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Advanced Solid Sorbents and Process Designs for Post-Combustion CO_2 Capture (DE-FE0007707)

RTI International

Justin Farmer, Atish Kataria, Marty Lail, Paul Mobley, Thomas Nelson, Mustapha Soukri, Jak Tanthana

Pennsylvania State University

Chunshan Song, Dongxiang Wang, Xiaoxing Wang

Energy Research at RTI International

RTI International

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One of the world's leading research organizations

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Work in 75 countries

2,600+
Active projects

Scientific staff
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$788 million
Research budget

Energy Technologies

Developing advanced process technologies for energy applications by partnering with industry leaders

Biomass Conversion

Natural Gas

Carbon Capture & Utilization

Industrial Water

Syngas Processing

Emerging Sustainable Energies

Project Overview

Objective

Address the technical hurdles to developing a solid sorbent-based CO_2 capture process by transitioning a promising sorbent chemistry to a low-cost sorbent suitable for use in a fluidized-bed process

This project combines previous technology development efforts: RTI (process) and PSU (sorbent)

Project Funding: **$3,847,161**

- DOE Share: $2,997,038
- Cost Share: $850,123

Period of Performance:

- 10/1/2011 to 12/31/2015

RTI INTERNATIONAL

- Project management
- Process design
- Fluidized-bed sorbent

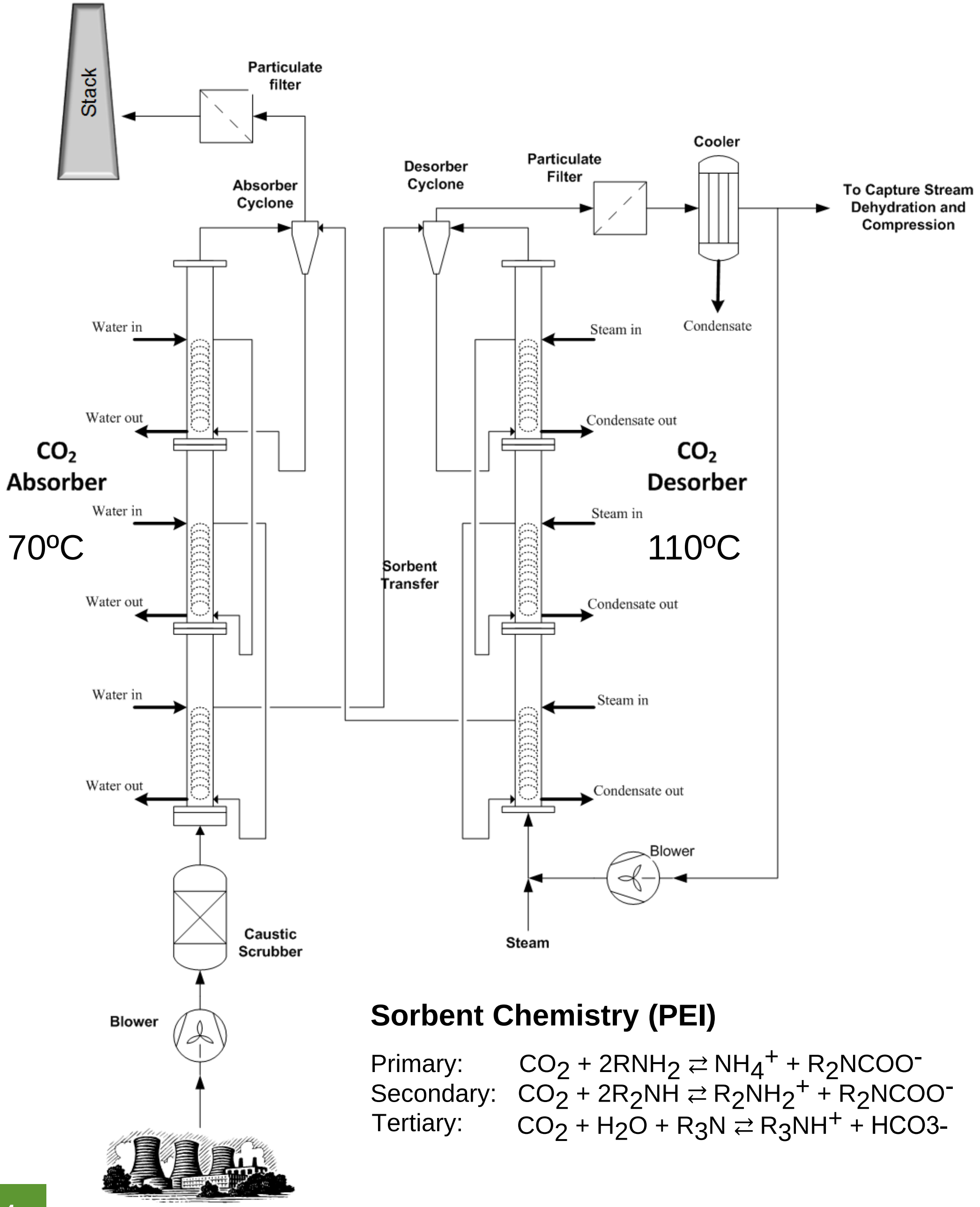
PENNSTATE 1855

- PSU's EMS Energy Inst.
- PEI and sorbent improvement

Masdar A MUBADALA COMPANY

- Masdar New Ventures
- Masdar Institute
- TEA of NGCC application

Solid Sorbent CO_2 Capture



Sorbent Chemistry (PEI)

