SRI International

Project Kick-Off Meeting
FE0031597

Mixed-Salt Based Transformational Solvent Technology for CO_2 Capture

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SRI International

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Presentation Outline

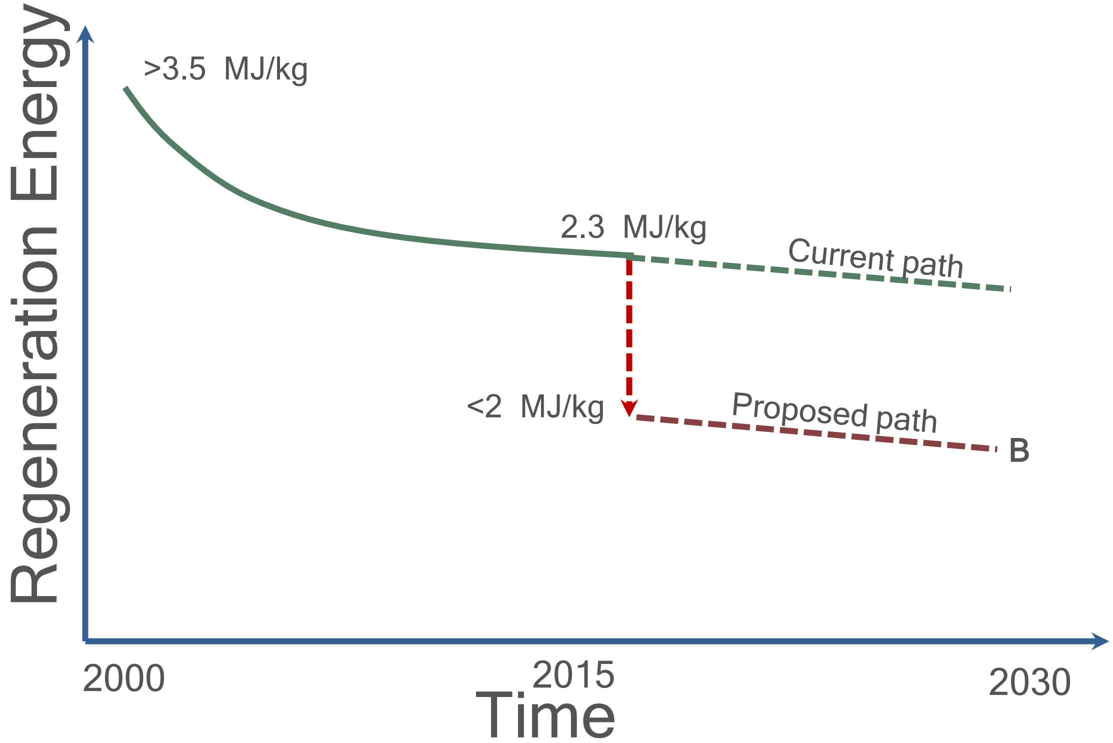
- Technology Background
  - Needs to reduce CO_2 capture costs
  - Advanced Mixed-Salt Process
  - Process Benefits
- New Project Structure
  - Objectives and Budget
  - Project Team and Organization
  - Development Path
  - Work Organization
  - Project Tasks
  - Available Resources
  - Project Status Update
  - Milestones
  - Risk Management

- Acknowledgements

Reducing Capture Costs Beyond the Current Values

New transformational technologies

-A step reduction of the regeneration energy is required



- Low regeneration energy by solvent pairing
- Energy recovery by heat integration

Advanced Mixed-Salt Process Details

How it works:

Selected composition of potassium carbonate , ammonium salts and an amine

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

Absorber operation at 20º - 40º C at 1 atm

Regenerator operation at 90º - 120º C at ~10 atm

- Produce high-pressure CO_2 stream

K_2CO_3–NH_3–Amine-CO_2–H_2O system

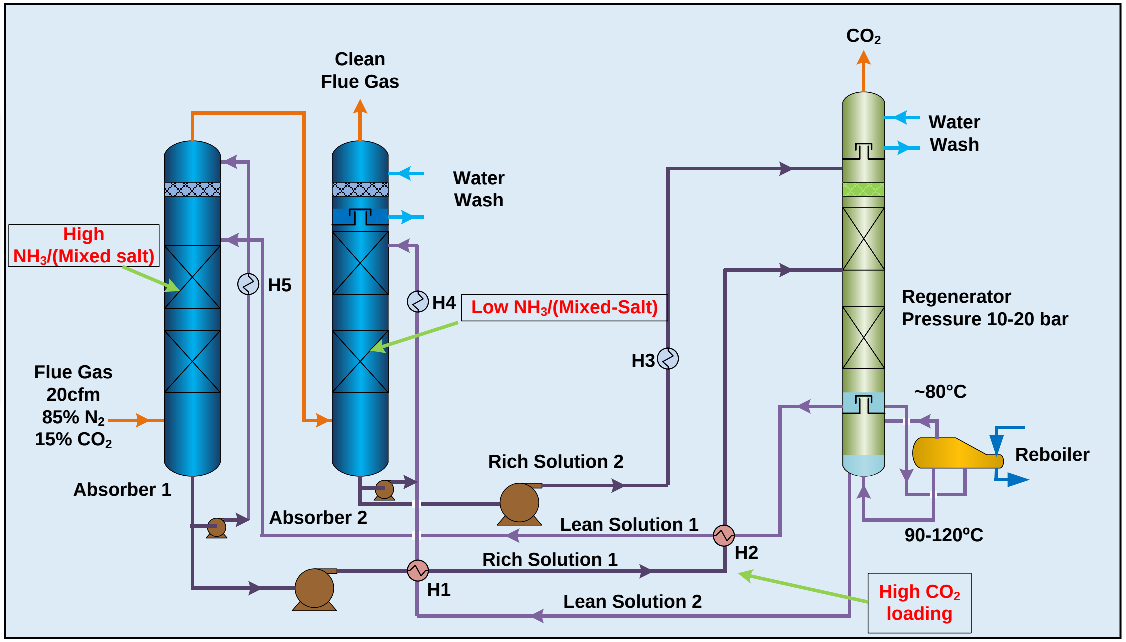
High CO_2 cycling capacity

Reduced Ammonia Emission

Reduced Reboiler duty

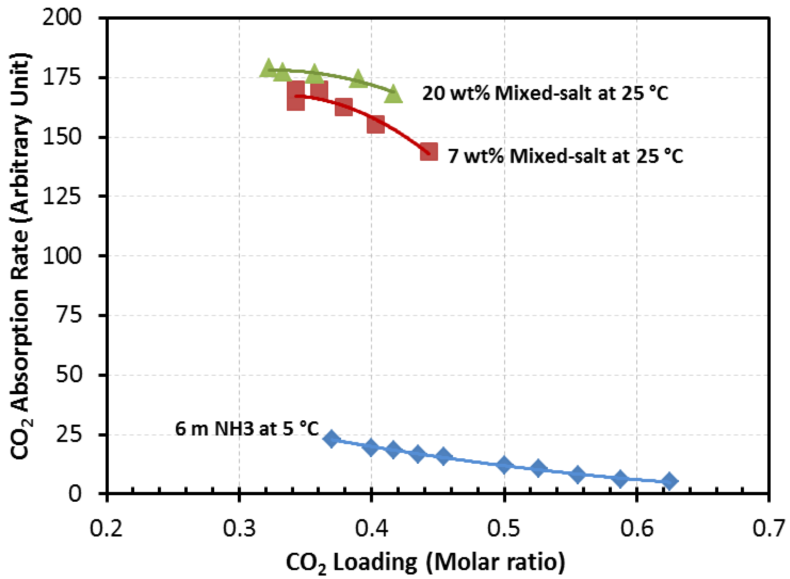
Reduced CO_2 Compression Energy

A significant step change for reaching DOE's reduced CO_2 capture cost targets.



