Session: Post-Combustion Solvent-Based Capture

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

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Sr. Staff Scientist and CO_2 Program Leader

SRI International

June 23-June 26, 2015 • Sheraton Station Square• Pittsburgh, Pennsylvania

Technology Background

Our Early Experience in Solvent-Based Technology Development from Proof-of-Concept to Pilot-Scale

Energy and Environment Center

Ammonia technology development started in 2004

EPRI, NEXANT
STATOIL & ALSTOM

SRI work with multiple clients!

Post-Combustion CO_2 Capture

Small Bench-Scale → Large Bench-Scale → Pilot-Scale (0.25 MW_{th}) **(For ALSTOM)**

Mixed-Salt Process Details

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Key benefits:

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

A SIGNIFICANT PARASITIC POWER REDUCTION COMPARED TO MEA !

How it works:

Selected composition of potassium carbonate and ammonium salts

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

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

Regenerator operation at 70 - 180º C at 10-20 atm

- Produce high-pressure CO_2 stream

High CO_2 cycling capacity

No Solids

CO_2 Lean **CO_2 Rich**

K_2CO_3–NH_3–$x$$CO_2$–$H_2O$ system ←→ K_2CO_3 –NH_3–$y$$CO_2$–H2O system

Published Data Showing Favorable Kinetics for CO_2 Absorption in Ammonia Solutions

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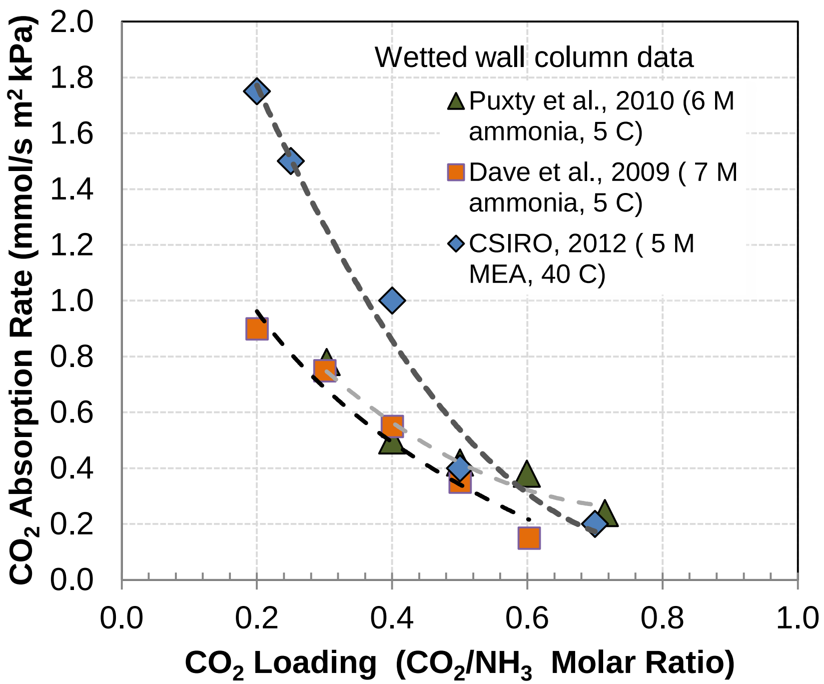


Comparison of CO_2 absorption rates for MEA and ammonia

Sources:

Dave et al., (2009). Energy Procedia 1(1): 949-954

Puxty et al., (2010). Chemical Engineering Science 65: 915-922

CSIRO Report (2012). EP116217

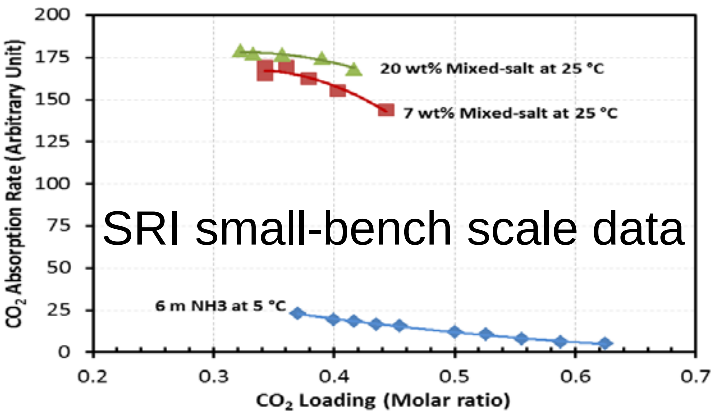
Absorber side: Enhanced kinetics

Pseudo first-order rate constants for CO_2 absorption in NH_3, MEA, and MDEA

Solvent	$k_{app}/10^3\ s^{-1}$
NH_3 at 5°C	0.3
NH_3 at 10°C	0.7
NH_3 at 20°C	1.4
NH_3 at 25°C	2.1
MEA at 25°C	6
MDEA at 25°C	0.58
Concentration = 1.0 kmol m^{-3}	

Source:

Derks and Versteeg (2009). Energy Procedia 1: 1139-1146



Mixed-Salt has a Low Energy Requirement for CO_2 Stripping

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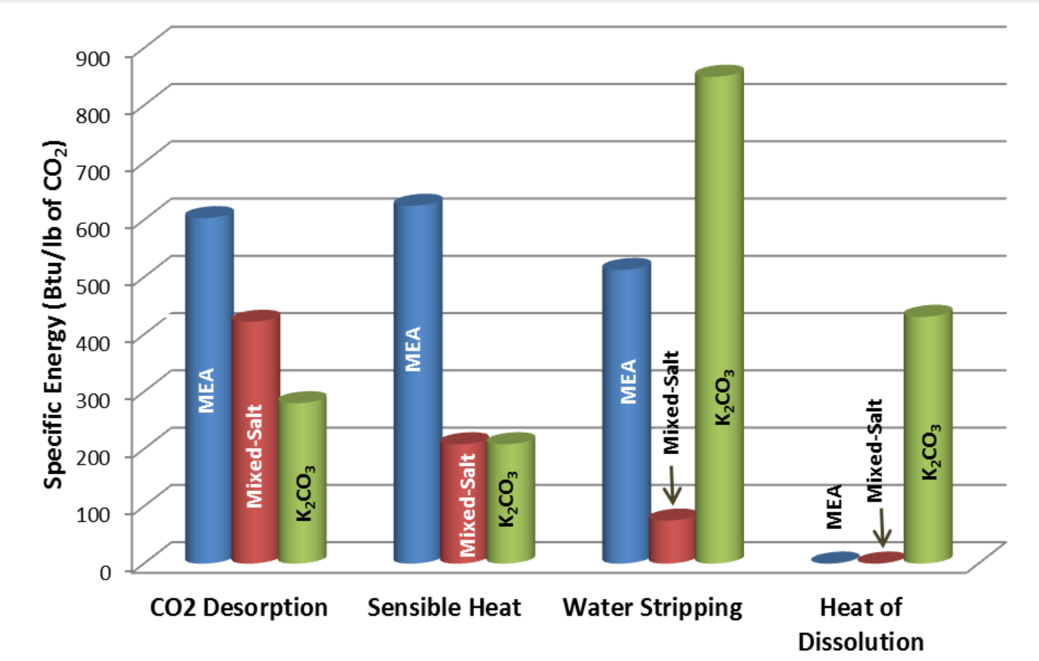
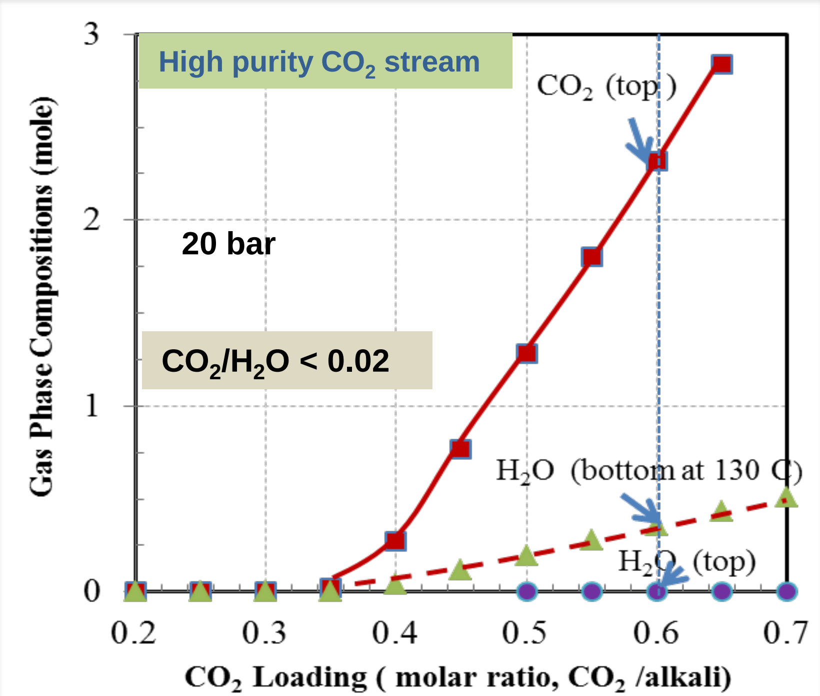


Estimated regenerator heat requirement for mixed-salt system with 0.2 to 0.6 cyclic CO_2 loading. Comparison with neat K_2CO_3 and MEA is shown.

