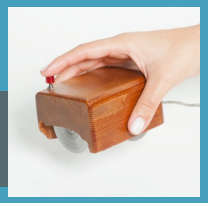
SRI International



First computer mouse

Created "Siri" for i-phone

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

DOE Contract: DE-FE0031588

Presented by Indira Jayaweera

Sr. Program Manager

Integrated Systems and Solutions Division

SRI International

NATIONAL ENERGY TECHNOLOGY LABORATORY

SRI International

ILLINOIS

TRIMERIC CORPORATION

Baker Hughes

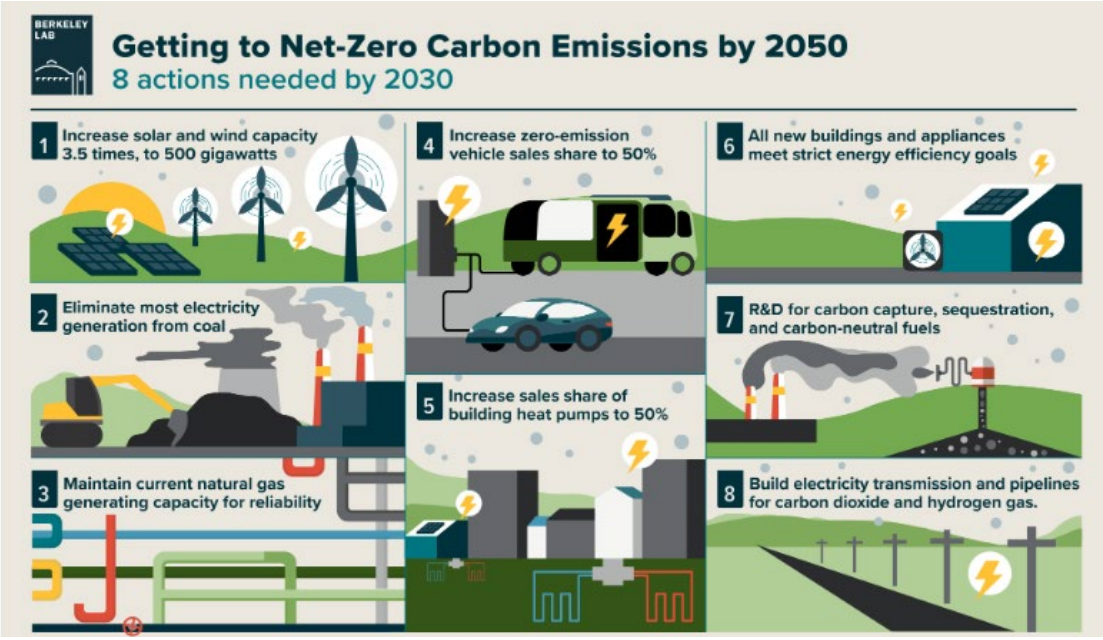
OLI systems, Inc.

PRVN

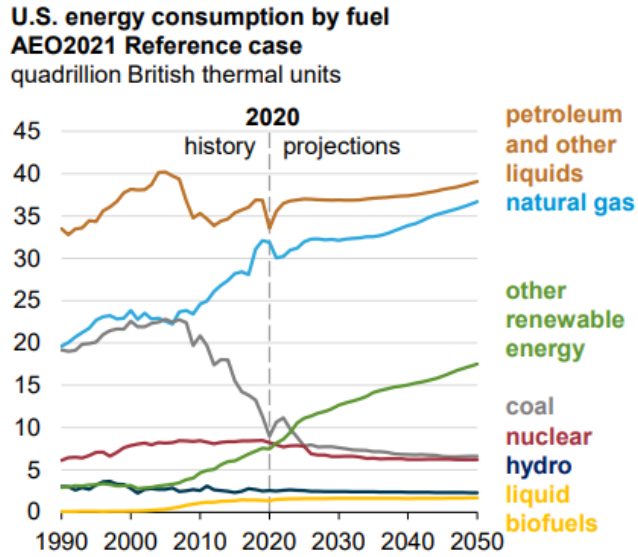
Carbon Management and Oil and Gas Research Project Review Meeting, August 12 -16, 2021

Outline

- Introduction and background
- Process description and historical data
- Current project details
- Project status update



Source: "Carbon-Neutral Pathways for the United States" by James H. Williams, Ryan A. Jones, Ben Haley, Gabe Kwok, Jeremy Hargreaves, Jamil Farbes, and Margaret S. Torn, 14 January 2021, AGU Advances.



U.S. Energy Information Administration, International Energy Outlook February 2021.

Solvent Development at SRI

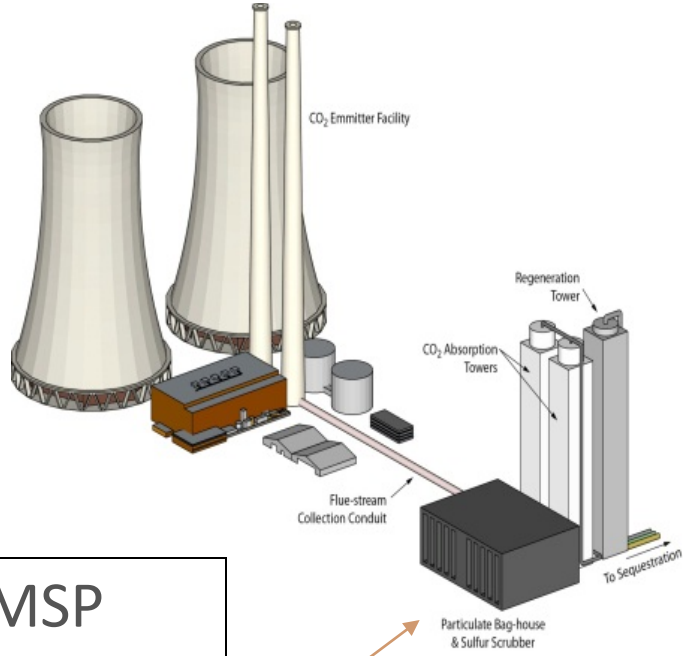
Ammonia technology development started at SRI in 2004

Chilled Ammonia Process (CAP)

2004

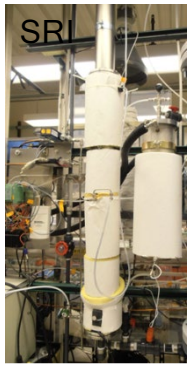
2006

2008-2016



Field testing at UIUC

Mixed-Salt Process (MSP)



2012

2014

2016

DOE Contract: DE-FE0012959

2015-2017

MSP Testing at Engineering Scale

2018 - 2025

DOE Contract: DE-FE0031588

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)

