Engineering-scale Demonstration of Mixed-Salt Process (MSP) for CO_2 Capture

FE0031588

Project Kick-off and BP1 Review meeting

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U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory
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SRI International

Presentation Outline

- **Project Objectives**
  - Budget Period 1 (BP1) Objectives
  - Budget Period 2 (BP2) Objectives
  - Budget Period 3 (BP3) Objectives
  - Project Team and Budget
- **Mixed-Salt Technology and Process Economics**
- **Work Conducted in BP1**
- **Proposed Work for BP2 and BP3**
  - TCM-CAP System Re-commissioning and Modification
  - Dynamic- and Steady-State Testing
  - Techno-Economic Analysis, Technology Gap Analysis, Maturation Plan, and EH&S
- **Project Risks, Milestones**
- **Wrap-up**

Project Objectives

- Budget Period 1
  - A detailed investigation of the Chilled Ammonia Process (CAP) infrastructure to determine the robust cost estimate for recommissioning and modifications. Work involves host plant inspection, site visits to discuss the inspection results, define the work scope & schedule for BP2, and prepare the initial contract drafts for BP2.
- Budget Period 2
  - CAP system recommission and operability tests.
  - Modeling the modifications.
  - CAP system modification and HAZOP evaluation
  - TCM Test site agreement
  - Chemical procurements and solvent preparation
  - Shakedown tests with Mixed-salt solutions.
  - Test plan development

Project Objectives (Continued)

- Budget Period 3
  - Operation of the system with Mixed-salt. MSP testing will include both dynamic and continuous steady state conditions with real flue gas stream.
  - Determine the process energy requirements and the strategies for reducing the water accumulation and material use.
  - Preparation and submission of the project key deliverables - TEA, Technology maturation plan, Identify technology gaps and Process EH&S.

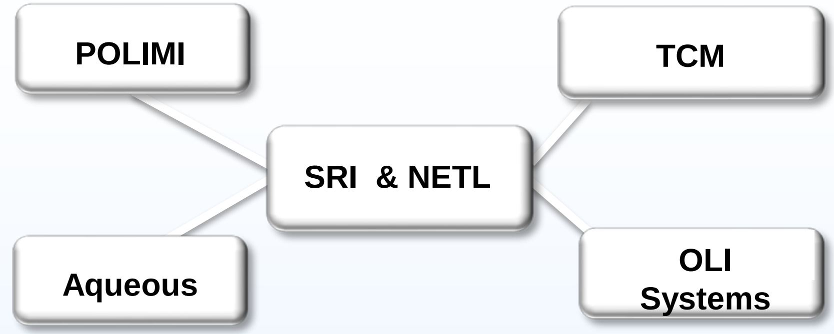
The overall project objective is to demonstrate that mixed-salt technology can capture CO_2 at 90% efficiency and regenerate CO_2 with 95% purity and demonstrate the pathway to reaching cost of ≤$30/tonne of CO_2 to meet the DOE program goals.

Project Team

Project Manager: Mr. Andrew Jones, NETL

Prime Contractor: SRI International

Project Team: US and International Partners



- TASK 1.0 (BP1,BP2 & BP3) - Project Management and Execution (SRI)
- Task 2 (BP1) – Detailed investigation of required changes to the TCM CAP Plant to run MSP
- TASK 3.0 (BP2) - Re-commissioning of the CAP Pilot at TCM (SRI & TCM)
- TASK 4.0 (BP2) - System Modification, Modeling and Initial Testing (SRI, TCM, OLI and PoliMi)
- TASK 5.0 (BP3) - Dynamic and Steady-state Testing of MSP (SRI and TCM)
- TASK 6.0 (BP3) - Process Economics, Technology Gaps and Technology Maturation (SRI, OLI and PoliMi)
- TASK 7.0 (BP3) - Environmental, Health and Safety (EH&S) Assessment (SRI)
- TASK 8.0 (BP3) - PILOT shutdown and Project Closure (SRI and TCM)

Work Organization

SRI International

Technology provider

Technology Center Mongstad (TCM), Norway

Host site and cost-share partner

OLI Systems, USA

Process modeling (energy and mass balance)

Aqueous Systems Aps, Denmark

Thermodynamic modeling

POLIMI, Italy

Techno-economic analysis

Project Budget

DE-FE0031588
BP1: 7/12/2018 to 10/31/2018
DOE Funding: $566,135

DE-FE0031588
Proposed BP2 & BP3 : 11/1/2018 to 7/31/2021
DOE Funding : ~$11.1 M
TCM: In-kind cost-share (~$9.2M)

Project Funding Profile — Updated 9/28/18 R1

Project Team Member	Budget Period 1 (07/01/18-10/31/18)		Budget Period 2 (11/01/18-07/31/20)		Budget Period 3 (08/01/20-07/31/21)		Government Share for the Total Project	Cost Share for the Total Project
	Government Share $	Cost Share $	Government Share $	Cost Share $	Government Share $	Cost Share $		
SRI International	566,135		3,319,749		2,418,148		6,304,031	
Technology Centre Mongstad (TCM)		68,092	4,932,988	22,320		9,120,000	4,932,988	9,210,412
OLI Systems, Inc.			126,647		23,352		149,999	
Politecnico di Milano-Polimi			135,203		95,271		230,474	
Total	**566,135**	**68,092**	**8,514,587**	**22,320**	**2,536,771**	**9,120,000**	**11,617,492**	**9,210,412**
Percentage							**56%**	**44%**

June, 2018 Submission

Project Funding Profile

Project Team Member	Budget Period 1 (07/01/18-10/31/18)		Budget Period 2 (11/01/18-07/31/20)		Government Share for the Total Project	Cost Share for the Total Project
	Government Share $	Cost Share $	Government Share $	Cost Share $		
SRI International	566,135		12,608,180		13,174,315	
Technology Centre Mongstad (TCM)		68,092		3,320,605		3,388,697
OLI Systems, Inc.			149,999		149,999	
Politecnico di Milano-Polimi			230,474		230,474	
Total	**566,135**	**68,092**	**12,988,653**	**3,320,605**	13,554,788	3,388,697
Percentage					**80%**	**20%**

Mixed-salt Process (MSP)

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 - 40ºC at 1 atm with 30-40 wt.% mixture of salts