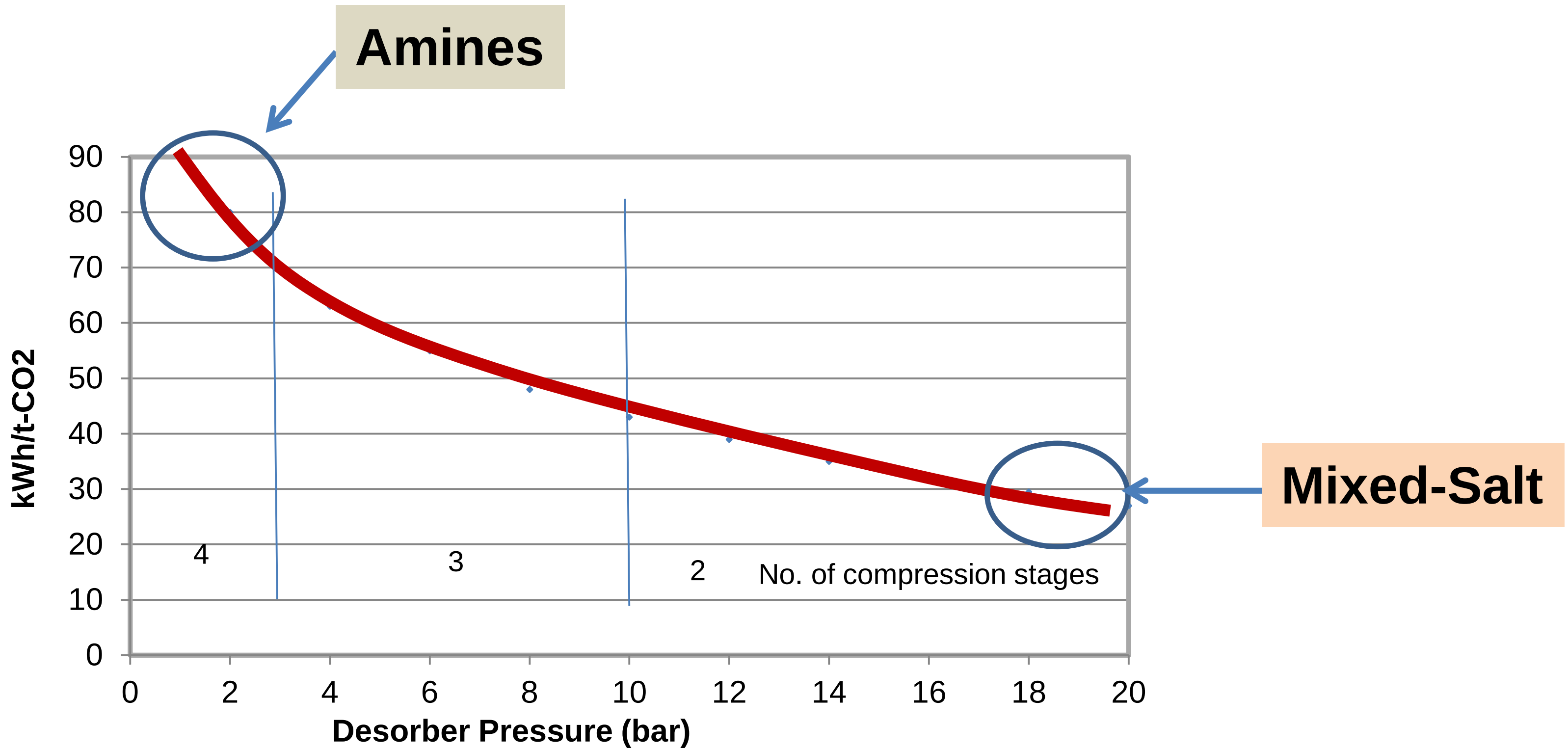
Sources: MEA data: CSIRO report (2012), EP116217
K_2CO_3 data: GHGT-11; Schoon and Van Straelen (2011), TCCS-6
Mixed-salt data; SRI modeling



Mixed-salt process requires minimal energy for water stripping

Regenerator side: Reduced water evaporation

Mixed-Salt 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)

CO_2 Compression: High-pressure CO_2 release

Mixed-Salt Process Flow Diagram

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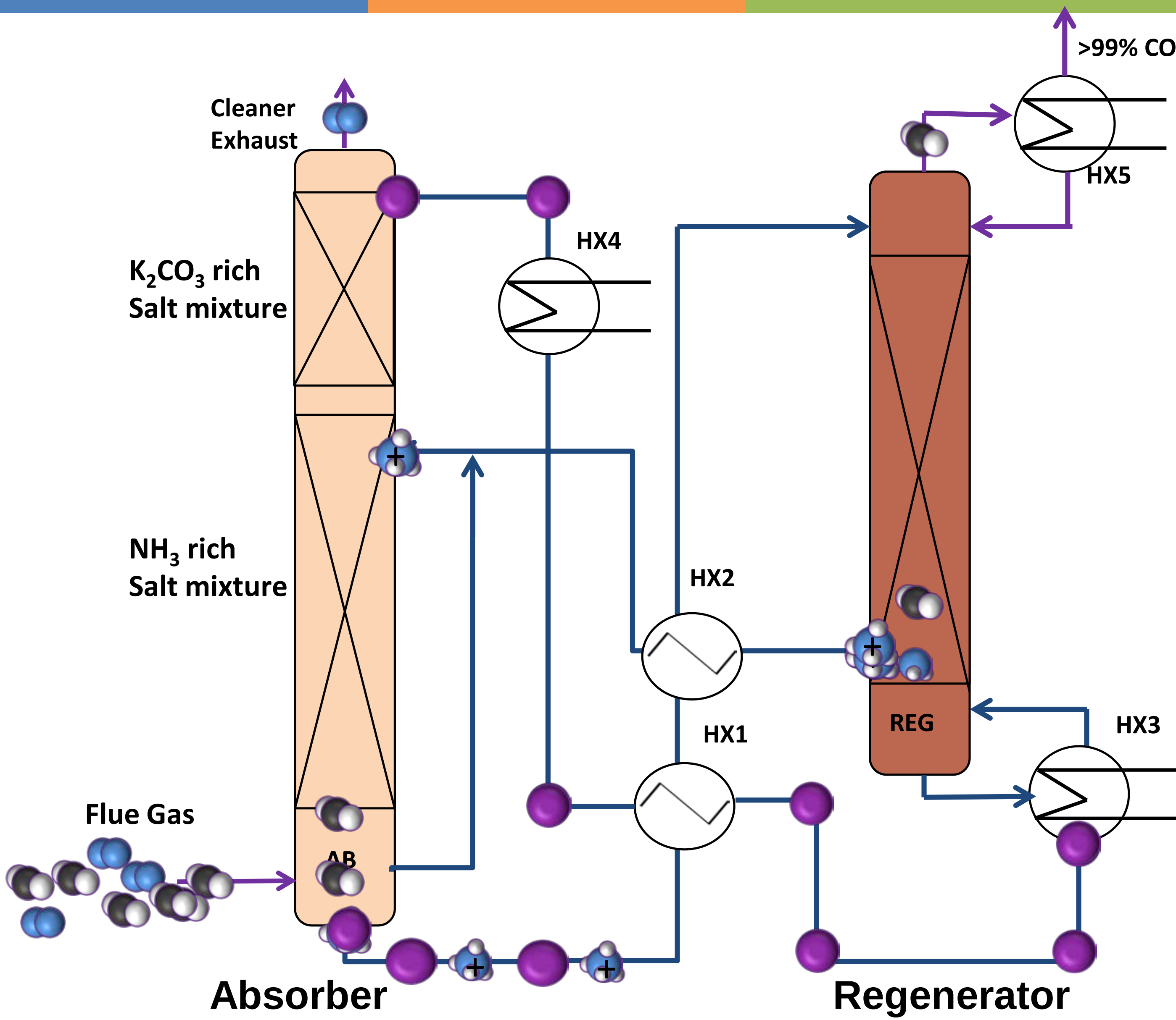