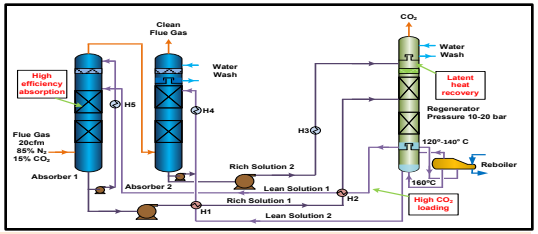
Absorber operation at 20° - 40°C at 1 atm with 30-40 wt.% mixture of salts

Regenerator operation at 120° - 175°C at 10-12 atm

- Produce 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 (due to reduced sensible heat and water evaporation)
- Reduced CO_2 compression energy

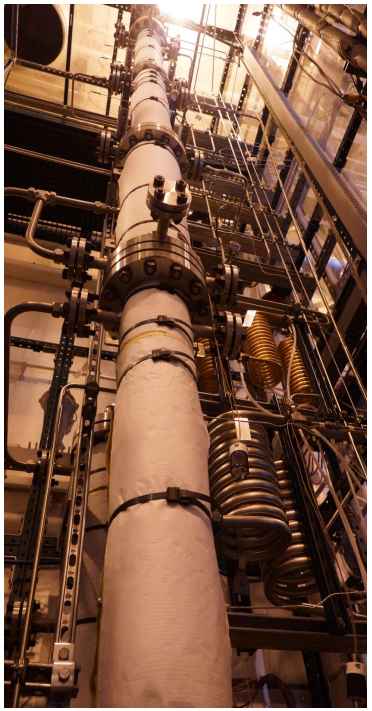
A significant parasitic power reduction compared to MEA!

MSP Mini-pilot at SRI

Large Bench-Scale System at SRI

Analytical and Control Systems

Absorbers



Regenerator

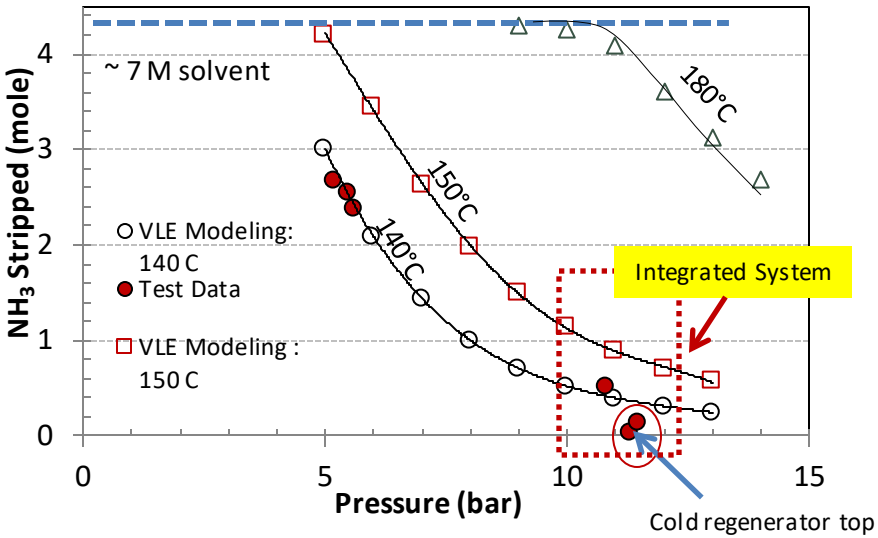
Integrated system after modification in 2020

This system was commissioned in May 2014 and operated till June 2017.The system is recently modified and is now operational.

Selected Bench-Scale Data: Component Testing

This work was conducted under DOE contract FE0012959

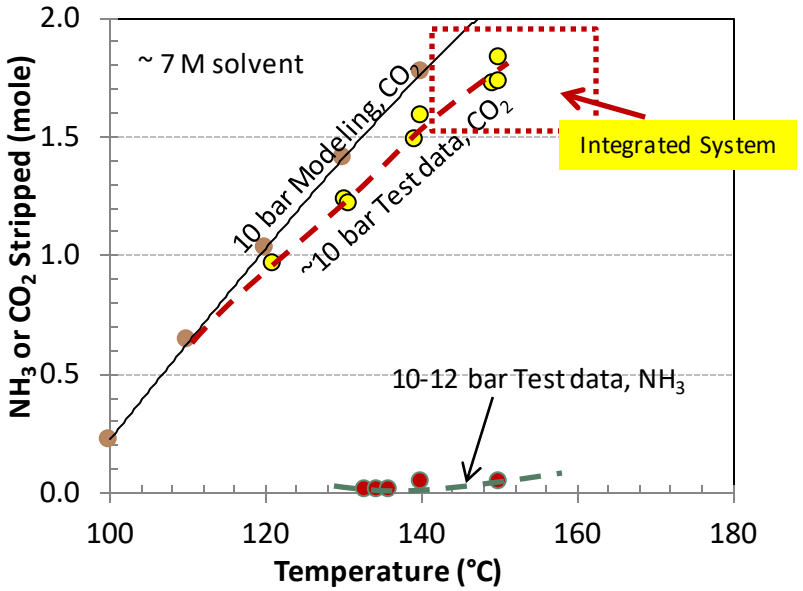
Dynamic tests: NH_3 and CO_2 evaporation as a function of temperature and pressure with continuous rich-in / lean-out flow. The regenerator column temperature profile is controlled to manipulate the ammonia stripping.



Comparison of test data with modeling data for mixed-salt solution. Data from both cold regenerator top and warm regenerator top.

Simulation of the ammonia stripping section of the regenerator

Rich loading ~ 0.45



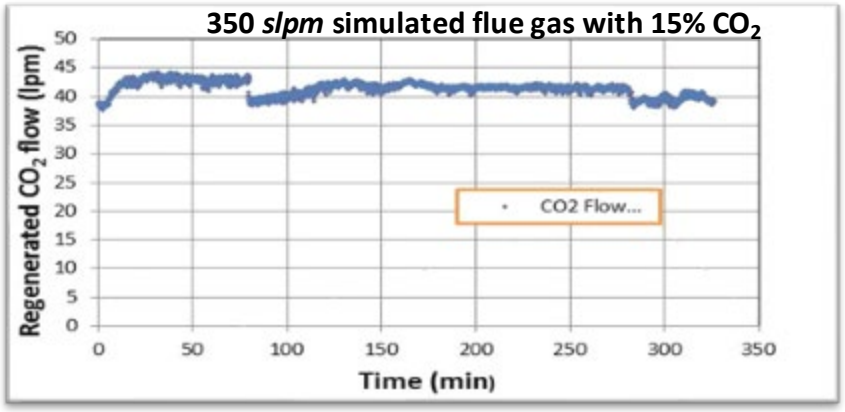
Comparison of test data with modeling data for mixed-salt solution. Operated with a cold regenerator top to retain ammonia.

