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2016 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 8-12, 2016 • Sheraton Station Square • 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

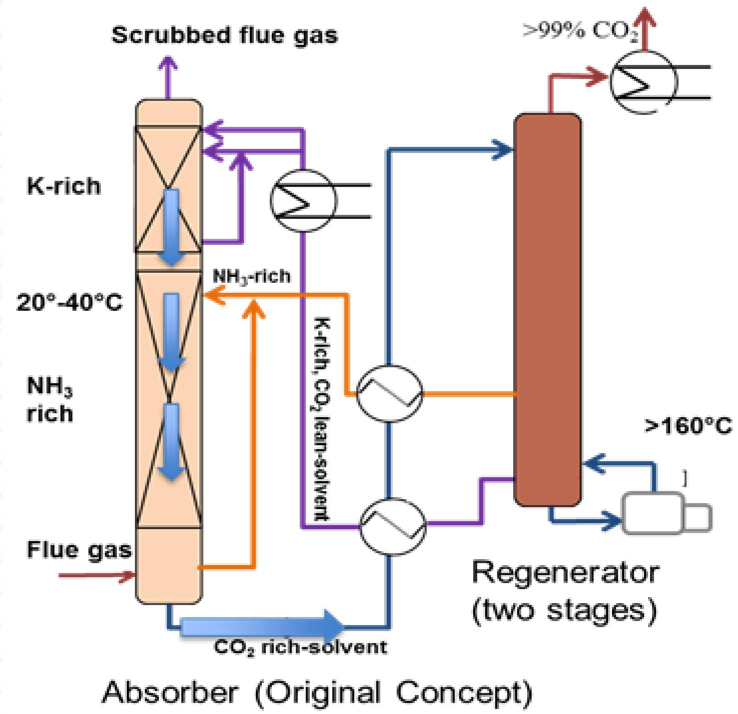
Regenerator operation at 120º - 180º C at 10-20 atm

- Produce high-pressure CO_2 stream

K_2CO_3-NH_3-CO_2-H_2O system

High CO_2 cycling capacity

No Solids

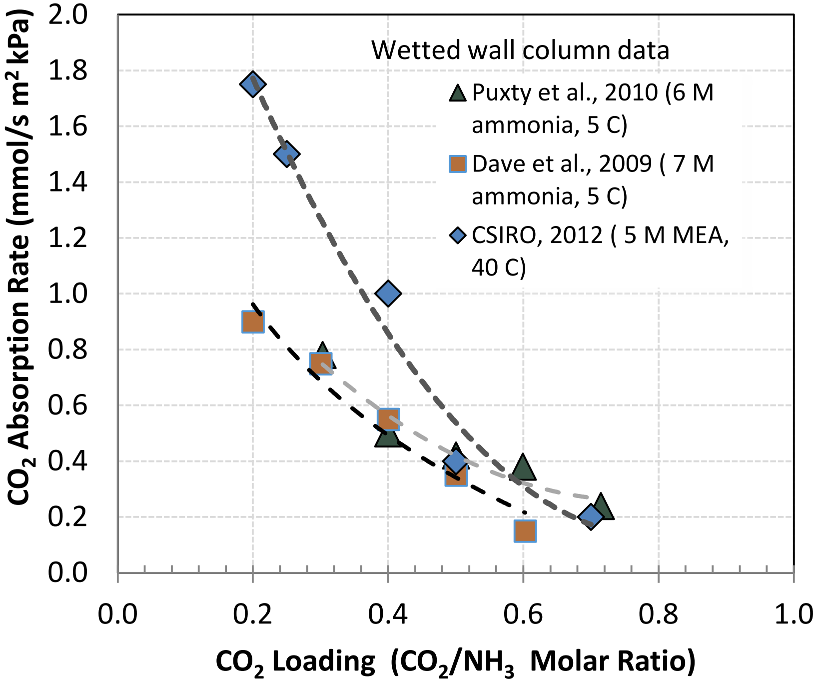


Key benefits:

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

A SIGNIFICANT PARASITIC POWER REDUCTION COMPARED TO MEA !

Published Data Showing Favorable Kinetics for CO_2 Absorption in Ammonia Solutions



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

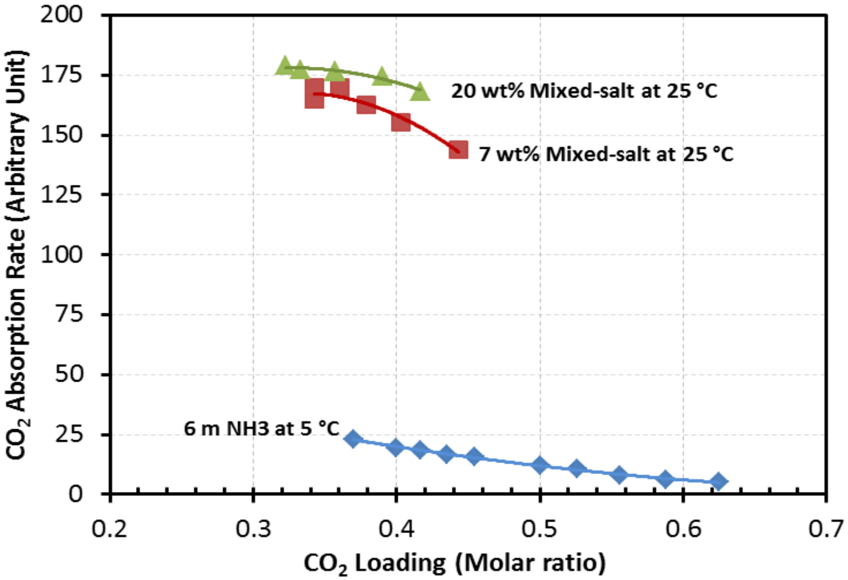
Absorber side: Enhanced kinetics

Pseudo first-order rate constants for CO_2 absorption in NH_3

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
Concentration = 1.0 kmol m^{-3}	

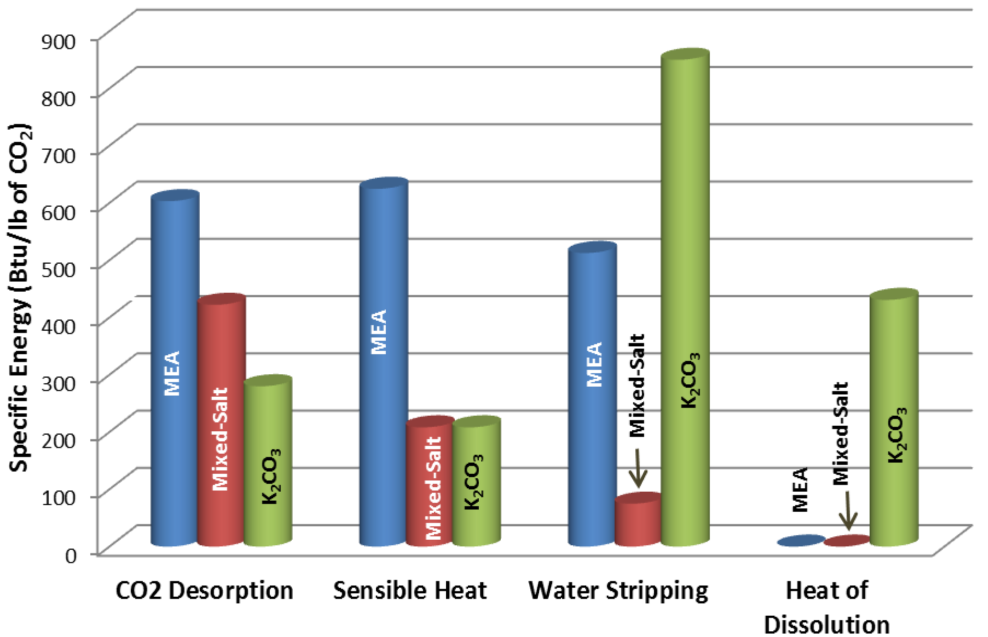
Source:

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



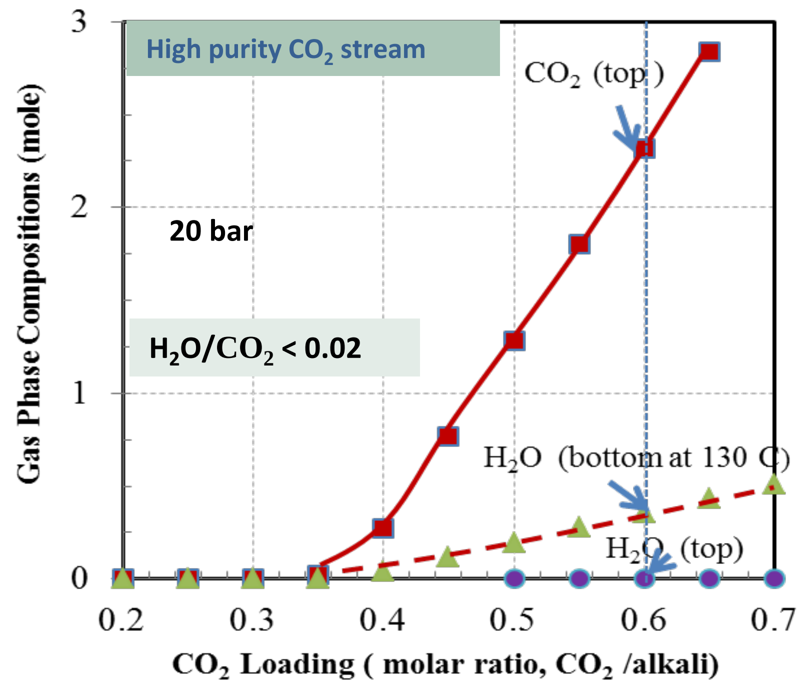
SRI small-bench scale data

Mixed-Salt has a 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

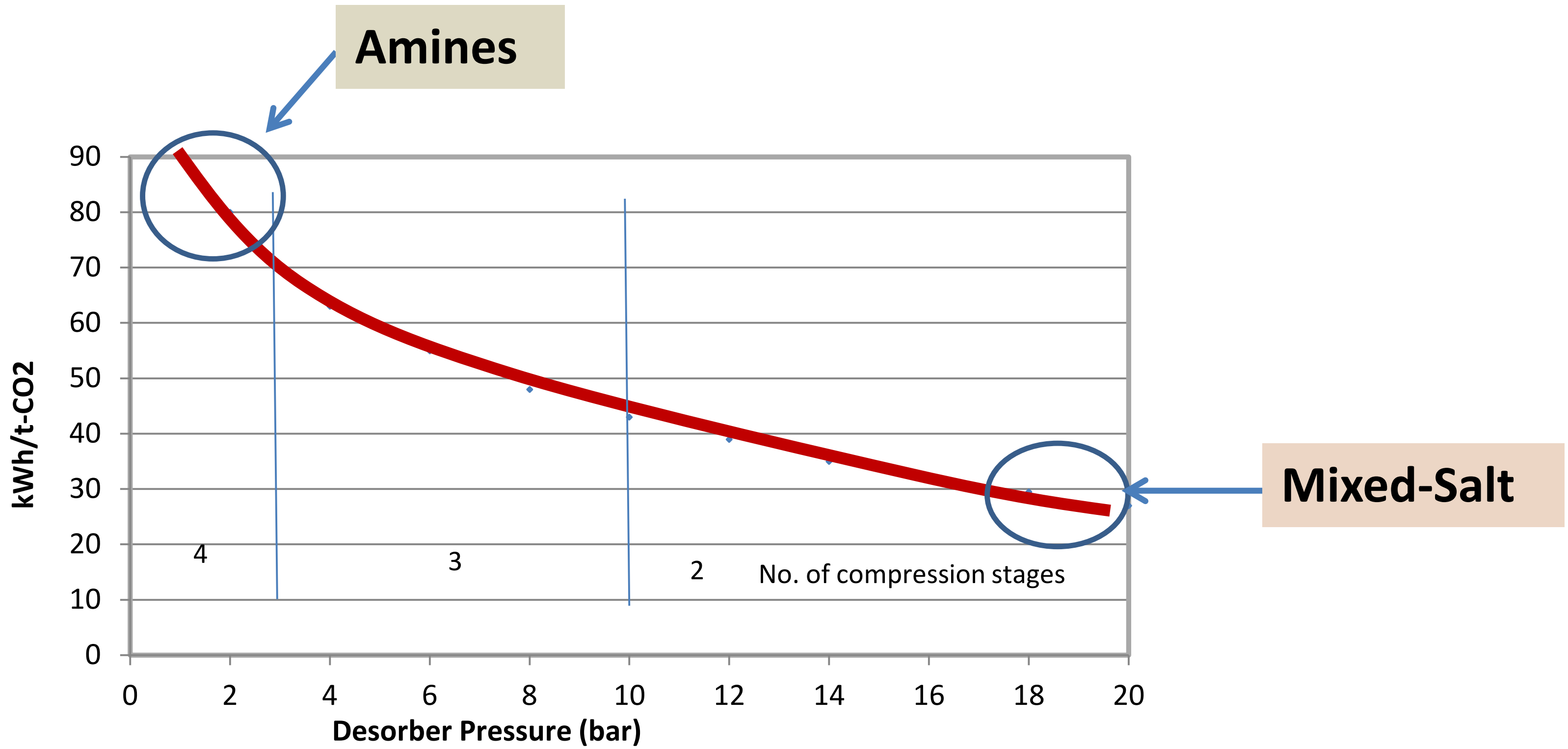
Sources: MEA data: CSIRO report (2012), EP116217
K_2CO_3 data: GHGT-11; Schoon and Van Straelen (2011), TCCS-6
Mixed-salt data; SRI modeling



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

Project Goals

- Budget Period 1
  - Demonstrate the absorber and regenerator processes individually with high efficiency and low NH_3 emissions
  - Development of comprehensive thermodynamic modeling package
- Budget Period 2
  - Demonstrate the complete CO_2 capture system, optimize system operation, and collect data to perform the detailed techno-economic analysis of CO_2-capture process integration to a full-scale power plan
  - Test two alternative flowsheets for process optimization and determine the steam usage for regeneration
  - 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 ≤$40/tonne to meet the DOE program goals.

Project Team and Project Budget

Project Budget

	Budget Period 1 10/1/13 - 12/30/14	Budget Period 2 1/1/15 - 6/30/17	Total 10/1/13-6/30/17
Total Project Cost	$1,019,650	$2,503,999	$3,523,649
DOE Share	$819,534	$1,998,455	$2,817,989
Cost Share	$200,116	$505,544	$705,660

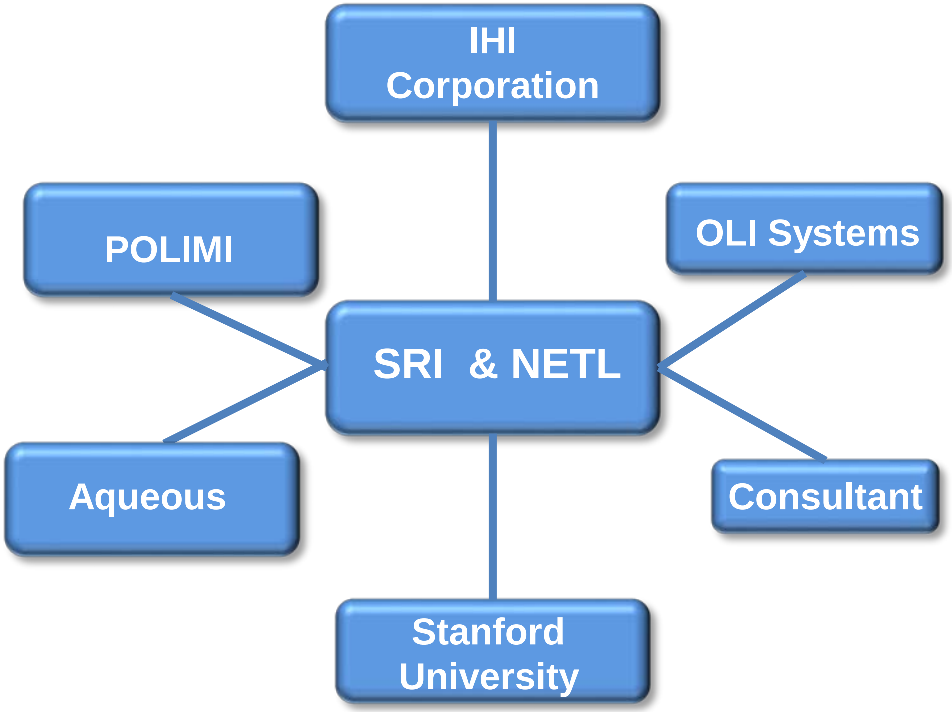
DE-FE0012959

Project Manager: Mr. Steven Mascaro, NETL

Prime Contractor: SRI International

Project Team: US and International Partners

Project Team



- SRI International
  - System design, installation and testing
- IHI Corporation, Japan
  - Industrial partner
- OLI Systems, USA
  - Modeling of process mass and energy (rate-based)
- Aqueous Systems Aps, Denmark
  - Thermodynamic modeling (Dr. Kaj Thomsen)
- POLIMI, Italy
  - Techno-economic analysis
- Stanford University (BP1), USA
  - Technology comparisons