DOE Project Overview
(Large-Bench Scale Testing)

Project Goals

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Budget Period 1:

– Demonstrate the absorber and regenerator processes individually with high efficiency, low NH_3 emissions, and reduced water use compared to state-of-the-art ammonia-based technologies

Budget Period 2:

– Demonstrate the high-pressure regeneration and integration of the absorber and the regenerator

– Demonstrate the complete CO_2 capture system, optimize system operation, and collect data to perform the detailed techno-economic analysis of CO2-capture process integration to a full-scale power plan

– Conduct EH&S analysis of the process

The overall project 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 ≤$40/tonne to meet the DOE program goals.

Project Team and Project Budget

Energy and Environment Center

Project Budget

	Budget Period 1 10/1/13 - 12/30/14	Budget Period 2 1/1/15 - 3/31/16	Total 10/1/13-3/31/16
Total Project Cost	$1,019,650	$1,278,975	$2,298,626
DOE Share	$819,534	$1,018,474	$1,838,009
Cost Share	$200,116	$260,501	$460,617

Cost share by SRI, OLI Systems, POLIMI, Aqueous Solutions Aps, Stanford University, and IHI Corporation

Project Manager: Mr. Steven Mascaro, NETL

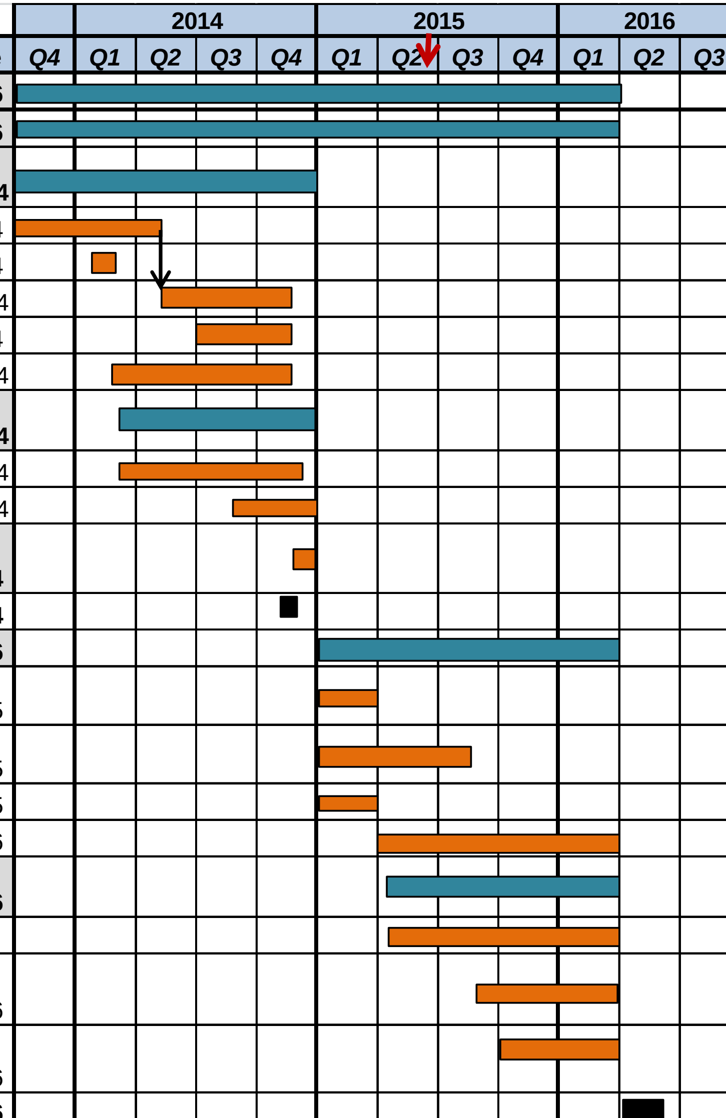
Prime Contractor: SRI International

US Partners: OLI Systems, Stanford University, Dr. Eli Gal

International Partners: Dr. Kaj Thomsen, POLIMI, IHI Corporation

Project Tasks

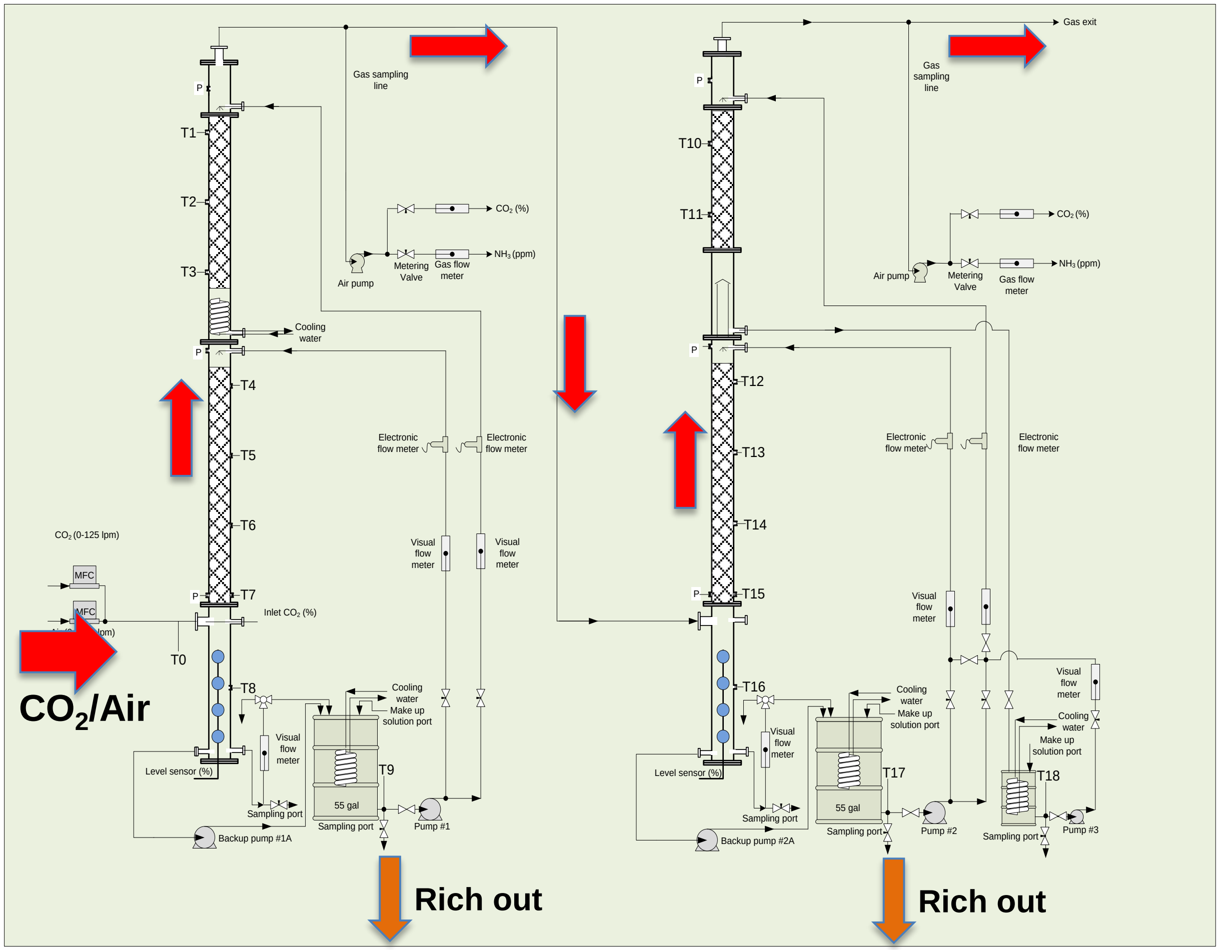
Task	Start Date	End Date
Mixed-Salt BP1 and BP2	**10/1/2013**	**3/31/2016**
Task 1.0 - Project Management and Planning	**10/1/2013**	**3/31/2016**
Task 2-0: Individual Absorber and Regenerator Testing in Semi-Continuous mode	**10/1/2013**	**11/30/2014**
Subtask 2.1 - Test Systems Design and Installation	10/1/2013	4/28/2014
Subtask 2.2 - Test Plans	2/1/2013	2/30/2014
Subtask 2.3 - Absorber Tests	4/30/2014	11/30/2014
Subtask 2.4 - Regenerator Tests	7/1/2014	11/3/2014
Subtask 2.5 - Bench-Scale Test Data Analysis	2/28/2014	11/30/2014
Task 3.0 - Preliminary Process Modeling and Techno-Economic Analysis	**3/1/2014**	**12/15/2014**
Subtask 3.1 - Process Modeling	3/1/2014	11/30/2014
Subtask 3.2 - Preliminary Economic Analysis	8/1/2014	12/15/2014
Task 4.0 - Budget Period 2 Continuation Application	**9/15/2014**	**9/30/2014**
Continuation Report Submission	**9/15/2014**	**9/30/2014**
Task 5.0 - Bench-Scale Integrated System Testing	**1/15/2015**	**3/31/2016**
Subtask 5.1 - Design of the Bench-Scale Integrated Test System	1/15/2015	3/31/2015
Subtask 5.2 - Installation of the Bench-Scale Continuous, Integrated Test System	1/15/2015	3/31/2015
Subtask 5.3 - Bench-Scale Test Plans	1/15/2015	2/15/2015
Subtask 5.4 - Bench-Scale Tests and Data Analysis	4/1/2015	3/31/2016
Task 6.0 - Process Modeling and Techno-Economic Analysis	**5/1/2015**	**3/31/2016**
Subtask 6.1 - Process Modeling	5/1/2015	3/1/2016
Subtask 6.2-Techno-Economic Analysis	8/1/2015	3/30/2016
Subtask 6.3- Technology EH&S Risk Assesment	9/1/2015	3/30/2016
Final Report Submission	**4/30/2016**	**5/30/2016**



