Transformational Sorbent-Based Process for a Substantial Reduction in the Cost of CO_2 Capture

(DE-FE0031722)

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Executive Summary

- CO_2 Capture with physical sorbents with low heats of sorption (~0.8 GJ/MT)
  - High purity CO_2 (>98%) at high recovery (>90-95%),
    - Up to 99% recovery possible with some process modifications
  - The absolute energy requirement (excluding compression) of 1.6-1.8 GJ/MT of CO_2, needed at about 110^{o}C
    - Absolute energy requirement is 40% lower than Shell Cansolv and 57% lower than MEA
    - The relative energy requirement, based on lost work analysis, is 66% lower than Shell Cansolv and 73% lower than MEA assuming160^{o}C steam extraction temperature for amines
- Significantly lower capital (>45% reduction), and parasitic power (>45% reduction) leading to >45% lower capture cost
  - <$30/MT capture cost for pipeline quality CO_2
- Lab scale testing, process simulation, and a preliminary TEA during BP1; bench scale testing at TCM and a final TEA during BP2

The DOE Project (FE0031722)

- Objectives: >90% CO_2 recovery, >95% purity with a potential pathway for <$30/MT capture cost by 2030
- The total project budget is U.S. $4 million ($3.13 MM DOE, $0.87 MM match including significant match from TCM)
- In the first budget period (May 2019 to March 2021) we
  - Optimized the sorbent and the regeneration process through lab testing, Monte Carlo simulations, and process simulation
  - Did a detailed design and costing of the bench unit, a preliminary TEA, and a HAZOP addressing TCM integration issues
- In the second budget period (April 2021 to Dec 2022) we are
  - Constructing a field test unit (500 Nm^3/hr scale)
  - Will carry out testing at TCM, a detailed engineering design, and a Rev 4 techno-economic evaluation for a commercial scale unit (550 MW power plant)

Project Participants

DOE/NETL

- Project oversight, feedback, funding (Project Manager: Mariah Richardson)

InnoSepra

- Technology development at lab and bench scale, coordinate with partners, project management and reporting