    Applied Energy 179 (2016) 1209–1219
- Consultant (BP1)

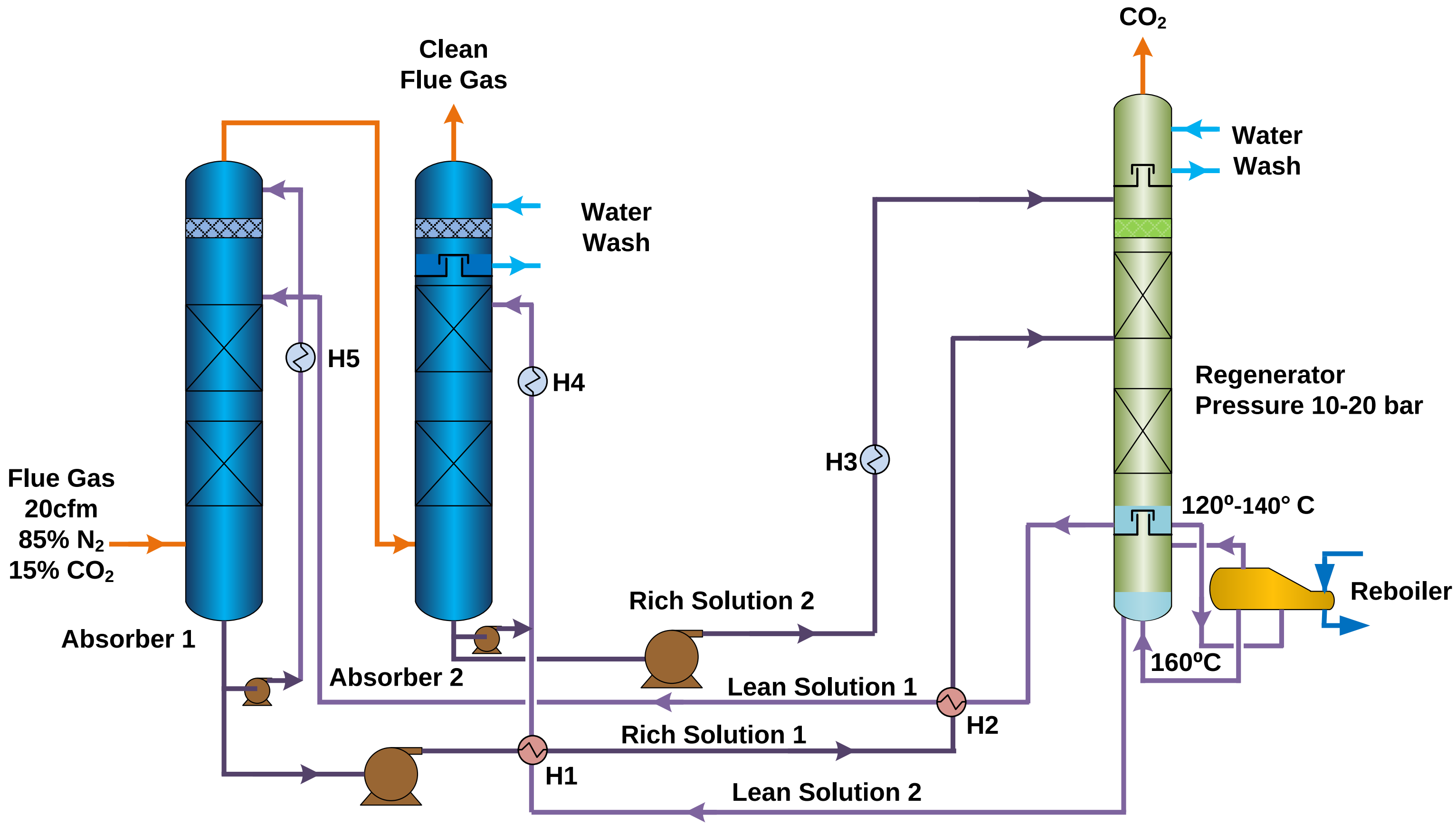
Work Performed

Project Tasks

Task	Start Date	End Date	Status
Mixed-Salt BP1 and BP2	10/01/13	06/30/17	
Task 1.0 - Project Management and Planning	10/01/13	06/30/16	On Going
Task 2-0: Individual Absorber and Regenerator Testing	10/01/13	11/30/14	COMPLETED
Task 3.0 - Preliminary Process Modeling and TEA	03/01/14	12/15/14	
Task 4.0 - Budget Period 2 Continuation Application	12/15/14	12/31/14	
Continuation Report Submission	12/31/14	12/31/14	
Task 5.0 - Bench-Scale Integrated System Testing	01/05/15	03/31/16	
Task 6.0 - Process Modeling and Techno-Economic Analysis	05/01/15	06/30/17	
Task 7.0 -Integrated System Testing (Variant 1)	07/01/17	12/30/16	Started
Task 8.0- Integrated System Testing (Variant 2)	12/01/16	03/31/17	Not Yet Started
Task 9.0- High Capacity Runs and Modeling Update	08/01/16	06/30/17	Started
Task 10.0-Regenerator Steam Use Measurement and IHI System Testing and Modeling	08/01/16	06/30/17	Started
Final Report		07/30/17	

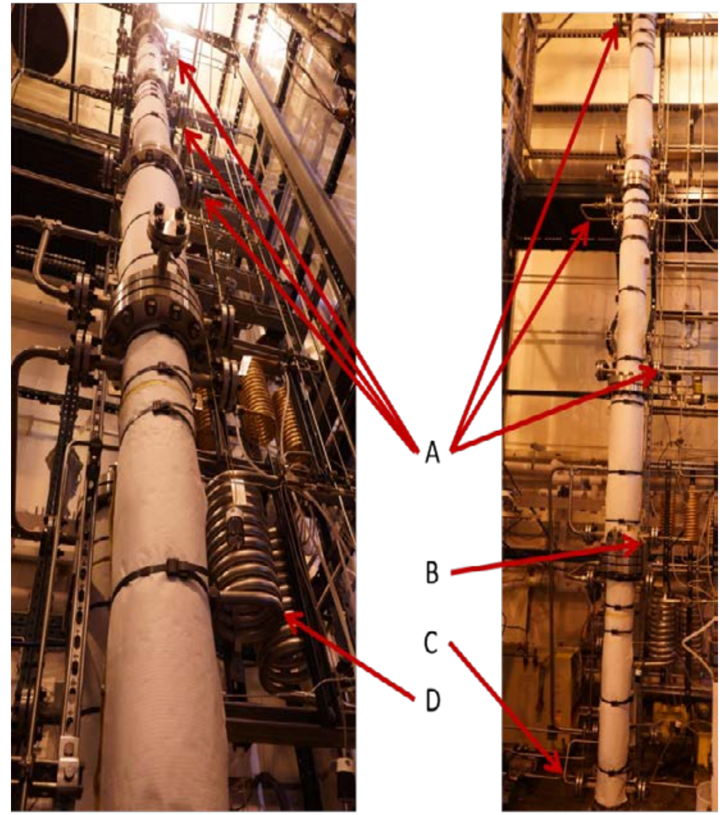
Project is on schedule

Simplified PFD of the Integrated System



Absorbers and the Dual Stage Regenerator

Absorbers (0.25 to 1 t-CO_2/day capacity)