Project is on time and on schedule

Work Performed in BP1

Schematic and Photograph of the Absorber System



0.25 to 1 t-CO_2/day capacity

Bench-Scale Absorber Performance

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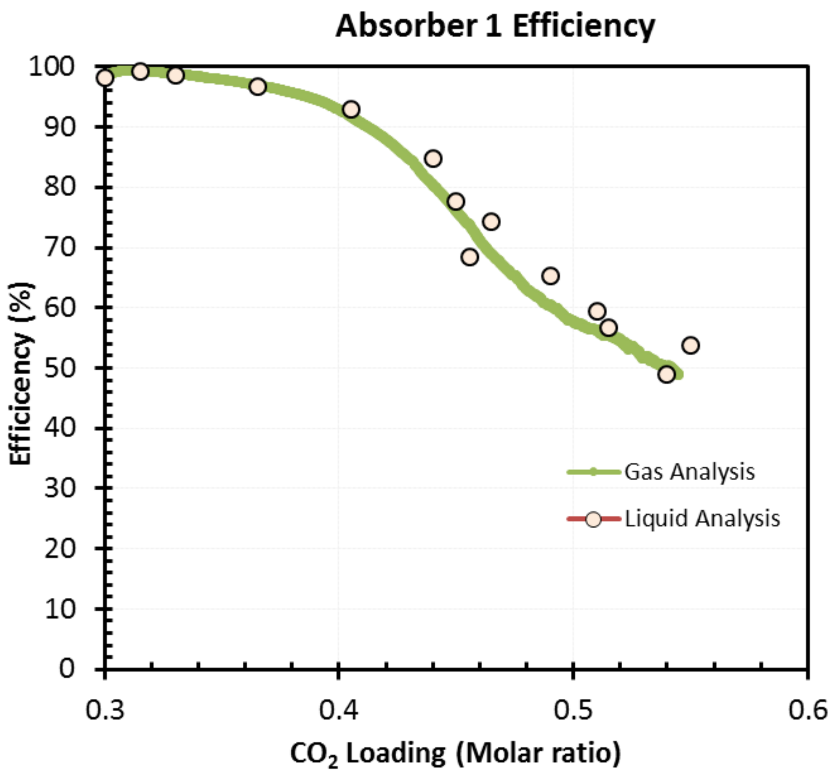
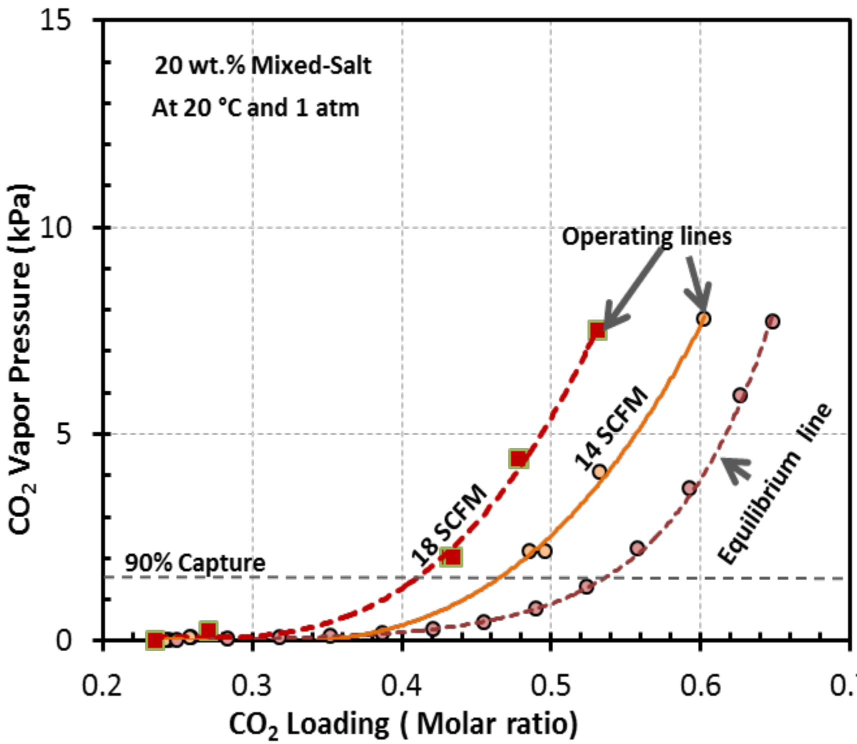
Test Data



Better than 90% efficiency with incoming lean absorption solution and < 0.4 CO_2 loading