Regenerator operation at 120º - 160ºC at 10-20 atm

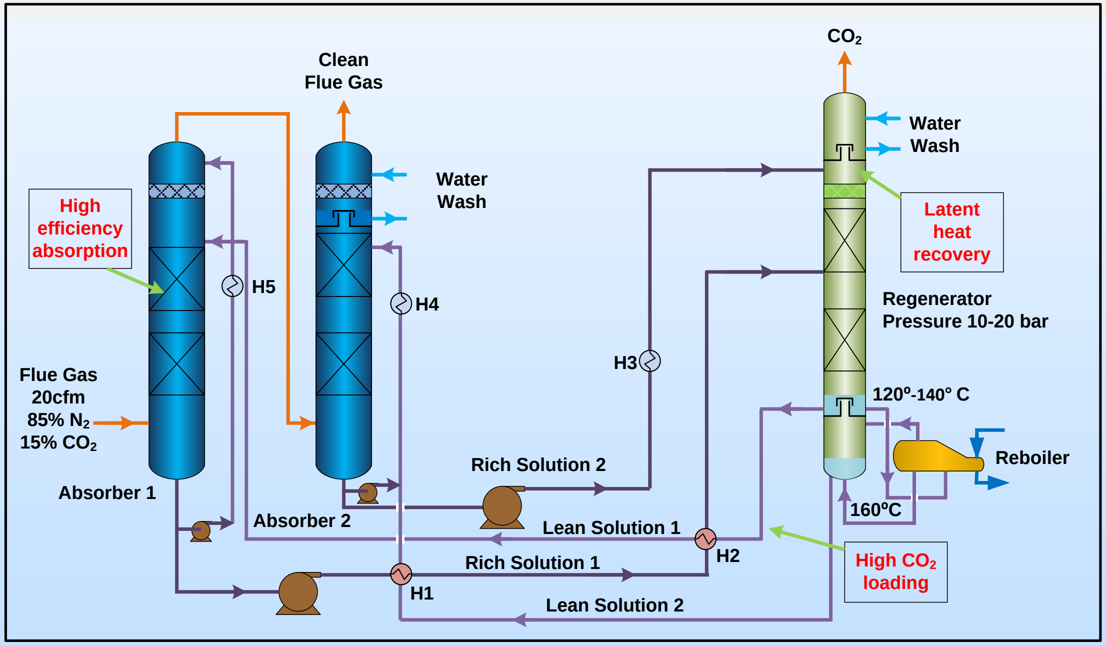
- Produces high-pressure CO_2 stream

K_2CO_3-NH_3-CO_2-H_2O system

High CO_2 cycling capacity

Process Highlights:

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



Key benefit:

Compared to the first generation technologies, the SRI Process will save:

- 50% in cost of carbon capture ($30-40/tonne -$CO_2$ vs. $60-100/ton today)
- 25% in the Capture Plant Capital Costs (Compared to NETL Case 12B)

Process Economic Data

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

Table. Cost of Electricity (COE) Estimation by POLIMI using in-house cost model

	NETL, Case 12 (2013)	NETL, Case 12B (2015)	SRI
Component, $/MWh	**Econamine**	**Cansolv**	**MSP**
Capital	66.4	72.2	57.1
Fixed	14.5	15.4	15.4
Variable	12.1	14.7	12.6
Fuel	35.3	30.9	32.3
Total (Excluding T&S)	**128.2**	**133.2**	**117.4**
CO_2 T&S	11.0	9.6	10.0
Total (including T&S)	**139.2**	**142.8**	**127.3**

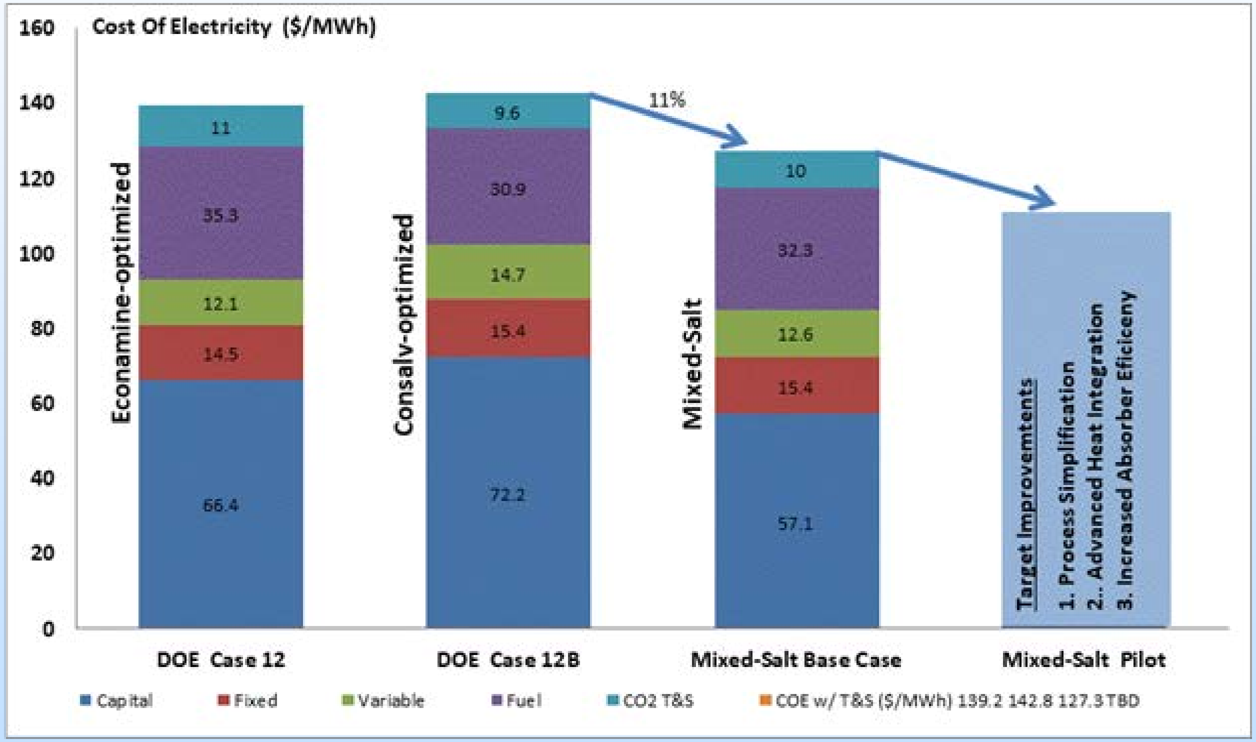
Total Auxiliary Consumption [MWe]	112.8	91.0	72.0

- MSP has a COE almost 11% lower than CANSOLV
- The Econamine costs from NETL report (2013) are updated - capital cost and fixed cost from $-2007 to $-2011, using CEPCI index, in agreement with NETL report (2015); variable and fuel costs are substituted with costs NETL report 2015 (*fuel cost in 2013 and 2015 reports are 38,18 $/ton and 68,54 $/ton, respectively*).
- The auxiliary consumption of the Mixed-Salt technology are the lowest, mainly due to the lower consumption of the CO_2 compression because the regeneration pressure is 15 bar compared to 2 bar for ammine technologies.

Techno-Economic Data (Cont.)