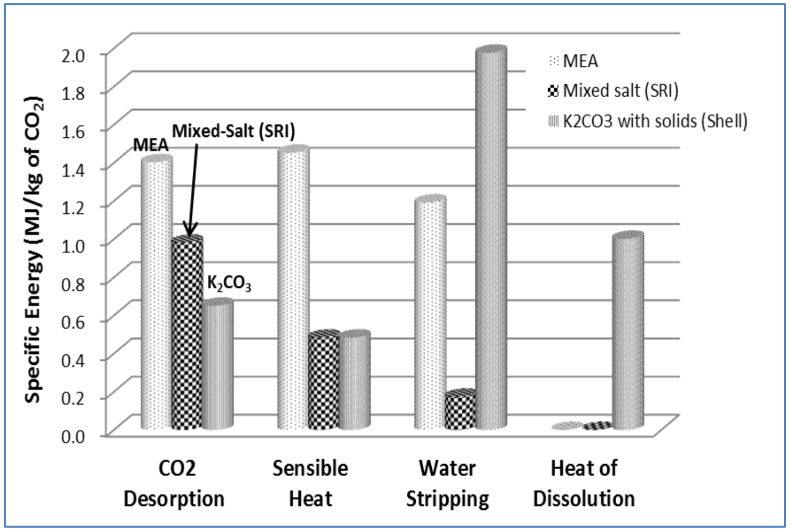
Process Enhancements

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

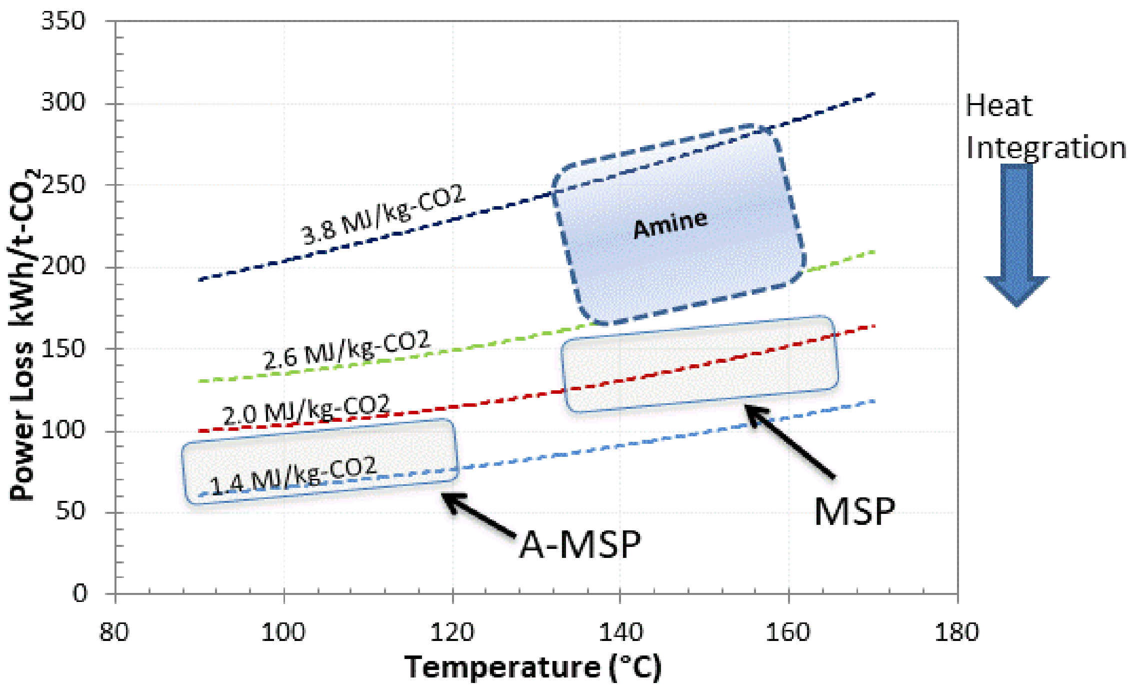


Estimated regenerator heat requirement for mixed-salt system with 0.2 to 0.6 cyclic CO_2 loading. Comparison with neat K_2CO_3 and MEA is shown

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

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

Power Loss due to Steam Extraction

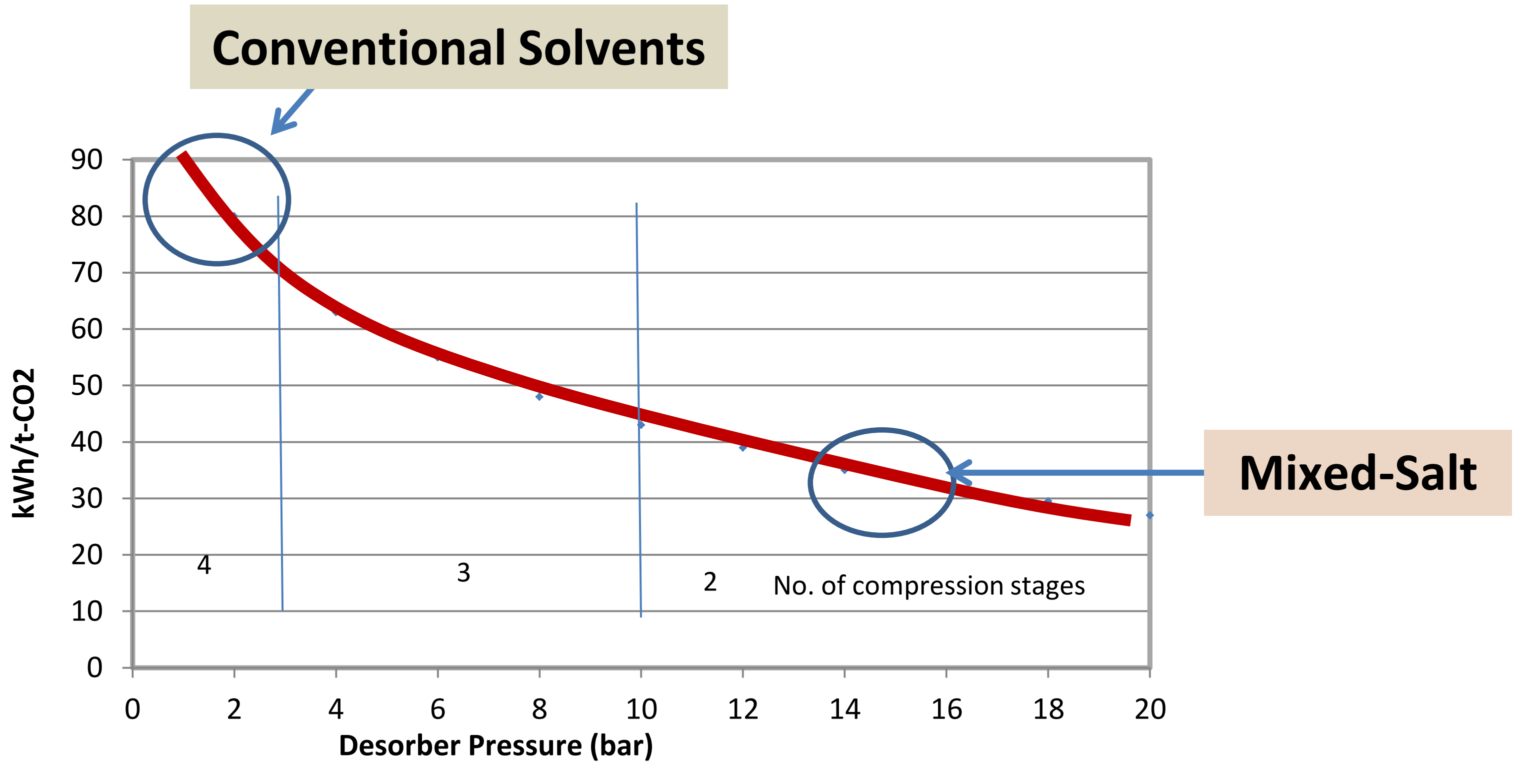


The net loss in power output from the steam cycle due to steam extraction for capture as a function of solvent regeneration temperature and the solvent heat requirement for regeneration.

Source: Adapted from Luquiaud and Gibbins, Chem Eng Res Des (2011); the Mixed-Salt data are from SRI's TEA

CO_2 Compression Energy

Both MSP and A-MSP require 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).