Main Line Engineering

- Engineering design of the full scale plant, TEA, cost share

TCM

- Field testing, commercial feedback and cost share

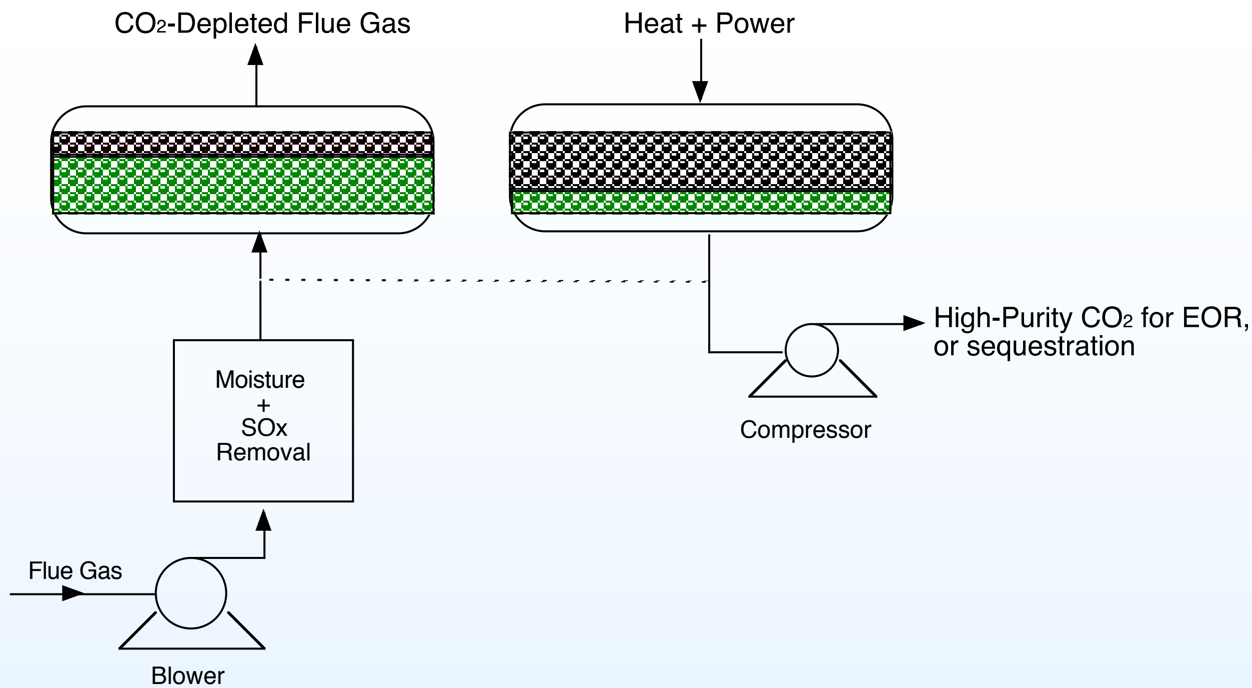
Adroitech

- Monte Carlo Simulation, fabrication of structured sorbents

Adsorptech / Fabrication Partners

- Bench unit design and fabrication, cost share

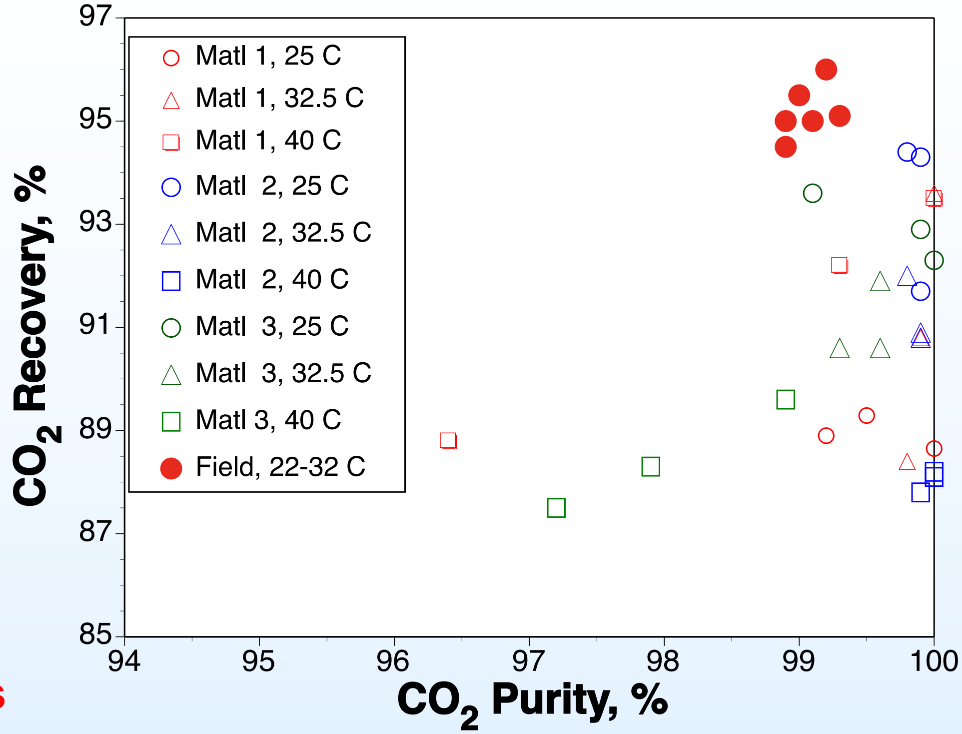
Technology Background



- **Flue gas pretreatment for NO_2 and SO_X removal to sub-ppm levels, removal of substantial amounts of aerosols**, and moisture removal to ppm levels
  - NO_2, SO_X and aerosol removal demonstrated at pilot scale; applicable to solvent capture
- Physical sorbents with a very high surface area (>10 million m^2/m^3), low heats of adsorption (0.8 GJ/MT of CO_2)
  - Adsorption at 25-40°C, regeneration at 90-110°C, high net CO_2 capacity (>8-wt%)
  - Pipeline quality CO_2 (>98% purity, <1 ppm H_2O and SO_X, <10-ppm O_2), >90% recovery
- Key innovation is ***the novel combination*** of process, sorbent regeneration and materials leading to >45% reduction in parasitic power
  - Performance similar to or better than amines, much lower regeneration energy requirement