Modeling and Test Data

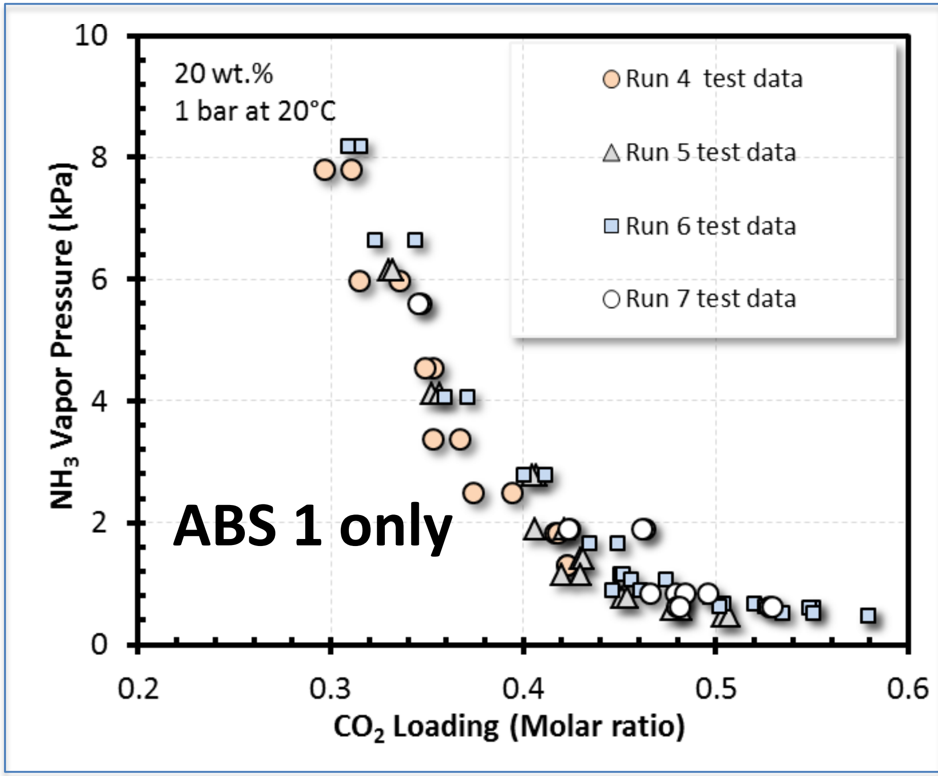


CO_2 vapor pressure at the absorber exit under various CO_2-loading conditions

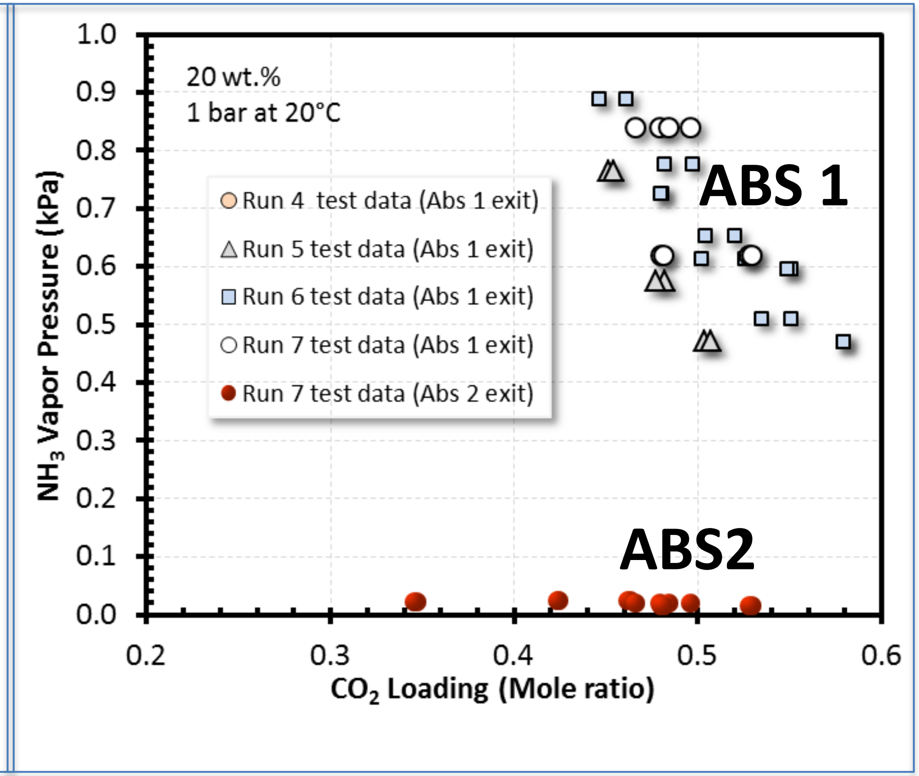
The observed overall rates for CO_2 absorption are on the same order as those of MEA-based systems and about 5-7x higher than chilled ammonia systems

Process Ammonia Management

Test Data

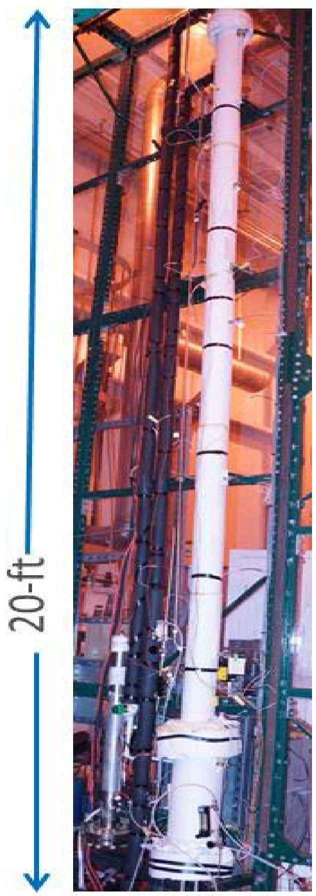


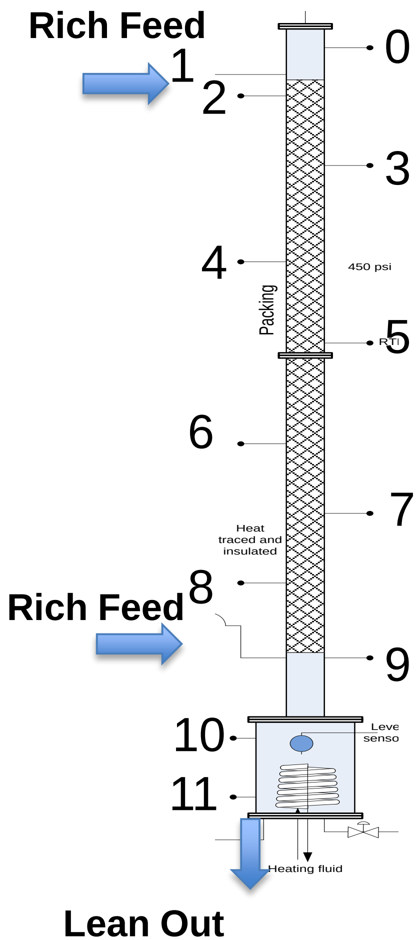
NH_3 vapor pressure at the Absorber 1 exit under various CO_2-loading conditions

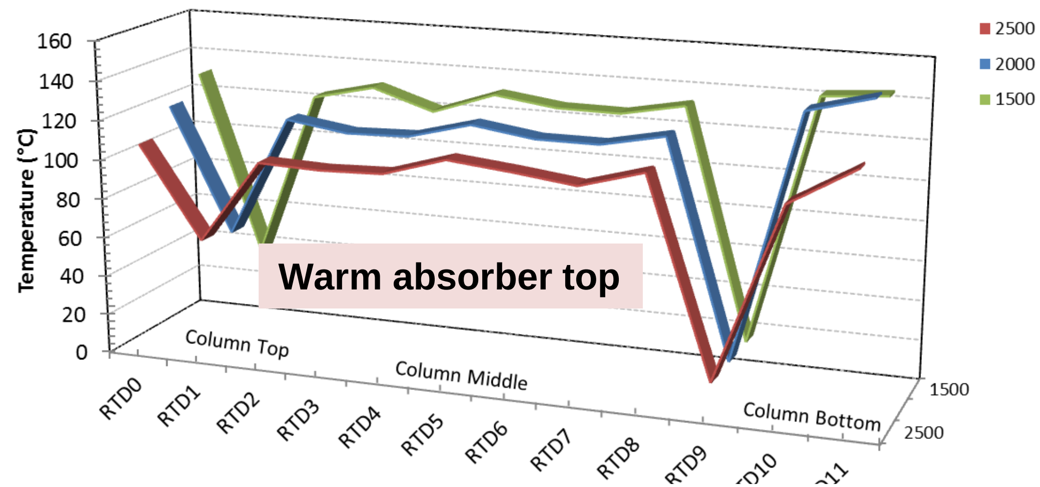


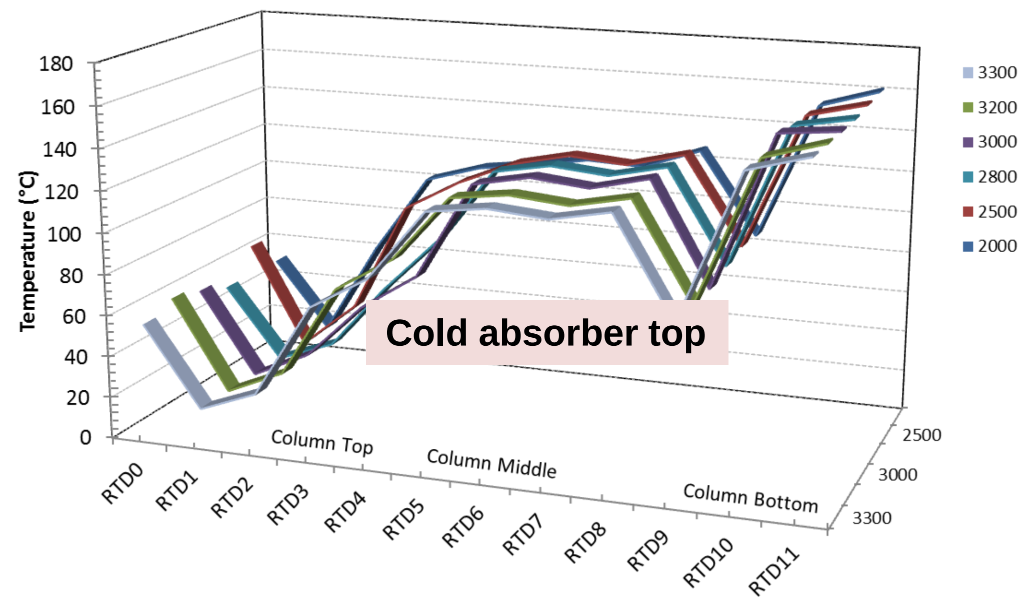
NH_3 vapor pressure at the Absorber 1 and 2 exits under various CO_2-loading conditions