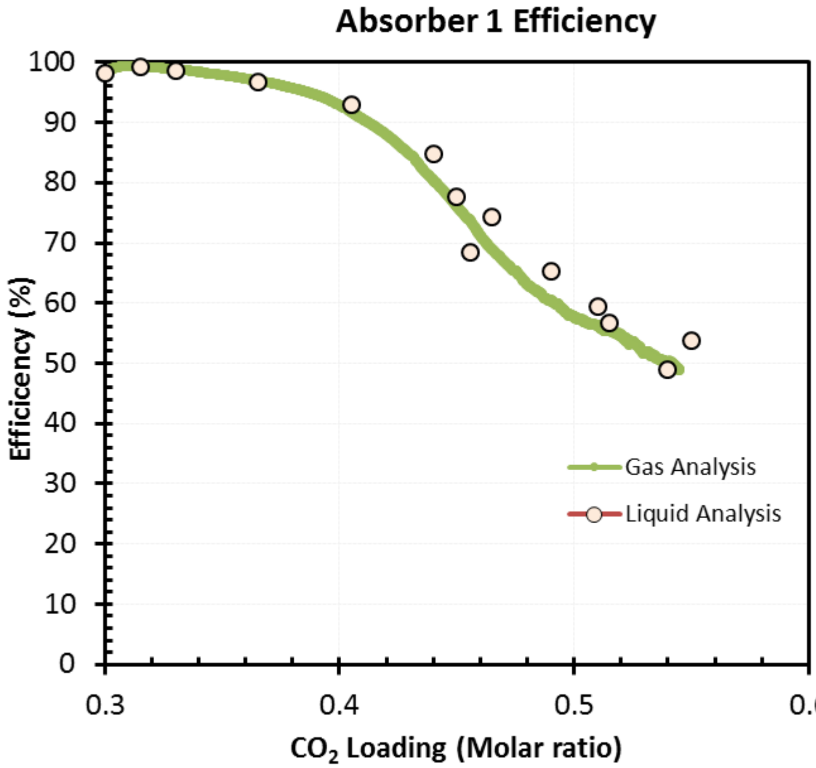
A : Rich solution inlet locations.
B : Discharge location for high NH3/K ratio solution
C : Discharge location for low NH3/K ratio solution
D: Heat exchangers (Cold rich ↔ Hot lean)

Regenerator pictures taken from different angles are shown

Continuous operation of the integrated system was smooth and the observed results were as expected

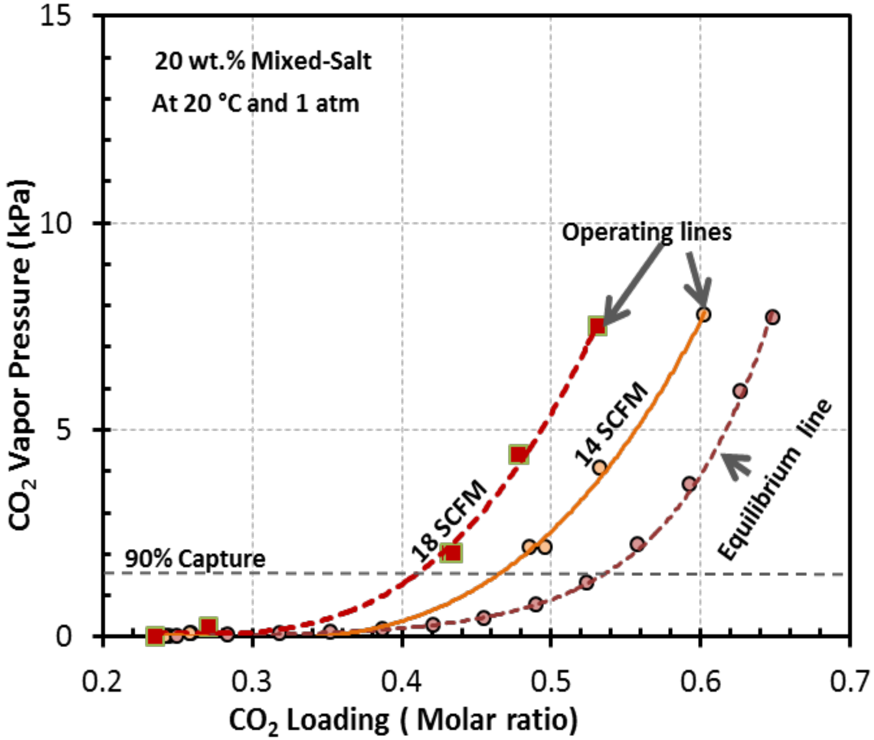
Bench-Scale Absorber Performance (BP1)

Test Data



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

Modeling and Test Data

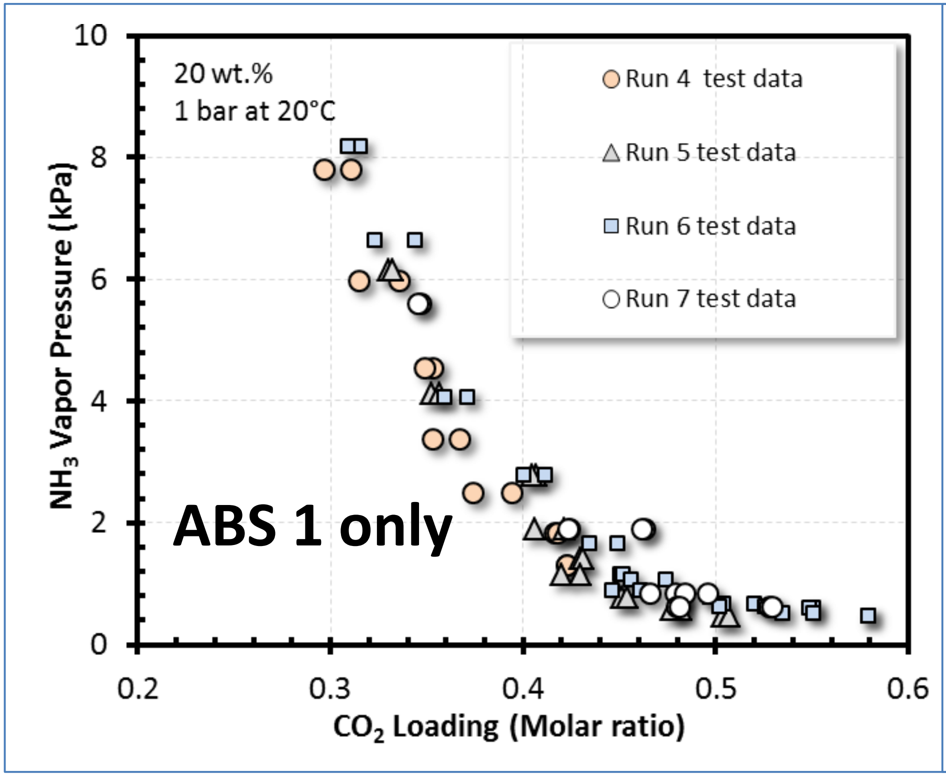


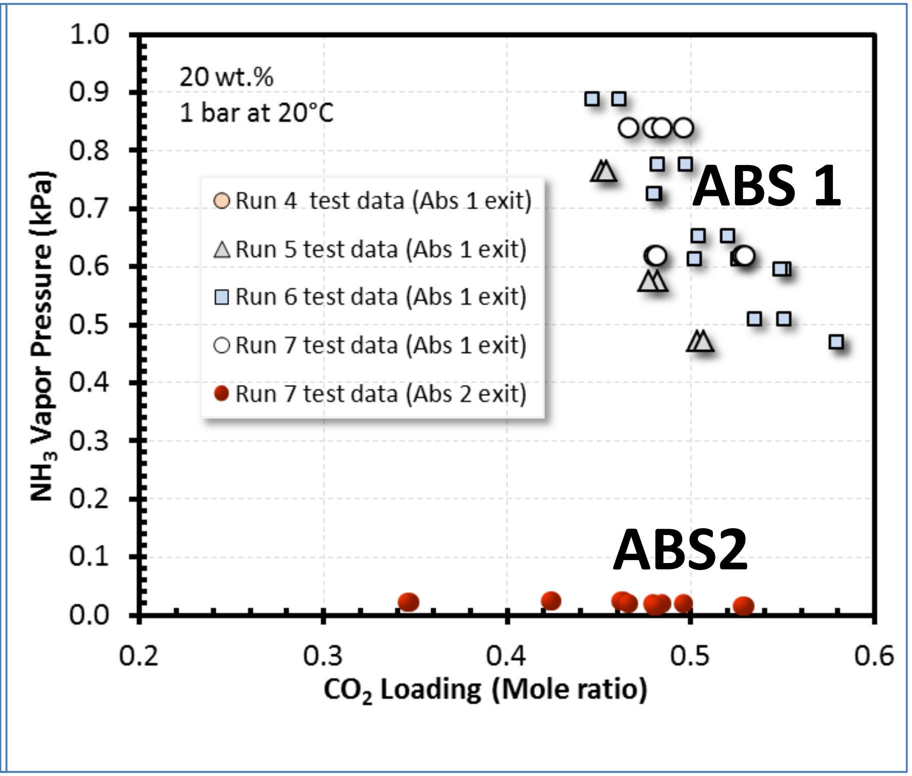
CO_2 vapor pressure at the absorber exit under various CO_2-loading conditions

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.