Selected Reactions

CO_2 (g) $\leftrightarrow$ CO_2 (aq) (1)

NH_3(aq) + CO_2 (aq) + H_2O (liq) $\leftrightarrow$ $(NH_4)HCO_3$ (aq) (2)

$(NH_4)_2CO_3$ + 2CO_2 (aq) + H_2O (liq) $\leftrightarrow$ 2$(NH_4)HCO_3$ (aq) (3)

2NH_3(aq) + CO_2(aq) $\leftrightarrow$ $(NH_4)NH_2CO_2$ (4)

$(NH_4)NH_2CO_2$ (aq) + CO_2 (aq) + 2H_2O(liq) $\leftrightarrow$ 2$(NH_4)HCO_3$ (aq) (5)

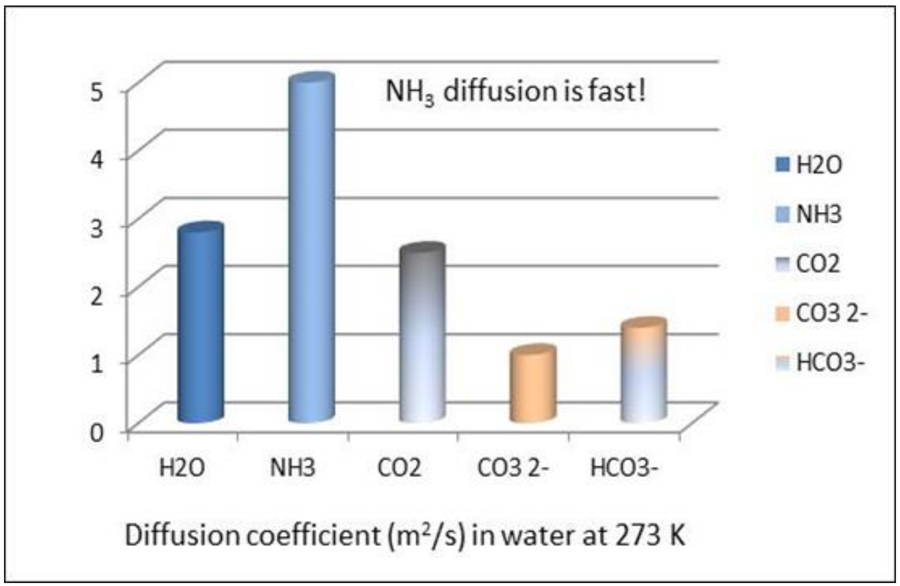
K_2CO_3 (aq) + CO_2 (aq) + H_2O(liq) + Catalyst $\leftrightarrow$ 2$KHCO_3$(aq)) + Catalyst (6)

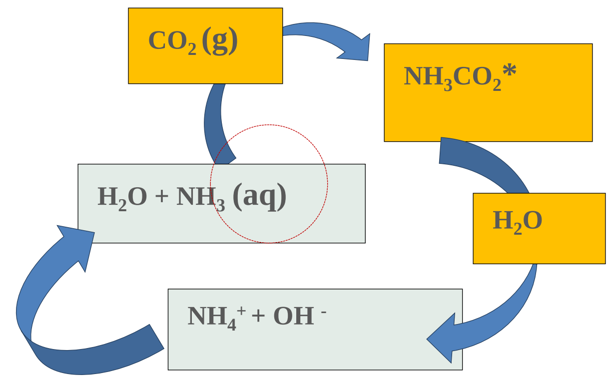
In the A-MSP, the tertiary amine is added to the MSP system.

The K_2CO_3-NH_3- R1R2R3N-H_2O-CO_2 system has an additional equilibrium reaction given in Eq. (7).

R1R2R3N (aq) + CO_2 (aq) + H_2O(liq) + Catalyst $\leftrightarrow$(R1R2R3NH)HCO_3 (aq)) +Catalyst (7)

Ammonia as a Catalyst





NH_3 Cycle

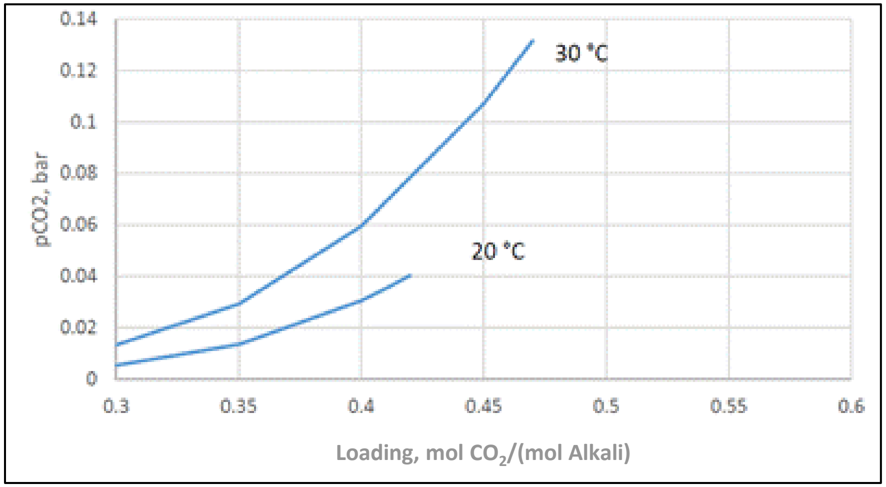
NH_3 cycle at the gas-liquid boundary.

Boiling Point and Measured Henry's Constant Values for Amines.

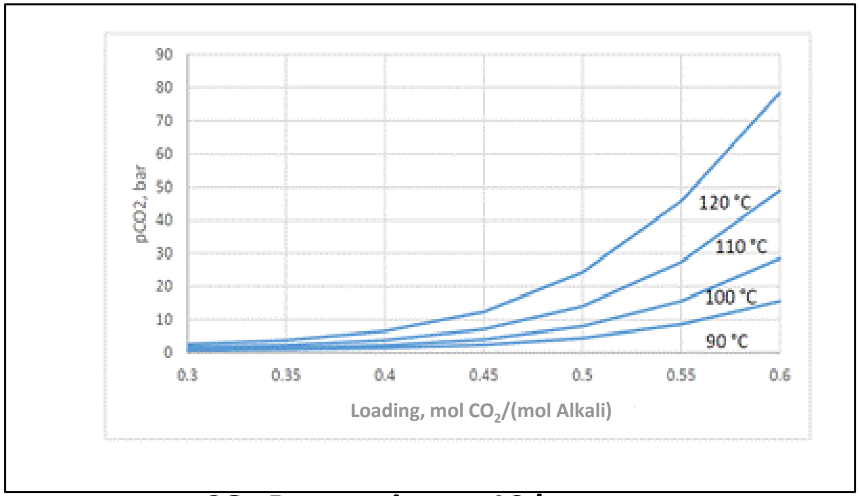
Amine	Boiling Point (°C)	Henry's Constant (Pa)
Methyl-diethanolamine (MDEA)	245	12.7
Diglycolamine (DGA)	223	13.9
Piperazine (PZ)	146	43.4
2-Methyl-piperazine (2-MPZ)	155	48.2
Ethylenediamine (EDA)	117	62.7
Monoethanolamine (MEA)	170	70.7
1-Methyl-piperazine (1-MPZ)	119	114
2-Amino-2-methyl-1-propanol (AMP)	166	288

Modeling Data

CO_2 Partial Pressure of 10 molal Advanced Mixed-Salt Solution



CO_2 Absorption at 20 ˚ and 30˚C .