Regeneration Operation Modes









Regenerator Performance

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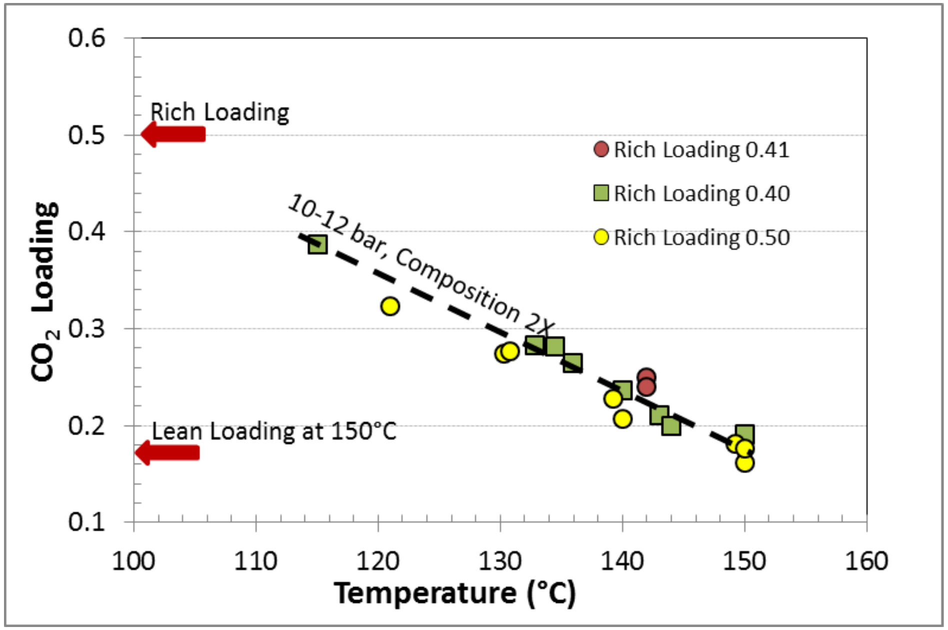
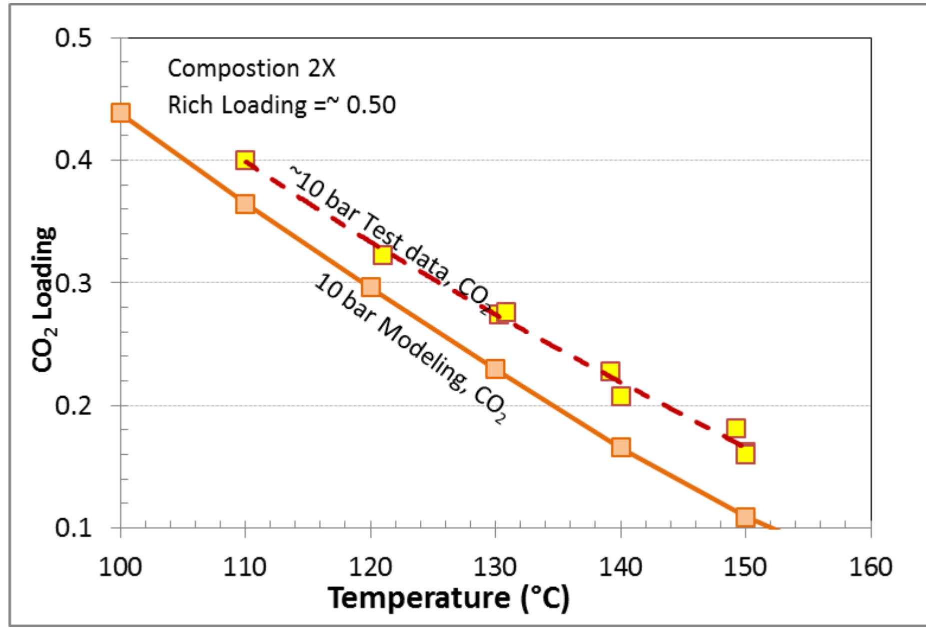
Test Data



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 ºC

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

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

Modeling Results: Preliminary Net Power Efficiency

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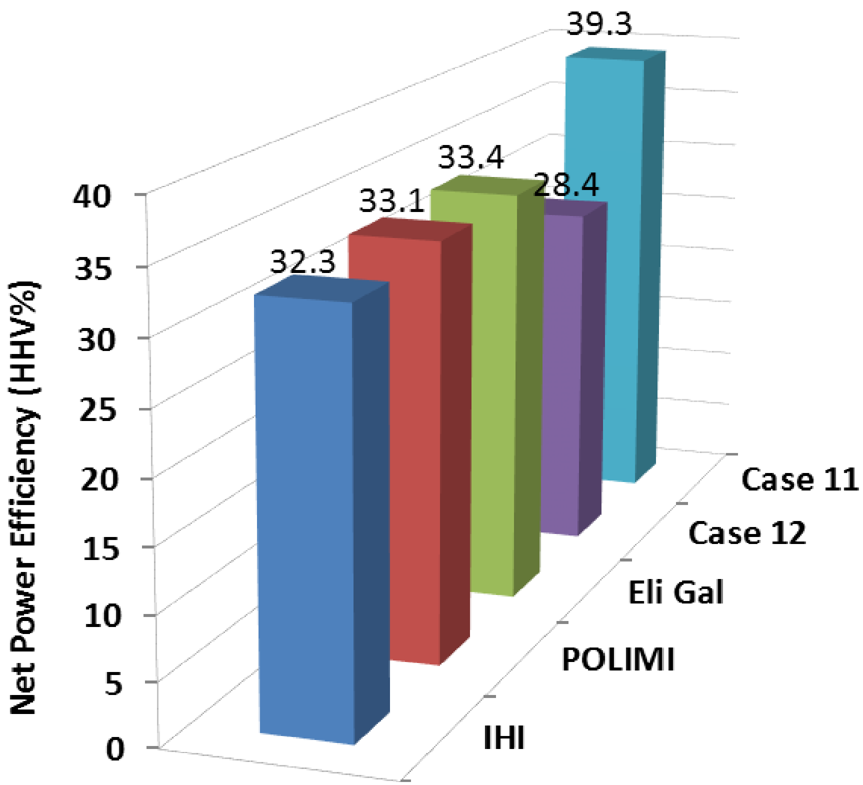
Thermodynamic Model → **ASPEN Modeling** → **Mass & Energy Balance**



- Software package was developed for thermodynamic modeling of mixed-salt system
- Process layout with two regenerator options were modeled, regenerator energy requirement was in the range 1.8 to 2.2 MJ/kg-CO_2, lowest energy option was chosen for BP2 regenerator design