This work was conducted under FE0012959

Cost of Electricity Comparison Between MSP and DOE Baseline Cases



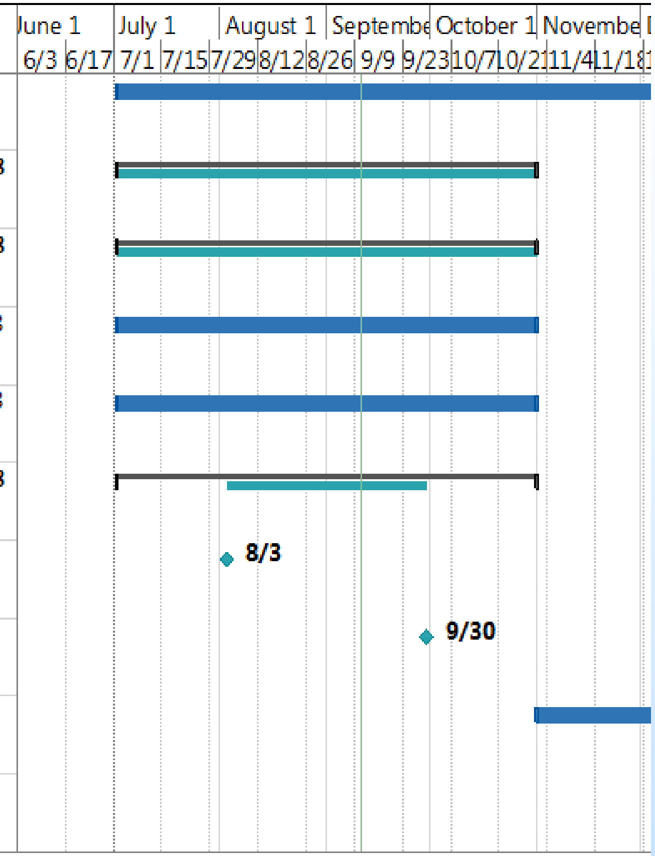
Preliminary Technology Gap Analysis

Process to be Tested	Method
Recycle method for ammoniated water	• Collect NH_3 removal efficiency and energy usage data from the overhead stripper installed in the CAP system at TCM • Demonstrate low ammonia emissions (<10 ppm) from MSP • Option: Compare overhead stripper performance with membrane based system
Water balance (CAP process accumulates water over time due to the low temperature operation of the absorber and therefore requires an auxiliary stripper)	• Operate MSP at room temperature to avoid water accumulation. • Assess water balance over time to confirm that MSP does not require an auxiliary stripper
Heat integration to reduce overall energy use	• Measure energy usage in heat-integrated CAP system at TCM • Evaluate the effect of varying the regeneration temperature on overall energy consumption
CO_2 capture technologies need to be validated at pilot scale	• Scale up MSP to 10-MW scale and utilize CAP equipment at TCM • Reduce commercialization risks by demonstrating 24/7 operation while maintaining high CO_2 capture efficiency, low ammonia emissions, and low energy consumption
CO_2 Capture cost	• Utilize data from pilot-scale system to improve the accuracy of techno-economic analyses of the MSP • Reduce the CO_2 capture cost from $40/ton to $30/ton

Work Conducted in BP1

BP1 Schedule

ID	Task Name	Start	Finish
1	**Engineering Scale Demonstration of MSP for CO2 Capture.**	Mon 7/2/18	Fri 7/30/21
2	**BP1: Host-Site Facility Assessment**	**Mon 7/2/18**	**Wed 10/31/18**
3	**Task 1.0 (BP1) - Project Management and Planning**	**Mon 7/2/18**	**Wed 10/31/18**
4	Subtask 1.1 - Project Status Reporting and Briefing	Mon 7/2/18	Wed 10/31/18
5	Subtask 1.2 - Financial Management	Mon 7/2/18	Wed 10/31/18
6	**Task 2.0 (BP1) -Detailed Investigation of the TCM-CAP Plant**	**Mon 7/2/18**	**Wed 10/31/18**
7	Milestone a	Fri 8/3/18	Fri 8/3/18
8	Milestones b, c, d, & e	Sun 9/30/18	Sun 9/30/18
9	**BP2 Mixed-Salt Testing at TCM**	Thu 11/1/18	Fri 7/30/21
10			



BP1 Work Details

- Workshop at TCM (June 28-29)
  - Discussions on the program details, TCM requirements
  - TCM-CAP system P&IDs and modification requirements
  - Current status of the TCM-CAP system.
- TCM-CAP system inspection meeting at TCM (Aug. 28-29)
  - Project progress evaluation information exchange
  - BP2 project schedule.
- Series of WebEx meetings with DOE/TCM/SRI
  - Discussions on contractual issues and the project update.
  - DOE and Federal flow-downs
  - Liabilities
- Project progress
  - SRI kept the FPM informed of the project progress and updated the PMP accordingly.

BP1 Work Details (Cont.)

BP1: TCM-CAP System Inspection

- The following items were tested to assess their operation: all valves (control valves, and other valves with remote control); rotation of all pumps (tightness and leak test), normal lighting, instrumentation according to maintenance scope; tightness and leak test of all manual valves.
- The following equipment were inspected for corrosion or other damage: Absorber, DCC, DCH and Water Wash columns (Gaskets, Insulation and surface protection; complete inspection of all lines and equipment that have insulation and/or surface protection); Regenerator column (random packing, pressure transmitter membrane, adaptors); Regenerator Reboiler (tube bundle); and Buffer Tank (wall thickness, nozzles).
- The physical accessibility of the plant for adding the piping to modify the CAP plant was investigated and as a result the system modification process flow diagram was updated.

BP1 Results and Accomplishments

BP1: TCM-CAP System Inspection Results

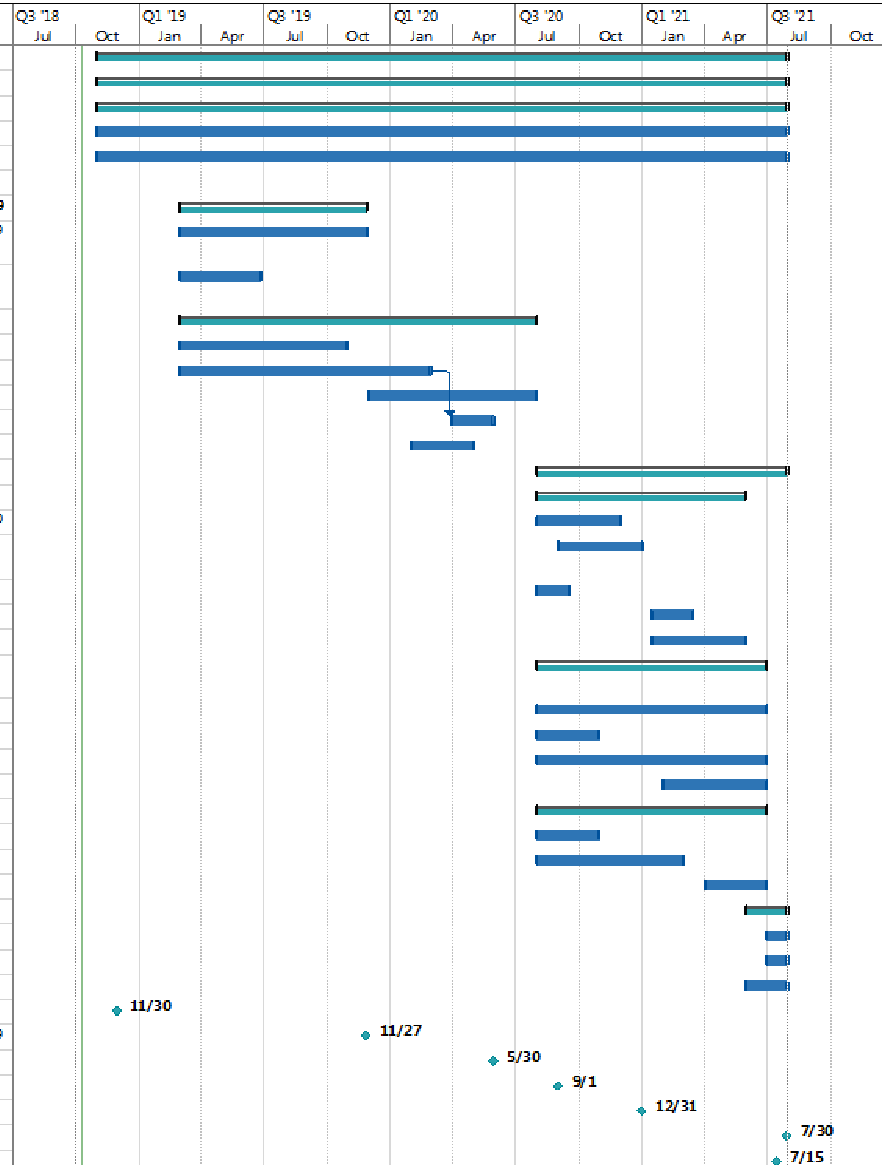
- Identified the heat tracing, insulation, packing, electrical motors, control valves, normal lighting, and instrumentation that needs to be change or require further maintenance.
- Heat Exchangers: Gasket change on all HEX with glued gaskets.
- Column lining: DCH had one area that needs a new lining
- Regenerator reboiler Tube Bundle: One tube had been found damaged mechanically at the outside. No repair needed.
- The following items are identified to be fully reconditioned: All Heat Exchangers, all PSV valves and Seepex pumps

Significant Accomplishment:

- During the inspection scope, TCM has used SAP® maintenance planner for registration of work required to recommission the CAP plant. In SAP®, TCM can create work orders (WO) very quickly at the start of BP2 for the required work.
- Confirmed the accessibility of the plant for modification and simplified the process flow diagram to implement MSP.