Primary: $CO_2 + 2RNH_2 \rightleftarrows NH_4^+ + R_2NCOO^-$
Secondary: $CO_2 + 2R_2NH \rightleftarrows R_2NH_2^+ + R_2NCOO^-$
Tertiary: $CO_2 + H_2O + R_3N \rightleftarrows R_3NH^+ + HCO3-$

Technology Features

- *Sorbent*: supported polyethyleneimine
- *Process*: fluidized, moving-bed

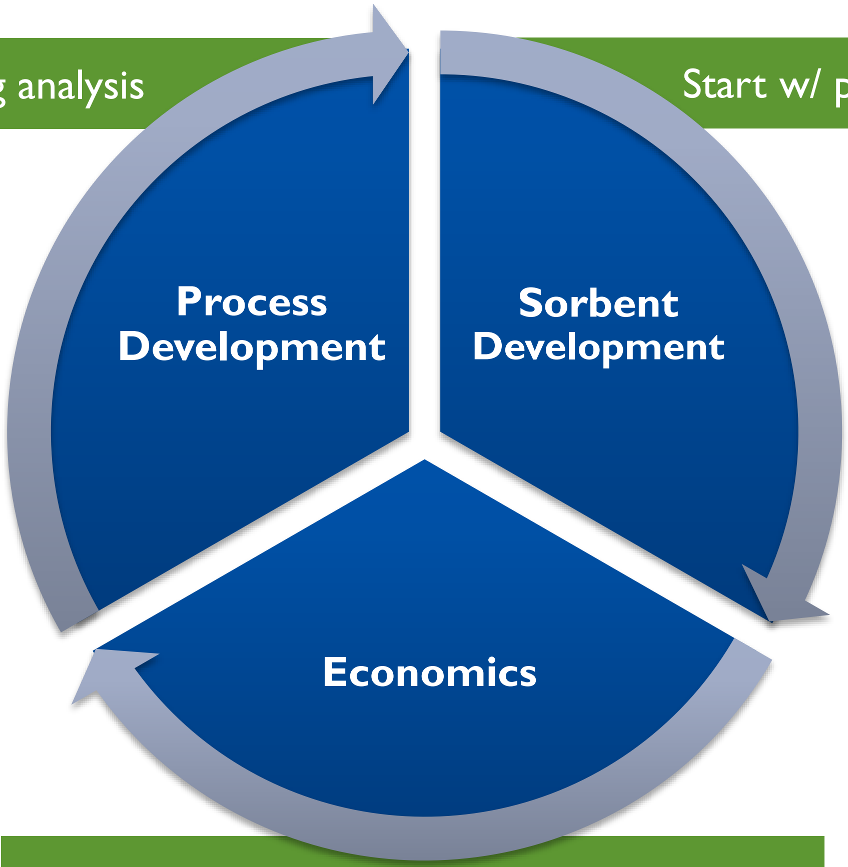
Advantages

- Potential for reduced energy loads and lower capital and operating costs
- High CO_2 loading capacity; higher utilization of CO_2 capture sites
- Relatively low heat of absorption; no heat of vaporization penalty
- Avoidance of evaporative emissions
- Superior reactor design for optimized and efficient CO_2 capture performance

Challenges

- Heat management / temperature control
- Solids handling / solids circulation control
- Physically strong / attrition-resistant
- Stability of sorbent performance

Technical Approach & Scope



Start w/ process engineering analysis

- Concluded that circulating, staged, fluidized-bed design exhibits significant promise.

Development Needs:

- Optimize reactor design and process arrangement.

Development Approach:

- Detailed fluidized bed reactor modeling.
- Bench-scale evaluation of reactors designs.
- Demonstration of process concept.

Start w/ promising sorbent chemistry

- PSU's Molecular Basket Sorbents offer high CO_2 loading; reasonable heat of absorption (66 kJ/mol).

Development Needs:

- Improve thermal stability.
- Reduce leaching potential.
- Reduce production cost.
- Convert to fluidizable form.

Development Approach:

- Modify support selection.
- Simplify amine tethering.
- Scalable production methods.