Simulation of the CO_2 stripping section of the regenerator

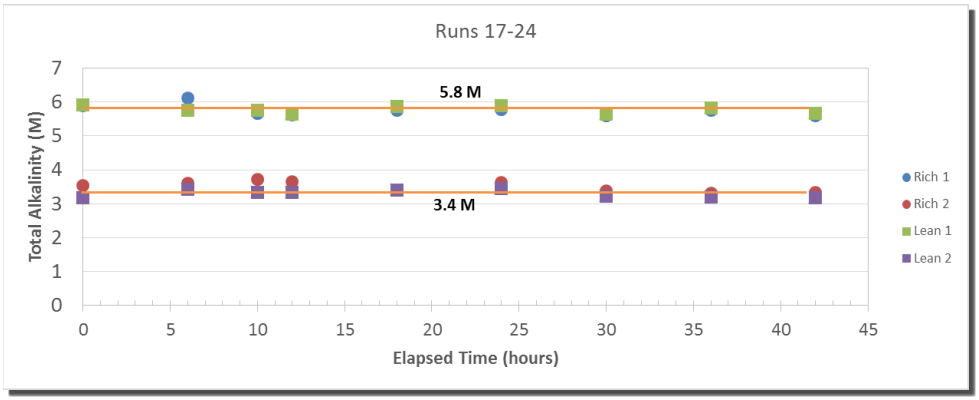
Rich loading ~ 0.50

Data from Large -Bench Testing

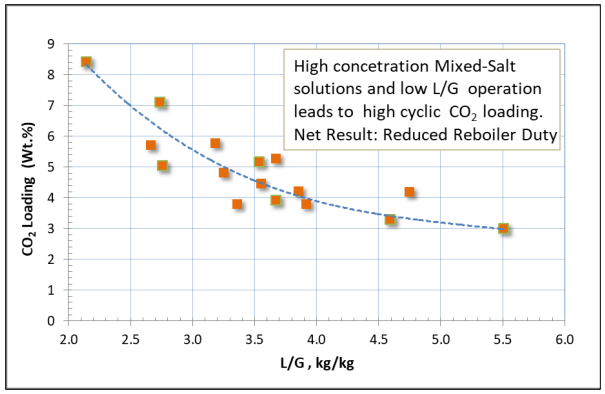
This work was conducted under DOE contract FE0012959



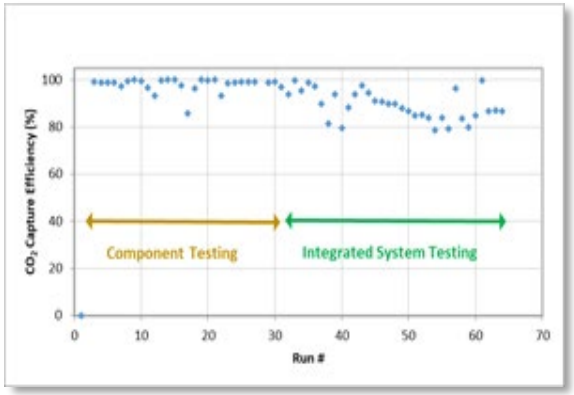
Observed 90% capture efficiency and regeneration with cyclic loading of ~0.7 mole of CO_2/mole of ammonia.



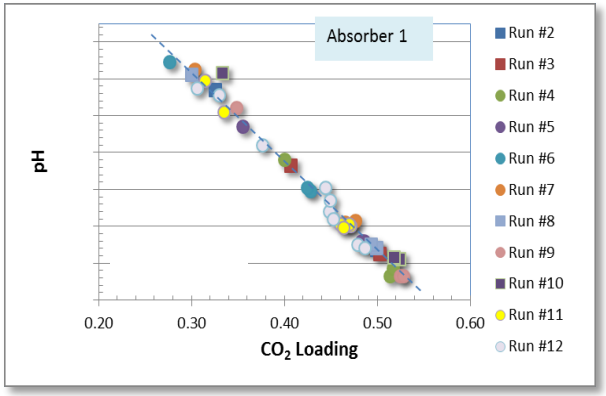
Alkalinity of rich and lean solutions circulating in the integrated system.