Proposed BP2 and BP3 Work Schedule

ID	Task Name	Start	Finish
1	**Engineering Scale Demonstration of MSP for CO2 Capture.**	**Thu 11/1/18**	**Fri 7/30/21**
2	**BP2 SYSTEM PREPERATION**	**Thu 11/1/18**	**Fri 7/30/21**
3	**TASK 1.0 - Project Management**	**Thu 11/1/18**	**Fri 7/30/21**
4	Subtask 1.1. - Project Status Reporting and Briefing	Thu 11/1/18	Fri 7/30/21
5	Subtask 1.2 - Financial Management	Thu 11/1/18	Fri 7/30/21
6	Subtask 1.3 - Technical, Legal, H&S		
7	**TASK 3.0 - Re-commissioning of the Pilot at TCM**	**Fri 3/1/19**	**Wed 11/27/19**
8	Subtask 3.1 - System Recommissioning (Procurement, Refurbish and Test with Water)	Fri 3/1/19	Wed 11/27/19
9	Subtask 3.2 - Process HAZOP Evaluation and Process HAZOP Evaluation/ update System Startup Shutdown Protocols	Fri 3/1/19	Thu 6/27/19
10	**TASK 4.0 - System Modification and Initial Testing**	**Fri 3/1/19**	**Fri 7/31/20**
11	Subtask 4.1 - Flowsheet Modeling	Fri 3/1/19	Tue 10/29/19
12	Subtask 4.2 - Engineering/ Procurement and Fabrication	Fri 3/1/19	Fri 2/28/20
13	Subtask 4.3 - Procurement/ Solvent Preparation	Sun 12/1/19	Fri 7/31/20
14	Subtask 4.4 - Mixed-Salt Baseline Tests	Tue 3/31/20	Fri 5/29/20
15	Subtask 4.5 - Test Plan Development	Sat 2/1/20	Thu 4/30/20
16	**BP3 SYSTEM TESTING**	**Sat 8/1/20**	**Fri 7/30/21**
17	**TASK 5.0 - Dynamic and Steady-state Testing of MSP**	**Sat 8/1/20**	**Sun 5/30/21**
18	Subtask 5.1 - Dynamic Operation of the Pilot	Sat 8/1/20	Mon 11/30/20
19	Subtask 5.2 - Dynamic Test Data Analysis/ Basis for Steady-state Testing	Tue 9/1/20	Thu 12/31/20
20	Subtask 5.3 - Update the Test Plan for Steady-state Testing	Sat 8/1/20	Wed 9/16/20
21	Subtask 5.4 - Steady-State Operation of the Pilot	Fri 1/15/21	Mon 3/15/21
22	Subtask 5.5 - Steady-state Test Data Analysis	Fri 1/15/21	Sun 5/30/21
23	**TASK 6.0 - Process Economics, Technology Gaps and Technology Maturation**	**Sat 8/1/20**	**Wed 6/30/21**
24	Subtask 6.1 - Techno-Economic Analysis	Sat 8/1/20	Wed 6/30/21
25	Subtask 6.2 - Update the State Point Data Table	Sat 8/1/20	Fri 10/30/20
26	Subtask 6.3 - Technology Gap Analysis	Sat 8/1/20	Wed 6/30/21
27	Subtask 6.4 - Preparation of Technology Maturation Plan	Mon 2/1/21	Wed 6/30/21
28	**TASK 7.0 - Environmental, Health and Safety (EH&S) Assessme**	**Sat 8/1/20**	**Wed 6/30/21**
29	Subtask 7.1 - Preliminary Analysis of EH&S	Sat 8/1/20	Fri 10/30/20
30	Subtask 7.2 - Update Stream Mass Balance Information	Sat 8/1/20	Mon 3/1/21
31	Subtask 7.3 - Final Analysis of the EH&S	Fri 4/2/21	Wed 6/30/21
32	**TASK 8.0 - PILOT shutdown and Project Closure**	**Tue 6/1/21**	**Fri 7/30/21**
33	Subtaks 8.1 - Pilot Reconfiguration back to the Original Form	Thu 7/1/21	Fri 7/30/21
34	Subtask 8.2 - Project Closure	Thu 7/1/21	Fri 7/30/21
35	Subtask 8.3 - Final Report Preparation	Tue 6/1/21	Fri 7/30/21
36	Milestone f	Fri 11/30/18	Fri 11/30/18
37	Milestone g and h	Wed 11/27/19	Wed 11/27/19
38	Milestones l, j and m	Sat 5/30/20	Sat 5/30/20
39	Milestone k	Tue 9/1/20	Tue 9/1/20
40	Milestone l	Thu 12/31/20	Thu 12/31/20
41	Milestones n, o, p, q, r, s t, and u	Fri 7/30/21	Fri 7/30/21
42	Milestone t	Thu 7/15/21	Thu 7/15/21



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Proposed Work in BP2

Task 1 (BP2 &BP3). Project Management: This activity includes all work elements required to maintain and revise the Project Management Plan (PMP), and to manage and report on activities in accordance with the plan for the continuation of the project in BP2. It also includes the necessary activities to ensure coordination and planning of the project with DOE/NETL and other project participants and subcontractors.

Tasks 3 (BP2). Re-commissioning of the CAP Pilot at TCM: This activity includes refurbishing the existing infrastructure structure to it's original specifications, and test the operability of the plant.

Task 4 (BP2). CAP System Modification and Baseline testing : This activity includes (i) engineering, purchasing, fabrication installation of the piping for CAP system reconfiguration to match the MSP flowsheet, (ii) modeling of MSP-CAP flowsheet (iii) operation of the system to collect the initial baseline data, (iv) Test Site Agreement and (v) Test Plan development.

Outcome: The expected results are reliable start-up when tested with water, and reliable operation of each component of the system when tested with Mixed-salt solution. In particular, SRI is keen to observe the performance of the lean/rich heat exchanger, ammonia recovery system and the ammonia rich-lean solution recovery from the reboiler.

Proposed Work in BP3

Task 5 subtask. Dynamic Testing of MSP: In this activity, a selected parameters- L/G, CO_2 stripping pressure, reboiler temperature, and cooling water will be varied. The ranges (basis) was selected based on the results from the mini-pilot testing and the process modeling

Ranges:	L/G	2 to 6
	CO_2 Pressure	10 to 15 bar
	Reboiler Temperature	140-160°C

Outcome: The basis for the steady-state testing will be determined (e.g., Cooling water requirements, steam flowrates, recycle flowrates etc.); material balances.