Start w/ preliminary economic screening

- Conducted detailed technical and economic evaluations
- ***Basis:*** DOE/NETL's Cost and Performance Baseline for Fossil Energy Plants
- Further reduction needed → reduced power consumption & capital cost

Technology Development Approach

Previous Work	Current Project	Future Development		
< 2011	2011-15	2016-18	2018-22	> 2022
Proof-of-Concept / Feasibility		**Pilot** 0.5 - 5 MW (eq)	**Demo** ~ 50 MW	**Commercial**

Laboratory Validation (2011 – 2013)

Economic analysis

- ***Milestone:*** Favorable technology feasibility study

Sorbent development

- ***Milestone:*** Successful scale-up of fluidized-bed sorbent

Process development

- ***Milestone:*** Working multi-physics, CFD model of FMBR
- ***Milestone:*** Fabrication-ready design and schedule for single-stage contactor

Prototype Testing (2015)

Prototype Testing

- ***Milestone:*** Operational prototype capable of 90% CO_2 capture
- ***Milestone:*** Completion of 1,000 hours of parametric and long-term testing

Updated Economics

- ***Milestone:*** Favorable technical, economic, environmental study (i.e. meets DOE targets)

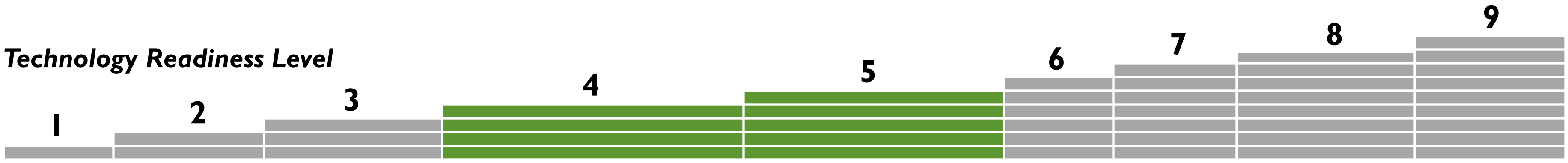
Relevant Environment Validation (2013 – 2014)

Process development

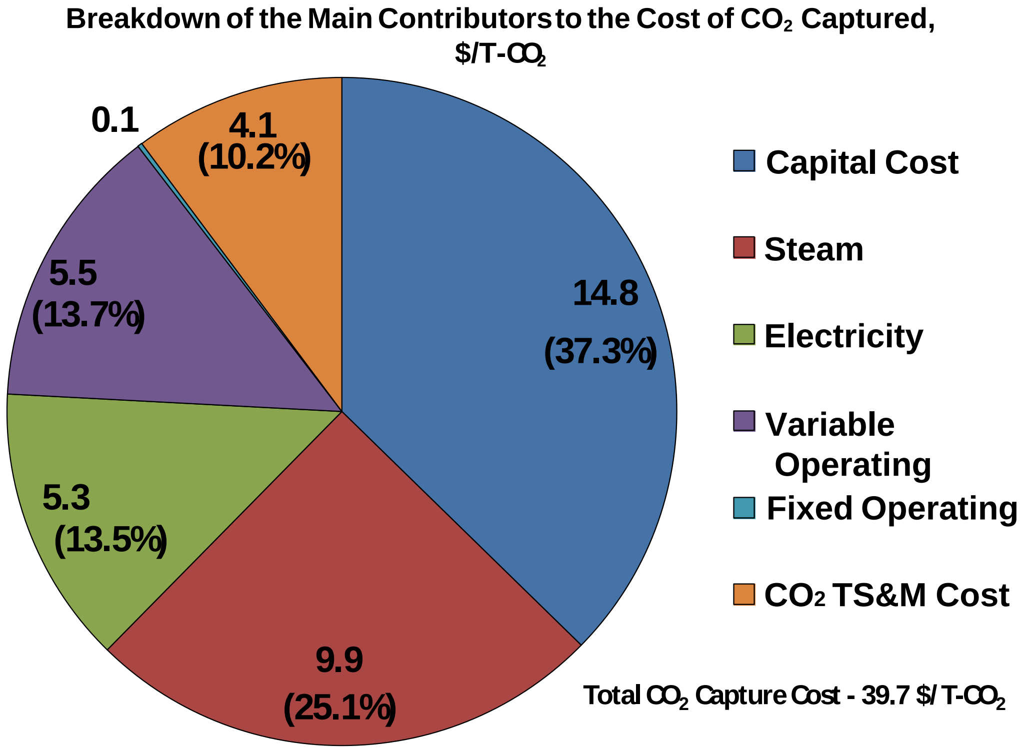
- ***Milestone:*** Fully operational bench-scale FMBR unit capable of absorption / desorption operation
- ***Milestone:*** Fabrication-ready design and schedule for high-fidelity, bench-scale FMBR prototype

Sorbent development

- ***Milestone:*** Successful scale-up of sorbent material with confirmation of maintained properties and performance



Preliminary Technology Feasibility Study



TEA to be revised in 2015 using bench-scale test data and updated guidelines from NETL

Summary

- Total cost of CO_2 captured ~ **39.7 \$/T-CO_2**
- **> 25% reduction** in cost of CO_2 capture, with > 40% reduction possible with advances in sorbent stability and reactor design
- **~ 40% reduction** in energy penalty; significant reduction in total capture plant cost (compared to SOTA)