Field Demonstration of First Generation CO_2 Capture Process

Pilot Plant for the First Generation Process



- NRG's Indian River, DE coal fired power plant, more than 8 weeks of testing
- 80-100 scfm flue gas, 22-32^{0}C feed, 50-ppm SO_2, 10-12% CO_2
- 8-10.5 wt% net CO_2 capacity in the field
- >94% CO_2 recovery, 98.5- 99.5% CO_2 purities, pipeline / EOR quality gas (<10 ppm oxygen and moisture)
- Flue gas purification demonstrated at the Abbott power plant (800 scfm)

Second Generation InnoSepra Process

- A breakthrough regeneration method has allowed reduction in the absolute energy requirement to 1.6-1.8 GJ/MT (based on lab testing and process simulation) at about 110^{o}C
  - **The process is also simpler, significant capital savings over the first generation process**
- Effective parasitic load of 0.96 GJ/MT based on a steam extraction temperature of 160^{o}C (74 psia) for MEA and Cansolv
  - **About 67% lower than Cansolv, and about 73% lower than MEA**
  - **Less than 16% of plant's output for CO_2 capture and compression**
- The technology is to be demonstrated at the bench scale at TCM (Technology Centre Mongstad) in 2022

Technical Approach

Experimental Design and Work Plan

- The Work Plan for BP1 involved
  - Identification of suitable materials based on lab testing and Monte Carlo simulations
  - Testing the materials in a lab scale unit for purity and recovery
  - Process simulation to estimate the energy requirements and equipment sizing
  - A techno-economic analysis to estimate the capital cost and the CO_2 capture cost
- The Work Plan for BP2 involves
  - Bench unit fabrication, HAZOP, shipping and installation
  - Testing at TCM with simulated SCPC flue gas as a function of flow rate, feed temperature, and regeneration temperature
  - Process simulation to update the energy requirements and equipment sizing
  - A final techno-economic analysis to estimate the capital cost and the CO_2 capture cost

Technical Approach

Key Milestones

- Identification of suitable materials with at least 6-wt% capacity for >95% purity
- Process model completion and initial techno-economic analysis
- Detailed bench unit design, costing and HAZOP
- Bench unit fabrication, shipping & installation, and testing
- Detailed engineering design for a 550 MW SCPC plant
- Final TEA with Rev 4 guidelines to determine potential capture cost

Project Success Plan

- Thermal requirements below 1.8 GJ/MT and a capture cost below $40/MT based on lab testing & simulation
- Thermal requirements below 1.8 GJ/MT and a capture cost below $40/MT based on field testing & detailed engineering design

Project Risks and Mitigation Strategies

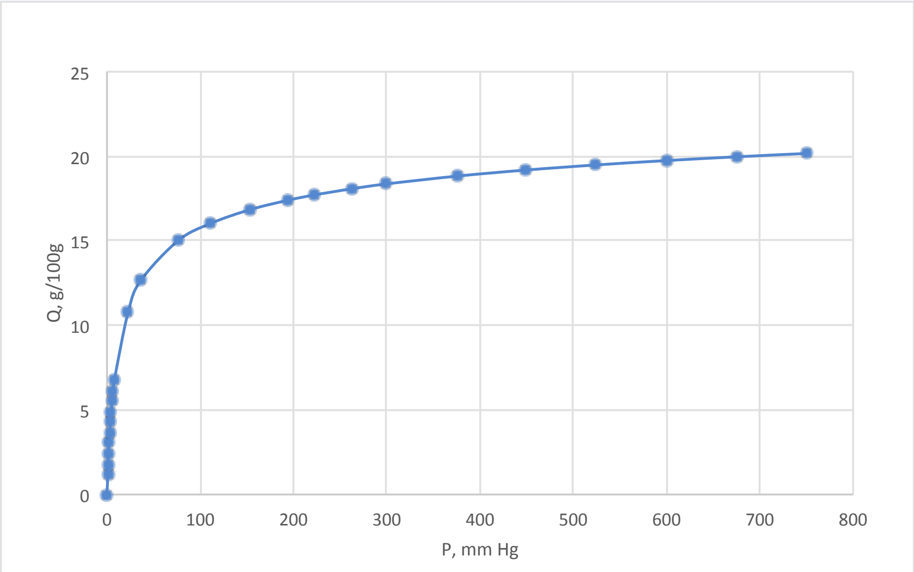
- The key risks include resource availability, and sorbent regeneration. Back up resources and regeneration approaches have been identified.