Absorber Ammonia Management (BP1)

Test Data





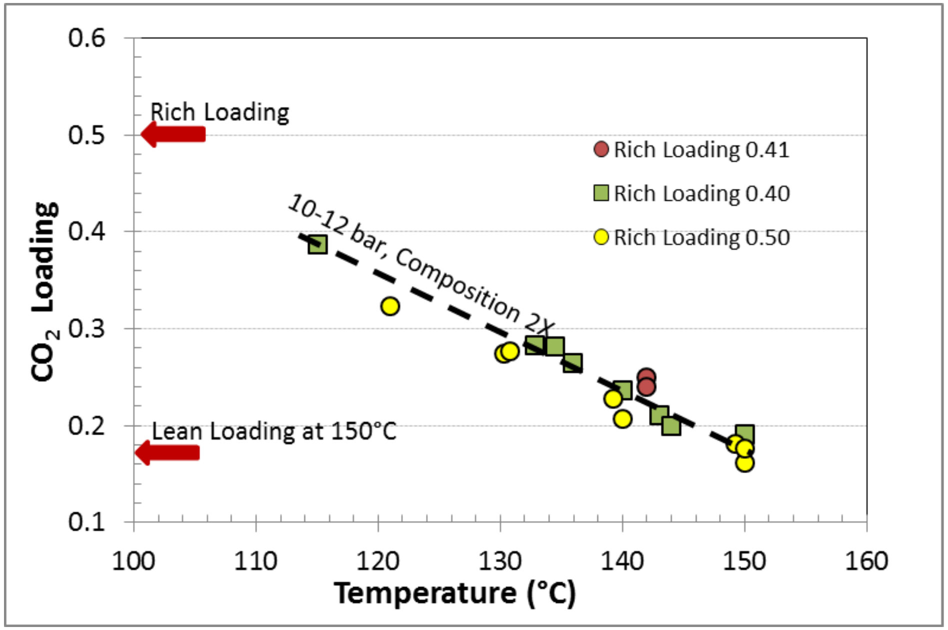
NH_3 vapor pressure at the Absorber 1 exit under various CO_2-loading conditions

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

Regenerator Performance (BP1)

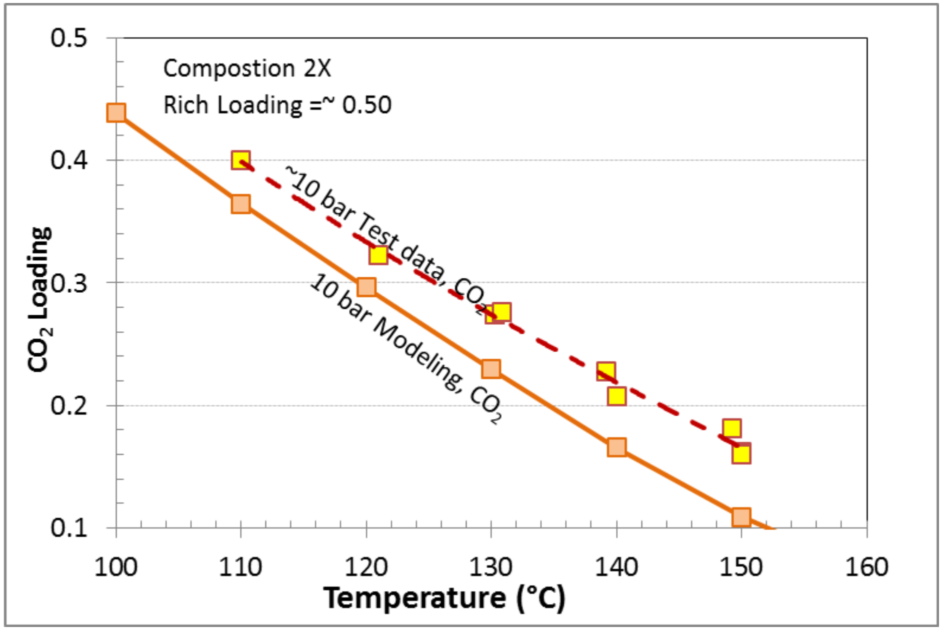
Single-Stage Regenerator

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



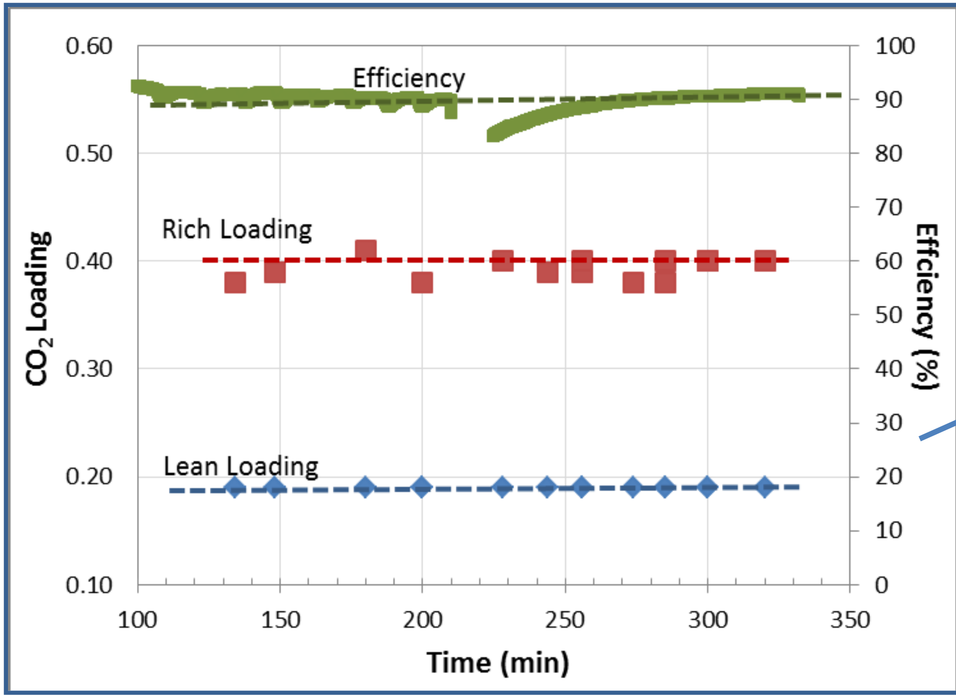
Comparison of measured and modeled attainable CO_2-lean loading at 100 to 150 ˚C.

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

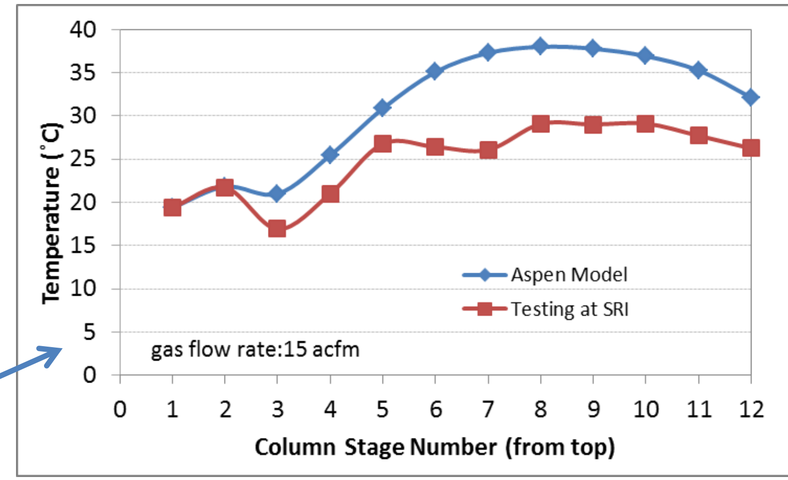
The produced lean loading well exceeds that required for > 90% CO_2 capture from flue gas streams