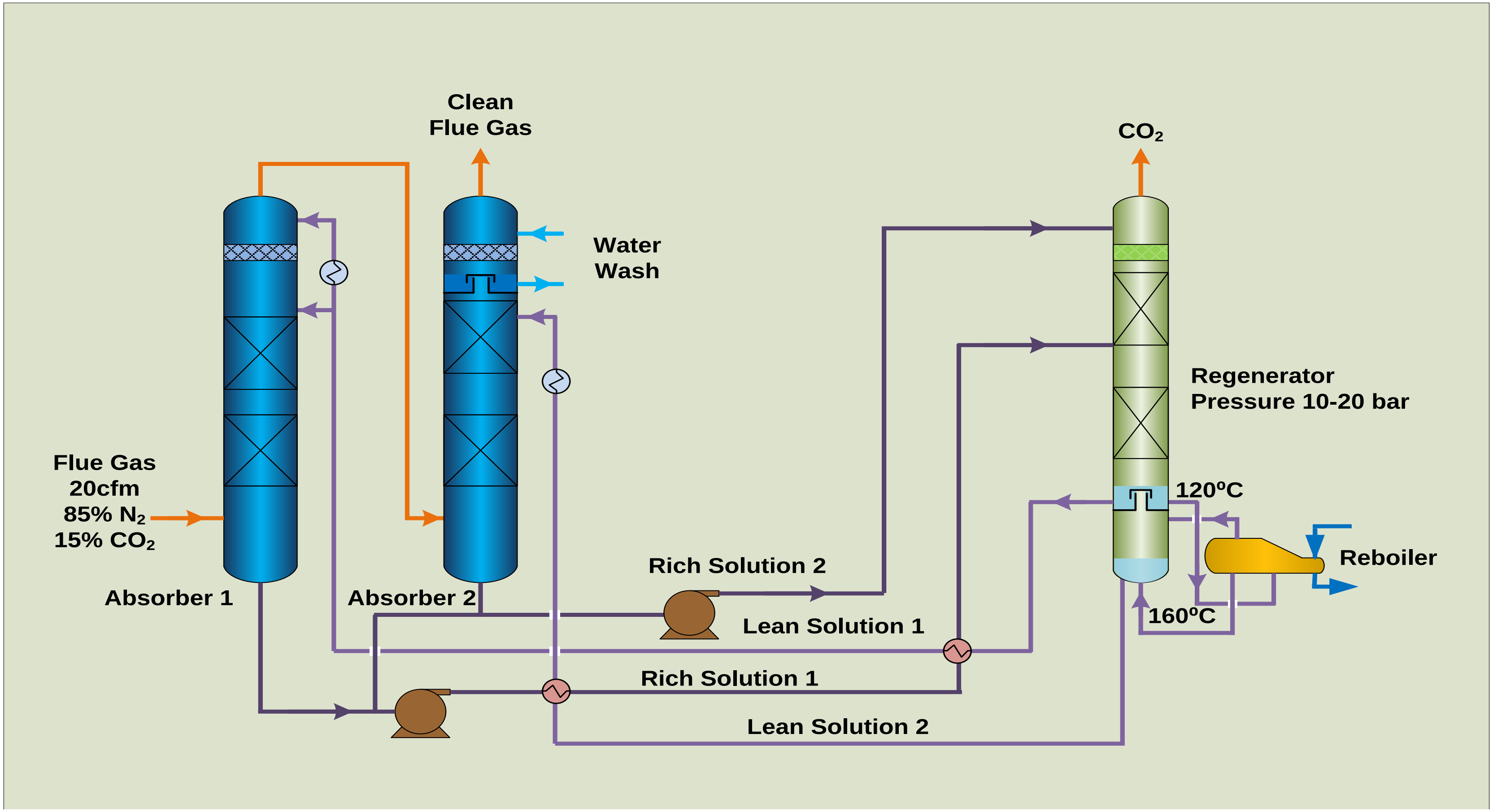
Progress in BP2

Ongoing and Planned Activities in BP2

Energy and Environment Center

- Absorber modification (completed and continuous operation in progress)
- Novel regenerator design and fabrication (80% complete)
- Integrated system operation (to begin in August)
- Complete system modeling in ASPEN (complete)
- Complete system modeling with rate-based approach (continuing)
- Process technoeconomic analysis (TEA) (to start in August 2015)
- Process EH&S analysis (to start in September 2015)

Simplified PFD of the Integrated System



1. System is currently in operation with buffer tanks for lean and rich solution storage
2. Continuous operation of the absorber system was smooth and the observed results were as expected based on the BP1 work

System Testing in Continuous Mode

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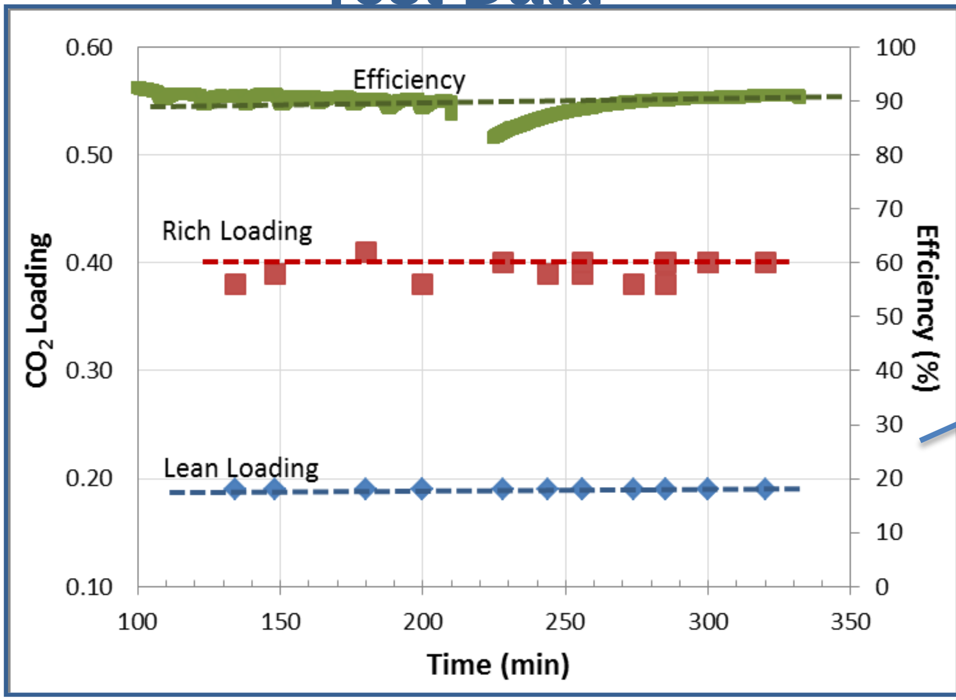
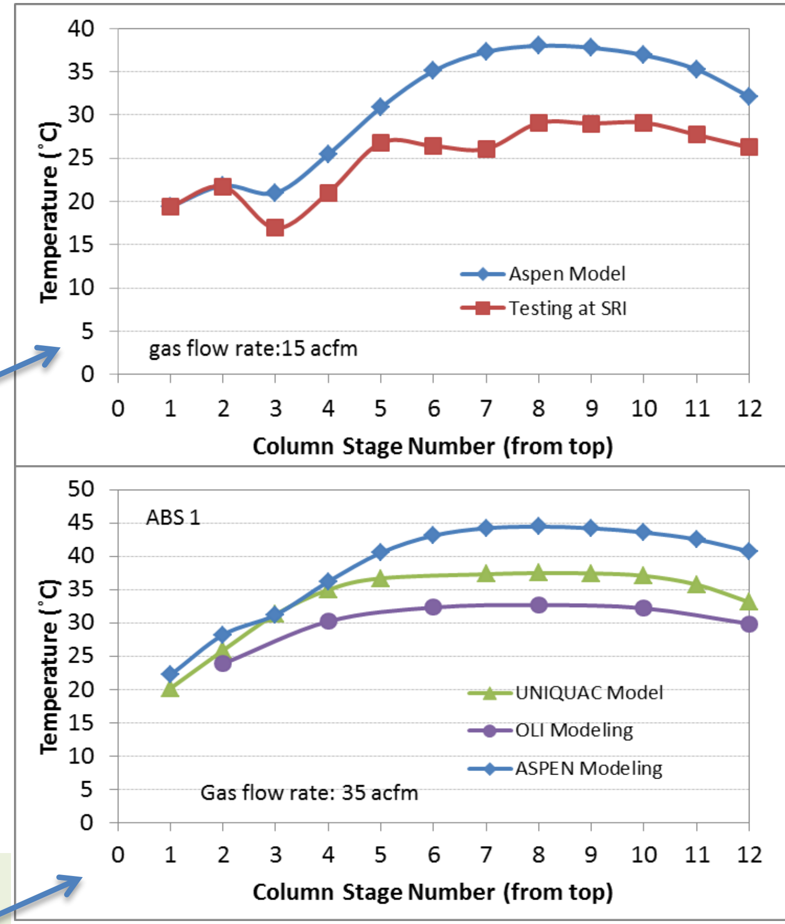
Test Data