Key Activities for BP1

- Monte Carlo simulations to identify the suitable sorbents
  - **Sorbent structure variation can provide absolute CO_2 capacities (15% CO_2 at 25^{o}C) between 18-wt% (CO_2-N_2 separation factors of 15-20), and 12-wt% (CO_2-N_2 separation factor over 200)**
  - **Confirmed through microbalance and breakthrough testing**
- The regeneration process was optimized through cyclic testing
  - **No loss in performance after multiple cycles, >8-wt% net CO_2 capacity**
- Process simulation, integration with the host site, preliminary TEA
  - **A detailed process simulation confirmed a power penalty of <16% of plant's output**
  - **A new CO_2 compression cycle for up to 20% reduction in energy needed for CO_2 compression**
  - **A detailed HAZOP and test site integration with TCM**
  - **A preliminary TEA indicating the potential for a capture cost of about $30/MT**

Identification of Suitable Materials

- A number of materials were identified based on Monte Carlo simulations and tested in the adsorption microbalance for CO_2 and N_2 capacities, and CO_2-N_2 separation
- A typical CO_2 isotherm (30^{o}C, Micromeritics ASAP 2020) is shown below



- Depending on the material structure CO_2 capacities between 12-wt% and 18-wt%, separation factors between 15 and 650 can be obtained
  - **High separation factors are associated with low CO_2 capacities**

Process Simulation Summary (Retrofit)

- Simulation of the CO_2 capture plant integrated with the coal-fired power plant with Aveva's Pro^{II} software
- The feed and product conditions (for a 550 MW SCPC plant) are:
  - **Flue gas: 74,092 kmol/hr, 57^{0}C, 100 kPa, 68.1% N_2, 13.5% CO_2, 15.2% water**
  - **Product CO_2: 9,517 kmol/hr, 99% CO_2, 15,270 kPa**
- Energy required for CO_2 capture and compression
  - **Pumps, blowers and compressors: 54.8 MW**
  - **Lost electrical output in LP turbine: 24.2 MW**
  - **Total loss in electrical output: 79 MW**
  - **Electrical output loss as a percent of total output: 14.4%**
- Very significant operational flexibility
  - **Five capture modules for a 10,000 MTD plant**
  - **Continuous operation between 10 and 100% of design is possible**

Techno-Economic Evaluation Summary (Retrofit)