Task 5 subtask. Steady-state Testing of MSP: In this activity, the system will be operated for 2 to 3 months.

Outcome: The process cooling water requirements, steam flowrates, recycle flowrates, material use, emission results, and energy use for the optimized operation of the pilot will be determined. The data will be used to determine the basis for modeling a 550 MW coal fired power plant will be determined.

Proposed Work in BP3 (Cont.)

Task 6. Techno Economic Analysis (TEA) , Technology Gap Analysis, (TGA) and Technology Maturation Plan (TMP)

Outcome of TEA: Itemized cost of all installed equipment and materials used at the PC power plant including CO_2 capture and compression systems such as pumps, blowers, compressors, vacuum pumps, heat exchangers, refrigeration equipment, absorber/stripper vessels, etc. Estimated supercritical PC plant efficiency with CO_2 capture. Estimated marginal increase in levelized cost of electricity (LCOE) due to CO_2 capture and sequestration relative to NETL Case 11 without capture.

Outcome of TGA: Identify the issues observed in the pilot testing, and report which components or systems should be the focus of future R&D and large scale demonstration efforts.

Outcome of TMP: Determination of the technology readiness level for coal power plant application. The readiness levels for all the sub-systems will be fully described in the updated TMP.

Proposed Work in BP3 (Cont.)

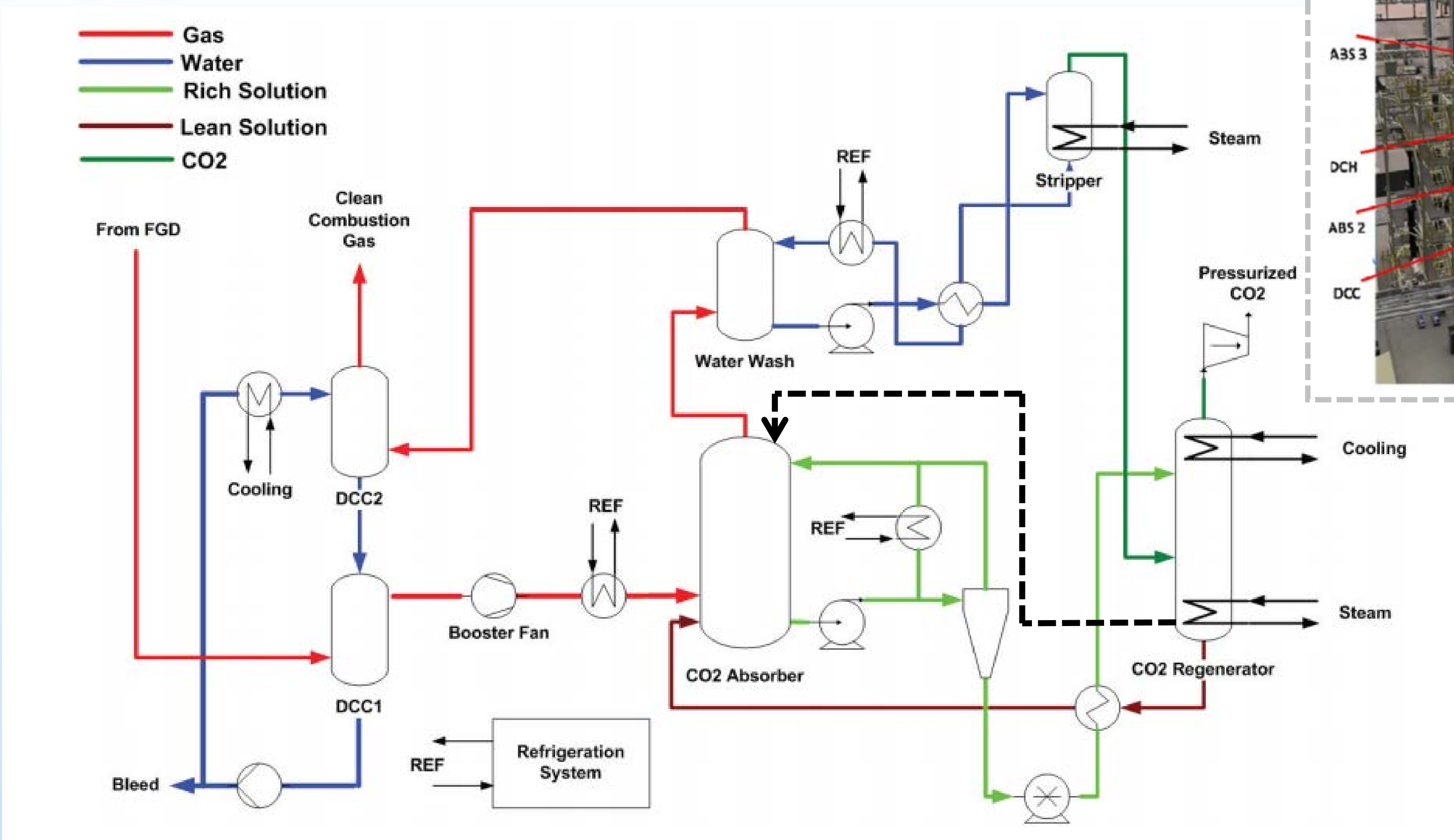
Task 7. Environmental, Health & Safety Assessment (EH&S) : This task will be performed in accordance with the guidelines given by DOE. The EH&S assessment will be conducted in coordination with the TCM. Outcome: All potential air and water emissions, and liquid/solid wastes produced their amounts and fate will be determined..

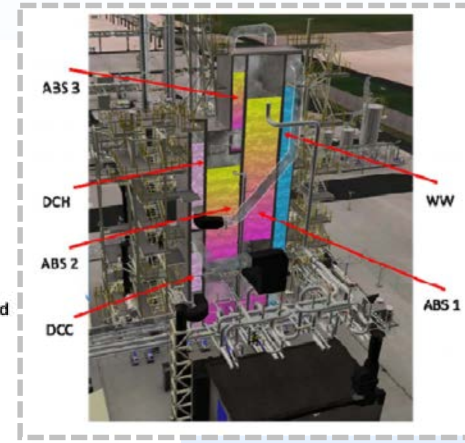
Task 8. Pilot Shutdown and Project Closure. This activity involves the activities at TCM to revert the CAP plant back to it is original form. This activity may include removal of the piping and valves added to the CAP system to implement the MSP. This activity will also include the removal of any remaining wastes and solvents from the host site.

Note: The testing at the host-site will be conducted under a Test Agreement with TCM.

Process Flow Diagrams

CAP System Modification/Reconfiguration (BP2- Task 2)





Solid Mode CAP system (Energy Procedia 114 (2017) 5593 – 5615)

---- Proposed New Piping to Demonstrate MSP

Project Risks and Milestones

Risk Register

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 an SOP to avoid shut downs with rich solutions. General SOPs for operating ammonia-based processes are available at TCM.
Residual ammonia in the exit gas stream	Moderate	Moderate	Increase water-wash column fresh water flow to capture ammonia vapor. The CAP system at TCM has already demonstrated this capability.
High-pressure drop in the absorber column	Low	Moderate	Monitor and control the recycled liquid flow and flooding level.
Solvent interaction with acid gases	Low	Low	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.
Condensation of solids in regenerator gas exit lines during long-term operation	Moderate	Low	Ensure proper heat tracing of susceptible lines and control valves; periodic inspections of suspect places and maintenance of the temperature above the condensation point. GE is interested in helping resolve this issue.