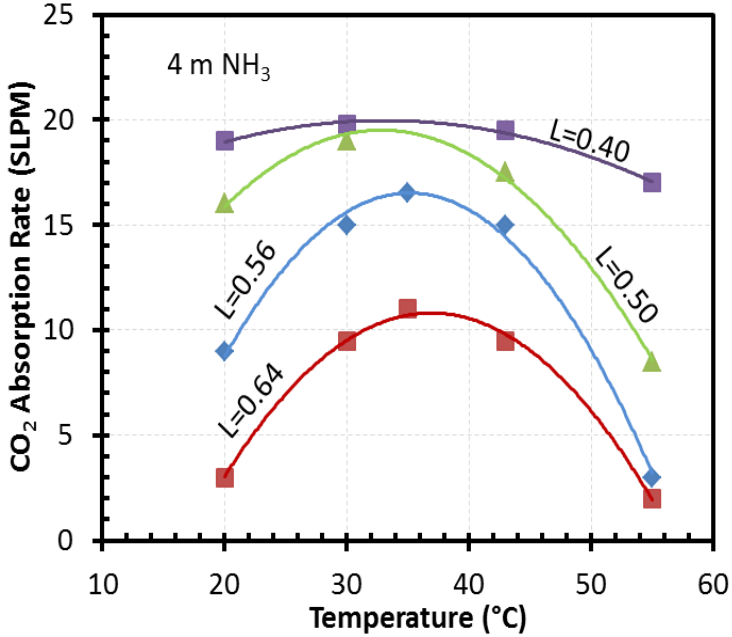


CO_2 Desorption at 10 bar

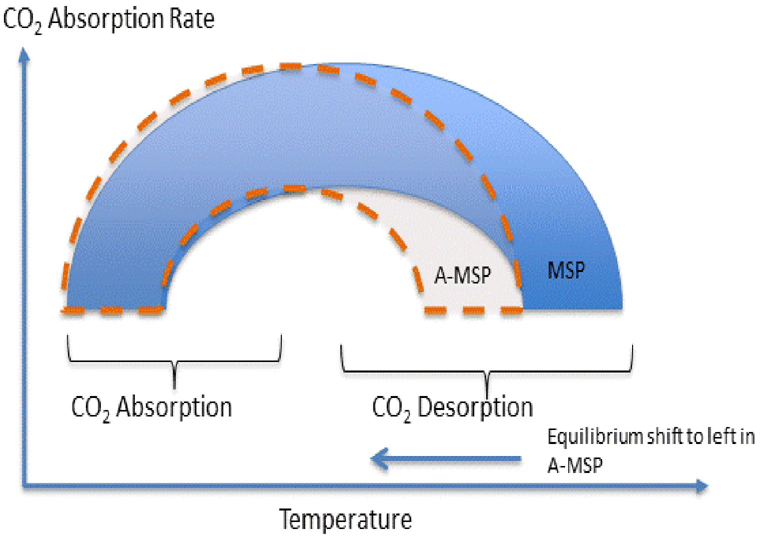
For the regeneration, the modeled composition can desorb CO_2 at > 10 bar at 100° C, a much lower temperature than MSP.

AMSP ⟶ Pathway to reach DOE 2030 CO_2 capture goals

Temperature Dependence of the Rate of CO_2 Absorption

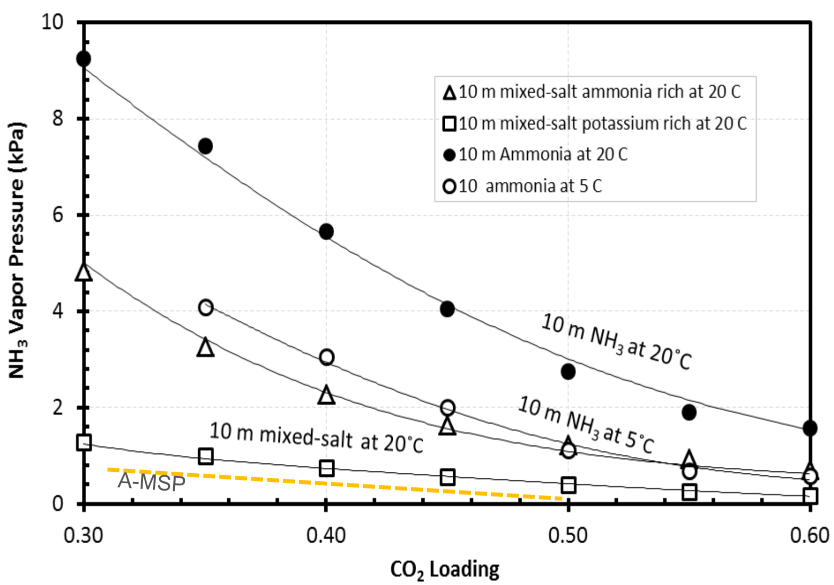


Measured
(ammonia solution)



Predicted

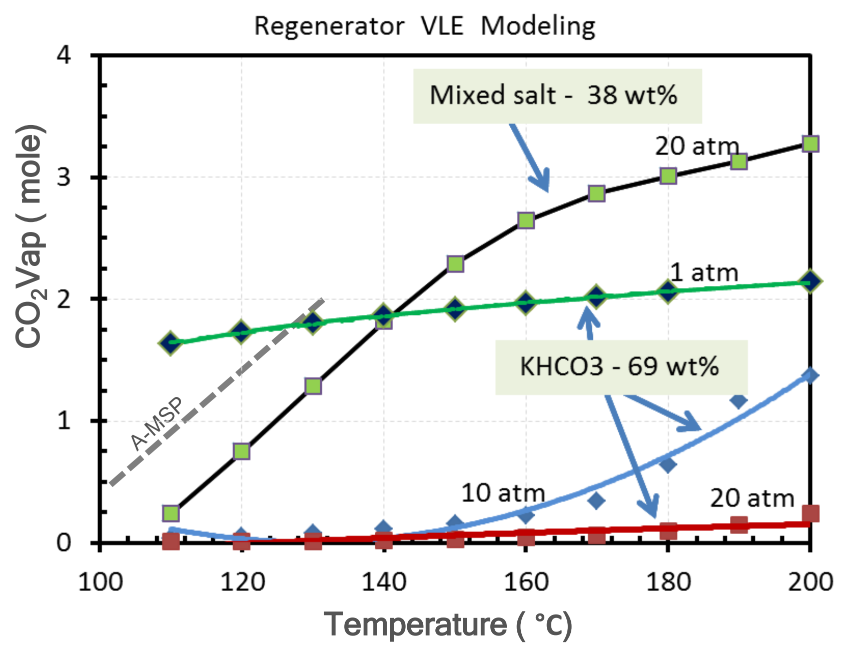
Advanced Mixed-Salt Comparison with Ammonia and K_2CO_3



NH3 vapor pressure as a function of CO_2 loading. A comparison between MSP and 10 m aqueous ammonia at 20°C is shown.

Reference. Jayaweera et al, "Mixed-Salt Solutions for CO_2 Capture," in *Absorption-Based Post-combustion Capture of Carbon Dioxide*, Elsevier, 2016, pp. 167-200.

Absorber-Side



Comparison of CO_2 released to the vapor phase during regeneration for CO_2-rich Mixed-Salt (0.6 CO_2 loading) and K_2CO_3 solutions