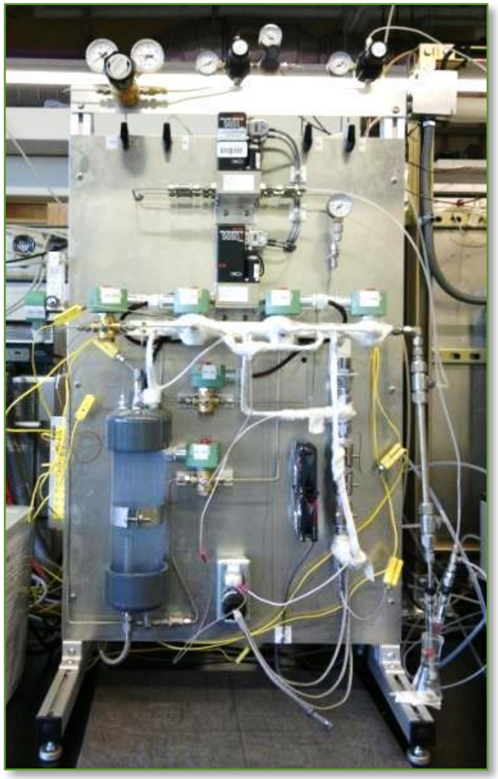
Cost Reduction Pathway

- Sorbent
  - Improve CO_2 capacity
  - Improve long-term stability; minimize losses
  - Reduce production costs
- Process
  - Heat recovery from absorber / compression train and integration into process
  - Recycle attrited sorbent particles for removal of acid gases
  - Explore lower cost MOCs and compatibility

Current Status of Project

- Test Equipment
- Sorbent Scale-up
- Bench-scale Prototype Testing
- Next Steps – Bench-scale Testing
- Next Steps – Sorbent Development
- Application to Other Industrial CO_2 Sources

Test Equipment – PBR and vFBR

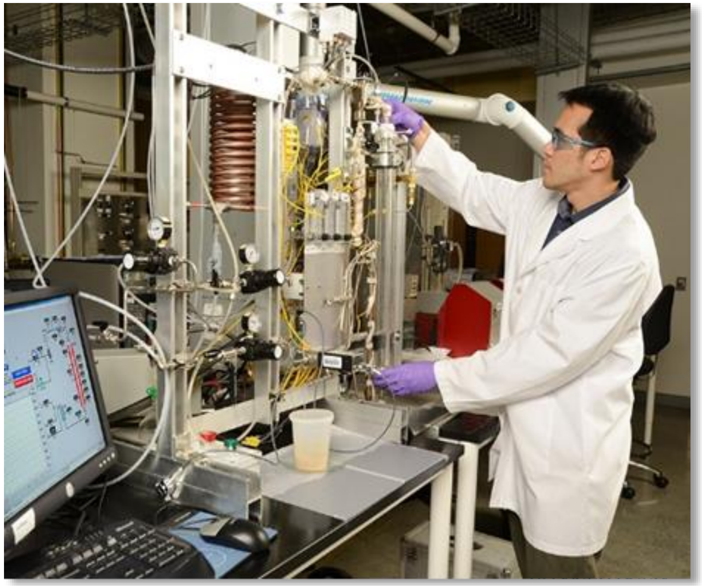


Packed-bed Reactor

- Fully-automated operation and data analysis; multi-cycle absorption-regeneration
- Rapid sorbent screening experiments
- Measure dynamic CO_2 loading & rate
- Test long-term effect of contaminants

- Verify (visually) the fluidizability of PEI-supported CO_2 capture sorbents
- Operate with realistic process conditions
- Measure ΔP and temperature gradients
- Test optimal fluidization conditions

“visual” Fluidized-bed Reactor



RTI's Bench-scale Solid Sorbent CO_2 Capture Prototype System

- *Flue gas throughput:* 300 and 900 SLPM
- *Solids circulation rate:* 75 to 450 kg/h
- *Sorbent inventory:* ~75 kg of sorbent

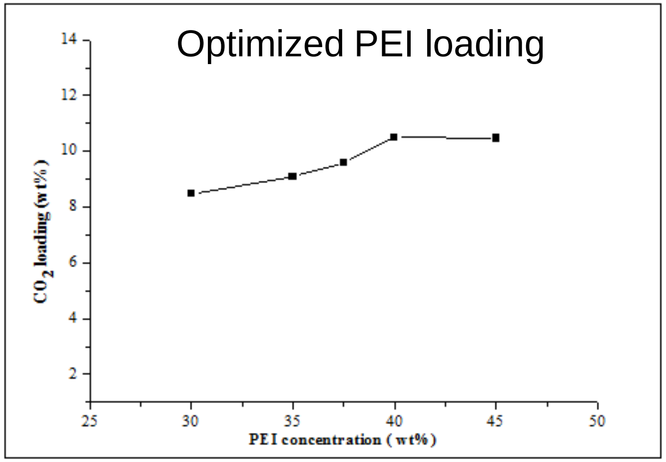
- Currently conducting prototype testing to evaluate sorbent performance and process design effectiveness

Development Progress – Sorbent Scale-up

Objective Improve the thermal and performance stability and production cost of PEI-based sorbents while transitioning fixed-bed MBS materials into a fluidizable form.

Previous Work

- Stability improvements through addition of moisture and PEI / support modifications.
- Suitable low-cost, commercial supports identified (1000x cost reduction).
- Converted sorbent to a fluidizable form.



Current Work

Gen1 Sorbent (chosen for scale-up)

- PEI on a fluidizable, commercially-produced silica support.
- Optimized Gen1 sorbent through: solvent selection; drying procedure; PEI loading %; regeneration method; support selection; etc.

