SRI International

2017 NETL CO_2 Capture Technology Project Review Meeting

Development of Mixed-Salt Technology for CO_2 Capture from Coal Power Plants

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Energy and Environment Center

SRI International

August 21-25, 2017 • Omni William Penn Hotel • Pittsburgh, Pennsylvania

Technology Background and Project Details

Mixed-Salt Process Details

How it works:

Selected composition of potassium carbonate and ammonium salts

- Overall heat of reaction 35 to 60 kJ/mol (tunable)

Absorber operation at 20º - 40º C at 1 atm with 30-40 wt.% mixture of salts

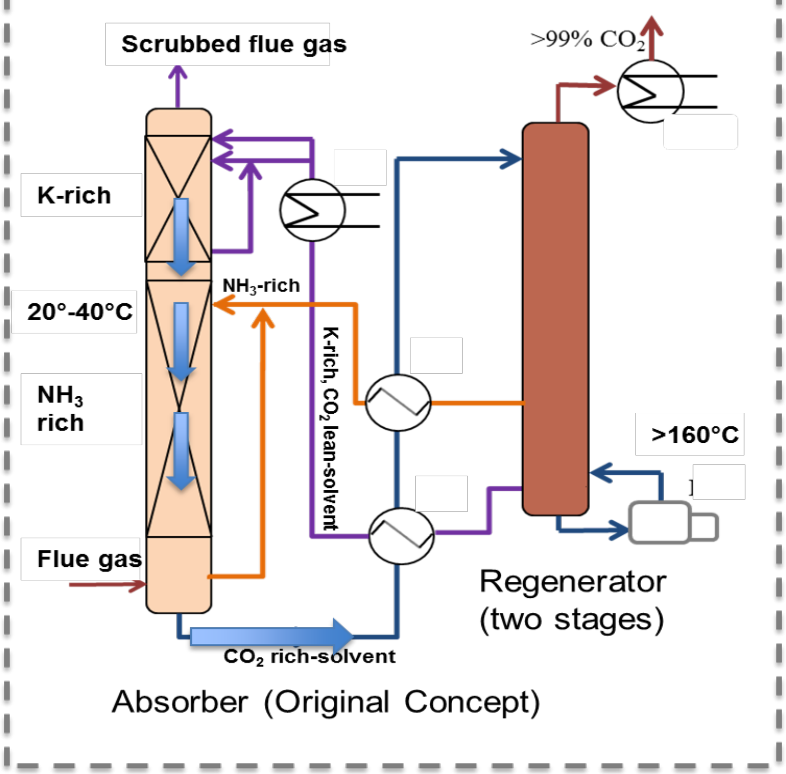
Regenerator operation at 120º - 180º C at 10-20 atm

- Produce high-pressure CO_2 stream

K_2CO_3–NH_3–CO_2–H_2O system

High CO_2 cycling capacity

No solids

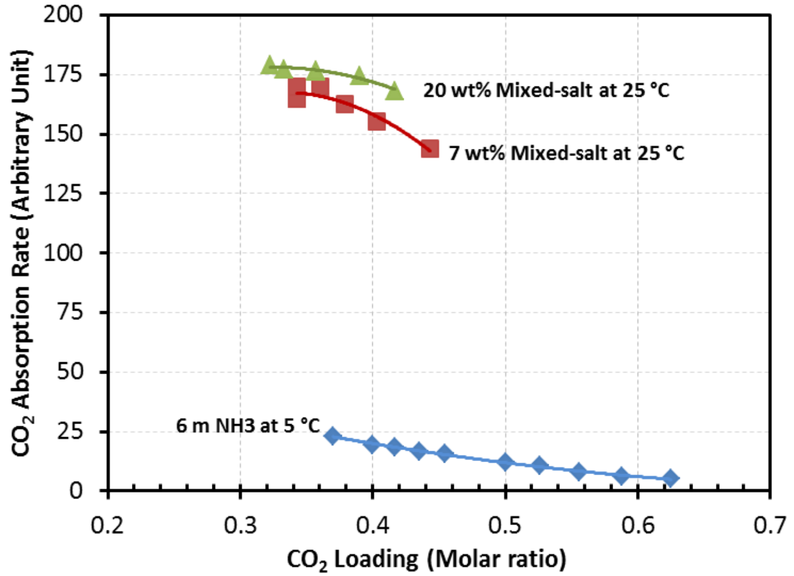


Key benefits:

- Reduced ammonia emissions
- Enhanced efficiency
- Reduced reboiler duty
- Reduced CO_2 compression energy

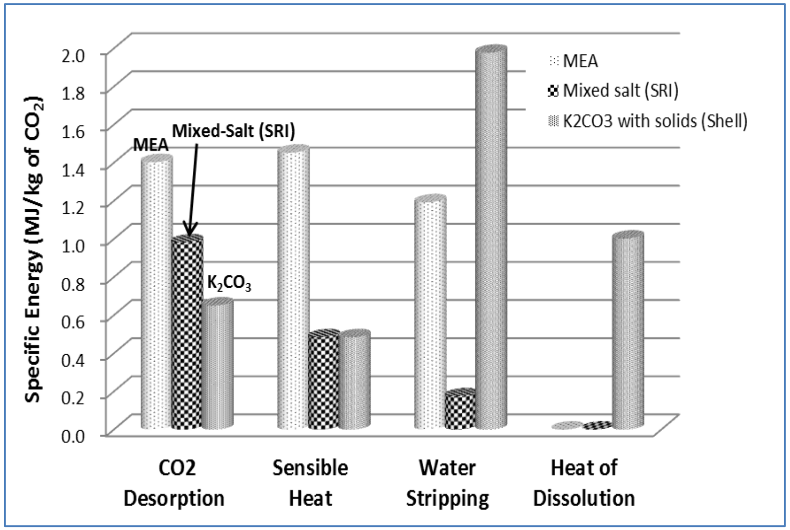
A SIGNIFICANT PARASITIC POWER REDUCTION COMPARED TO MEA !

Enhanced Kinetics at High Temperature



Observed rate enhancement of CO_2 absorption efficiency by comparison of mixed-salt with NH_3