90% CO_2 capture efficiency with 0.19 to 0.40 cyclic CO_2 loading in Absorber 1
Gas flow rate = 15 acfm

Process Modeling: SRI (ASPEN) and OLI (ESP)
Cyclic Loading = 0.18 to 0.58
Reboiler Duty ~ 1.8 to 1.9 MJ/kg-CO_2
Ammonia Emission < 10 ppm

Modeling and Test Data



Comparison of observed and modeled temperature profiles for Absorber 1

Mixed-Salt Technology Summary

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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

Expected Benefits

- Reduced energy consumption compared to MEA
- Reduced auxiliary electricity loads compared to the chilled ammonia process
- Possible flexible carbon capture operation

Plans for Future Testing and Commercialization

Bench-scale Technology Development Timeline

SRI Project

Proof of Concept
(6 *slph*)
2012

SRI/IHI Project

Small Bench-Scale Testing
(50 *slpm* or 1.7 *scfm*)
2013

Current DOE-funded Project

Large Bench-Scale Testing (Component Testing)

Budget Period 1

Up to 20 *scfm*

Large Bench-Scale Testing (Integrated Testing)

Budget Period 2

Scale: 0.25 to 1 ton/day

Scale-up Plan of Mixed-Salt Process for CO_2 Capture from Coal Power Plants

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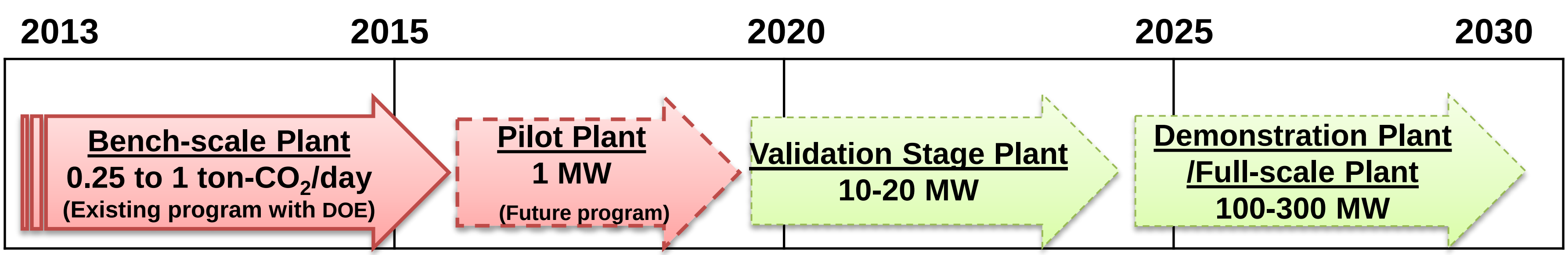
SRI's Bench-scale System

Development Plan Proposed by IHI Corporation



Current Project Location

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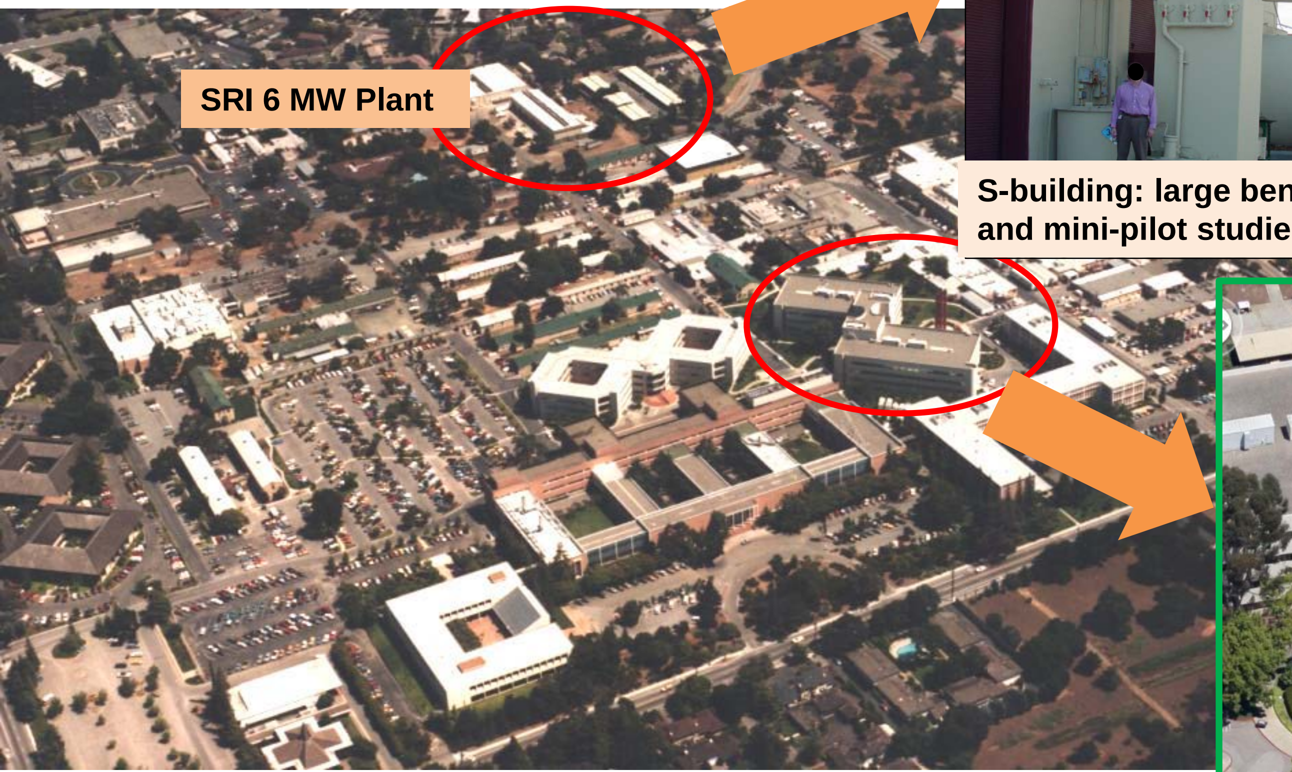
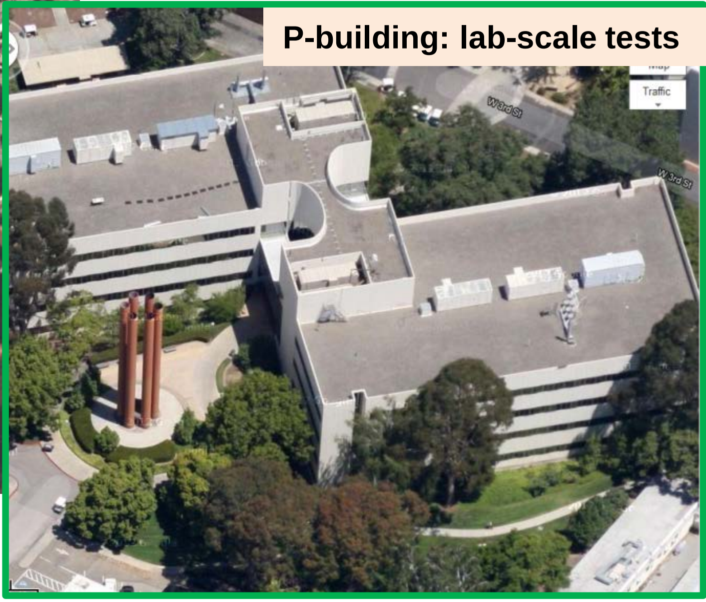


S-building: large bench and mini-pilot studies

CO_2 yard for mini-pilot testing (up to 100 acfm)



P-building: lab-scale tests

SRI's site in Menlo Park, CA (~ 65 acres)
SRI also has a test site near Livermore, CA (480 acres)

Acknowledgements

NETL (DOE)

- Mr. Steve Mascaro, Ms. Lynn Bricket, and other NETL staff members

SRI Team

- Dr. Indira Jayaweera, Dr. Palitha Jayaweera, Dr. Jianer Bao, 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, Dr. Kubota Nabuhiko, Mr. Yuichi Nishiyama, and others)

Disclaimer

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