Regenerator-Side

New Project

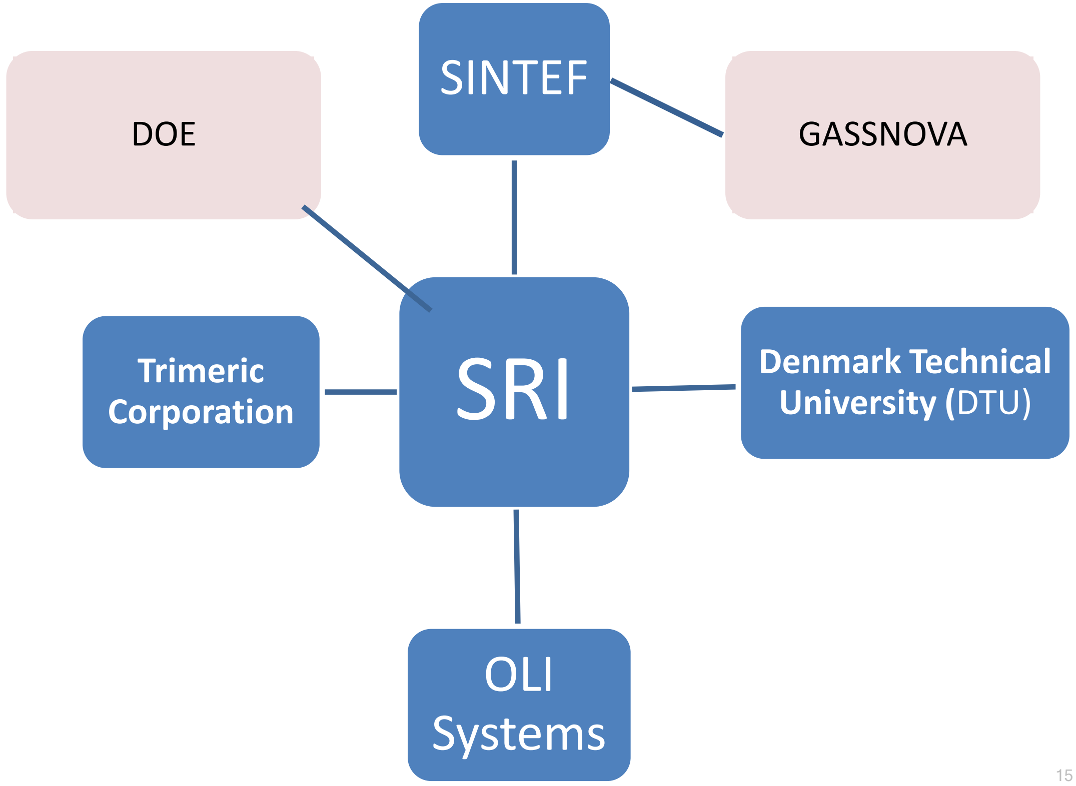
Mixed-Salt Based Transformational Solvent Technology for CO_2 Capture

- Project Objectives
  - Very high CO_2 loading capacity
  - Solvent rich system
  - Regenerate CO_2 at >10 bar at temperatures less than 120°C
  - Collect the experimental V-L-E data for the AMSP.
  - Develop predictive equilibrium and rate based models for the AMSP
  - Potential to reach DOE cost target $30/ton CO_2 by 2030

Project Team

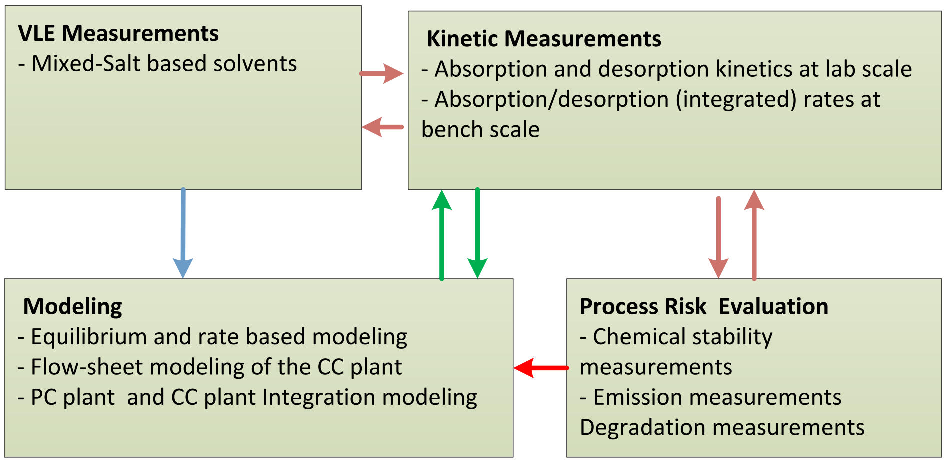
Mixed-Salt Based Transformational Solvent Technology for CO_2 Capture

Project Manager: Andrew Jones, NETL
Prime Contractor: SRI International
Project Team: US and International Partners



Opportunities for US-Norway Collaborations leading to new IP and new markets

Work Organization

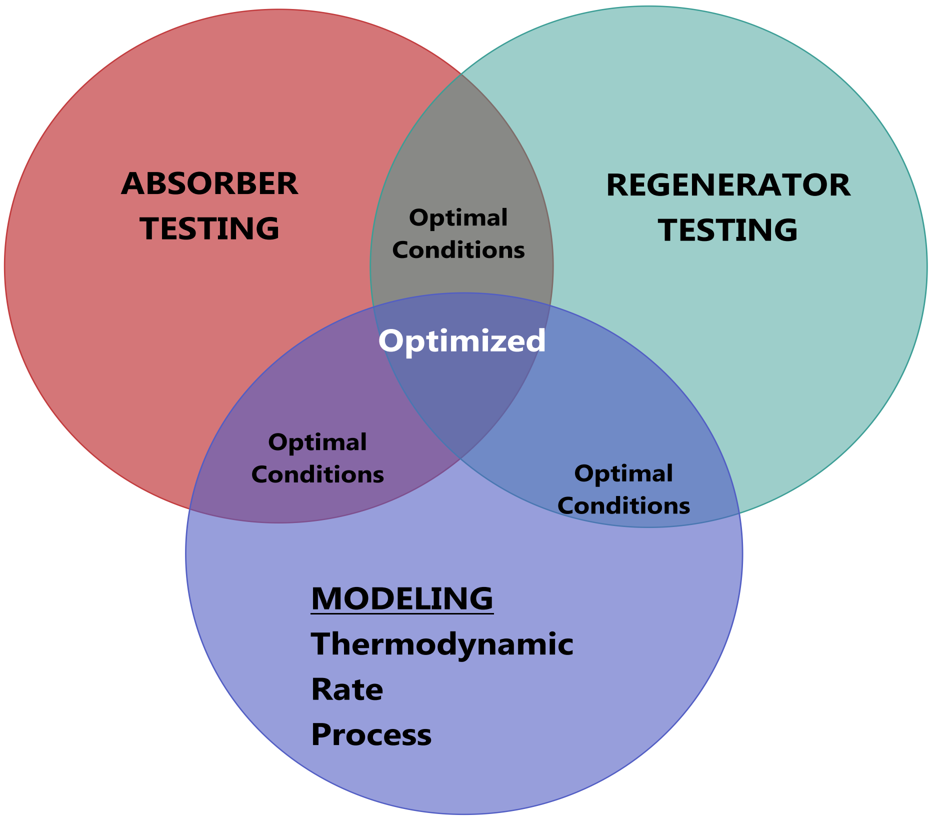


- SRI International, USA
  - Advanced mixed-salt composition development and testing
- DTU, Denmark (Cost-share partner)
  - VLE Measurements & Thermodynamic modeling
- OLI Systems, USA
  - Flowsheet Model Design (energy and mass balance)
- Trimeric, Corp., USA
  - Process Techno Economic Analysis
- SINTEF, Norway (Cost-share partner)
  - Emission and degradation studies
  - Alternative Mixed-salt composition development and testing

Project Budget

Contract No: DE-E0031597
DOE Funding: $2,999,992 (~79%)
Partner Share: $782,817 (~21%)

Our Systematic Technology Development Approach



Advanced Mixed-Salt Process optimization with experimental and modeling approach

Testing

- SRI
- DTU
- STINTEF

Modeling

- OLI Electrolyte Model
- OLI FOWSHEET MODEL
- DTU UNIQAC
- TRIMERIC cost model

1. Equilibrium Model (DTU Data)
2. Rate based Model (SRI Data)

⇨

1. ASPEN Modeling
2. OLI ESP Modeling

⇨

Mass & Energy Balance

Test Matrix

Parameter	BP1	BP2
Gas flow rate	<20 lpm	>100 lpm
Packing density	Fixed	Mellapak 250-450
Absorber temperature	20-30°C	15-40°C
Absorbent composition	Variable	Fixed
Regenerator temperature	100-120°C	100-120°C

Measurement of VLE Data and Thermodynamic Modeling at DTU

- Two systems are considered:
  - CO_2-NH_3-R1R2R3N-H_2O
  - CO_2-NH_3-R1R2R3N-K_2CO_3-H_2O
- For both systems, the following measurements will be performed:
  - Measurement of equilibrium pressure for Vapor-Liquid-Equilibrium (VLE)
  - Water activity measurements
  - Solid-Liquid-Equilibrium analysis
- No data for these systems have previously been reported in the open literature
- The measured data will be used for determining parameters in the thermodynamic model, Extended UNIQUAC.
- After the model parameters have been determined, the model can be used for process simulation in AspenPlus®.