Low Energy Requirement for CO_2 Stripping

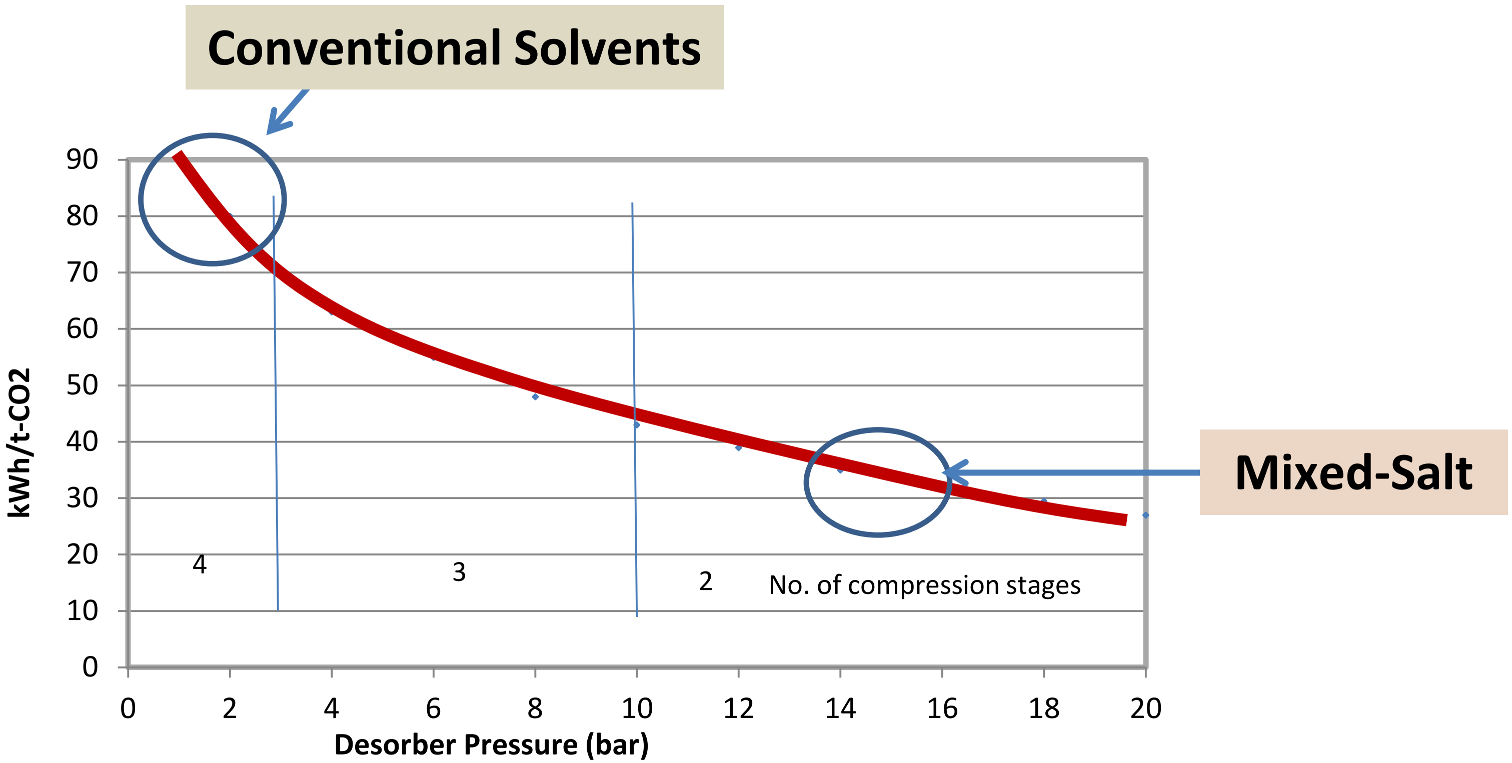


Estimated regenerator heat requirement for mixed-salt system with 0.2 to 0.6 cyclic CO_2 loading. Comparison with neat K_2CO_3 and MEA is shown

(Source for the Shell K_2CO_3 process, Schoon and van Straelen, 2011).

Absorber side: Reduced packing height
Regenerator side: Reduced water evaporation

Mixed-Salt System Requires Less Energy for CO_2 Compression



Electricity output penalty of compression to 100 bar as a function of desorber pressure

Source: Luquiaud and Gibbins, Chem Eng Res Des (2011).

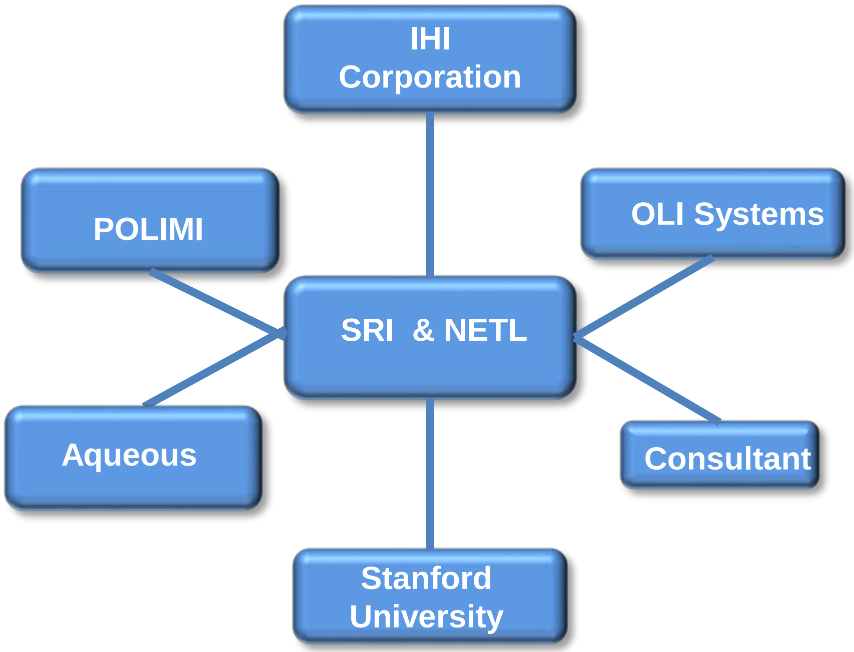
Project Budget, Team, and Work Organization

DE-FE0012959
DOE Funding: $2,817,989
Partner Share: $705,660 (50% in-kind)

Project Manager: Mr. Steven Mascaro, NETL

Prime Contractor: SRI International

Project Team: US and International Partners



Work Organization

- SRI International
  - System design, installation and testing
- IHI Corporation, Japan
  - Industrial partner/ technology evaluator
- OLI Systems, USA
  - Process modeling (energy and mass balance)
- Aqueous Systems Aps, Denmark
  - Thermodynamic modeling (Dr. Kaj Thomsen)
- POLIMI, Italy
  - Techno-economic analysis
- Stanford University (BP1), USA
  - Technology comparisons
- Consultant (BP1)

Project Goals

- Budget Period 1 (BPI)
  - Demonstrate the absorber and regenerator processes individually with high efficiency and low NH_3 emissions
  - Develop comprehensive thermodynamic modeling package

- Budget Period 2 (BP2)
  - Demonstrate the complete CO_2 capture system, optimize system operation, and collect data to perform the detailed techno-economic analysis (TEA) of the CO_2-capture process integration to a full-scale power plan
  - Test two alternative flowsheets for process optimization, test the system at highest possible CO_2 loadings, and determine the steam usage for regeneration
  - Update the TEA and conduct EH&S analysis of the process

The overall program objective is to demonstrate that mixed-salt technology can capture CO_2 at 90% efficiency and regenerate (95% CO_2 purity) at a cost of $\leq$\$40/tonne to meet the DOE program goals.