System Testing in Continuous Mode (BP1)

Test Data



Modeling and Test Data



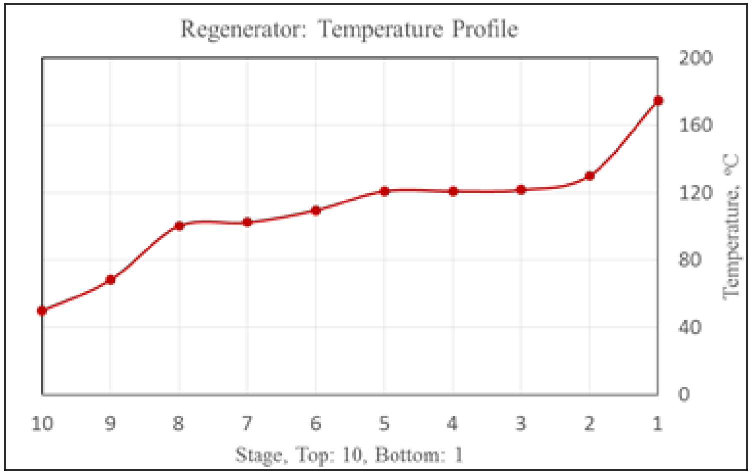
90% CO_2 capture efficiency with 0.19 to 0.40 cyclic CO_2 loading in Absorber 1

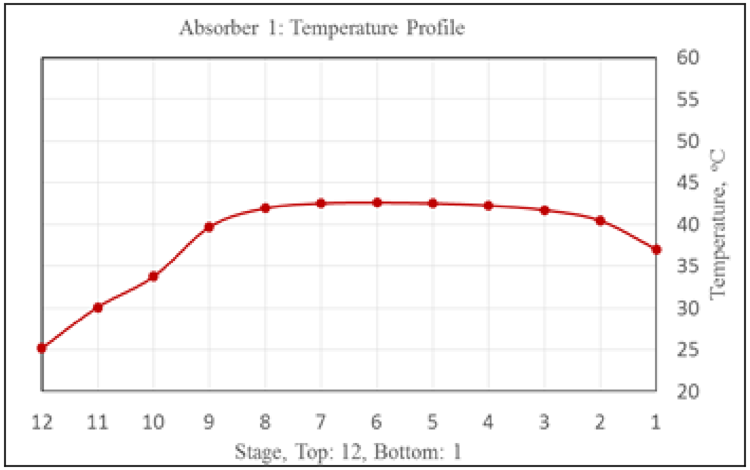
Gas flow rate = 15 acfm

Absorber and Regenerator Temperature Profiles (BP2)

Integrated System

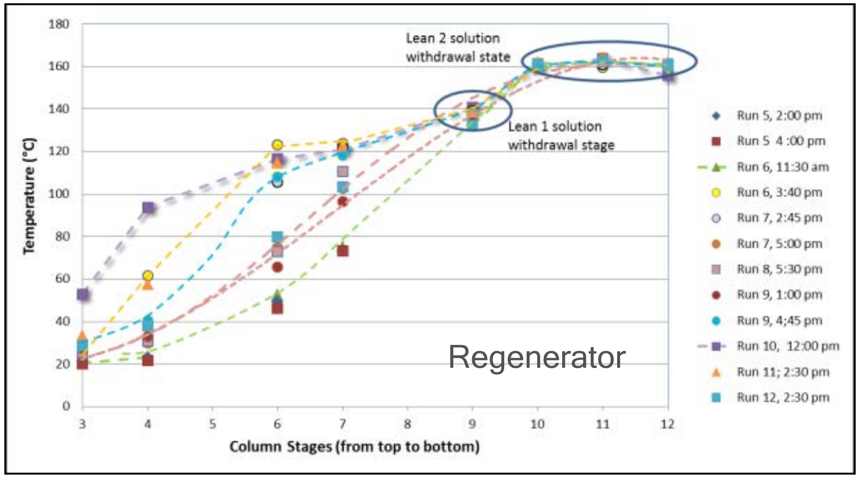
Modeling Data

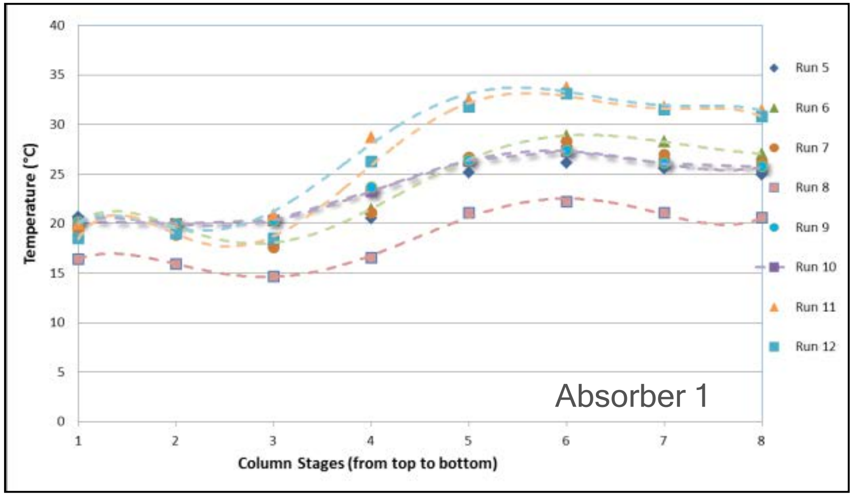




OLI modeling 550 MW system

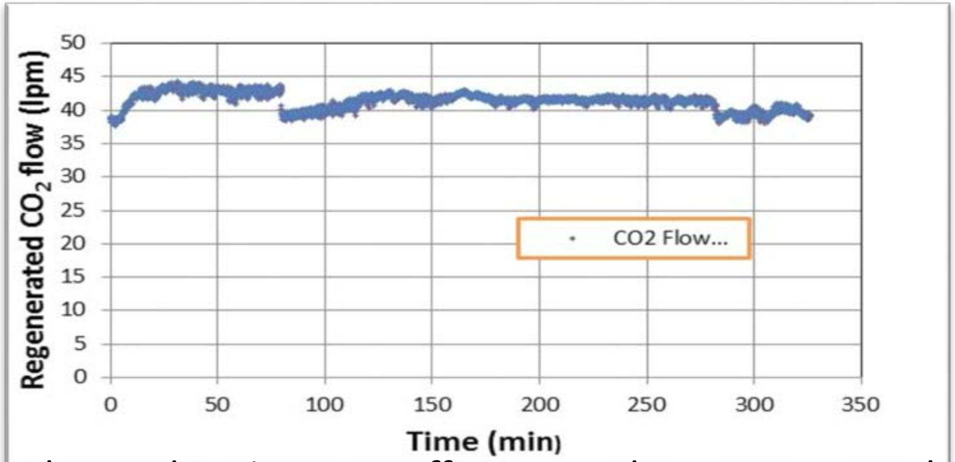
Test Data



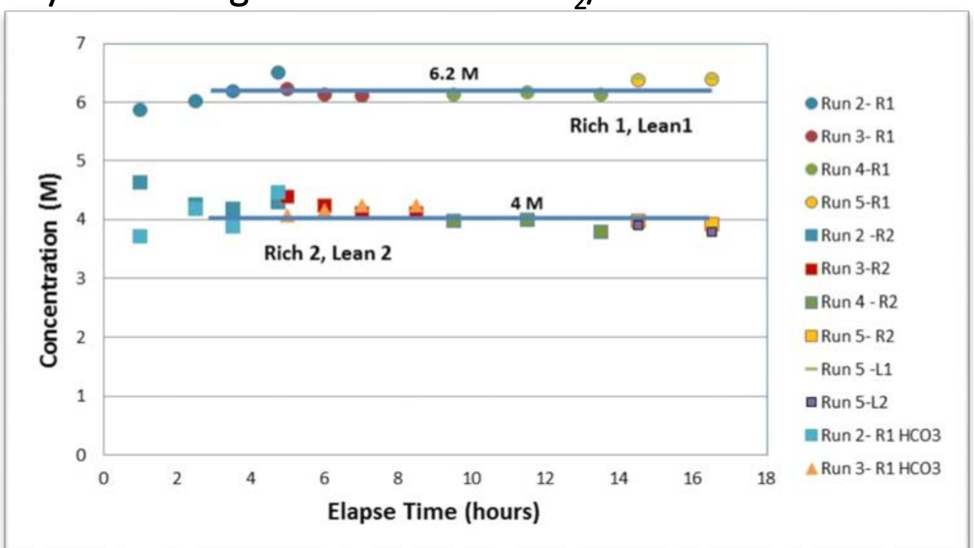


SRI Bench-Scale System

Data from Integrated System Testing in Feb-March 2016 (BP2)