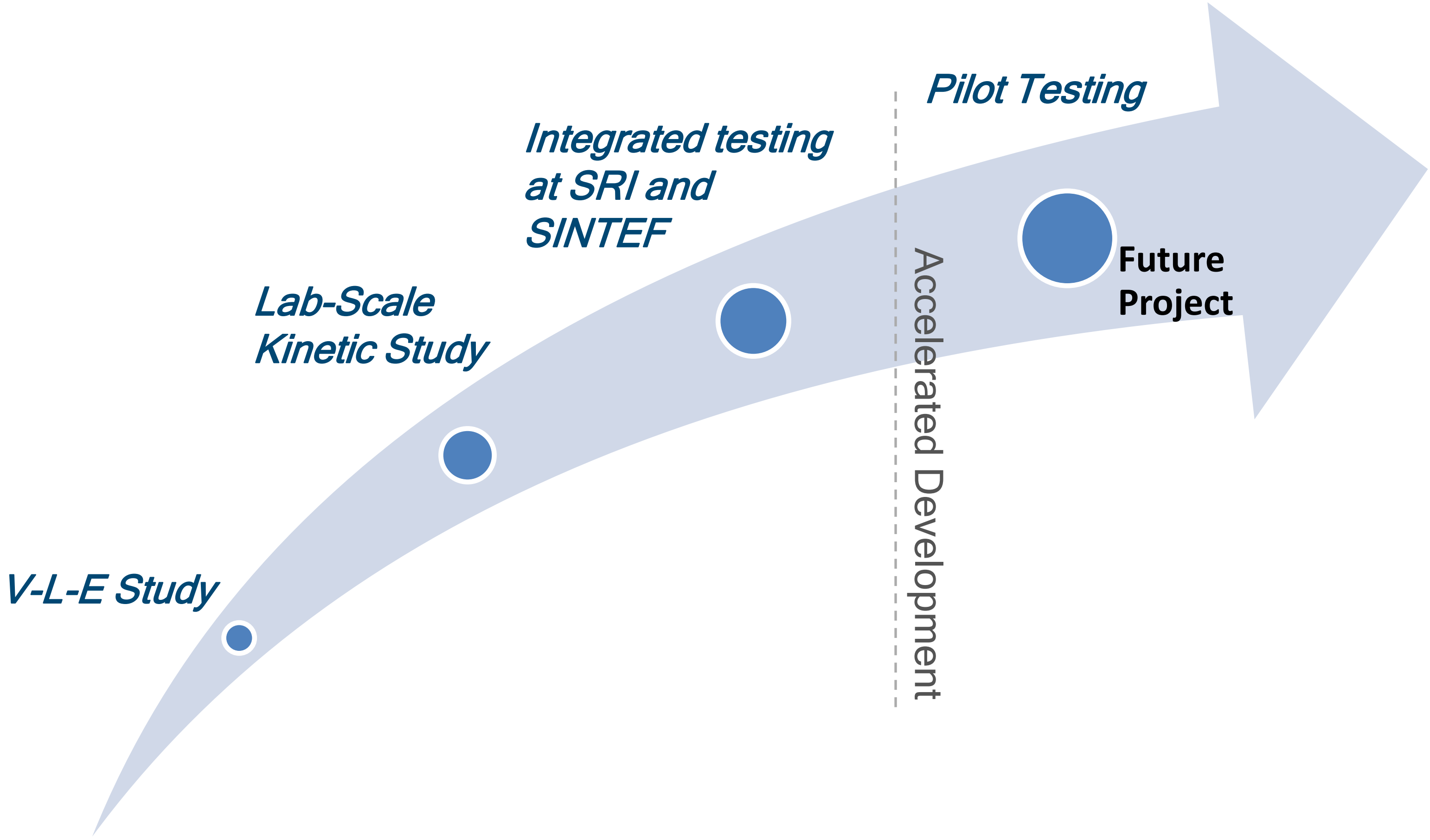
Flow-Sheet Modeling at OLI Systems

- Incorporation of DTU VLE data into the ESP model
- Incorporation of SRI test Data to develop the rate based model.
- Develop the flowsheet model to produce heat and mass balance information
- Trimeric will use the OLI flowsheet model to prepare TEA

1. Equilibrium Model 2. Rate based Model (SRI Data)	⇨	1. ASPEN Modeling 2. OLI ESP Modeling	⇨	Mass & Energy Balance

Mixed-Salt Based Transformational Solvent Technology for CO_2 Capture

Team : SRI (USA), SINTEF (Norway), OLI (USA), DTU (Denmark), Trimeric (USA)
Funding : US DOE (SRI Project) & CLIMIT (SINTEF Project)



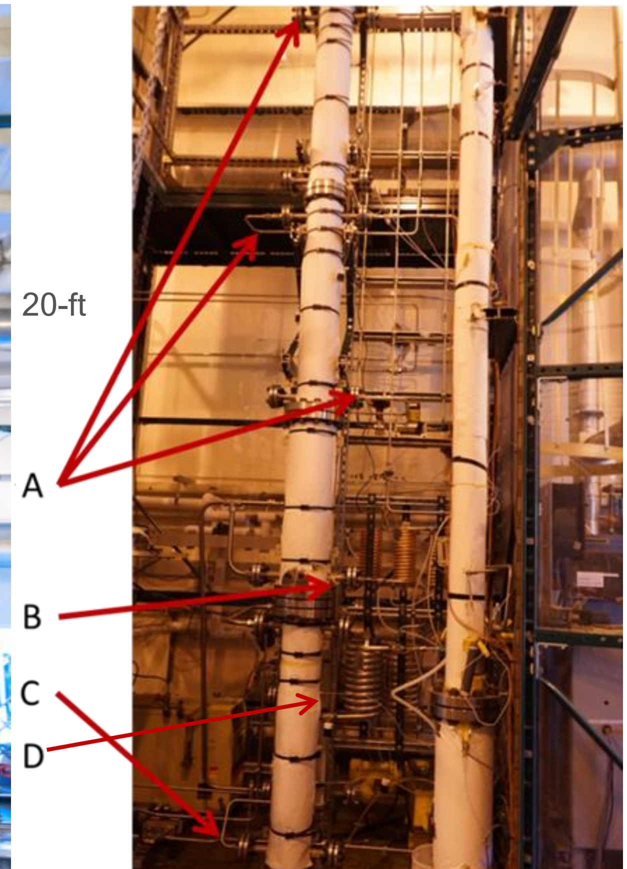
Opportunities for reducing CO_2 from small and large-scale applications

Existing Infrastructure for Testing

Photographs of lab and large bench scale setups

Lab scale system


Large bench scale system

A: Rich solution inlet locations

B: Discharge locations for high NH_3/K solution

C: Discharge locations for low NH_3/K solution

D: Heat exchangers (Cold rich↔ Hot lean)

Project Tasks

BP1: 18 months BP2: 18 months

- Task 1: Project Management and Planning (SRI)
- Task 2: Vapor-Liquid-Equilibria Measurements (DTU)
- Task 3: Process Kinetic Assessment (SRI)
- Task 4: Emission and Degradation Measurements (SINTEF)
- Task 5: Rate-Based Model Development (OLI)
- Task 6: Preliminary Techno-economic Analysis (Trimeric)
- Task 7: Integrated System Testing (SRI)
- Task 8: Process Flowsheet Model Development (OLI)
- Task 9: Techno-economic Analysis (Trimeric)

*** Tasks in Red will be performed in BP2**

Project Timeline

BP1: 18 months; BP2:18 months

Year	2018			2019				2020				2021
Budget Period	BP1						BP2					
Start	6/1/18	9/1/18	12/1/18	3/1/19	6/1/19	9/1/19	12/1/19	3/1/20	6/1/20	9/1/20	12/1/20	3/1/21
Quarter	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12