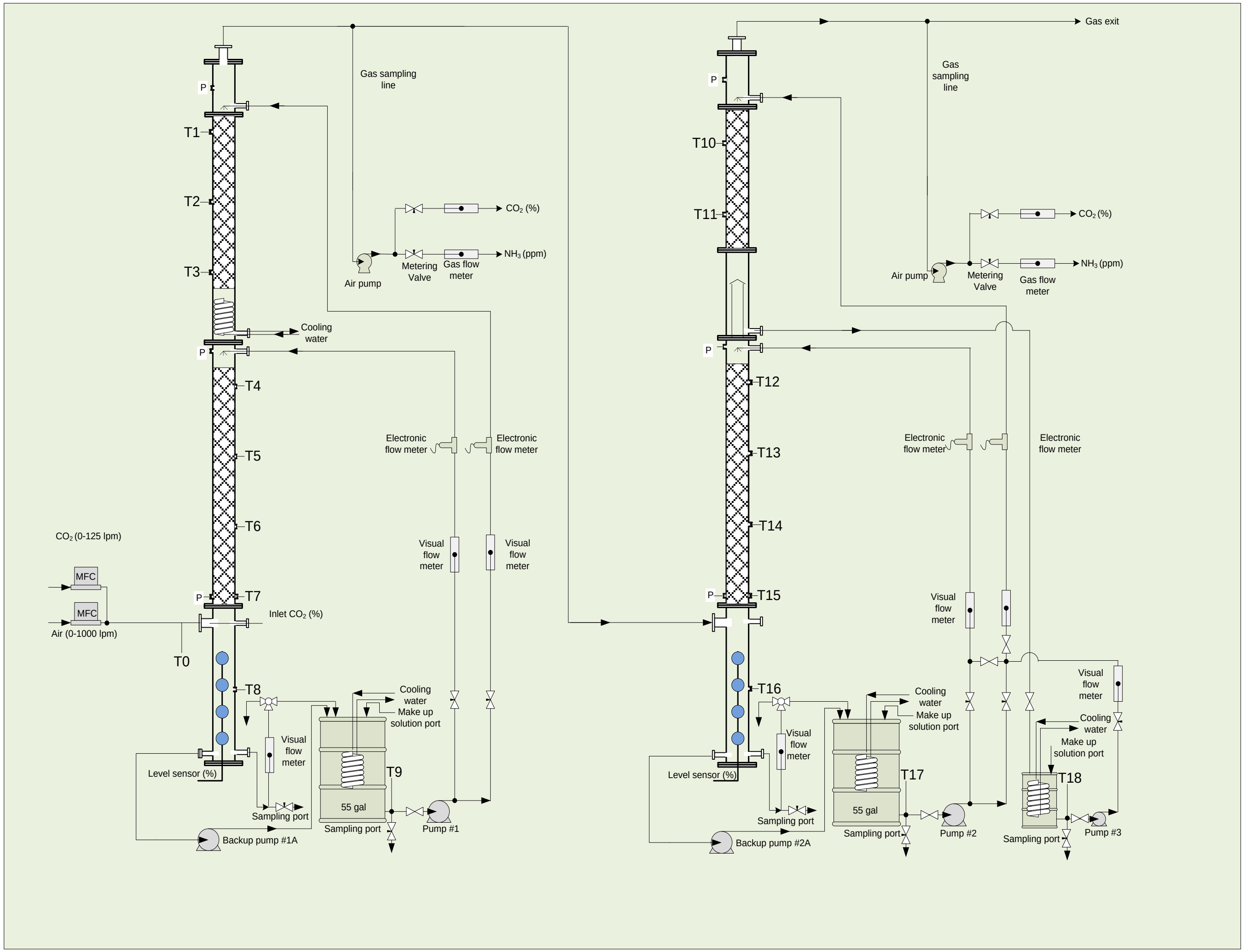
Work Performed

Project Status Update

BP2 Extended Program (2/28/2018)	Status
Task 1.0 - Project Management and Planning	
Task 7.0 - Integrated System Testing (Variant 1)	**Completed**
Subtask 7.1 - System Modification	
Subtask 7.2 - Operation with Variant 1	
Subtask 7.3 - Operational Data Analysis	
Task 8.0- Integrated System Testing (Variant 2)	**Completed**
Subtask 8.1 - System Modification	
Subtask 8.2 - Operation with Variant 2	
Subtask 8.3 -Operational Data Analysis	
Task 9.0- High-Capacity Runs and Modeling Update	
Subtask 9.1 - Modeling of High-capacity Solvent	Completed
Subtask 9.2 - System Operation at High Capacity	Ongoing
Subtask 9.3 - Mass Balance and Energy Update (OLI)	Completed
Subtask 9.4 - TEA update (POLIMI, SRI, & OLI)	Completed
Task 10.0- Regenerator Steam Use Measurement and Modeling	
Subtask 10.1 - Regenerator Steam Use Measurement	Ongoing
Subtask 10.2 - IHI System Testing and Modeling	Ongoing

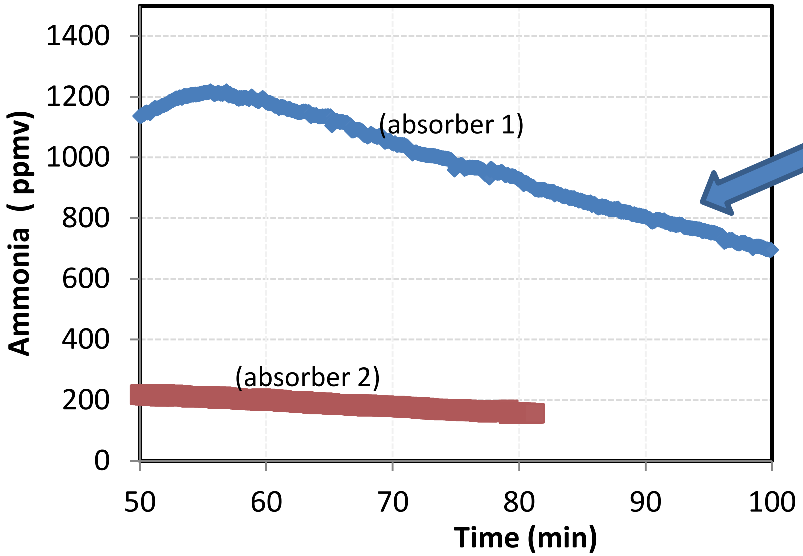
We completed the BP1 and BP2 Tasks 7 & 8 on time and updated the TEA after completing Task 8. Tasks 9 & 10 will be completed on schedule.

Schematic of the Absorber System (BP1)