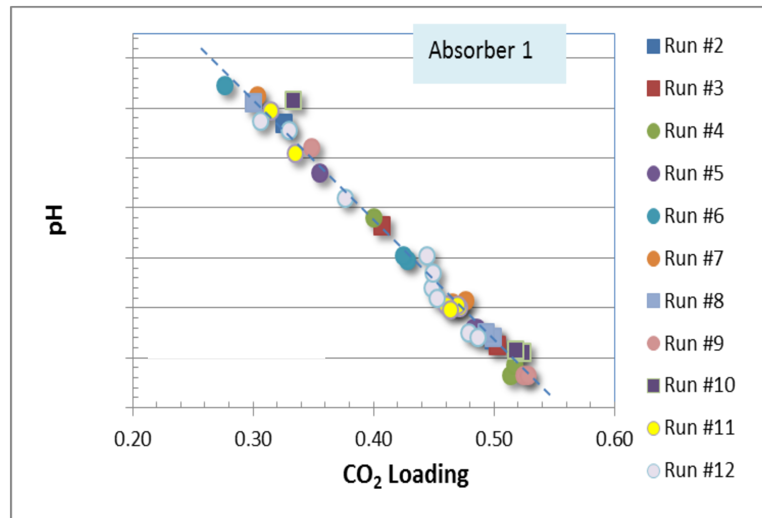


Observed 90% capture efficiency and regeneration with cyclic loading of ~0.7 mole of CO_2/mole of ammonia



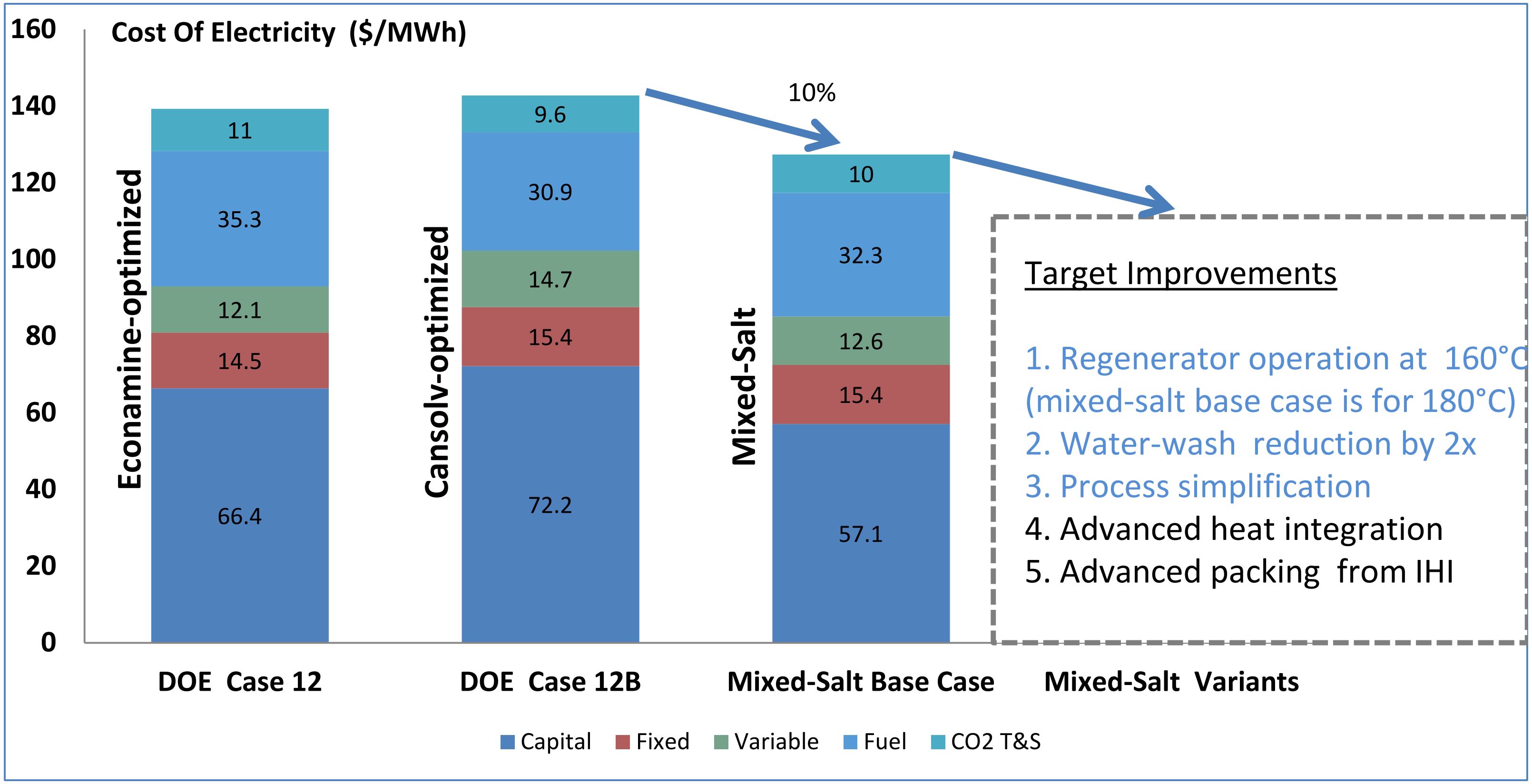
Alkalinity of rich and lean solutions circulating in the integrated system

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



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

Graphical Presentation of the Cost of Electricity Data (conducted by POLIMI)



Process Modeling: OLI , IHI and POLIMI

Cyclic Loading : 0.18 to 0.58

Reboiler Duty : 2.0 to 2.3 MJ/kg-CO_2

~ 3 point efficiency enhancement from DOE baseline case 12.

Ammonia Emission < 10 ppm

Project Accomplishment Summary

- Collected experimental and modeling data available in the literature for the H_2O-CO_2-NH_3-K_2CO_3 system were; 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 Case 12.
- 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 (~ 0.25 ton/day CO_2 capture) and the generation of lean solutions with two compositions (ammonia rich, potassium rich) using the novel two-stage regenerator.

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

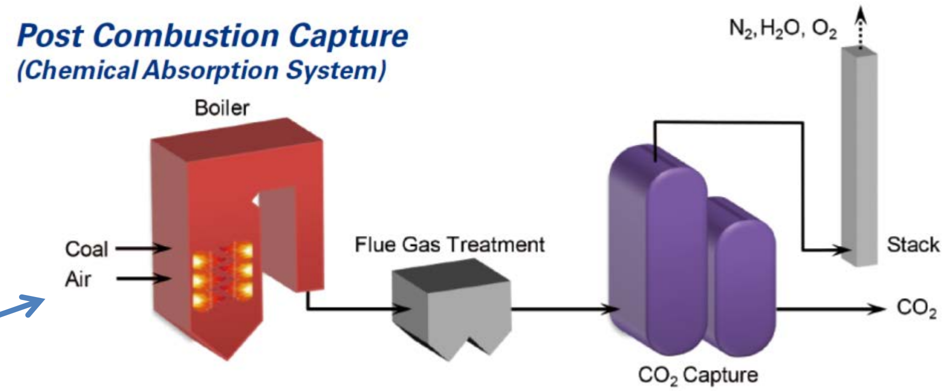
- Enhanced CO_2 capture efficiency
- High CO_2-loading capacity
- High-pressure release of CO_2
- Reduced energy consumption compared to MEA
- Reduced auxiliary electricity loads compared to the conventional ammonia processes
- Possible flexible carbon capture operation

Plans for Future Testing and Commercialization

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

SRI's Bench-scale System

Fully Integrated Slip Steam Testing



Development Plan Proposed by IHI Corporation

2013 **2015** **2020** **2025** **2030**

- Bench-scale Plant: 0.25 to 1 ton-CO_2/day (Existing program with DOE)
- Pilot Plant: 1 MW (Future program)
- Validation Stage Plant: 10-20 MW
- Demonstration Plant /Full-scale Plant: 100-300 MW

