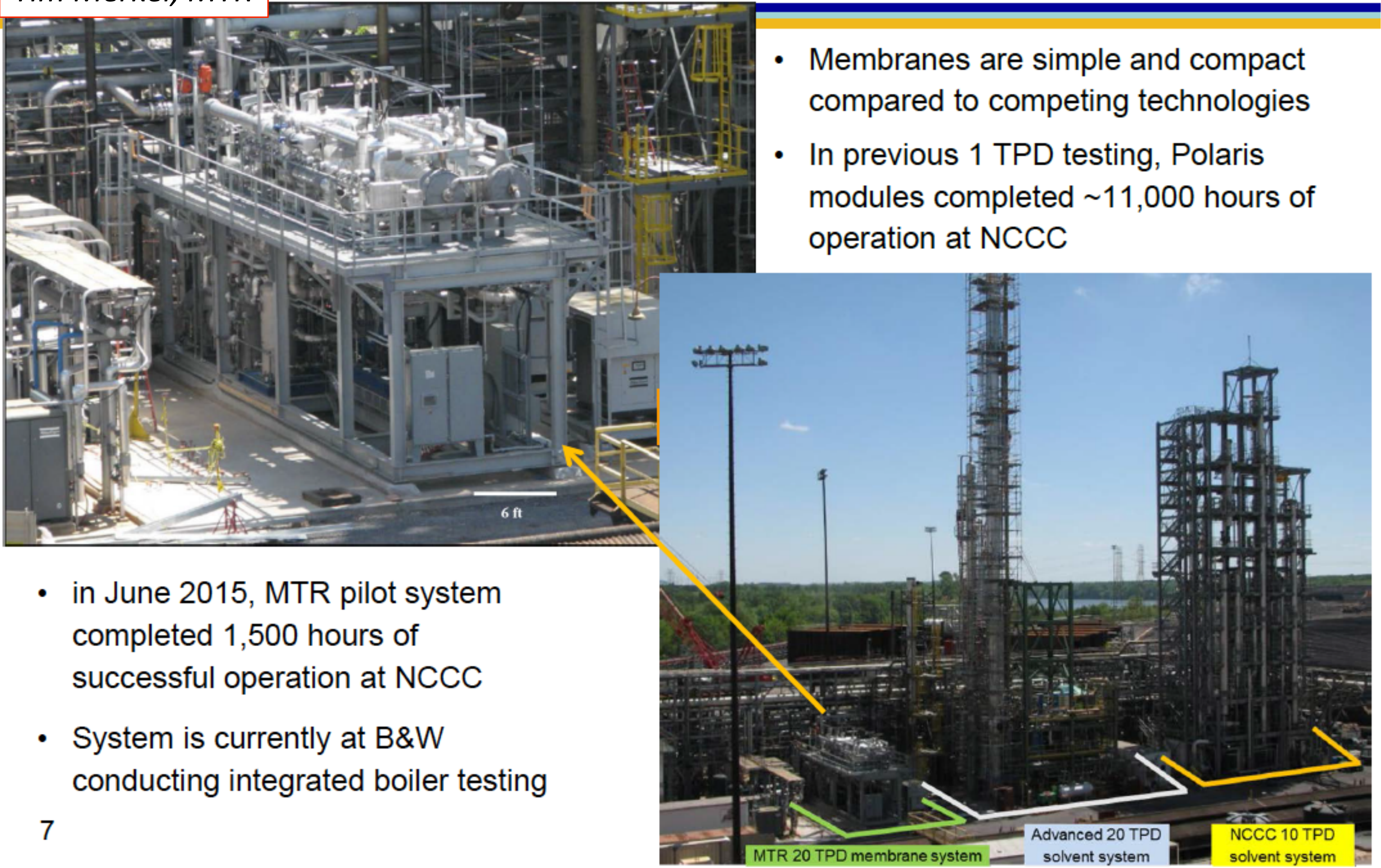
Scale-up simplified by numbering up repeatable modular elements

Presented by Sean Kelly, Praxair

Example of a Small Modular CO_2 Capture System (1 MW)