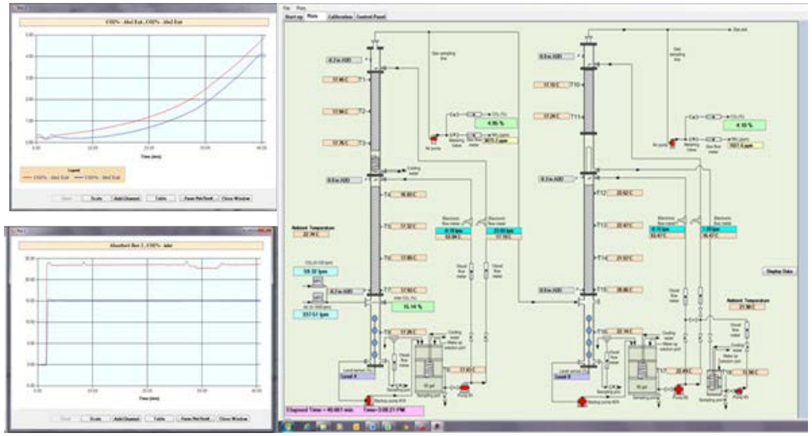


April, 2014

Process Control And Monitoring

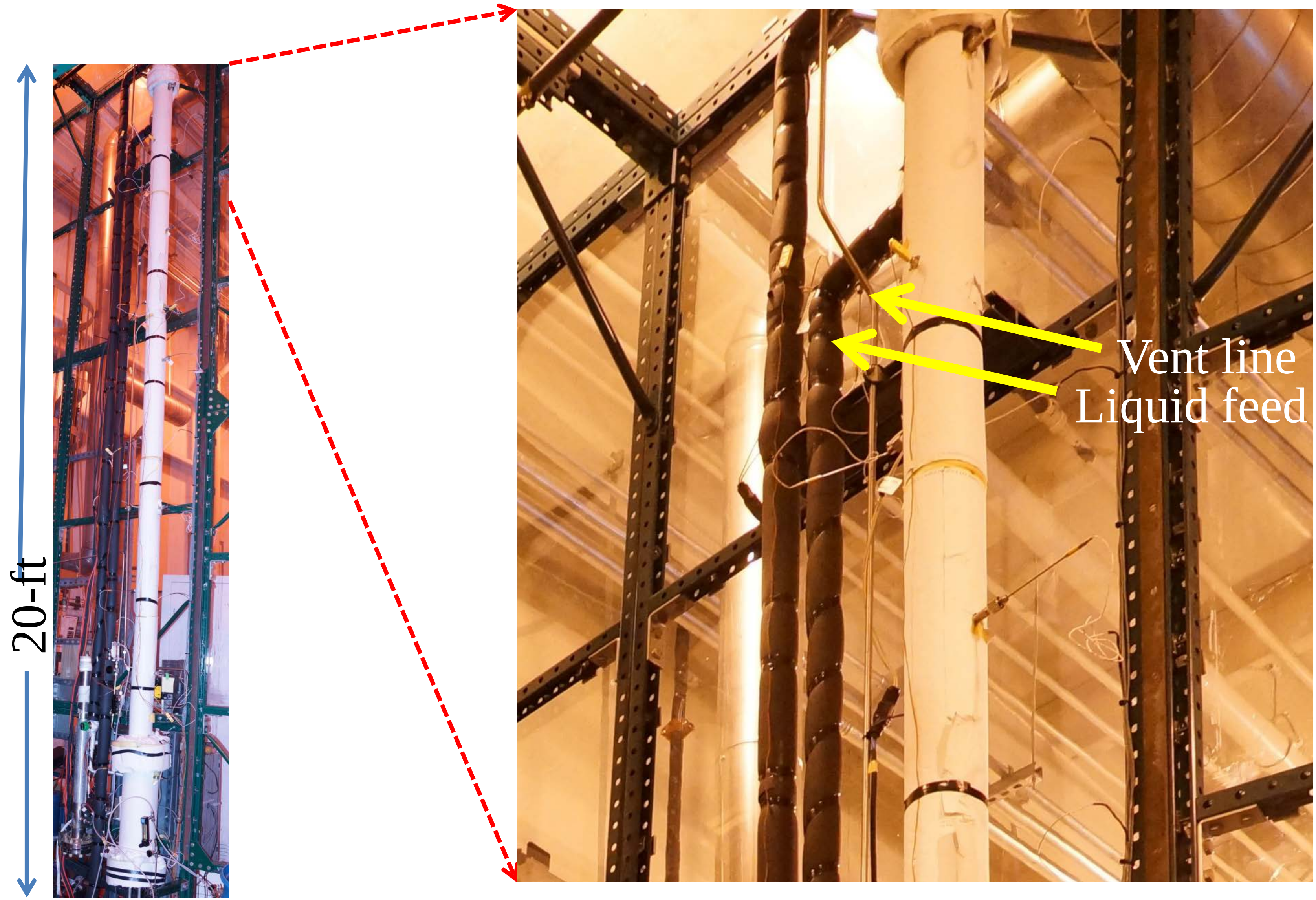


Data acquisition and control hardware
interface



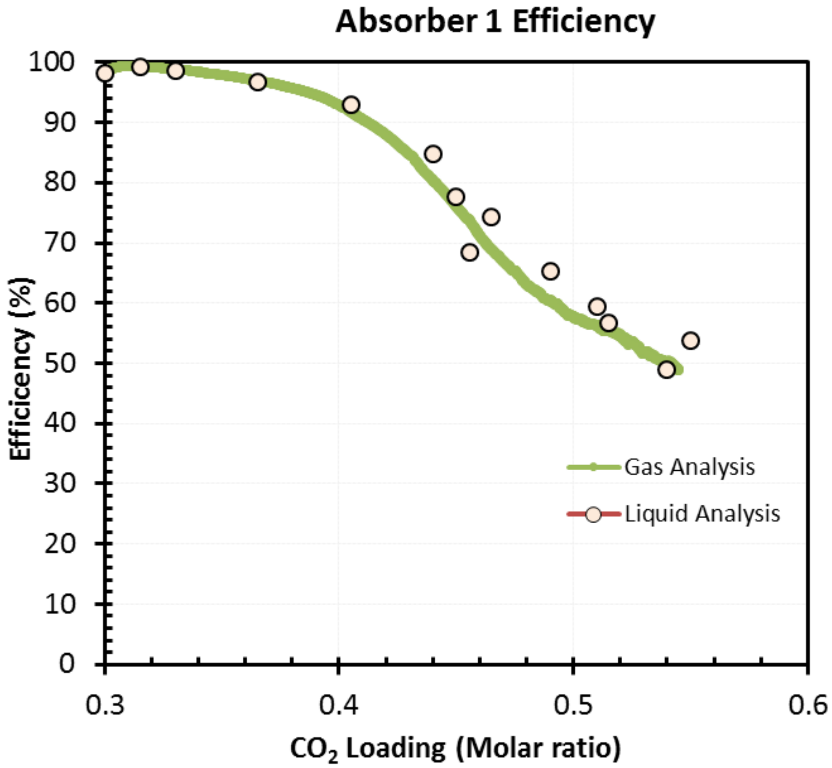
Online data monitoring

Regenerator System (BP1)



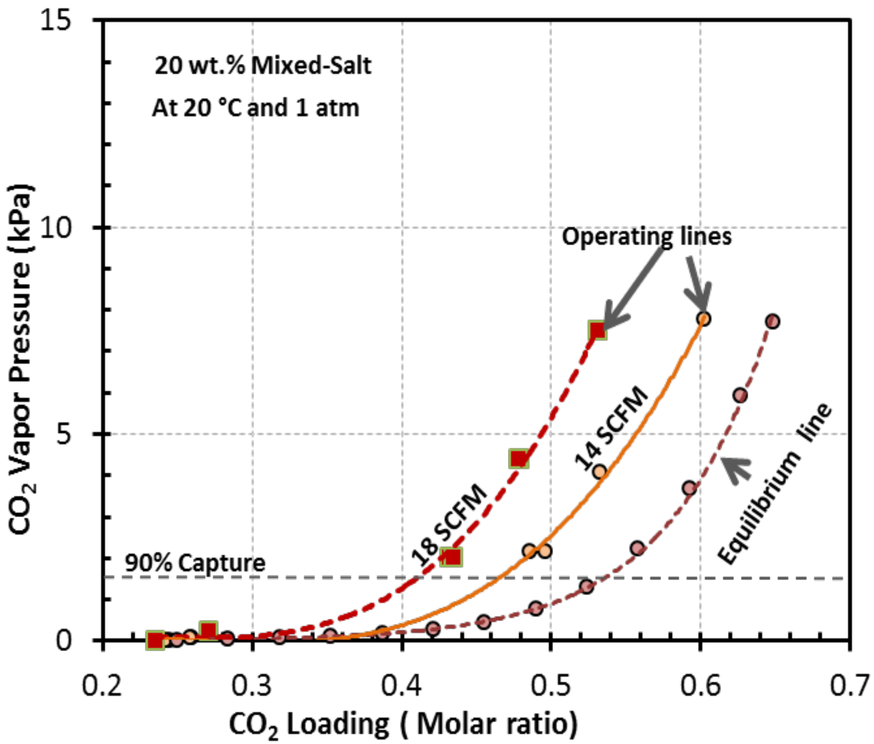
Bench-Scale Absorber Performance (BP1)

Test Data



Better than 90% efficiency with incoming lean absorption solution and < 0.4 CO_2 loading at 25°C.

Modeling and Test Data

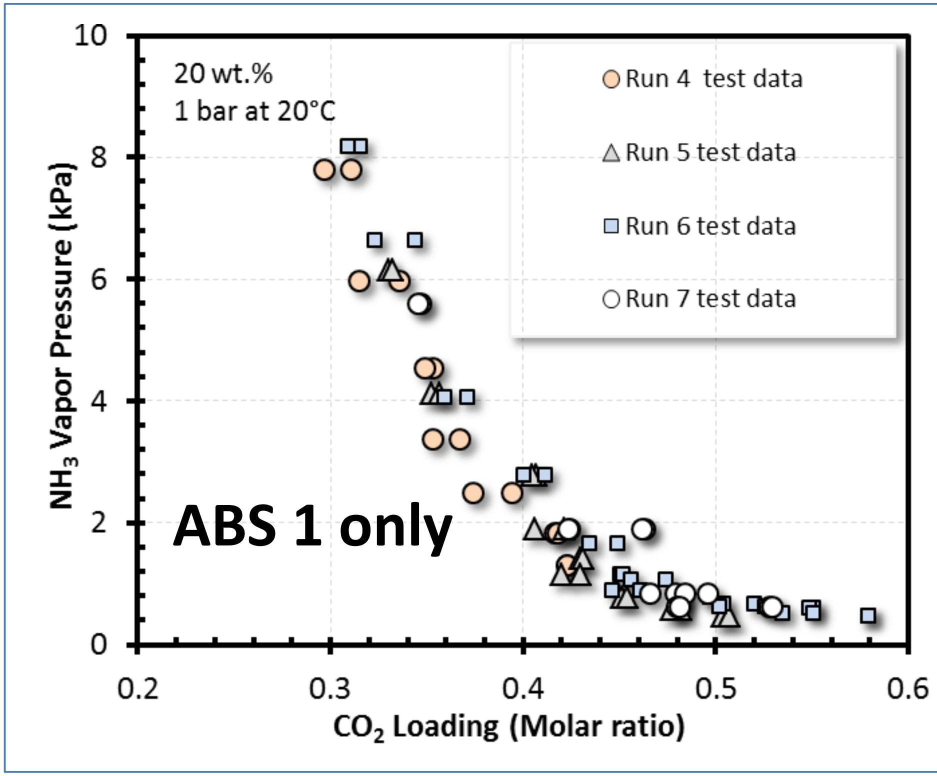


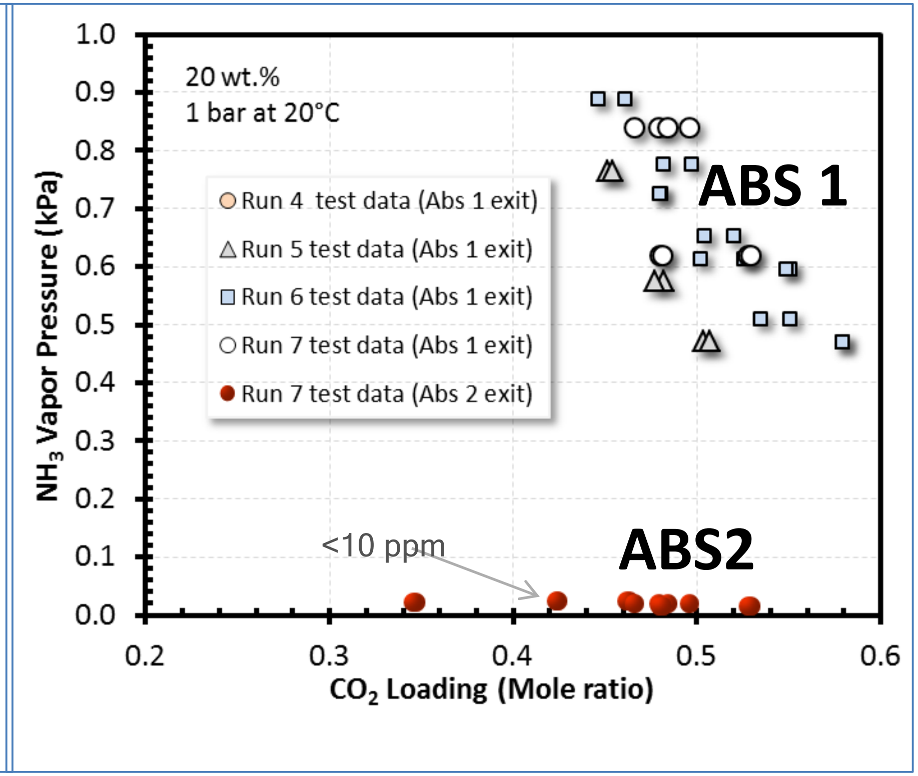
CO_2 vapor pressure at the absorber exit under various CO_2-loading conditions

The observed overall rates for CO_2 absorption are on the same order as those of MEA-based systems and about 5-7x higher than conventional ammonia systems.