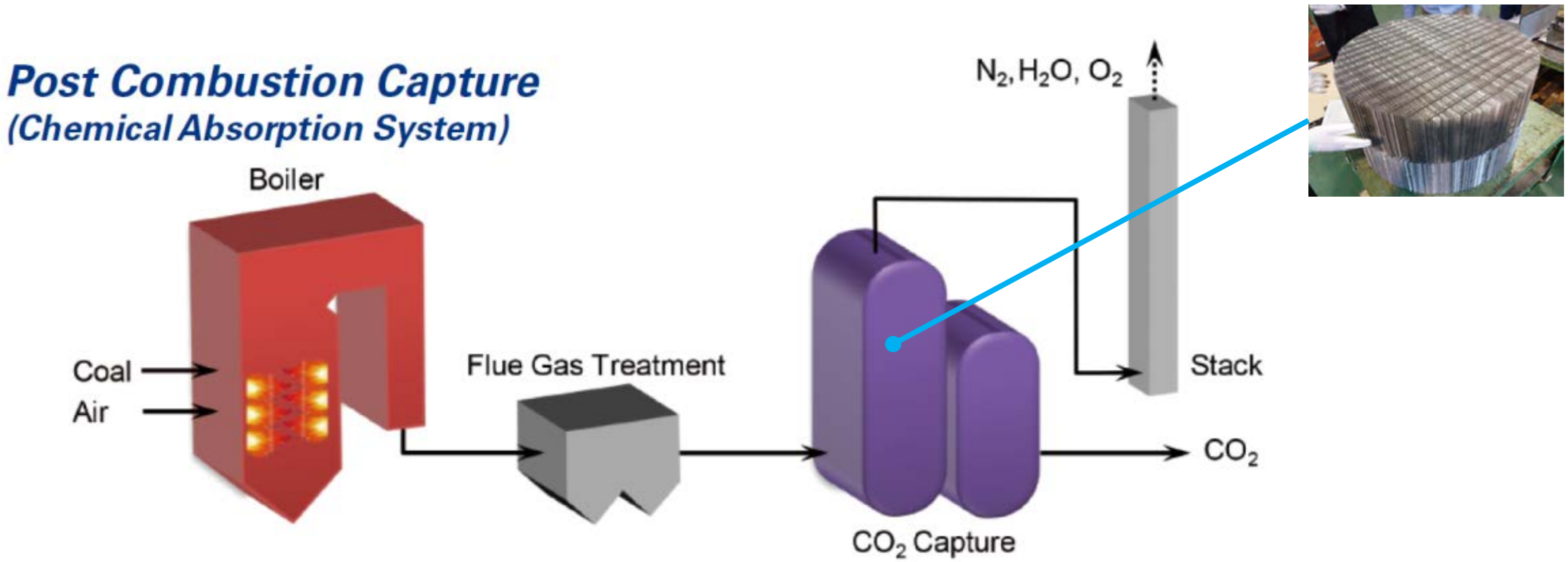
SRI / IHI Partnership

World-changing solutions making people safer, healthier, and more productive.

- Research organization
- Technology provider
- Process optimization
- System performance evaluation
- Design basis

Realize your dreams

- Supplier of boiler and related equipment including CCS plant
- Basic/ detailed engineering
- Process design & modeling
- Process scale-up expertise
- Gas-liquid mixing device technology



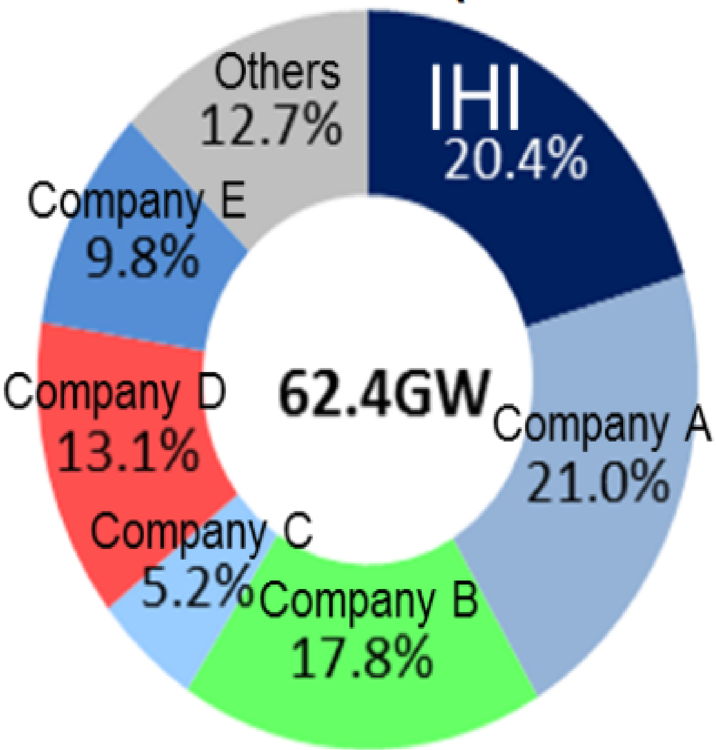
Plan for 1 MW demonstration

SRI / IHI Partnership

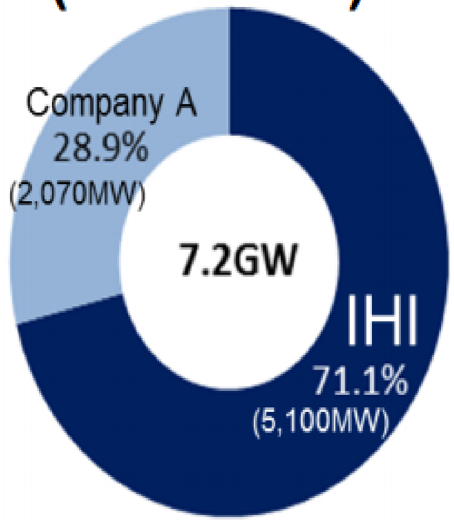
Source: IHI 2014 report

Coal-Fired Boilermaker Shares

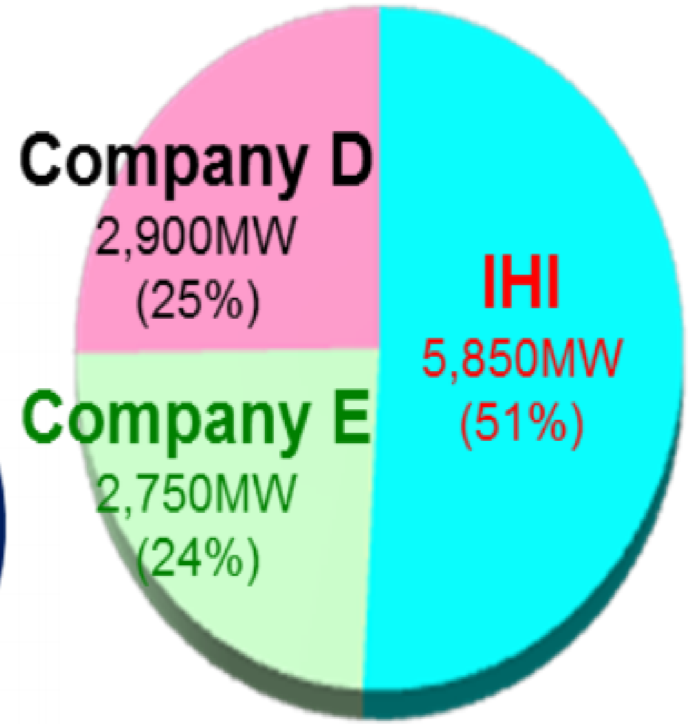
Southeast Asia (1980-2012)



Malaysia (1988-2013)



Japanese ultra-supercritical (USC) coal-fired boilers (2000–2010)



Source: Maccoy Report
Results for 1980–2012
Single plant capacity more than 100MW
Excluding Chinese maker production

Power output
from coal-fired USC units
(Total power generated: 11,500MW)

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, Mr. Yasuro Yamanaka, Dr. Kubota Nabuhiko and others)

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"Last year was the warmest globally since at least the mid-to-late 1800s, according to the State of the Climate in 2015 report published Tuesday (Aug. 2, 2016) in the Bulletin of the American Meteorological Society by the National Oceanic and Atmospheric Administration's National Centers for Environmental Information. "

Source: GHG Daily Monitor Vol. 1 No. 144, Aug 3, 2016