Risk Register (Cont.)

Description of Risk	Probability (Low, Moderate, High)	Impact (Low, Moderate, High)	Risk Management Mitigation and Response Strategies
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.
Problems with project coordination at the test site affecting CAP system availability	Low	High	Request dedicated host-site operators for the CAP unit. Plan ahead and work with the TCM to prepare a test schedule in advance.
Management risks:			
Project team availability	Low	Moderate	Identify backup team
Health and safety	Low	High	Prepare SOPs and train operators
Financial risks:			
Cost Overruns	Moderate	High	Work closely with the host-site team to execute the CAP-system recommissioning and modification. The expenditure will be closely monitored and any variation will be reported to

Risk Register (Cont.)

Description of Risk	Probability (Low, Moderate, High)	Impact (Low, Moderate, High)	Risk Management Mitigation and Response Strategies
Financial Risks:			
Cost overruns	Moderate	High	The recipient will work closely with the host-site team to execute the CAP-system recommissioning and modification. The expenditure will be closely monitored and any variation will be immediately reported to the project manager (PM). The recipient will have a dedicated project administrator (PA) to monitor the project spending. The CAP system recommissioning and modification will be done by the host-site personnel and host-site-selected vendors; as we understand, they have a good purchasing order (PO) system. However, this project needs exhaustive planning to avoid cost overruns. The recipient will strictly adhere to the project scope and avoid any unplanned work.
Problems with host site project coordination leading to cost share accumulation	Low to Moderate	High	We have reduced the risk for BP1 by arranging at least 10% of the cost-share to be accumulated at the start of the project. However, in BP2 most of the cost-share is accumulated toward the end of the project. The recipient will work with the host-site team and consider the experiences of previous technology vendors that conducted similar work at TCM to find a solution.

Project Milestones

Budget Period	Task/ Subtask No.	Milestone Description	Planned Completion	Actual Completion	Verification Method
1	1	a. Updated PMP submitted	8/3/2018	8/3/2018	PMP file
1	1	b. Kickoff / BP1 Review Meeting convened	10/3/2018		Presentation file
1	2	c. Work scope and firm cost estimate for the Chilled Ammonia Plant (CAP) recommissioning submitted	9/30/2018		BP2 Continuation Application
1	1	e. Technology Maturation Plan	9/30/2018		Topical Report
2	1	f. Updated PMP submitted	11/30/2018		PMP file
2	3.1	g. Completion of the system recommissioning	11/30/2019		RPPR quarterly
2	1	h. Test Site Agreement with TCM	11/30/2019		Agreement documents
2	4.5	i. Completion and submission of the test plans	5/30/2020		RPPR quarterly
2	4.1-4.4	j. Completion of flow-sheet modeling, Modeling and initial testing	5/30/2020		Presentation File

Project Milestones (cont.)

Budget Period	Task/ Subtask No.	Milestone Description	Planned Completion	Actual Completion	Verification Method
	1	k. Updated PMP Submitted	9/1/2020		PMP file
3	5.1 -5.2	l. Completion of dynamic testing and data analysis	12/31/2020		RPPR quarterly
3	5.4 to 5.5	m. Completion of the steady-state testing and data analysis	5/30/2021		RPPR quarterly
3	6.1	n. Techno-Economic Analysis topical report submitted	7/31/2021		Topical Report and summary in Final Report
3	6.2	o. Updated State-Point Data Table	7/31/2021		RPPR quarterly
3	6.3	p. Technology Gap Analysis topical report submitted	7/31/2021		Topical Report and summary in Final Report
3	6.4	q. Updated Technology Maturation Plan	7/31/2021		Topical Report and summary in Final Report
3	7	r. Environmental Health & Safety Risk Assessment topical report submitted	7/31/2021		Topical Report and summary in Final Report
3	8	s. Project closure at TCM	7/31/21		Presentation file
3	8	t. Project review at TCM	7/15/21		RPPR quarterly
3	1	u. Final report submission	7/31/2021		Final report

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
	Acceptance of SRI's work scope and firm cost estimate for the Chilled Ammonia Plant (CAP) recommissioning and modifications at Technology Center, Mongstad, Norway (TCM) to accommodate Mixed-Salt Process (MSP) testing at engineering scale
	Acceptance of proposed scope, schedule, and budget modifications
B. Completion of Budget Period 2	Successful completion of all work proposed
	Host Site Agreement
	Completion of the CAP system recommissioning confirmed via baseline testing
	Acceptance of dynamic MSP test plan
	Acceptance of steady-state MSP test plan
C. Completion of Budget Period 3	Completion of integrated MSP large pilot-scale testing with selective, high-pressure regeneration of ammonia- and potassium-rich streams, including dynamic and steady-state testing with an actual flue gas stream from the residue catalytic cracker (RCC) at TCM, which closely resembles the coal-power plant flue gas stream; large pilot-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 ~2 GJ/tonne CO_2 that indicate significant progress toward achieving the DOE's 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 pilot-scale testing
	Submission of a Final Report

Technology Maturation Plan

Technology Maturation: MSP Development

Excellent Performance

Path to CC Technology Scale-Up

SRI

Lab Bench

IHI

Mini-Pilot

SRI

Mini-Pilot

Proof of Concept

Parametric Testing Process Optimization

Process Economics

Engineering Testing

TEA validation

TGA, TMP, and EH&S

Commercialization

2013-17 Successful DOE Project ($2.8M) with parallel IHI support ($1 M)

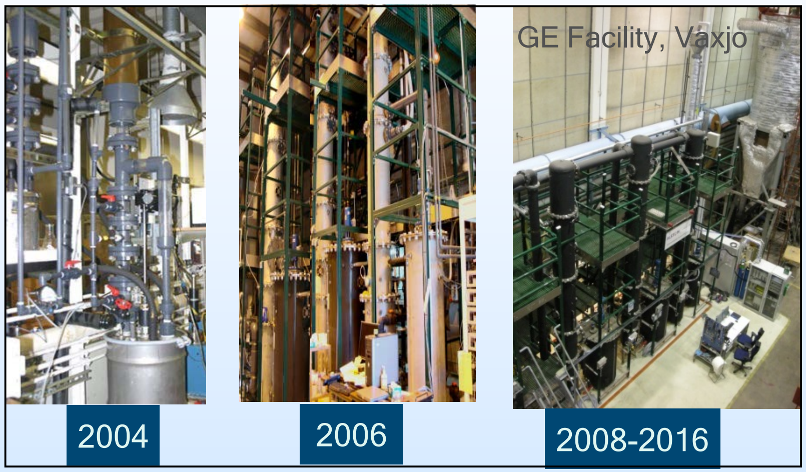
2018 to 21 Current Project

Technology Maturation: CAP to MSP

Small bench to mini pilot to large pilot

Ammonia technology development started at SRI in 2004

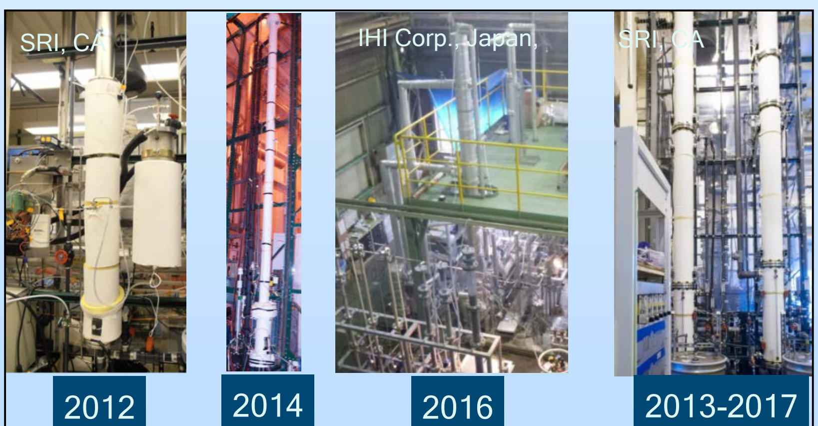
Chilled Ammonia Process (CAP)