Absorber Ammonia Management (BP1)

Test Data





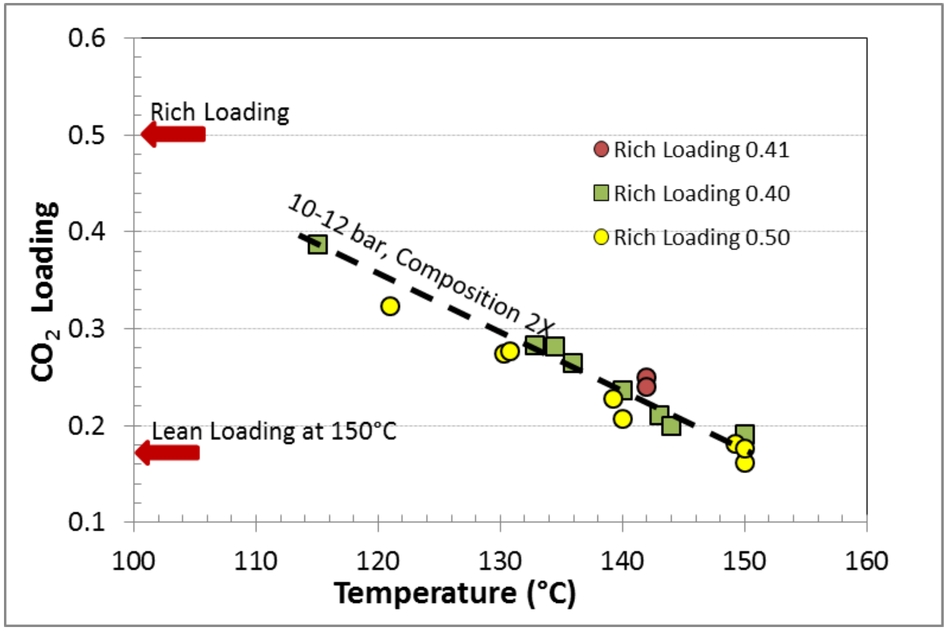
NH_3 vapor pressure at the Absorber 1 exit under various CO_2-loading conditions

NH_3 vapor pressure at the Absorber 1 and 2 exits under various CO_2-loading conditions

Regenerator Performance (BP1)

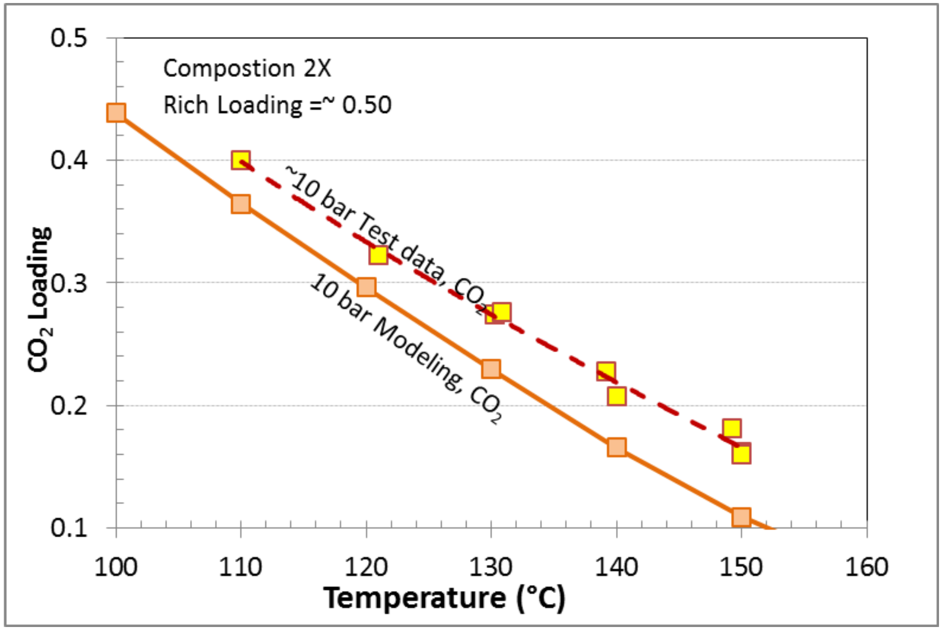
Single-Stage Regenerator (Oil heated)

Test Data



Variation of attainable CO_2-lean loading level with temperature for rich loadings of 0.40 to 0.50 at 10-12 bar.

Modeling and Test Data



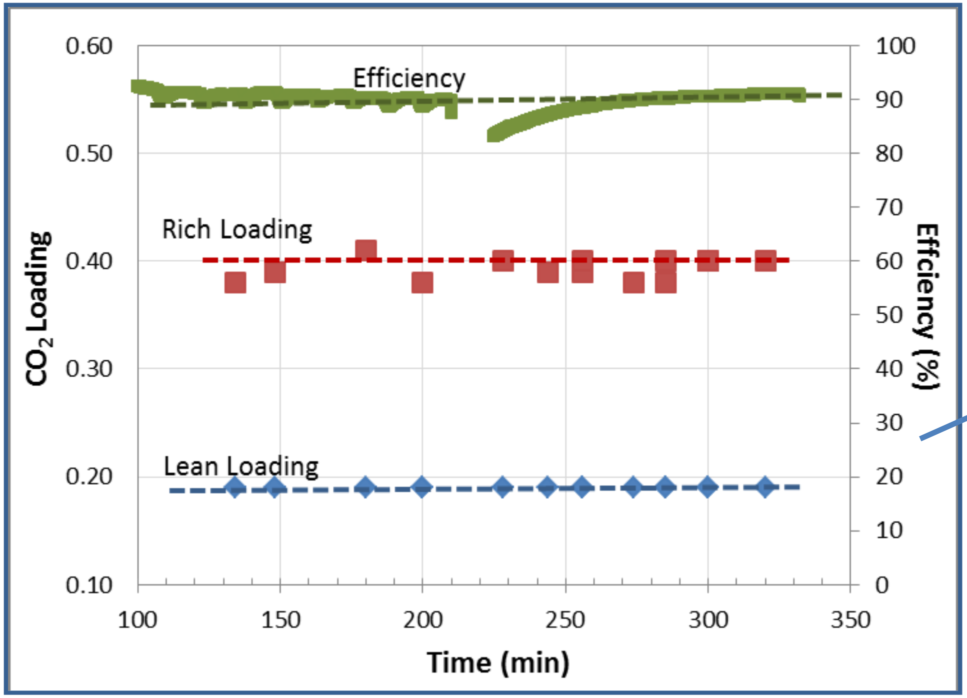
Comparison of measured and modeled attainable CO_2-lean loading at 100 to 150 ˚C.