Task	Start Date	End Date	Milestones
Advanced -Mixed-Salt Process (BP1 and BP2)	**6/1/2018**	**5/31/2021**	
Task 1.0 - Project Management and Planning	**6/1/2018**	**5/31/2021**	
Project Kick-Off Meeting	6/1/2018	8/31/2018	
Technology Maturation Plan	6/1/2018	5/31/2021	
Milestones			a, b, c; I, j
Task 2.0 : VLE Measurements	**6/1/2018**	**5/31/2021**	
Subtask 2.1 - VLE Measurements of the MDEA-NH3-CO2-H2O System	6/1/2018	4/30/2019	
Subtask 2.2 - Solid-Liquid Equilibrium Analysis	3/1/2019	11/30/2019	
Subtask 2.3 - VLE Measurements of the MDEA-K2CO3-NH3-CO2-H2O System	9/1/2019	11/30/2019	
Milestones			d
Task 3.0 - Process Kinetic Measurements	**9/1/2018**	**11/30/2020**	
Subtask 3.1 - Bench-Scale Test Plan Development	9/1/2018	1/31/2019	
Subtask 3.2 - Absorption Measurements	9/1/2018	11/30/2019	
Subtask 3.3 - Regeneration Rate Measurements	9/1/2018	11/30/2019	
Subtask 3.4 - Test Data Analysis	9/1/2018	11/30/2019	
Milestones			e; f
Task 4.0 - Process Kinetic and Emission Assesments	**12/1/2019**	**5/31/2021**	
Subtask 4.1 - Oxidative and Thermal Degradation Study	12/1/2019	5/31/2020	
Subtask 4.2 - Emission Measurements at the Recipient's Team Member Facility	12/1/2019	5/31/2021	
Subtask 4.3 - Integrated Testing with Amine and Mixed-salt blends	12/1/2019	5/31/2021	
SINTEF Submit the Data Report to SRI	4/1/2021	4/30/2021	
Milestones			k; l
Task 5.0 - Rate Based Model Development	**6/1/2018**	**11/30/2019**	
Subtask 5.1 - Thermodynamic model for the MDEA-K2CO3-NH3-CO2-H2O system	6/1/2018	11/30/2018	
Subtask 5.2 - Data Analysis and Predictive Model Development	12/1/2018	11/30/2019	
Milestones			g
Task 6.0 - Preliminary Techno-Economic Analysis	**12/1/2018**	**11/30/2019**	
Subtask 6.1 - Review of A-MSP Flow-sheet	5/1/2019	11/30/2019	
Subtask 6.2 - Techno-Economic Analysis	9/1/2019	11/30/2019	
Subtask 6.3 - First Decision Point (a. Report b. Continuation)	9/1/2019	11/30/2019	
Milestones			h
Task 7.0 - Integrated System Testing at the Recipient Site	**12/1/2020**	**5/31/2021**	
Subtask 7.1 - Development of Test Plan and Submission to DOE	12/1/2020	2/29/2020	
Subtask 7.2 - Integrated Testing with MSP and A-MSP Compositions	3/1/2020	2/28/2021	
Subtask 7.3 - Regenerator Steam use Measurements	12/1/2020	5/31/2021	
Subtask 7.4 - Test Data Analysis	5/1/2020	5/31/2021	
Milestones			m; n
Task 8.0 - Flow-Sheet Model Development	**6/1/2020**	**5/31/2021**	
Subtask 8.1 - Development of Process Flow-Sheet Model	6/1/2020	12/31/2020	
Subtask 8.2 - Evaluation of Process Heat and Mass Balances	9/1/2020	4/30/2021	
Milestones			o
Task 9.0 - Techno-Economic Analysis	**9/1/2020**	**5/31/2021**	
Subtask 9.1 - Techno-Economic Analysis	9/1/2020	3/31/2021	
Subtask 9.2 - Update the State Point Data Table	1/1/2021	3/31/2021	
Subtask 9.3 - Technology Gap Analysis	1/1/2021	3/31/2021	
Subtask 9.4 - Environmental Health and Safety Risk Assessment	1/1/2021	3/31/2021	
Submit the State Point Data Table	4/1/2021	4/30/2021	
Submit the Technology Gap Analysis	4/1/2021	4/30/2021	
Submit the Technology Maturation Plan	4/1/2021	4/30/2021	
Project Review at DOE	5/1/2021	5/31/2021	
Final Report Submission	5/1/2021	5/31/2021	
Milestones			p,q,r,s

Success Criteria and Decision Points

Decision Point	Basis for Decision/Success Criteria
A. Completion of Budget Period 1	Successful completion of all work proposed in Budget Period 1
	Submission of a Technology Maturation Plan
	Submission of Preliminary Techno-Economic Analysis topical report
	Experimentally validate at least 10 bar pressure in the regenerator ~120°C
	Partnering agreement finalized
	Successful completion of the VLE model development and demonstrating the lower regeneration (less than 120°C) potential of the A-MSP solution
	Completion of the spread-sheet model by OLI to demonstrate the regeneration energy to be less than 2.3 GJ/tonne CO_2
B. Completion of Budget Period 2	Successful completion of all work proposed
	Completion of integrated A-MSP bench-scale testing with selective, high-pressure regeneration of ammonia rich and potassium + amine rich streams, including parametric testing with a simulated flue gas, and continuous testing with a simulated flue gas at partner facility; bench-scale testing results showing ≥ 0.10 kg-CO_2/kg working solution loading capacity, ammonia emissions < 10 ppm in the stack gas, and total energy consumption < 1.8 GJ/tonne CO_2 (including the estimated compression work) that indicate significant progress toward achieving the DOE's Transformational CO_2 Capture goals of 95% CO_2 purity at a cost of $30/tonne of CO_2 captured
	Submission of (1) an updated State-Point Data Table; (2) a Techno-Economic Analysis topical report; (3) a Technology Gap Analysis topical report; and (4) an Environmental Health & Safety Risk Assessment topical report based on the results of bench-scale testing
	Submission of a Final Report

Risk Table

Description of Risk	Probability (Low, Moderate, High)	Impact (Low, Moderate, High)	Risk Management Mitigation and Response Strategies
Technical Risks:			
Precipitation of solids in the absorber	Low	Low	Store rich solution in a separate tank overnight; design a SOP to avoid shutdowns with rich solutions. General SOPs for operating ammonia-based processes are available at SRI.
Residual amine in the exit gas stream	Moderate	Moderate	Use a tertiary amine as the starting amine to reduce residual amine. Select lowest volatility among the commonly used amines. For any new amine blends, we will study the VLE before testing in the bench-scale test system.
Residual ammonia in the exit gas stream	Moderate	Moderate	Increase the water-wash column fresh-water flow to capture ammonia vapor.
High-pressure drop in the absorber column	Low	Moderate	Monitor and control the recycled liquid flow and flooding level.
Solvent interaction with acid gases	Moderate	Moderate	Monitor solvent composition and control the bleed and make-up flow of solvents.
Particulate accumulation	Low	Low	Monitor suspended particles in the absorption solution. Replace solution if too high.
Thermal management of absorber columns	Low	Moderate	Monitor column temperature closely and control cooling water flow accordingly.
Thermal management of regenerator	Low	Moderate	Control the steam flow and heat exchanger flow closely. Monitor temperature sensor profiles to avoid rapid temperature changes.
Resource risks:			
Delays in procurement of required components	Low	Moderate	Plan ahead with vendors. Place orders early and have backup vendors. We have been working with a reliable chemical broker for bench-scale testing.
Delays in construction	Low	Moderate	Plan ahead with realistic timelines. Meet with staff regularly and address issues early on.
Management risks:			
Project team availability	Low	Moderate	Identify a backup team.
Health and safety	Low	High	Prepare SOPs and train operators.