Observed CO_2 loading as a function of L/G



CO_2 capture efficiency in parametric test runs

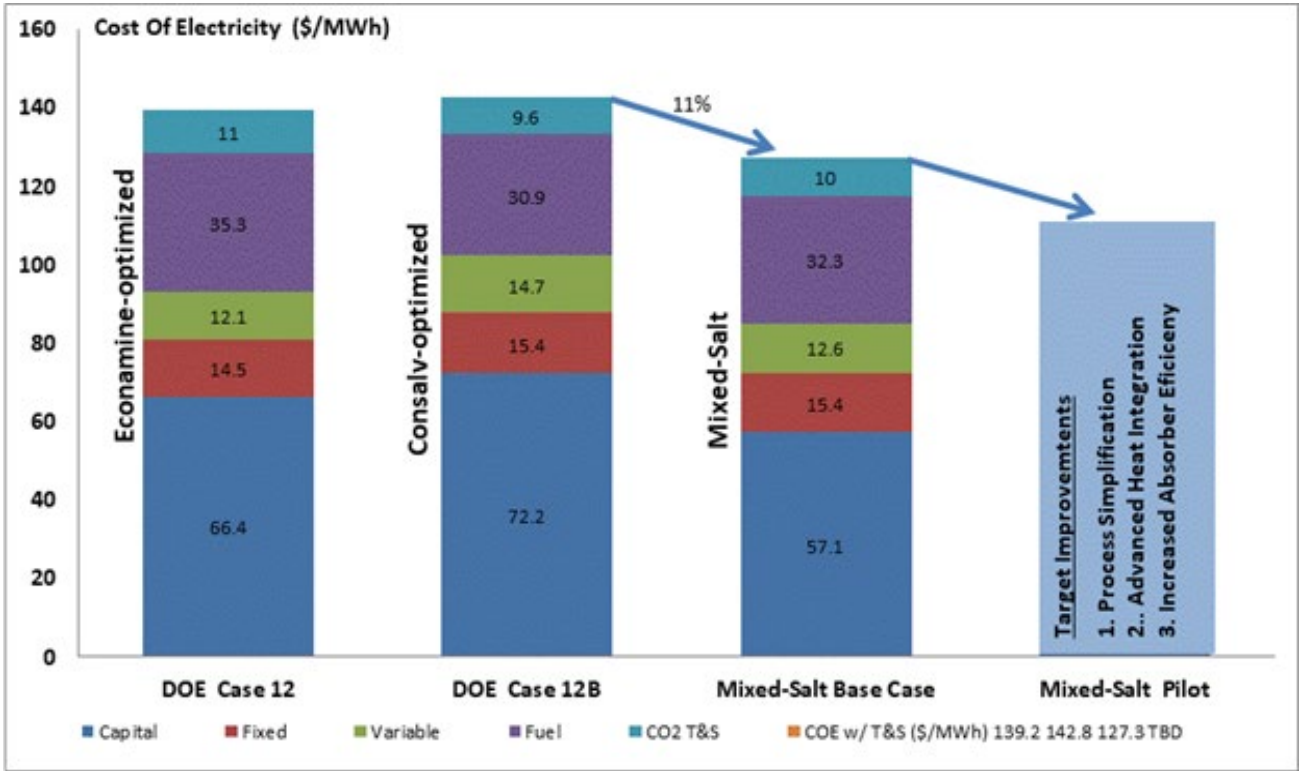


Observed pH as a function of CO_2 loading

Absorber: 20-35℃; Regenerator : 140℃; Reboiler: 160℃; L/G = 2 to 6 (kg/kg); Solvent composition: 5 to 8 m

Process Economics

This work was conducted under DOE contract FE0012959



Graphical presentation of the cost of electricity data for Econamine®, Cansolv®, and Mixed-salt processes

The TEA follows the analysis documented in the NETL report *"Cost and Performance Baseline for Fossil Energy Plants - Volume 1a: Bituminous Coal and Natural Gas to Electricity (Rev 3, July 6, 2015),"* aka Bituminous Baselines Study (BBS). Post-combustion capture technology analysis follows Case B12B, super-critical pulverized coal (PC) with CO_2 capture.
The economic analysis was done by Polytechnic University of Milan (PoliMi)
https://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/Rev3Vol1aPC_NGCC_final.pdf

Current Project Objectives

(DOE Contract: FE0031588)

- Perform integrated MSP testing at engineering scale for long-term periods under dynamic and continuous steady-state conditions with a real flue gas stream to address concerns relating to scale-up and integration of the technology to coal-based power plants;
- Operate the MSP with advanced heat integration to improve the process efficiencies;
- Study the solvent and water management strategies; and
- Collect critically important data for a detailed techno-economic analysis (TEA) and for further process advancements to reach the DOE's goal of \$30/tonne of CO_2 by 2030.

Key Focus:
(1) Process optimization, energy efficiency, chemical consumption and low emissions
(2) Dynamic and steady-state operations

Project Cost Period of Performance

Govt. Share: $15,002,571
Cost Share(BH & UIUC): $3,751,272
Total: $18,753,843

Project Period: 07/01/2018 through 03/31/2025
Budget Period 1: 07/01/2018 through 10/31/2018
Budget Period 2: 11/01/2018 through 07/31/2020
Budget Period 3: 08/01/2020 through 02/28/2022
Budget Period 4: 03/01/2022 through 02/29/2024
Budget Period 5: 03/01/2024 through 03/31/2025

DOE approval to start BP3 received on 4/7/2021

Project Partners:

University of Illinois (UIUC) Cost-sharing Host-Site and their Partner PRVN:

- Procurement, fabrication, installation and operation of the pilot
- Provide flue gas for testing
- Decommission the pilot

Trimeric Corporation

- Assist SRI in preparing the Process Design Package (PDP) for the pilot and Technoeconomic Evaluation (TEA)

OLI Systems

- Assist SRI in optimizing the process flowsheet for the 0.5 MW_e pilot and modeling of 550 MW_e (NETL Case B12B) for the power plant integration

Baker Hughes (BH)

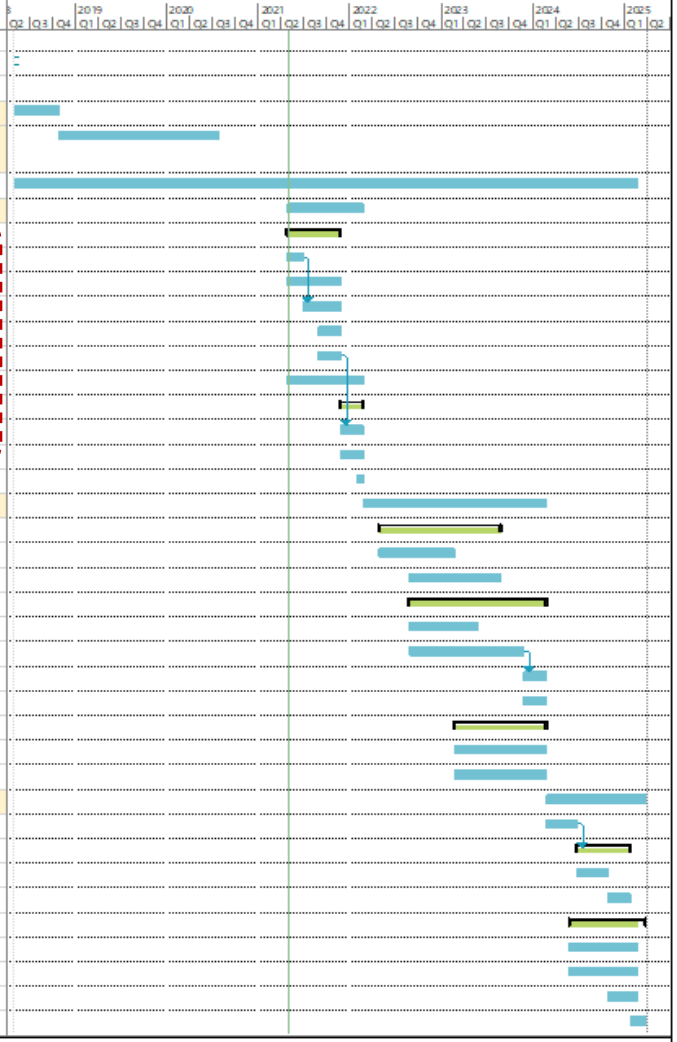
- Cost-sharing industry partner

Work Organization

Task Name	Work to be Done By
TASK 1.0 (BP2 & BP3) - Project Management and Planning	SRI
TASK 2.0 (BP2) Detailed Investigation of the required changes to TCM CAP Plant	SRI and TCM
TASKS 3.0 and 4.0 (BP2) - Process HAZOP Evaluation/Update System Startup Shutdown Protocols; Flowsheet Modeling	SRI, TCM, OLI and PoliMi
TASK 5.0 (BP3) - Pilot System Design and Production of Process Design Package	**SRI, Trimeric, OLI and UIUC**
TASK 6.0 (BP3) -Permit Preparation and Application	**UIUC**
TASK 7.0 (BP3) - Production of Detailed Engineering Package (DEP)	**SRI, OLI, UIUC and PRVN**
TASK 8.0 (BP4) - Procurement, Fabrication, Delivery of Subsystems/Components	**SRI, UIUC and PRVN**
TASK 9.0 (BP4) - Plant Construction, Installation and Shakedown	**SRI, UIUC and PRVN**
TASK 10.0 (BP4) - Test Plan Development, Chemical Procurement and Solvent Preparation	**SRI**
TASK 11.0 - (BP5) MSP system Commissioning and Startup	**SRI and UIUC**
TASK 12.0 – (BP5) MSP System Operation	**SRI and UIUC**
TASK 13.0 – (BP5) Final Technology Assessment	**SRI and Trimeric**