Process was demonstrated with cyclic loading from 0.2 to (lean) to 0.5 (rich) at 150° C

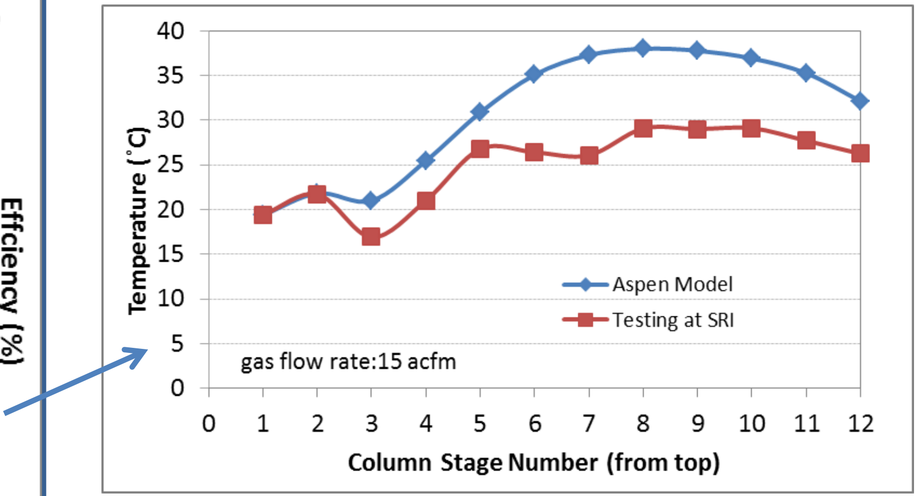
The produced lean loading far exceeds that required for > 90% CO_2 capture from flue gas streams

System Testing in Continuous Mode (BP1)

Test Data



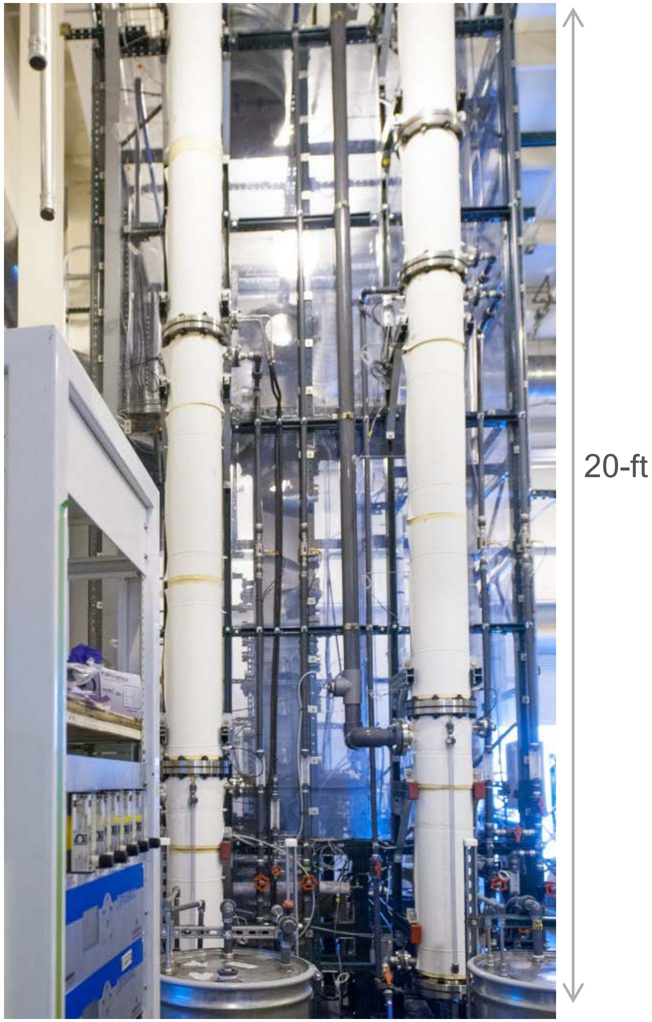
Modeling and Test Data



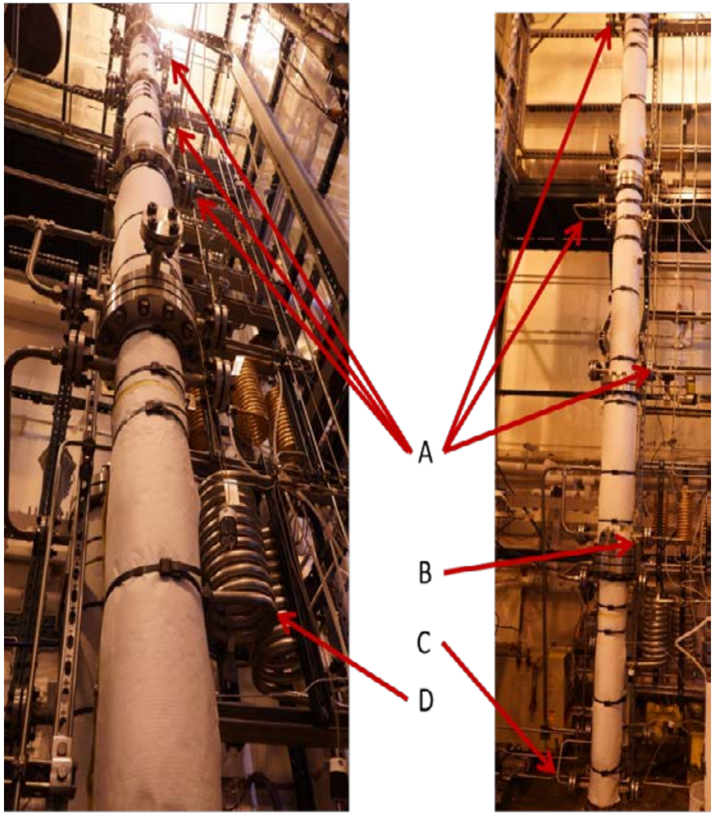
90% CO_2 capture efficiency with 0.19 to 0.40 cyclic CO_2 loading in Absorber 1 (regenerator at 140 ℃)
Gas flow rate = 15 acfm

Large Bench-Scale Mixed-Salt System at SRI (BP2)

0.25 t-CO_2/ day capacity; operational since January 2016



Absorbers



A : Rich solution inlet locations.
B : Discharge location for high NH3/K ratio solution
C : Discharge location for low NH3/K ratio solution
D: Heat exchangers (Cold rich ↔ Hot lean)

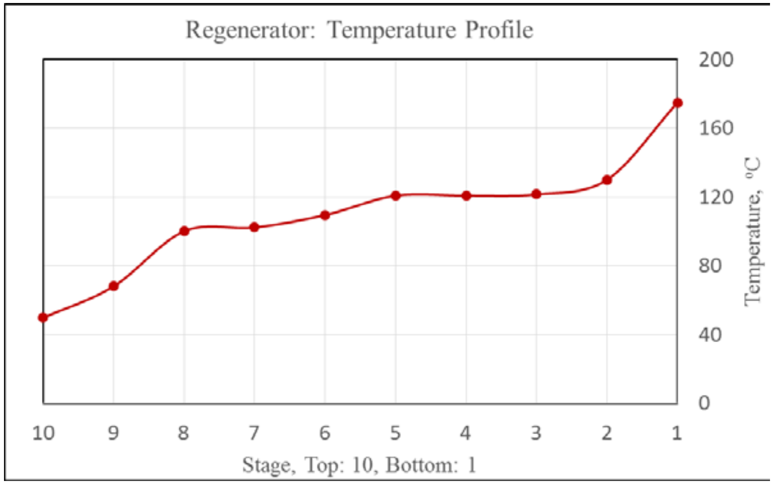
Regenerator pictures from different angles

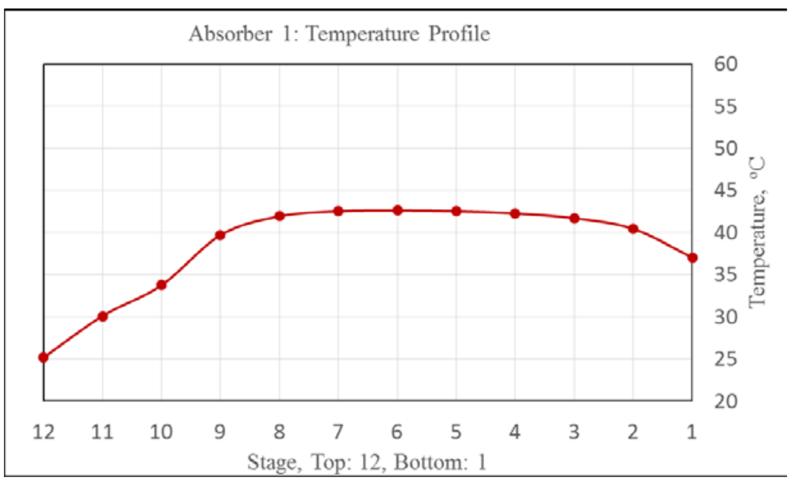
Continuous operation of the integrated system has gone very smoothly during 1.5 years of operation

Absorber and Regenerator Temperature Profiles (BP2)

Integrated System (Regenerator: Steam heated reboiler)