Gen2 Sorbent (promising next step)

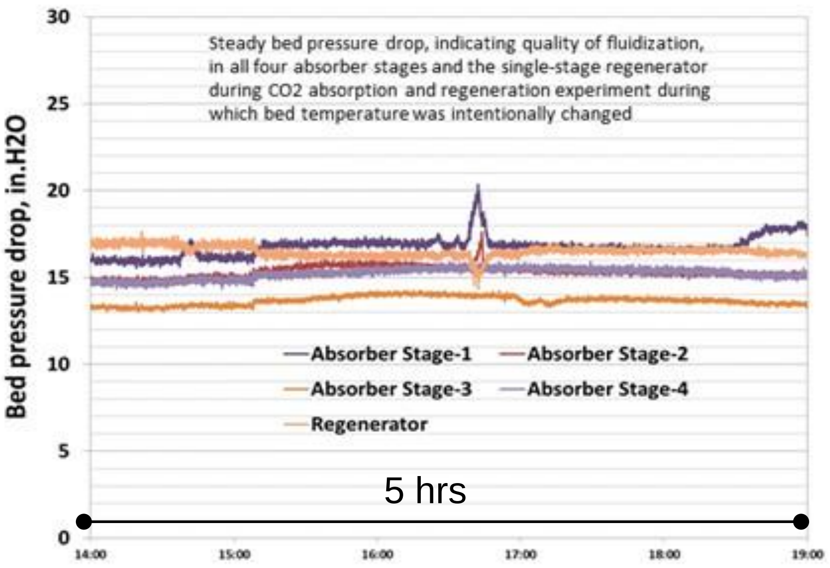
- Extremely stable sorbent, high CO_2 loadings (11 wt%).
- Provisional patent application filed.

Bench-scale Prototype Testing

Prototype system has gone through full construction, shakedown, and commissioning

Prototype system operation:

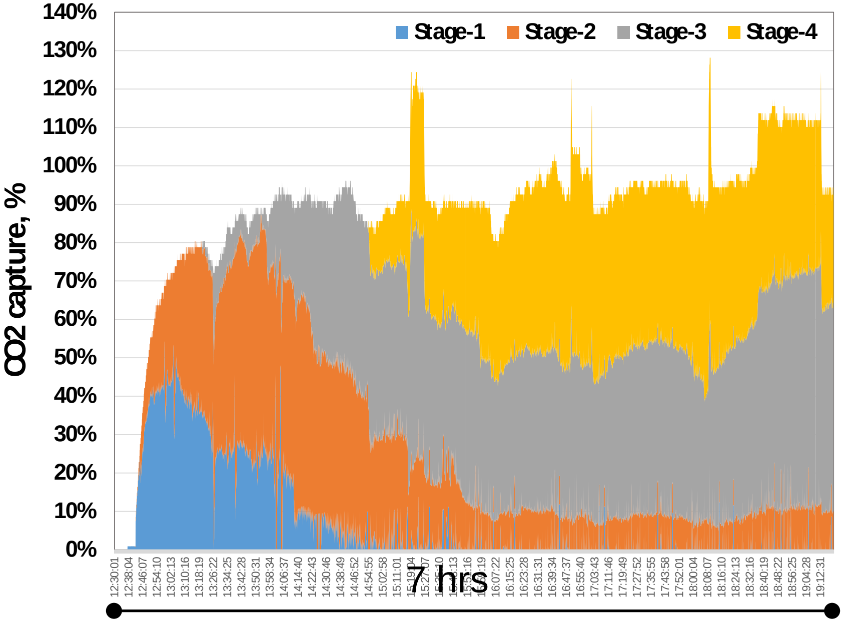
- Starting temperatures: 70˚C (Absorber); 110˚C (Regen)
- Heat exchange: CW in Absorber; Steam in Regenerator
- Pneumatic conveying of sorbent (Regen →Absorber)
- Sorbent circulation rate controlled and monitored by measurement of the riser pressure drop



FG Composition	**CO_2**	**H_2O**	**N_2**
	15 vol%	3 vol%	Balance

Highlights of prototype testing (to date)

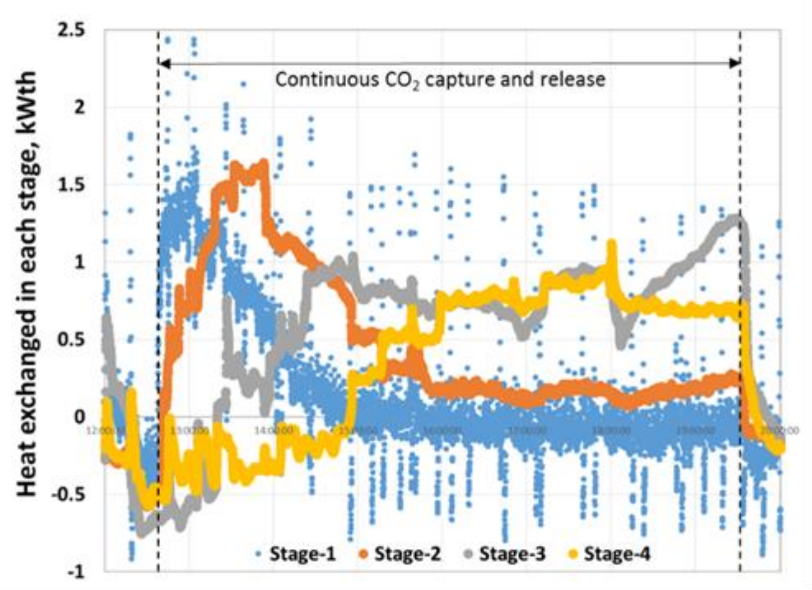
- Cumulative testing: 350+ circulation hours; 100+ CO_2 capture hours.
- The sorbent is capable of rapid removal of CO_2 from the simulated flue gas
- Sustained 90% capture of the CO_2 in the simulated flue gas stream is possible