Project Schedule

ID	Task Mode	Task Name	Start	Finish
1				
2		**Engineering Scale Demonstration of MSP for CO2 Capture**	**Tue 5/1/18**	**3/1/31/25**
3				
4		BP1: Detailed Investigation of the required changes to TCM CAP Plant	Tue 5/1/18	Wed 10/31/18
5		BP2: Process HAZOP Evaluation/Update System Startup Shutdown Protocols; Flowsheet Modeling	Thu 11/1/18	Fri 7/31/20
6		**TASK 1.0 - Project Management (BP1, BP2, BP3, BP4 and BP5)**	**Tue 5/1/18**	**Sat 3/1/25**
7		BP3: Pilot Design	Sat 5/1/21	Mon 2/28/22
8		**TASK 5.0 -Pilot System Design and Production of Process Design Package (PDP)**	**Sat 5/1/21**	**Tue 11/30/21**
9		Subtask 5.1 - Design Basis Review	Sat 5/1/21	Wed 6/30/21
10		Subtask 5.2 - Process Design Package (PDP) for Inside Battery Limit (ISBL)	Sat 5/1/21	Tue 11/30/21
11		Subtask 5.3 - PPD for Outside the Battery Limit (OSBL)	Thu 7/1/21	Tue 11/30/21
12		Subtask 5.4 - EH&S Risk Assessment	Wed 9/1/21	Tue 11/30/21
13		Subtask 5.5 - Process HAZOP Evaluation	Wed 9/1/21	Tue 11/30/21
14		**TASK 6.0 - Permit Preparation and Application**	**Sat 5/1/21**	**Mon 2/28/22**
15		**TASK 7.0 - Production of Detailed Engineering Package (DEP) for ISBL and OSBL**	**Wed 12/1/21**	**Mon 2/28/22**
16		Subtask 7.1 - Production of Detailed Engineering Package (DEP) for ISBL	Wed 12/1/21	Mon 2/28/22
17		Subtask 7.2 - Production of DEP for OSBL	Wed 12/1/21	Mon 2/28/22
18		Subtask 7.3 - Review of DEPs for ISBL and OSBL	Tue 2/1/22	Mon 2/28/22
19		BP4: Procurement and Construction of Pilot Plant	Tue 3/1/22	Thu 2/29/24
20		**TASK 8 - Procurement, Fabrication, Delivery of subsystems / components**	**Sun 5/1/22**	**Thu 8/31/23**
21		Subtask 8.1 - Procurement	Sun 5/1/22	Tue 2/28/23
22		Subtask 8.2 - -- Fabrication, inspection, and acceptance of subsystems / components	Thu 9/1/22	Thu 8/31/23
23		**TASK 9 - Plant Construction, Installation and Shakedown**	**Thu 9/1/22**	**Thu 2/29/24**
24		Subtask 9.1 - Site Preparation	Thu 9/1/22	Wed 5/31/23
25		Subtask 9.2 - Pilot Plant Installation at Site	Thu 9/1/22	Thu 11/30/23
26		Subtask 9.3 - Pilot Plant Pre-commissioning	Fri 12/1/23	Thu 2/29/24
27		Subtask 9.4 - Pilot plant Shakedown	Fri 12/1/23	Thu 2/29/24
28		**Task 10.0 – Test Plan Development, Chemical Procurement and Solvent Preparation**	**Wed 3/1/23**	**Thu 2/29/24**
29		Subtask 10.1 - Test Plan Development	Wed 3/1/23	Thu 2/29/24
30		Subtask 10.2 - Chemical Procurement and Solvent Preparation	Wed 3/1/23	Thu 2/29/24
31		BP5: Pilot Plant Operation & MSP Testing	Fri 3/1/24	Mon 3/31/25
32		**TASK 11.0 - Pilot Plant Commissioning and Startup**	**Fri 3/1/24**	**Sun 6/30/24**
33		**TASK 12.0 - Pilot Plant Operation**	**Mon 7/1/24**	**Fri 1/31/25**
34		Subtask 12.1 - Parametric Test Campaign	Mon 7/1/24	Thu 10/31/24
35		Subtask 12.2 - Steady-State Test Campaign	Fri 11/1/24	Fri 1/31/25
36		**TASK 13.0 - Final System Modeling/Engineering, Techno-Economic Analysis and EH&S**	**Sat 6/1/24**	**Mon 3/31/25**
37		Subtask 13.1 - Final System Modeling and Techno-Economic Analysis	Sat 6/1/24	Fri 2/28/25
38		Subtask 13.2 - Technology Gap Analysis and Technology Maturation Plan	Sat 6/1/24	Fri 2/28/25
39		Subtask 13.3 - Environmental Health and Safety Assessment (EH&S)	Fri 11/1/24	Fri 2/28/25
40		**Task 14. Project Review and Closure at UIUC**	**Sat 2/1/25**	**Mon 3/31/25**



Page 1

Note: System operation schedule will be updated after completion of the engineering design.