Presented by
Tim Merkel, MTR

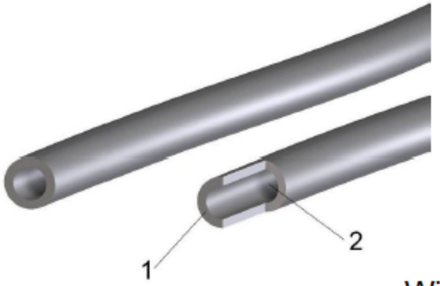
- Membranes are simple and compact compared to competing technologies
- In previous 1 TPD testing, Polaris modules completed ~11,000 hours of operation at NCCC



- in June 2015, MTR pilot system completed 1,500 hours of successful operation at NCCC
- System is currently at B&W conducting integrated boiler testing

Other technologies are promising.

A Modular Design



Wikimedia

Hollow Fibers

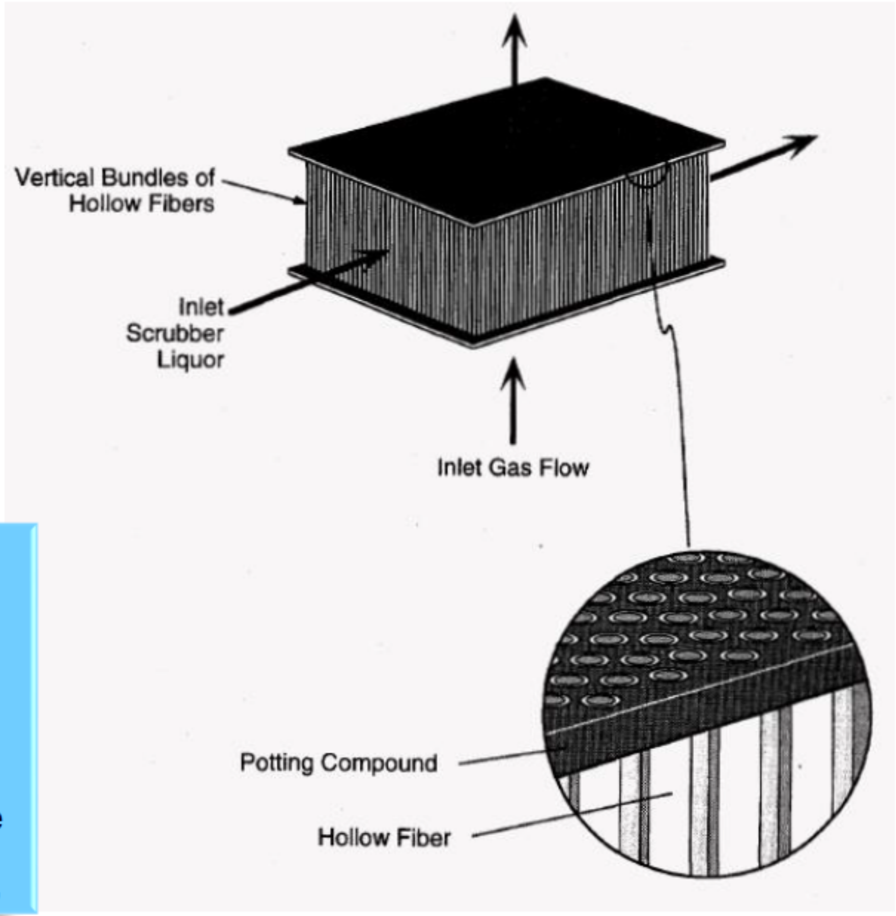
~200-500+ μm diameter

Billions of fibers needed for power plant flue gas

Arrange as rectangular modules

Stack side-by-side to accommodate large gas flowrate