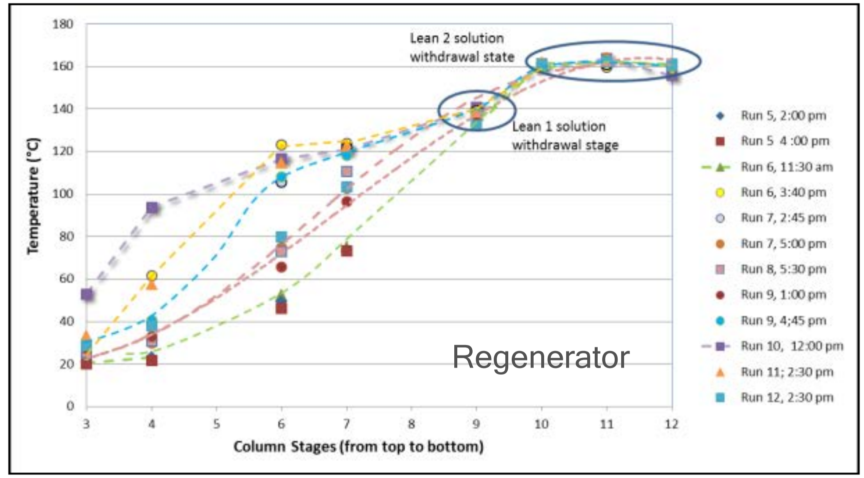
Modeling Data

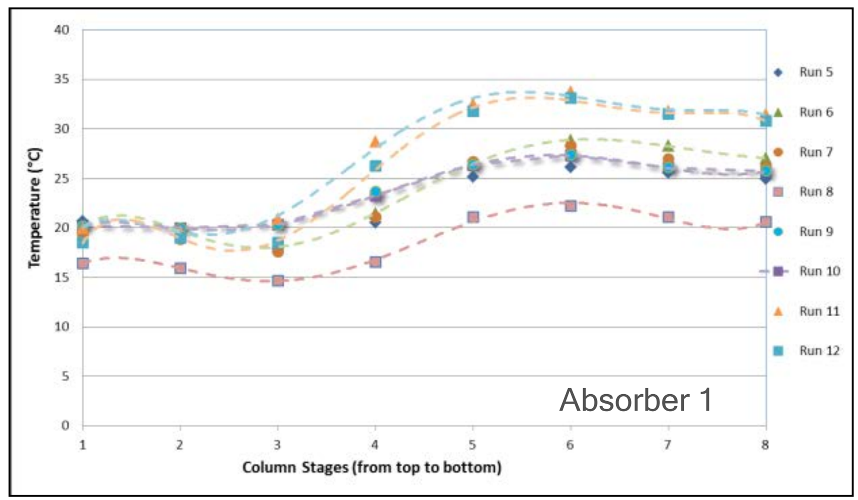




OLI Modeling 550-MW System

Test Data

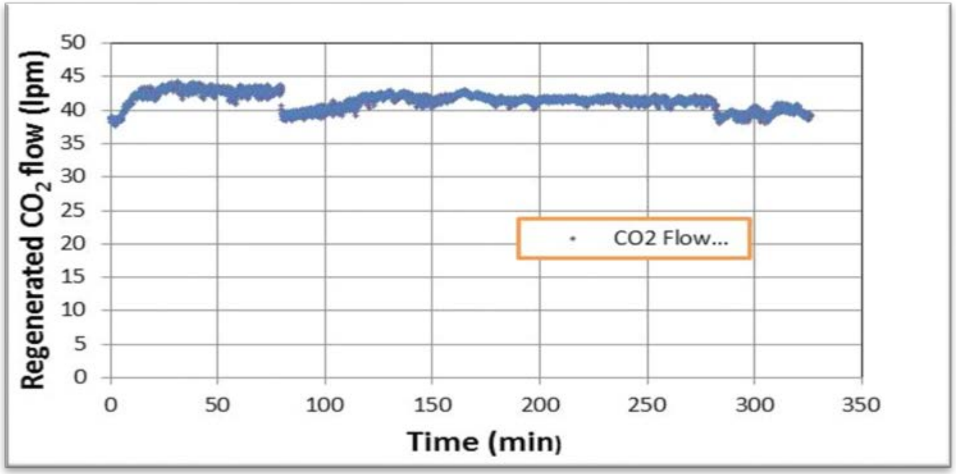




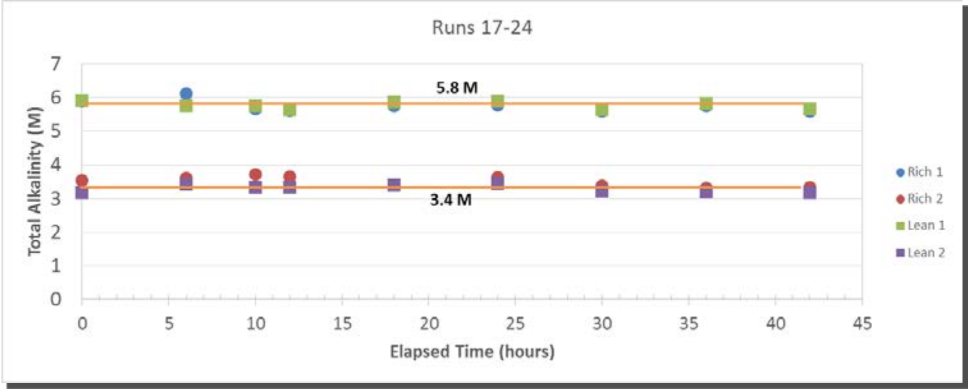
SRI Bench-Scale System

Data from Integrated System Testing in 2016

Excellent Performance

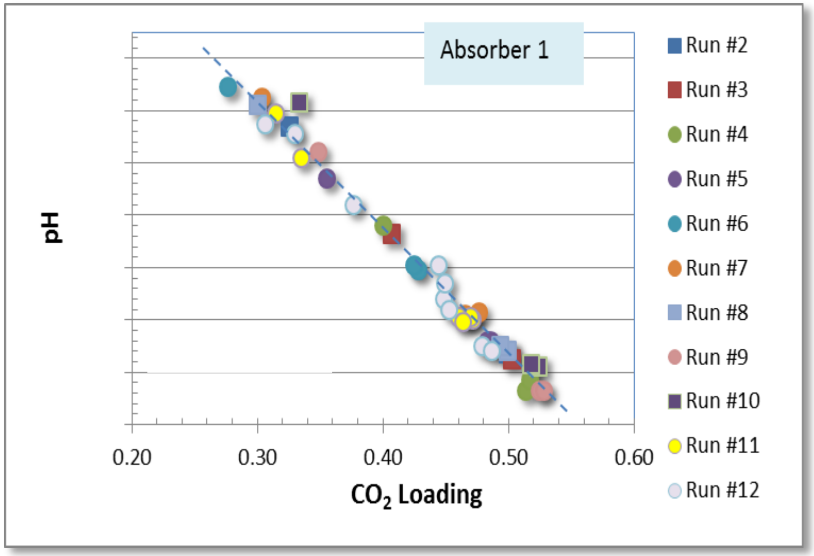


Observed 90% capture efficiency and regeneration with cyclic loading of ~0.7 mole of CO_2/mole of ammonia



Alkalinity of rich and lean solutions circulating in the integrated system

- 300 to 400 *slpm* simulated flue gas with 15% CO_2

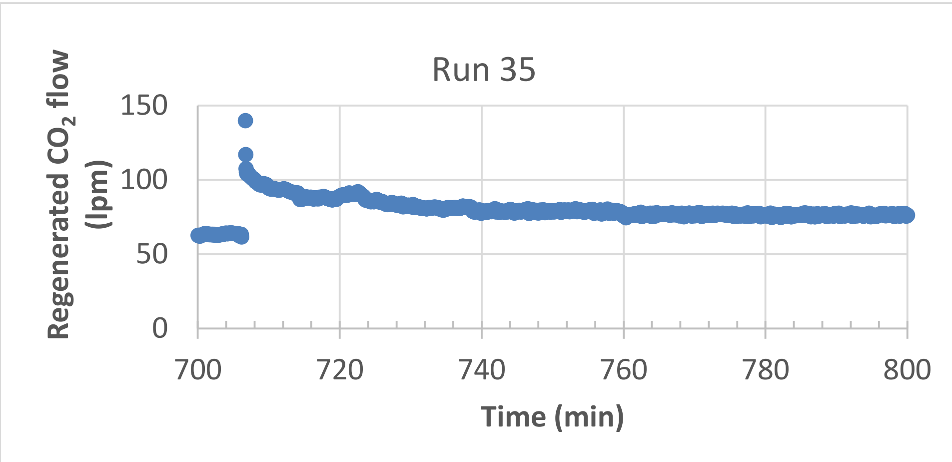


Data showing relationship of the measured pH of rich and lean solutions from Absorber 1