Project Milestone Log

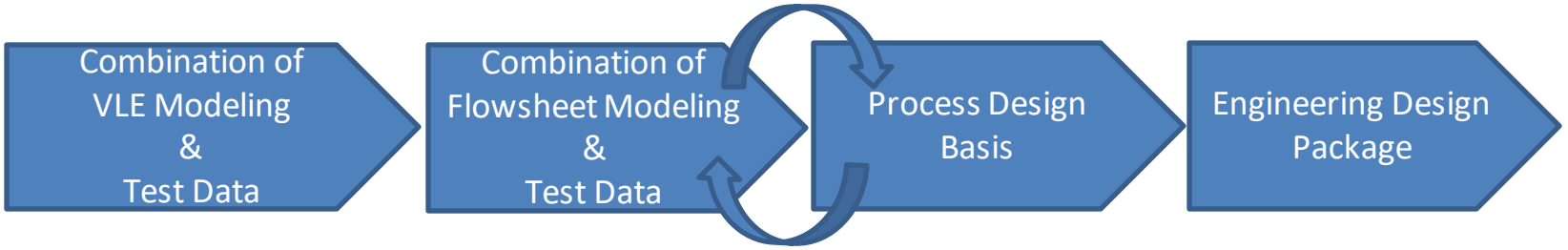
BP	Task/ Subtask No.		Milestone Description	Planned Completion	Actual Completion	Verification Method
1	1	a	Updated PMP submitted	8/3/18	8/3/2018	PMP file
1	1	b	Kickoff / BP1 Review Meeting convened	10/3/18	10/2/2018	Presentation file
1	2	c	Work scope and firm cost estimate for the Chilled Ammonia Plant (CAP) recommissioning submitted	9/30/18	10/12/2018	BP2 Continuation Application
1	1	d	Technology Maturation Plan	9/30/18	9/26/2018	Topical Report
1	1	e	Updated PMP submitted	12/31/18	12/18/2018	PMP file
2	1	f	Project re-baseline proposal submitted	7/30/20	9/1/20	Topical Report
3	1	A	PMP updated	4/30/21	4/23/21	PMP file
3	1	B	Host-site agreement signed	4/30/21	5/27/2021	RPPR quarterly
3	5.2	C	Completion of process Design Package (PDP)	11/30/21		RPPR quarterly
3	5.4,5.5	D	Completion of HAZOP and EH&S	11/30/21		RPPR quarterly
3	6	E	Required Permits for the capture system installation received	2/28/22		RPPR quarterly
3	7	F	Completion of the Detailed engineering package with AACE Class 2 cost estimate	2/28/22		RPPR quarterly
4	8.1	G	Completion of the submission of vendor package for the plant fabrication	2/28/23		RPPR quarterly
4	8.2	H	Completion of the plant construction; vessels and auxiliary system construction	8/31/23		RPPR quarterly
4	9.2	I	Completion of plant installation at the site	11/30/23		Presentation file
4	9.3	J	Completion of the SOP preparation and plant operator training	2/29/24		Presentation File
4	9.4	K	Completion of the slip-stream connection for a flowrate equivalent to 0.5 MWe and plant shakedown	2/29/24		RPPR quarterly
4	10.1	L	Completion of the Test Plan and DOE approval received.	2/29/24		Test Plan file
5	11	M	Completion of the pilot commissioning with dynamic operation tested (system operated > 100 hours)	6/30/24		RPPR quarterly
5	12.1	N	Completion of the parametric testing for identification of optimal operating conditions for steady-state testing	10/31/24		RPPR quarterly
5	12.2	O	Completion of the steady-state long-duration testing and data analysis (system operated for >1000 hours; evaluation of solvent CO_2 capture capacity, system energy requirement	1/31/25		RPPR quarterly
5	13.1	P	TEA topical report submitted	2/28/25		Topical & final reports
5	13.2	Q	Technology gap analysis (TGA) topical report submitted	2/28/25		Topical & final reports

Project Success Criteria

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 in Budget Period 2
	Host Site Agreement
Note: A corrective action plan (CAP) was submitted to re-align the project	
C. Completion of **Budget Period 3**	Successful completion of all work proposed
	Host Site Agreement
	Required permit application for the plant installation at the host-site complete.
	Successful completion of the preparation of the process design package, the detailed design packages. Successful completion of the HAZOP. Successful completion of the equipment & specification lists for construction of 0.5 MWe CO_2 capture system in budget period 4.
D. Completion of **Budget Period 4**	Successful completion of all work proposed
	Successful installation of the engineering scale MSP system at UIUC site
E. Completion of **Budget Period 5**	Completion of dynamic MSP testing and data analysis (system operated for at least 600 hours with at least two main process parameters – cooling water and steam varied). Identification of optimal operating conditions for steady-state testing.
	Completion of integrated, steady-state MSP large pilot-scale testing (> 1,000 hours) with results showing = 0.10 kg-CO_2/kg working solution loading capacity, ammonia emissions < 10 ppm in the stack gas, and total energy consumption about 2 GJ/tonne CO_2 during operation at 10 bar regeneration pressure 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

BP3 Project Work Update

- Task 1: Project Management
  - Subcontract, vendor and host-site agreement completed
  - PMP updated
  - Continued virtual meetings with project team
  - Visited Host-site on June 22, 2021
    - In person participation by Trimeric, UIUC & PRVN and virtual by DOE
  - Currently planning a Host-Site visit for the week of September 27.
    - This will be at the Abbott Plant Site
- Task 5: 0.5 MWe System Design and Production of the Engineering Package
  - In progress