Stack on top of each other to remove SOx, NOx, CO_2,



Bhown, et al., SRI International, DE-AC22-92PC91344 Final Report

Presented by Abhoyjit Bhown, Electric Power Research Institute

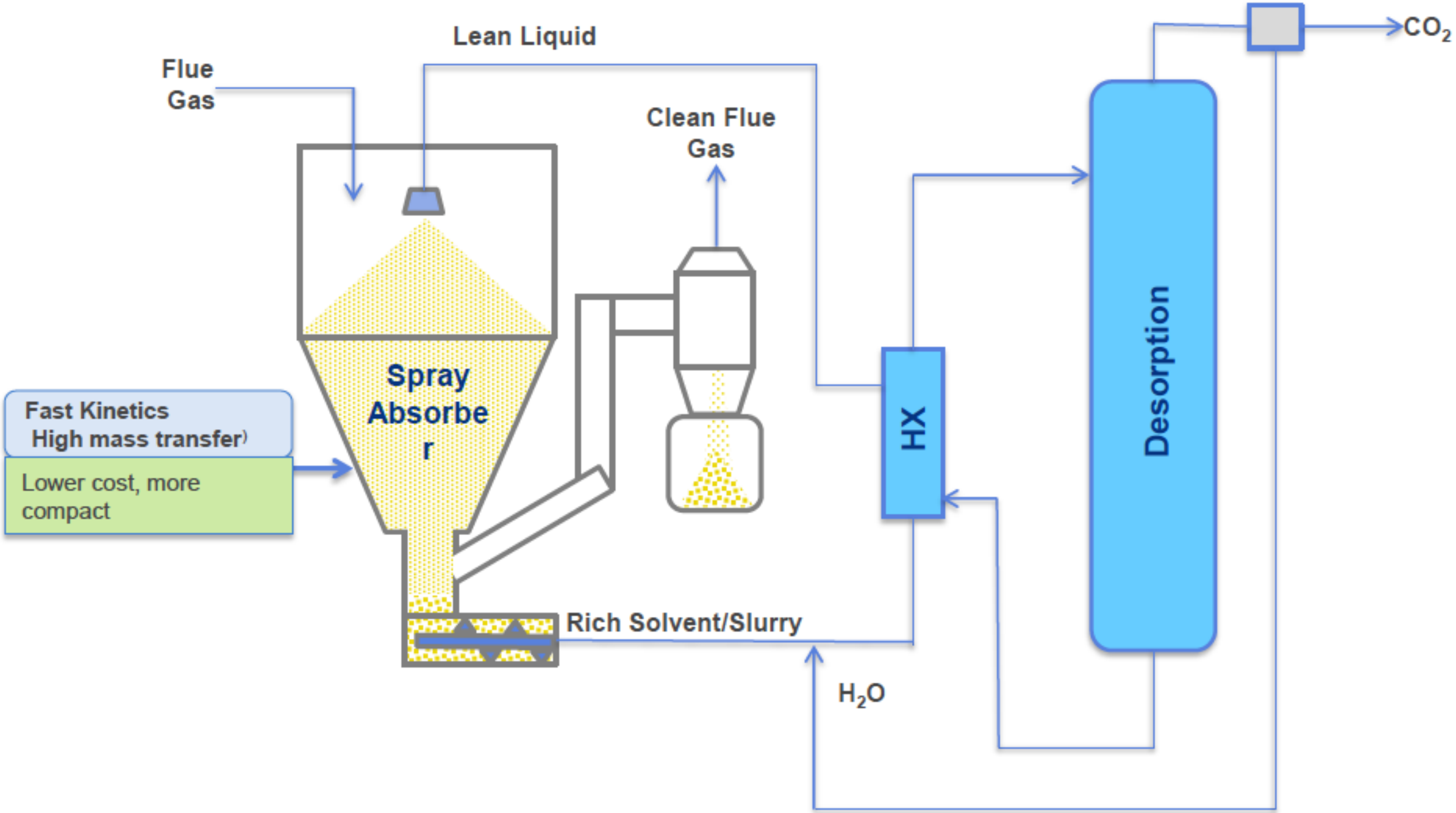
Potential Drawbacks

- Pressure drop
  - $\Delta P \sim d^4$ while area/volume $\sim d^{-1}$. Best to use flat pancake modules
- Fouling
  - Effect of particulate matter on pressure drop and mass transfer*
  - Effect of flue gas contaminants on various scrubbing solvents
- Costs
  - Can be estimated based on other membranes, but modules not made even now
  - Scrubbing chemistry can be a challenge
- Operability, reliability, lifetime, …