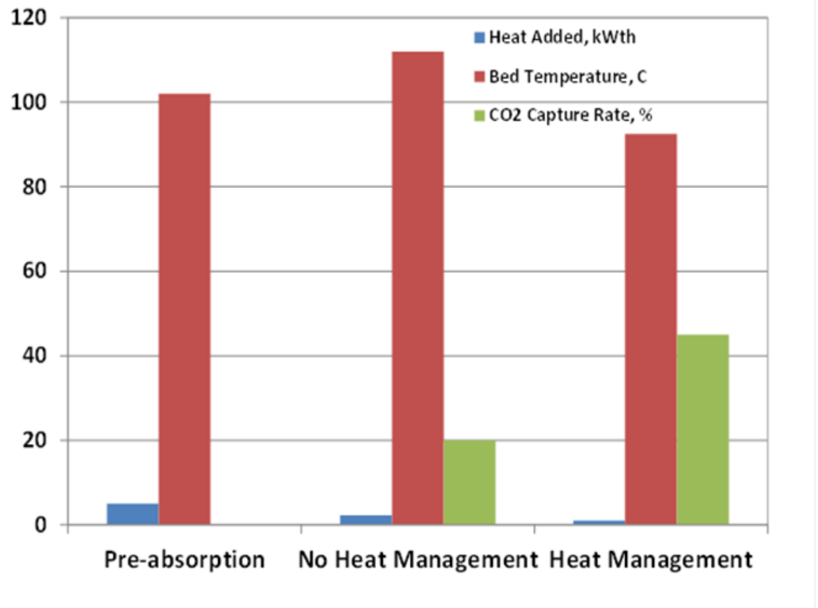


Bench-scale Prototype Testing

Highlights of prototype testing (cont'd)

- Sorbent has very good hydrodynamic properties
- Absorber temperature rise linked to CO_2 capture
- Immediately upon introduction of CO_2 to Absorber, a large exotherm is observed in the first stage and required ~1.5 kWth heat to be removed; Exotherm migrates up through the Absorber stages
- *Heat Management Demonstration*:
    - Complicated by large heat losses to environment
    - Mitigated heat loss effects through continuous heat delivery to Absorber / flue gas
    - Able to demonstrate superior CO_2 capture performance with heat management
    - 90% CO_2 capture achieved with CW heat management + heat loss to environment
- Additional parametric studies are needed to clearly correlate process variables with system performance and assumptions from economic analyses.





Other Lessons Learned

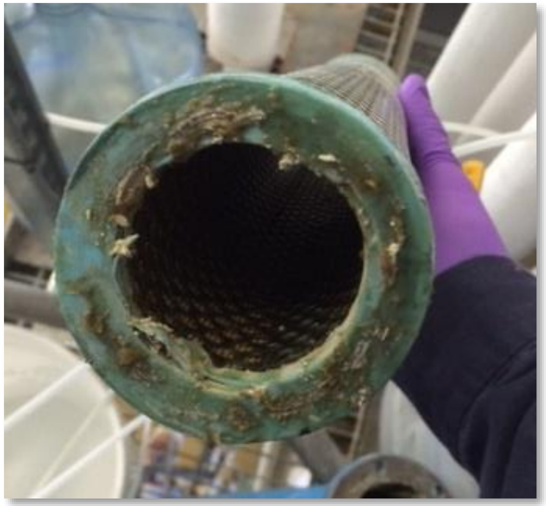

Concept Lab

Bench-scale testing

Pilot Demo

- Sorbent circulation and fluidization
  - Identified process conditions to pressure balance circulation loop
  - Calibrated circulation rate using extraction probes / ΔP measure
  - Optimized loop seal aeration approach to maximize solids circulation
  - Eliminated static electricity build-up which was causing solids agglomeration
  - Added pneumatic vibrators to downcomers to improve circulation reliability
  - Added larger diameter downcomers for additional circulation reliability
- Mechanical
  - Experienced cracking of polycarbonate viewing section due to thermal expansion differences– replaced with a SS pipe section
  - Identified need for cyclone maintenance to eliminate sorbent back-up potential
  - Modified gas entrance arrangement to primary cyclone and added secondary cyclone to improve sorbent recovery
  - Replaced rotameters with more reliable / less burdensome MFCs
- Performance
  - Minimal PEI leaching or vapor-phase degradation observed
  - Observed heat loss to the environment – requiring additional heat tracing
  - Observed oxidative degradation of sorbent which is being eliminated through modification of bench-scale riser section