Process Design Basis (PDB) Summary

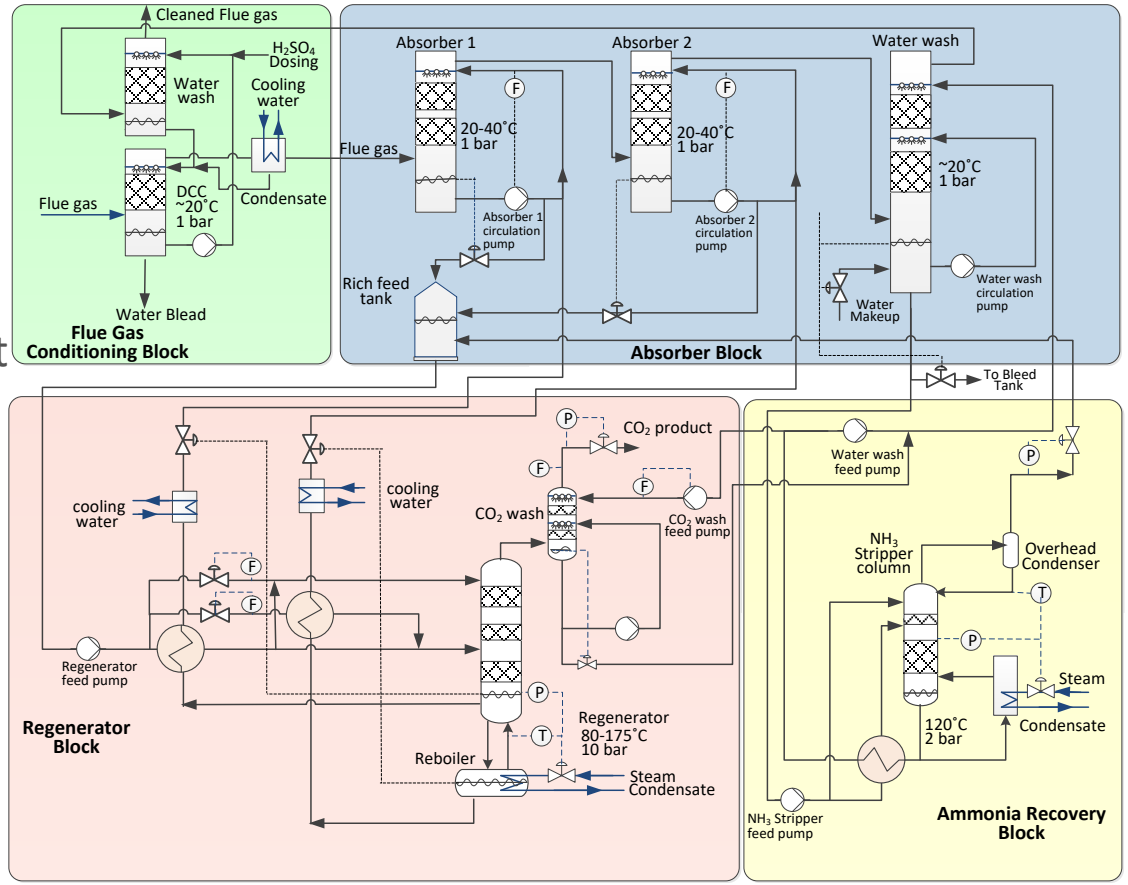
Items included in the PDB report

- General Facility Design
  - Process block flow diagram
  - Process description
  - Preliminary heat and material balance
- Site Conditions for Process Design
  - Ambient conditions at the site
  - Plot plan for the site
- Process Design Parameters
  - Flue gas conditions, process design margins, *etc*.
- Utilities Requirements and Availability
  - Steam temperature, pressure and flow rate
  - Electrical load
  - Cooling water supply

Process Blocks

- Flue Gas and Vent Gas Conditioning
- CO_2 Absorption and Water Wash
- Solvent Regeneration, CO_2 Product Wash, and Solvent Heat Exchange
- Ammonia Stripping and Recovery
- Water Wash Tank *
- Bulk Storage Tanks* (Chemical Make-Up Inventory, Produced/Wastewater)

*Not shown



Example: Integrated System Modeling

Sensitivity Analysis: Composition, reboiler temperature, split ratio etc.

Reboiler Energy

Case	Case SRI B-11	Case SRI B-12
Column Calculation Method	Equilibrium	Equilibrium
Regenerator Reboiler Temperature, ℃	170	179
Regenerator Reboiler Duty, MJ/KgCO2	1.82	1.78
NH3 Stripper Reboiler Duty, MJ/KgCO2	0.16	0.08
Total Reboiler Duty, MJ/KgCO2	1.99	1.86

Feed gas composition as given in NETL Case B12B was used in this modeling. Modeling work is by OLI Systems.

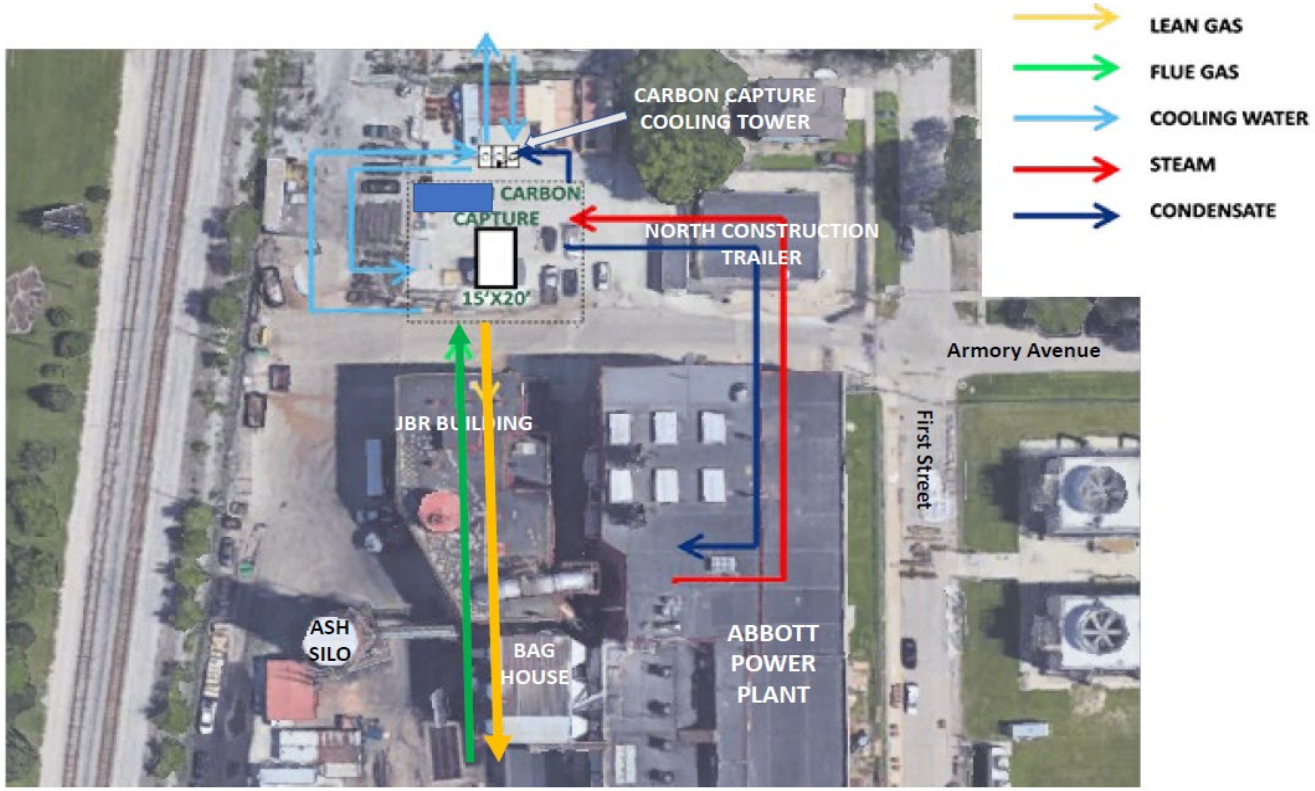
Table shows the modeling data for two cases with varying reboiler bottom temperatures in an optimized MSP system for flue gas composition as given in NETL Case B12B (Cost and Performance Baseline for Fossil Energy Plants - Volume 1a: Bituminous Coal and Natural Gas to Electricity Rev 3, July 6, 2015) for a 550 MW super-critical pulverized coal (PC) power plant.

Ambient Conditions Champaign, Illinois

Ambient Condition	Value	Units	Data Source
Elevation	764	ft	
Design Barometric Pressure	14.29	psia	Based on elevation
Seismic Design Details			Previous Abbott/UIUC Design Basis
Seismic Zone	UBC Zone 2A (0.15 g)		
Ambient Temperature			2005 ASHRAE
Extreme Annual Mean Max	96.9	°F	
Extreme Annual Mean Min	-11.6	°F	2005 ASHRAE
Yearly Average	61.7 (high), 41.7 (low)	°F	See Note 1
0.4% Cooling Dry Bulb	93.1	°F	2005 ASHRAE
0.4% Mean Coincident Cooling Wet Bulb	77.0	°F	2005 ASHRAE
99.6% Heating Dry Bulb	-2.1	°F	2005 ASHRAE
Rainfall			
Average monthly	3.57	Inches	See Note 1
Maximum monthly average	4.89	Inches	See Note 1
Design			
100 year, 1-hour storm		inches/hr	
100-year, 24-hour storm		inches/hr	
Snowfall			
Maximum monthly average	6.8	Inches	See Note 1

Note 1: https://www.isws.illinois.edu/statecli/cuweather/cu-averages.htm; for new 1981-2010 normal period for Champaign, IL.