Milestone Log - BP1

BP	Task/ Subtask No.	Milestone Description	Planned Completion	Actual Completion	Verification Method
1	1	a. Updated PMP	7/1/2018	8/1/2018	PMP file
1	1	b. Kickoff Meeting	8/31/2018		Presentation file
1	1	c. Technology Maturation Plan	9/30/2018		TMP file
1	2.1-2.3	d. Completion of quaternary system VLE measurements at DTU and submission of speciation curves	11/30/2019		Results reported in the QR report
1	3.1	e. Bench-scale absorber and regenerator test plans submitted	1/31/2019		Results reported in the QR report
1	3.1-3.4	f. Completion of at least 20 kinetic test runs at SRI	11/30/2019		Results reported in the QR report
1	5.1-5.2	g. Completion of rate-based model development at OLI	11/30/2019		Results reported in the QR report
1	6.2	h. Preliminary Techno-Economic Analysis topical report submitted	11/30/2019		Results reported in the QR report and a topical report
1	1	i. Partnering agreement	11/30/2019		Partnering Agreement submitted to DOE/NETL
1	1	j. Budget Period 1 summary topical report submitted	11/30/2019		Results reported in the QR report and a topical report

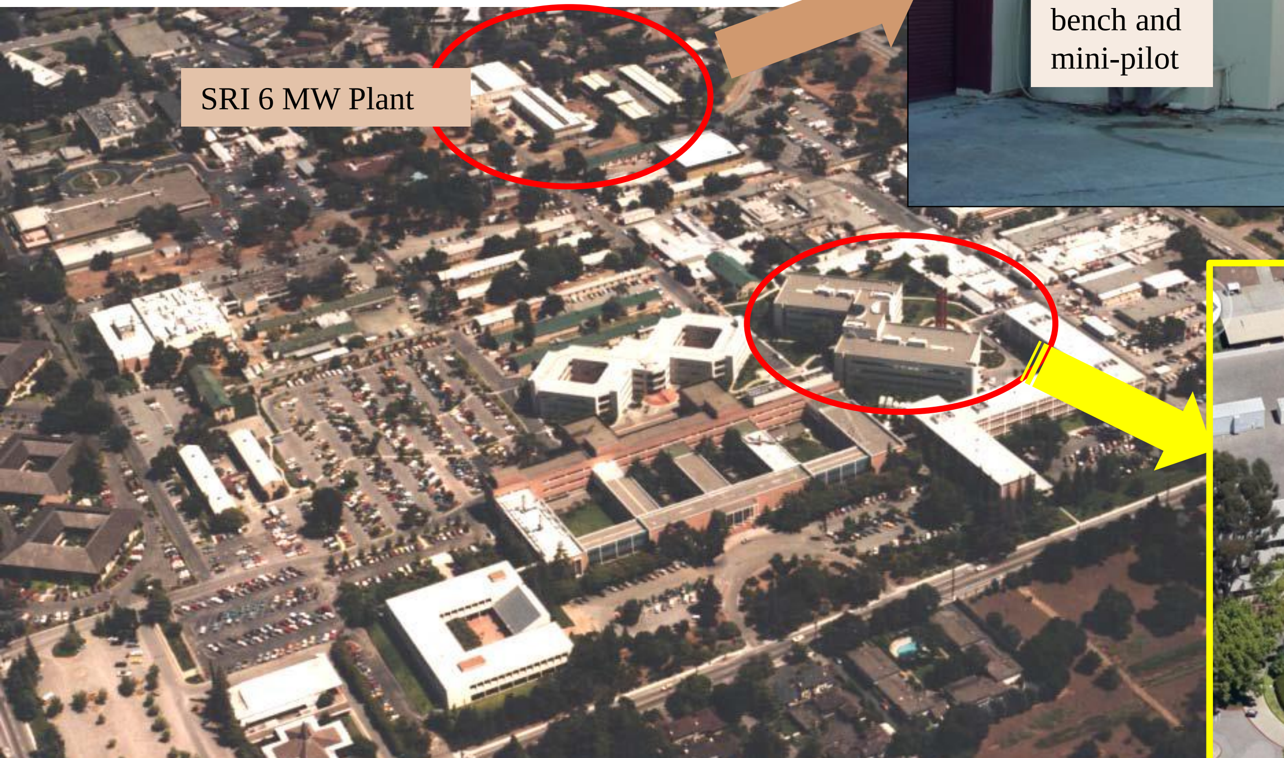
Milestone Log - BP2

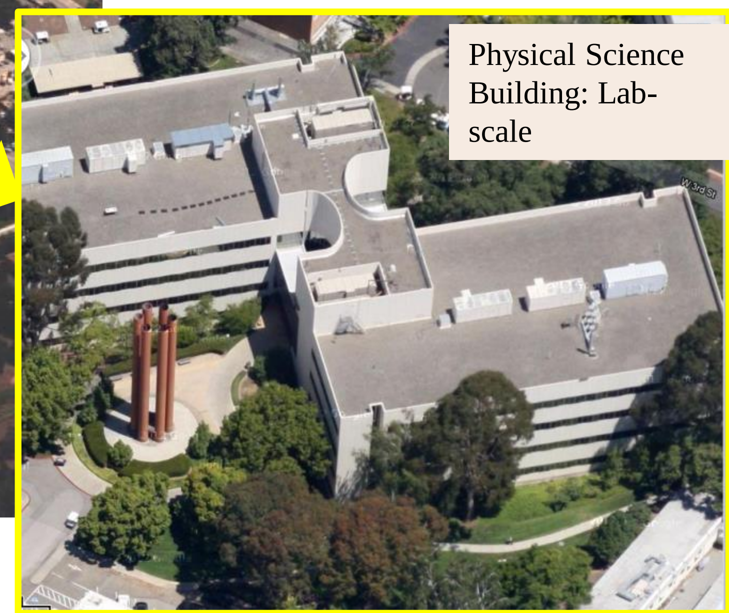
2	**4.1-4.3**	**k. Completion and submission of SINTEF report #1 providing properties and characterization for at least one new amine**	**5/31/2020**		**Results reported in the QR report**
2	4.2-4.3	l. Completion and submission of SINTEF report #2 to SRI providing emission information to support the EH&S report	3/31/2021		Results reported in the QR report
2	7.1	m. Integrated system test plan submitted	2/28/2020		Results reported in the QR report
2	7.1-7.4	n. Completion of integrated system testing for at least 100 hours at SRI	3/31/2021		Results reported in the QR report
2	8.1-8.2	o. Completion of flow-sheet model development at OLI and delivery of complete stream flow details, mass and energy balance for the optimal configuration	2/28/2021		Results reported in the QR report
2	9.1	p. Techno-Economic Analysis topical report submitted	3/31/2021		Topical Report and summary in Final Report
2	9.2	q. Updated State-Point Data Table submitted	3/31/2021		Final Report
2	9.3	r. Technology Gap Analysis topical report submitted	3/31/2021		Topical Report and summary in Final Report
2	9.5	s. Environmental Health & Safety Risk Assessment topical report submitted	3/31/2021		Topical Report and summary in Final Report
2	1	Draft Final Report submitted	6/30/2021		Final Report file

Project Status Update

As of (7/31/2018)		Status
Task 1.0 - Project Management and Planning		
Task 2.0 – VLE Measurements at DTU		
	Subcontract award	In progress
	VLE measurements	To begin soon
Task 3.0- Kinetic Measurements at SRI		
	Bench-scale setup and test plan development	Started
	Absorption measurements	To begin soon
Task 5.0- Rate Based Model Development at OLI		
	Subcontract award	Completed
	Flow-sheet modeling	To begin soon
Task 6.0- Preliminary Techno Economic Analysis (OLI/Trimeric/SRI)		
	Subcontract Award to Trimeric	Completed
	Preliminary TEA	To begin soon

Project Location





SRI's site in Menlo Park, CA (~ 65 acres)

Team Member Locations

Denmark

New Jersey

TRIMERIC CORPORATION

Texas

Norway

Acknowledgements

NETL (DOE)

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SRI Team

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

US and International Collaborators

- DTU (Kaj Thomsen, Philip Fosbol)
  OLI Systems (Prodip Kondu and Andre Anderko),
  Trimeric Corporation (Andrew Sexton)
  POLIMI (Gianluca Valenti, Davide Bonalumi, and Stefano Lillia),
  Stanford University (Adam Brant and Charles Kang),

Industrial Partner/Observer

- IHI Corporation

SRI International

Thank You

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