*Pakala and Bhown. J. Mem. Sci (1996)

Presented by Abhoyjit Bhown, Electric Power Research Institute

Phase Changing Solvent for Capture



Improved performance
through Spray Absorption

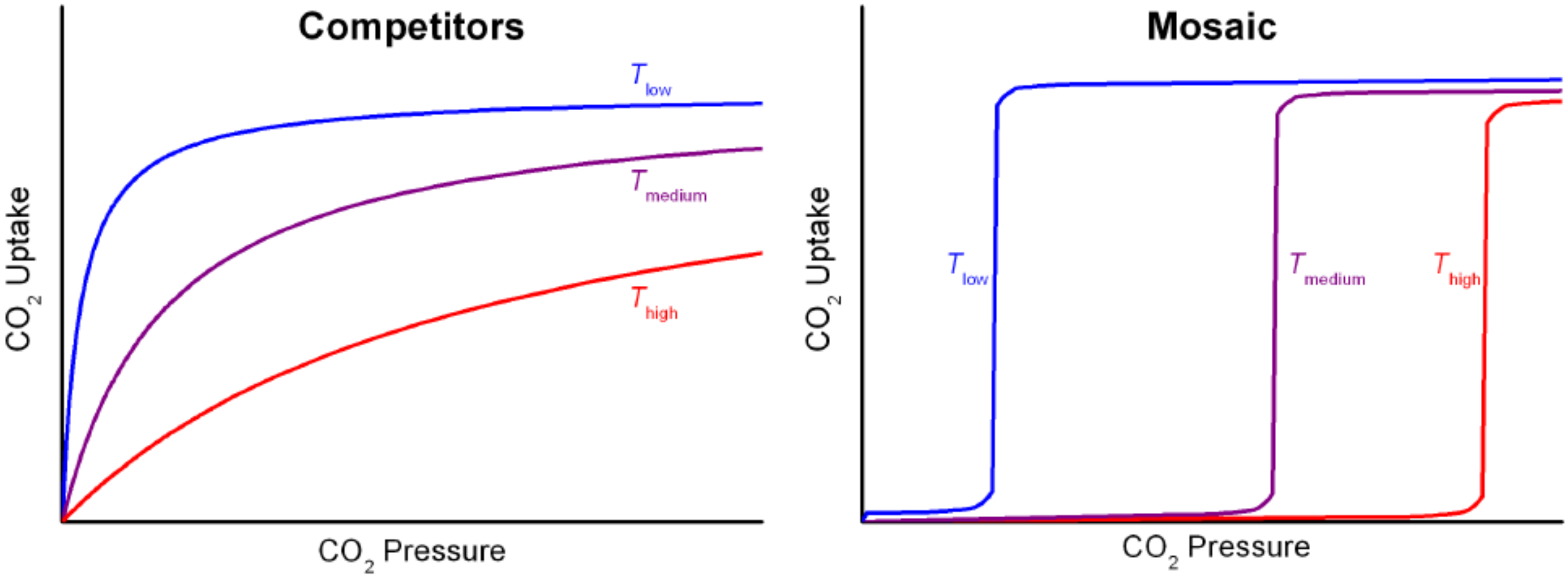
imagination at work

Presented by Teresa Grocela, General Electric

Back

Mosaic Advantage: Step-Change Adsorption

Presented by Thomas McDonald, Mosaic Materials



- Large CO_2 adsorption capacity: 12-15 wt.%
- Flexible regeneration conditions (TSA, PSA, or VSA)

Concluding thoughts

- Modules are a new paradigm in process engineering, just starting to find their best use.
- Same for additive manufacturing.
- Small-scale geologic storage would be very expensive – we need an aggregator or “market maker.”
- The “waste hierarchy for CO_2 came up repeatedly:

  Reduce > Reuse > Convert > Sequester
- Parametric design helps with matching a system to a custom scale.

Workshop presentations available at:

http://www.cvent.com/events/small-scale-and-modular-carbon-capture-workshop/custom-36-a8fdbad41e6d4dd49d32ccf72429c911.aspx

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