Mechanical failure of PC viewp


Fouling of bench system filters

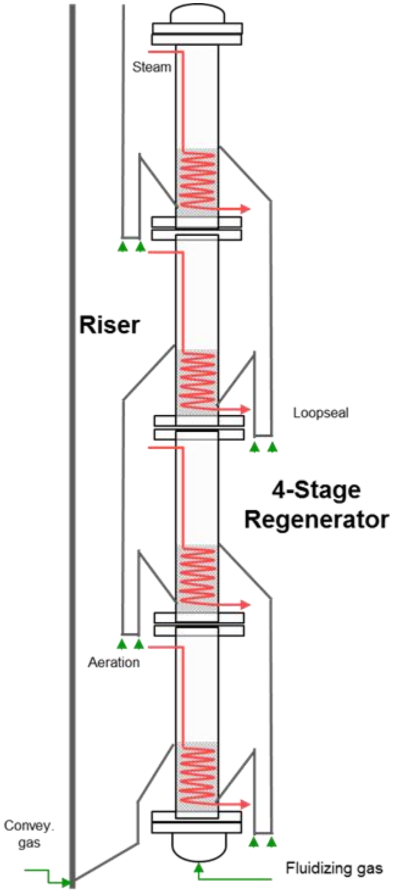
Next Steps – Parametric Testing

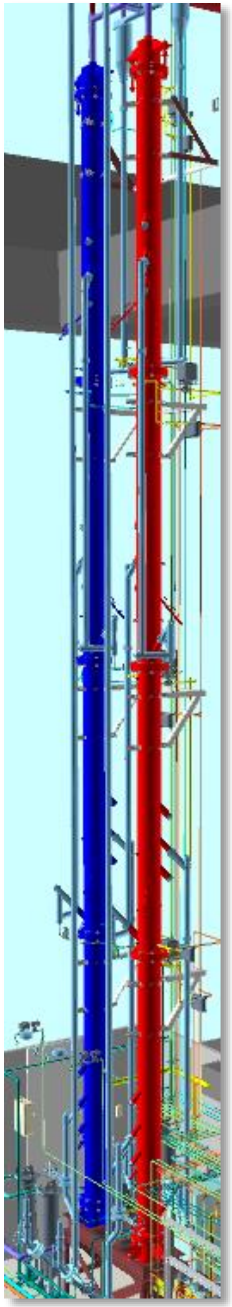
Parametric testing to be focused on key economic performance variables and assumptions

Process Variable	Range Evaluated	Notes
Focus Areas Studied		
Temperature profiles	65 to 95 °C (Absorber) 100 to 130 °C (Regen.)	• Regeneration performance improved at higher temperatures (> 120C) • Additional work will attempt to evaluate performance impact while maintaining Absorber stages at different temperatures.
Sorbent circulation rate	50 to 350 lbs/hr	• Additional work will focus on optimizing performance based on S/G ratios and will evaluate if higher circulation has impact on attrition.
Absorber temperature	65 to 95 °C	• CO_2 capture clearly improves with heat removal in Absorber. • Additional work to be performed while heat loss to environment is minimized
Focus Areas to be Studied		
% CO_2 Capture	10 to 99% capture	• Work will focus on improving S/G ratio, maximizing sorbent capacity, maximizing heat removal, and improving regenerator performance.
Sorbent stability	Stability indicators; 3 to 5 wt% loading	• PEI sorbent fluidizable under relevant process conditions. • Attrition to be quantified in parametric and long-term tests.
Sorbent bed height	Total bed height is 156”	• Work will correlate bed height with pressure drop in Absorber.
Flue gas velocity	0.4 to 0.65 ft/s	• There will be an optimization point which maximizes FG velocity > 1 ft/s, but does not entrain a significant amount of solids.
Pressure drop	3 to 4 psia	• Work will focus on minimizing pressure drop.
Heat transfer coefficient	Calc. 500-800 W/m^2K	• Work will continue to evaluate HX coefficient at different conditions.

Next Steps – Long-term Testing

- Parametric tests
- System modification: Regenerator
  - McCabe-Thiele method used to estimate optimal number of vessel stages needed for ideal CO_2 capture performance
  - Staging accomplished through separate vessels or effective staging using internals in a single column
  - Staged design is analogous to trayed columns used extensively in gas-liquid absorption/desorption processes.
  - Current regenerator configuration (single-stage) is not optimal for achieving very high sorbent working capacities.
  - Current regenerator will be replaced with staged column mimicking design of the absorber column.
- 500 hrs long-term testing goal
  - Conduct testing under optimal process conditions.