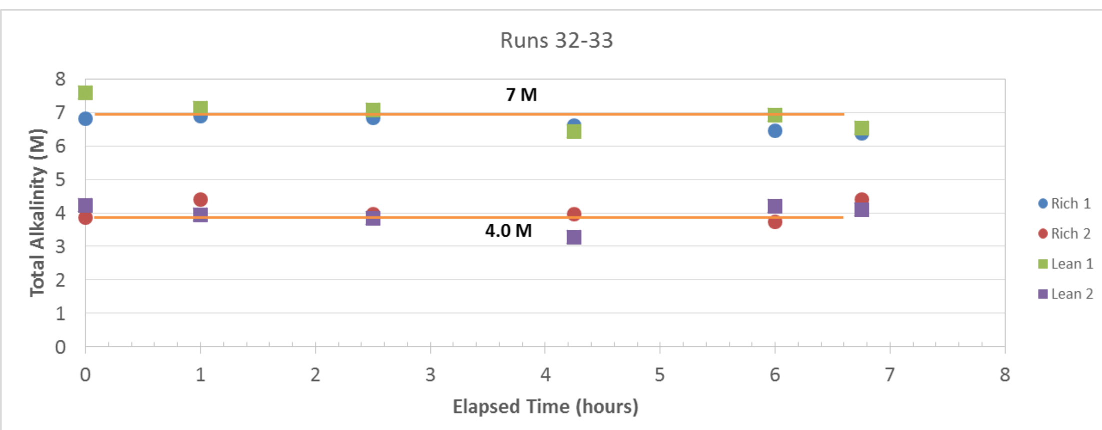
Absorber: 20-35℃
Regenerator stage 1:140 ℃
Regenerator stage 2:160 ℃

Data from Integrated System Testing in 2017

High-throughput Runs

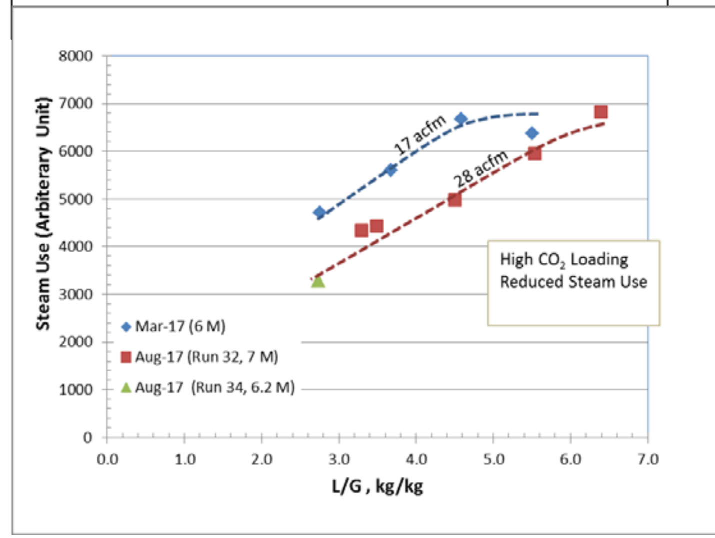


Observed 85-90% capture efficiency and regeneration with cyclic CO_2 loading of ~ 8 - 9 wt.%



Alkalinity of rich and lean solutions circulating in the integrated system

- 600-800 *slpm* simulated flue gas with 15% CO_2



Data showing specific steam consumption at varying L/G ratios

Absorber: 20-35℃
Regenerator stage 1:135 ℃
Regenerator stage 2:160 ℃

Techno-economic Data

Comparison between mixed-salt technology and DOE baseline case

Performance Factors	Econamine Baseline	SRI's Mixed-Salt Technology*
CO_2 capture, %	90.2	90.3
CO_2 purity (before compression), %	99.61	> 99.0
Stripper pressure, atm	1.0	10.0
Raw water recycle, gpm	~325,000	<100,000
Auxiliary power, KWe	20,600	3,581
Heat duty, MJ/kg of CO_2	3.56	2.0

Process Modeling: OLI, IHI and POLIMI

Cyclic loading: 0.18 to 0.58

Reboiler duty: 2.0 (OLI); 2.3 MJ/kg-CO_2 (POLIMI); 2.1 to 2.3 MJ/kg-CO_2 (IHI Measured)

Ammonia emission < 10 ppm

Cost of CO_2 Captured (Excluding T&S): ~$38/tonne-$CO_2$ for Mixed-Salt; $54/tonne-$CO_2$ for Case 12B

Reference: Jayaweera et al. Energy Procedia 63 (2014) 640-650 and Energy Procedia (2017)

Project Accomplishment Summary

- Collected experimental and modeling data available in the literature for the H_2O-CO_2-NH_3-K_2CO_3 system; developed a software package to determine speciation and compositions.
- Developed a rate-based model from the SRI test data; mass and energy balance were determined for a two-process layout to add a CO_2-capture system for DOE Case 11. The comparison was made between the mixed-salt process and DOE Cases 12 and 12B.
- Demonstrated the operation of the absorber at high temperature (20 to 40°C).
- Demonstrated ammonia emission reduction by using the two-stage absorber approach.
- Demonstrated system cyclic operation with cyclic loading between 0.2 and 0.59.

Project Accomplishment Summary (continued)

- Demonstrated high CO_2 loading and >90% CO_2 capture with regeneration of > 99% purity CO_2 at high pressure.
- Collected test data over a wide range of conditions. Parameters varied included feed gas flow rate, mixed-salt composition, CO_2 loading, and the L/G ratio.
- Demonstrated cyclic operation of the integrated system with 90% efficiency (~ 0.3 ton/day CO_2 capture) and the generation of lean solutions with two compositions (ammonia rich, potassium rich) using a two-stage regenerator.
- Demonstrated long-term operability of the integrated system (1.5-year operation).

Mixed-Salt Technology Summary

US Patent 9,339,757 issued on May 17, 2016

Process Summary

- Uses inexpensive, industrially available material (potassium and ammonium salts)
- Requires no feedstream polishing
- Does not generate hazardous waste
- Has the potential for easy permitting in many localities
- Uses known process engineering

Demonstrated Benefits

- Enhanced CO_2-capture efficiency
- High CO_2-loading capacity
- High-pressure release of CO_2
- Reduced energy consumption compared to MEA
- Reduced auxiliary electricity loads compared to the conventional ammonia processes
- Possible flexible carbon capture operation

Overall Strategy & Timeline

SRI

Lab Bench

Proof of Concept

IHI

Large Bench (Mini-pilot) Component Testing

Parametric Testing Process Optimization

Multiple Flow Sheets

TEA

SRI

Large Bench (Mini-pilot) Integrated System

Steady State; Dynamic Operation

Ammonia Emission Optimization

Baseline Testing & Design Upgrade

System Assessment for MST demo

Engineering Testing

TEA Validation

EH&S Validation

Operability Validation in an Existing System

Commercialization

2013-17 Successful DOE Project with parallel IHI support

Future Project

SRI has the patent coverage for mixed-salt technology in the US, Japan, and Europe

Multiple flow-sheets have been modeled and tested for process optimization
Next step in scale-up is to test the technology in an existing demonstration site

Acknowledgements

NETL (DOE)

- Mr. Steven Mascaro, Ms. Lynn Bricket, Mr. John Litynski and other NETL staff members

SRI Team

- Dr. Indira Jayaweera, Dr. Palitha Jayaweera, Ms. Elisabeth Perea, Ms. Regina Elmore, Dr. Srinivas Bhamidi, Mr. Bill Olsen, Dr. Marcy Berding, Dr. Chris Lantman, and Ms. Barbara Heydorn

Collaborators

- OLI Systems (Dr. Prodip Kondu and Dr. Andre Anderko), POLIMI (Dr. Gianluca Valenti and others), Stanford University (Dr. Adam Brant and Mr. Charles Kang), Dr. Eli Gal, and Dr. Kaj Thomsen

Industrial Partner

- IHI Corporation (Mr. Shiko Nakamura, Mr. Okuno Shinya, Mr. Yasuro Yamanaka, Dr. Kubota Nabuhiko, and others)

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Thank You

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