Host-Site: Abbott Plant at UIUC



- The total nameplate capacity of the plant is 84 MWe, 35 MWe being coal.
- Abbott plant will provide 2600 kg/hr flue gas stream up to 2000 hr for MSP testing.
- Plant can provide the required steam for the reboiler
- The existing flue gas ducting from the stack (8-inch) will be used

BP3-Task 5 Work Summary

Leading to the Process Design Package Delivery

Key Iems	Status	Estimated Completion Date
Host Site Information	COMPLETE	
Utility Requirements	COMPLETE	
Design Basis	COMPLETE	
Process Flow Diagrams	IN PROGRESS	8/13/2021
Heat and Material Balances	IN PROGRESS	8/13/2021
Process Control Narrative	IN PROGRESS	8/20/2021
Process Control Diagram		8/27/2021
Cause and Effect Diagrams		9/10/2021
First Pass P&IDs		9/15/2021
Safety Review Meeting		10/1/2021
HAZOP Report		10/15/2021
Equipment Process Datasheets		10/22/2021
Line List, Instrument and Control Valve Datasheets		11/5/2021
Final P&IDs		11/5/2021
Process Design Package		11/19/2021

Note: The estimated completion dates are based on the current work progress, and the actual completion dates may vary depending on the work restrictions in CA, IL, NJ, and TX due to the pandemic.

MSP Summary and Benefits

Process Summary

- Uses inexpensive, industrially available material (potassium and ammonium salts)
- No chemical degradation
- Has the potential for easy permitting in many localities
- Uses known process engineering
- Accelerated development possible

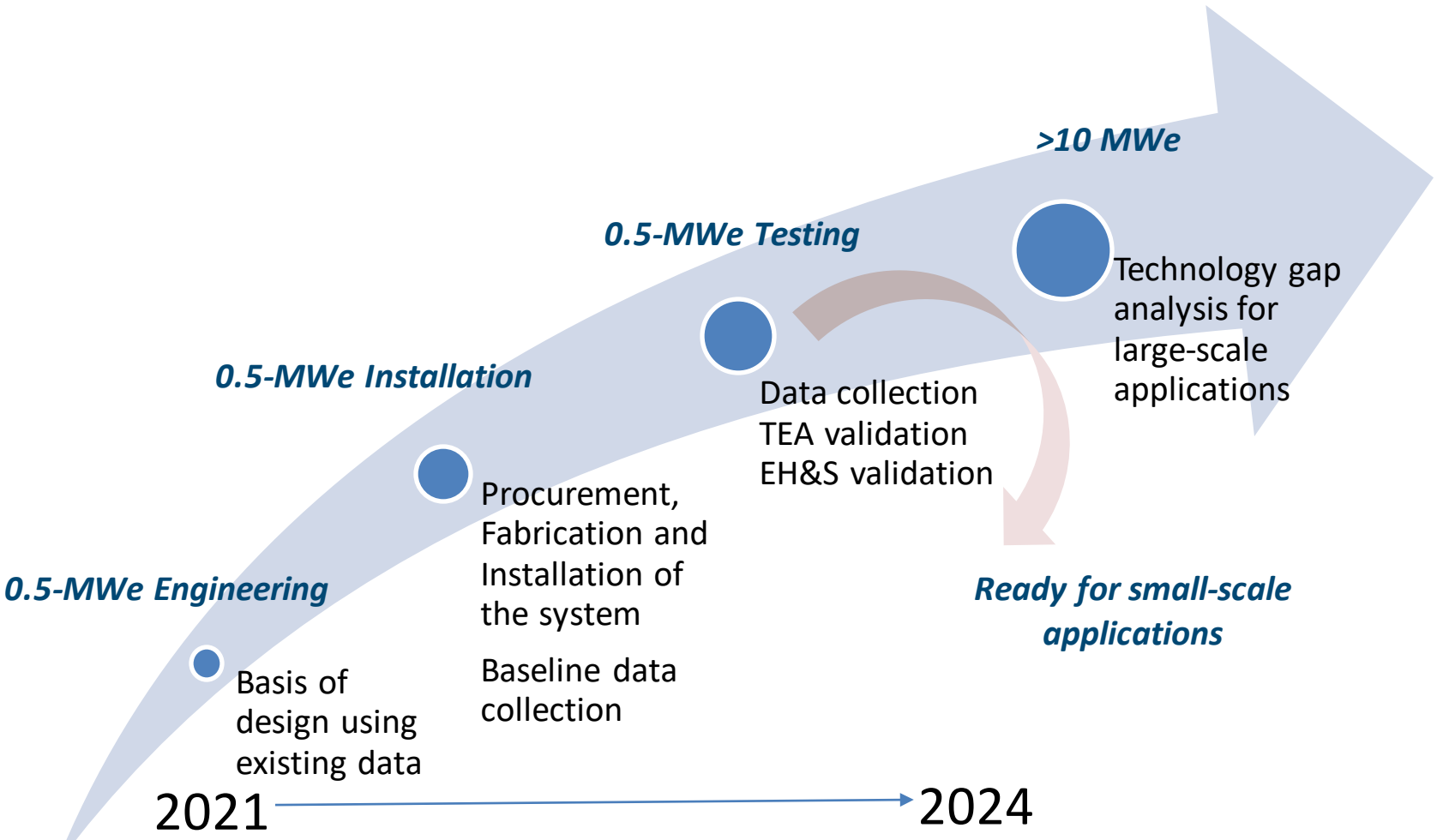
Demonstrated Benefits (By testing and modeling)

- Enhanced CO_2 capture efficiency
- High CO_2-loading capacity
- High-pressure release of CO_2 (10-12 bar)
- Reduced energy consumption (~ 2 MJ/kg-CO_2)

Expected Additional Benefits

- Flexible CO_2 capture possible
- > 95% capture possible
- Common acid pollutant and particulate removal

Pathway Toward Testing MSP at Scale



SRI has patent coverage for the MSP in the US, Japan, and Europe

SRI has entered into a global exclusive licensing agreement with Baker Hughes for MSP use for post-combustion CO_2 capture in 2021 (https://netl.doe.gov/node/10671), and this partnership will pave the pathway for early entry of the technology into the market.

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Thank You!

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