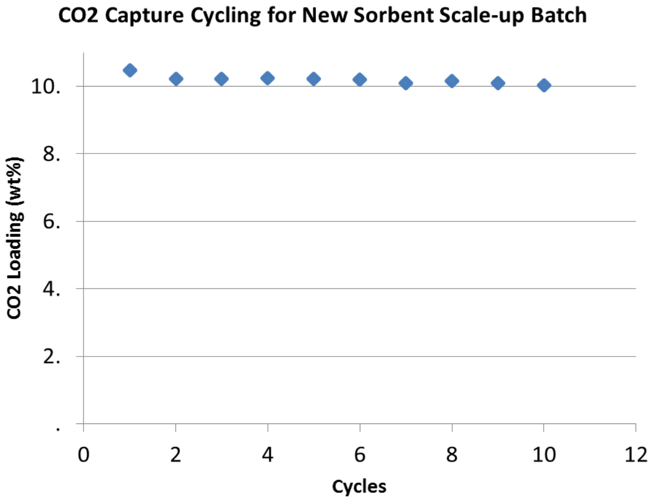




Next Steps – Sorbent Development

Supported PEI Sorbent Improvement ("Gen1")

- Fresh sorbent scale-up batch
  - 130 kg batch incorporated lab-scale improvements
  - ~ 20% increase in CO_2 loading capacity (preliminary data)
- Identifying additional optimization approaches
  - Preparation/manufacturing variables
  - Support modifiers
  - Blended amines
- Working with commercial manufacturers on silica support modifications/tailoring and to streamline production process



Water-stable Sorbents (Potential "Gen2" materials)

- Two key benefits
  - Stability in presence of liquid water
  - Very high CO_2 loading capacities (> 11 wt%)
  - Other applications (e.g. water treatment)
- These materials have other applications (potentially in water treatment applications)
- Development efforts for these water-stable sorbents are focused on key challenges:
  - Increase density and physical strength
  - Convert to fluidizable form

Application to Other Industrial CO_2 Sources

Objective

Demonstrate the technical and economic feasibility of RTI's advanced, solid sorbent CO_2 capture process in an operating cement plant

Period of Performance:

- 5/1/2013 to 10/31/2016

NORCEM
HEIDELBERGCEMENT Group

Location:

- Cement plant in Brevik, Norway

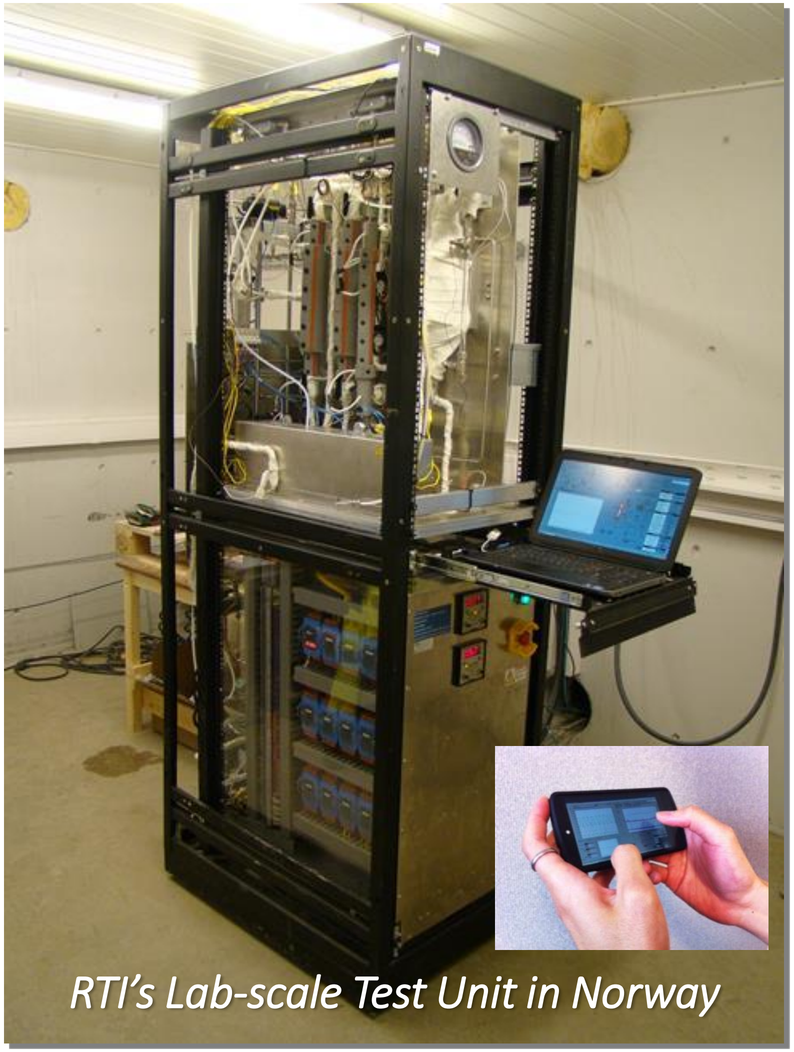
Project is structured in two phases:

Phase I - *Complete*

- Evaluate sorbent performance using simulated and actual cement plant flue gas (testing in Norway)
- Prove economic viability of RTI's technology through detailed economic analyses
- Develop commercial design for cement application

Phase II

- Design, build, and test a pilot-scale system of RTI's technology at Norcem's Brevik cement plant
- Demonstrate long-term stability and effective CO_2 capture performance
- Update economic analyses with pilot test data



RTI's Lab-scale Test Unit in Norway

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- Xiao Jiang
- Wenying Quan
- Siddarth Sitamraju
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