CAP Validation at TCM

Step change

Mixed-salt Process (MSP)



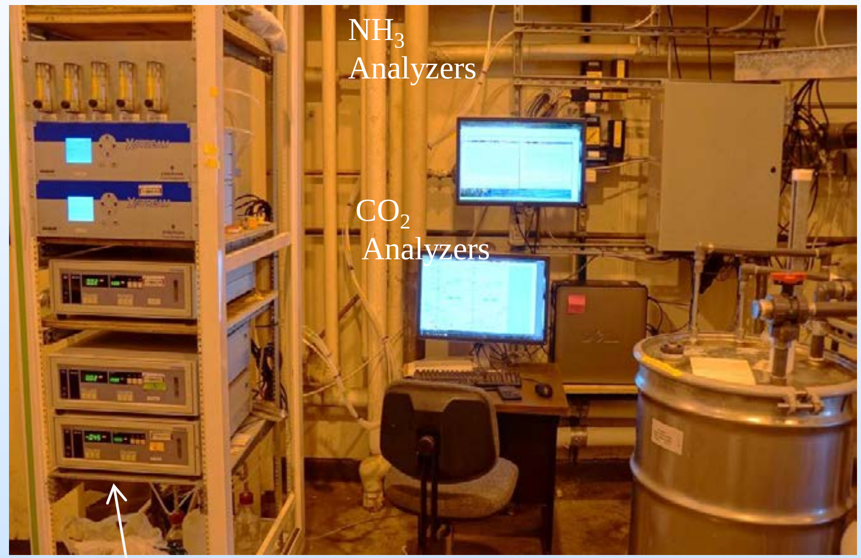
(DE-FE0012959)

MSP Testing in TCM-CAP System (DE-FE0031588)

Large Bench-Scale (Mini-Pilot) Mixed-Salt System at SRI

This work was conducted under FE0012959

0.25 to 1 t-CO_2 per day capacity system

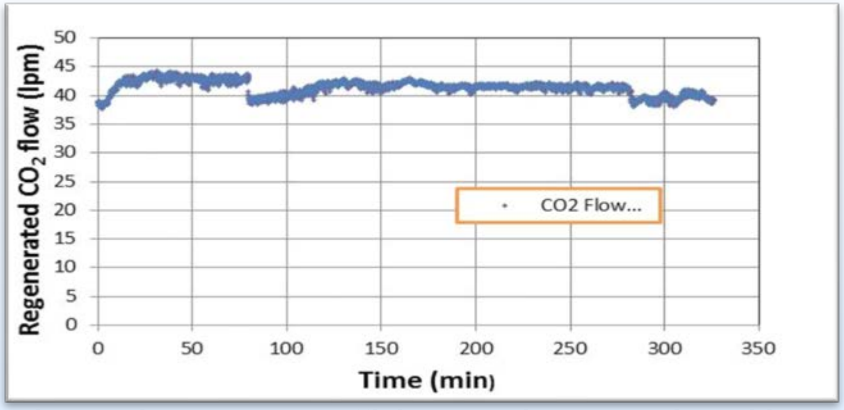


The process uses in-house developed software for real-time process control and data monitoring.

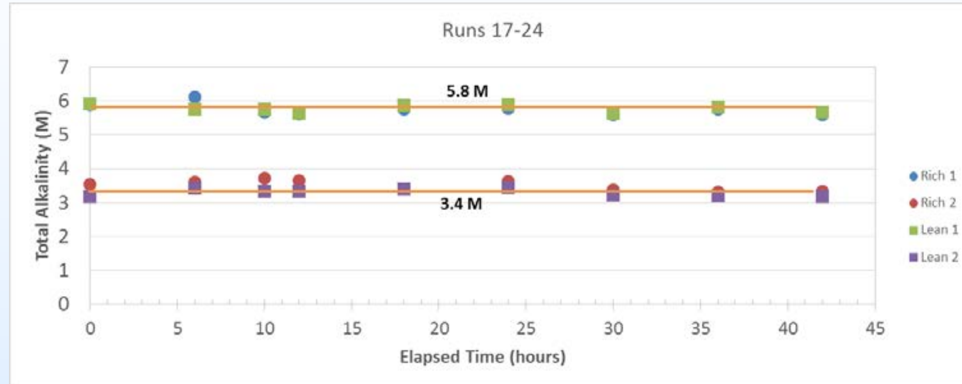
Identify Technology GAPS: This system will be used to resolve any issues that come up during the testing of the MSP at TCM

Examples of Steady-State and Dynamic Testing of the Large Bench-Scale System

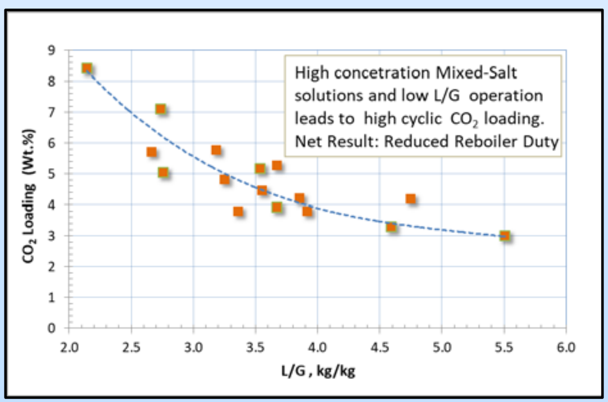
This work was conducted under FE0012959



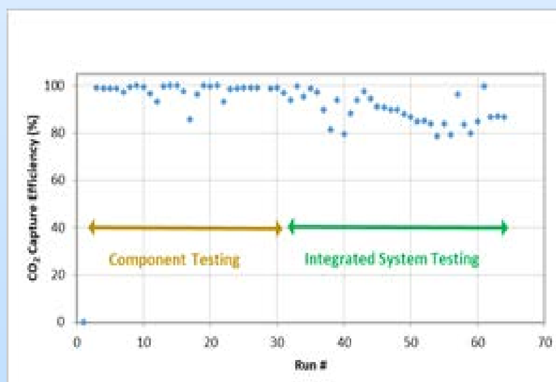
Observed 90% capture efficiency and regeneration with cyclic loading of ~0.7 mole of CO_2/mole of ammonia



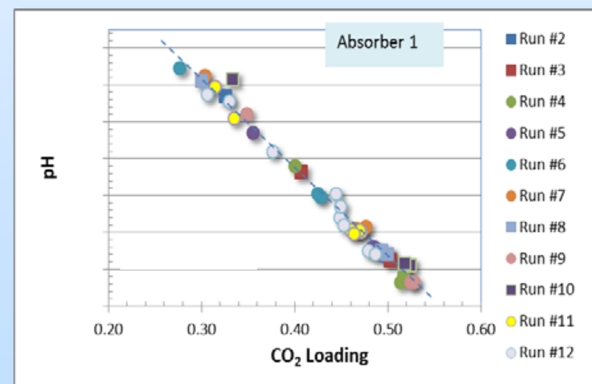
Alkalinity of rich and lean solutions circulating in the integrated system



Observed CO_2 loading as a function of L/G



CO_2 capture efficiency in parametric test runs



Observed pH as a function of CO_2 loading

Wrap-up

Key Findings to Date

– No new issues identified for restarting the CAP system

Lessons Learned and Risks

– Delayed contract negotiation could shift the project schedule

– TCM's experienced staff made it possible to determine the cost and schedule for restarting the engineering scale plant.

– SRI mini-pilot is available to resolve any issues that come up during the MSP testing at TCM

– Timing of in-kind contribution

Outstanding Project Issues

– Contractual issues, scope and budget approval

Our Plan is to Market the Technology Proactively

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

Small-Scale Capture Systems for Industry Applications

~0.1 MW → 10 MW → >100 MWe

Large-Scale Capture Systems

MSP Development progress is being observed by industrial partners:
(1) GHBE, Germany- Owner of CAP
(2) IHI Corporation, Japan - One of the largest boiler manufacturers

SRI International

Selected Publications on SRI NH_3 Based CO_2 Capture Developments

MSP

1. **Jayaweera, I**, P. Jayaweera, P. Kundu, A. Anderko, K. Thomsen, G. Valenti, D. Bonalumi, and S. Lillia "Results from Process Modeling of the Mixed-salt Technology for CO2 Capture from Post-combustion-related Applications," Energy Procedia (2017), 114 (GHGT-13), 771-780.
2. Kang, C.A., Brandt, A.R., Durlofsky, L.J., and **Jayaweera, I**, "Assessment of advanced solvent-based post-combustionCO2 capture process using bi-objective optimization technique", Applied Energy, 179 (2016), 1209-1219.
3. **Jayaweera, I.** , Jayaweera, P., Krishnan, Gopala N., Sanjurjo, Angel, "Rate enhancement of CO_2 absorption in aqueous potassium carbonate solutions by an ammonia-based catalyst," US Patent 9,339,757, issued May 17, 2016
4. **Jayaweera, I**., Jayaweera, P., Yamasaki, Y., and Elmore, R, "Mixed-Salt Solutions for CO_2 Capture," Book Chapter 8 in *Absorption-Based Post-Combustion Capture of Carbon Dioxide*; Elsevier, 2016 (pp 167-200)
5. **Jayaweera, I**., P. Jayaweera, R. Elmore, J. Bao, S. Bhamidi, "Update on mixed-salt technology development for CO_2 capture from post-combustion power stations," Energy Procedia 63 (2014) 640-650.
6. **Jayaweera, I.,** P. Jayaweera, P., Krishnan, G. and A. Sanjurjo, The race for developing promising "CO_2 capture technologies ready for 2020 deployment: novel mixed-salt based solvent technology. Pap.-Am. Chem. Soc., Div. Energy Fuels 2013, (1):58.

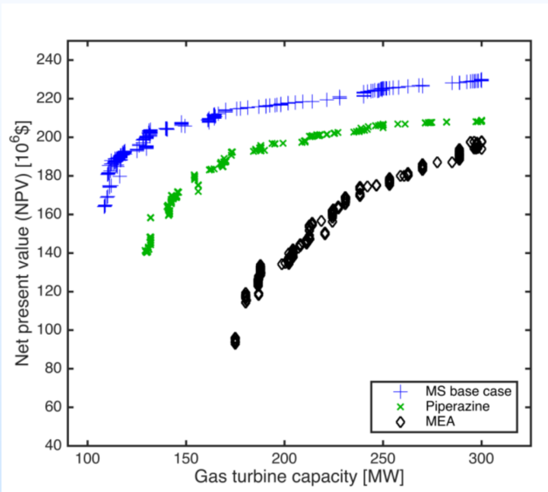
CAP

1. Bade, M, E. Gal, **I. Jayaweera** and G.Krishnan , " Promoter Enhanced Chilled Ammonia Based System and Method for Removal of CO_2 from Flue Gas Streams," US 8168149 B2, 2012
2. Bade, M, E. Gal**, I. Jayaweera** and G. Krishnan , " Promoter Enhanced Chilled Ammonia Based System and Method for Removal of CO_2 from Flue Gas Streams," US 7862788, 2011
3. Gal. E and **I. Jayaweera**, "Chilled Ammonia Based CO_2 Capture System with Water Wash System", US Patent NO. 2011004823, 2010

Notable Publications

Modeling of Auxiliary Gas-fired CCS for Retrofits of Coal-fired Power Stations (Stanford University)

This was conducted under FE0012959

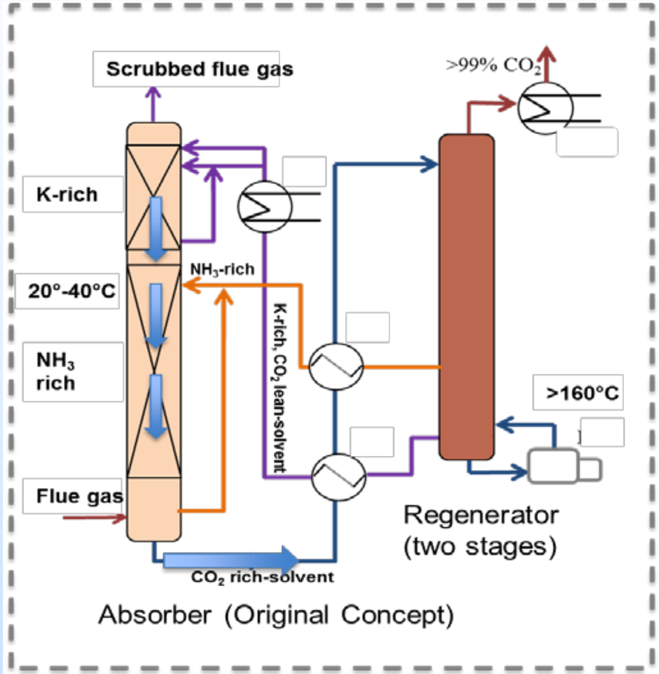


Comparison of mixed-salt and amine systems

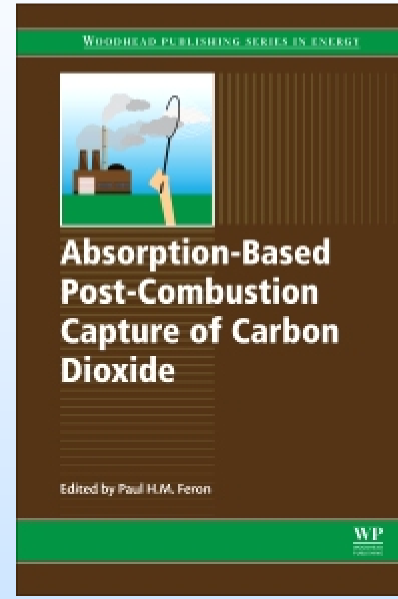
Charles A. Kang, Adam R. Brandt, Louis J. Durlofsky, Indira Jayaweera, " Assessment of advanced solvent-based post-combustion CO2 capture processes using a bi-objective optimization technique", Applied Energy 179 (2016) 1209–1219

"A salty way to scrub CO_2"

By Gerald Ondrey. *Chemical Engineering*, July 2013, p. 11.



Chapter 8: Mixed-Salt Solutions for CO_2 Capture



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Thank You

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