550 MW SCPC Power Plant, 2.86 MM MT/year of CO_2 Captured*

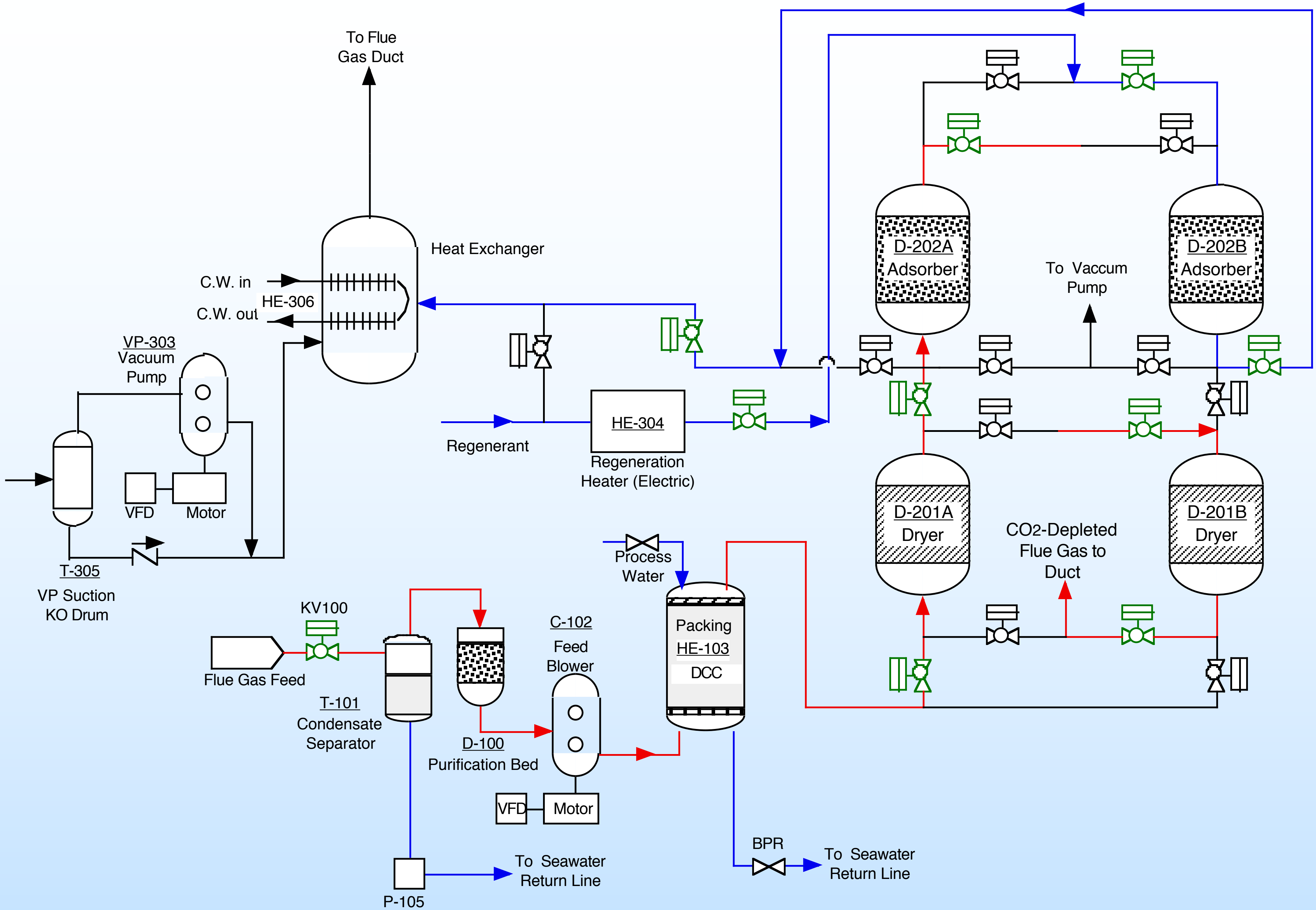
	Shell Cansolv	1st Generation InnoSepra Process	2nd Generation InnoSepra Process
Indicative TOC, U.S.$MM	891	561	482
Power Loss Due to Steam Extraction, MW	70	32	**24**
Electrical Power (compression, auxiliaries), MW	67	67	**55**
Total Power Loss, MW	137	99	**79**
Power Loss as % of Base Output	25	18	**14.4**
CO_2 Capture Cost at the plant gate, $/tonne	62	41	**34**
CO_2 Capture Cost including TS&M, $/tonne	67	46	39

- 10% capital recovery factor + 2.5% maintenance charge (7% CRF in 2019 Baseline Report), $64/MWh replacement power, 85% on stream factor
- A capture cost of $29/MT for the 2nd generation InnoSepra Process with a CRF of 7%
- Higher capture rate, ~95%, for the InnoSepra Process not accounted for in the calcs

Key Activities for BP2

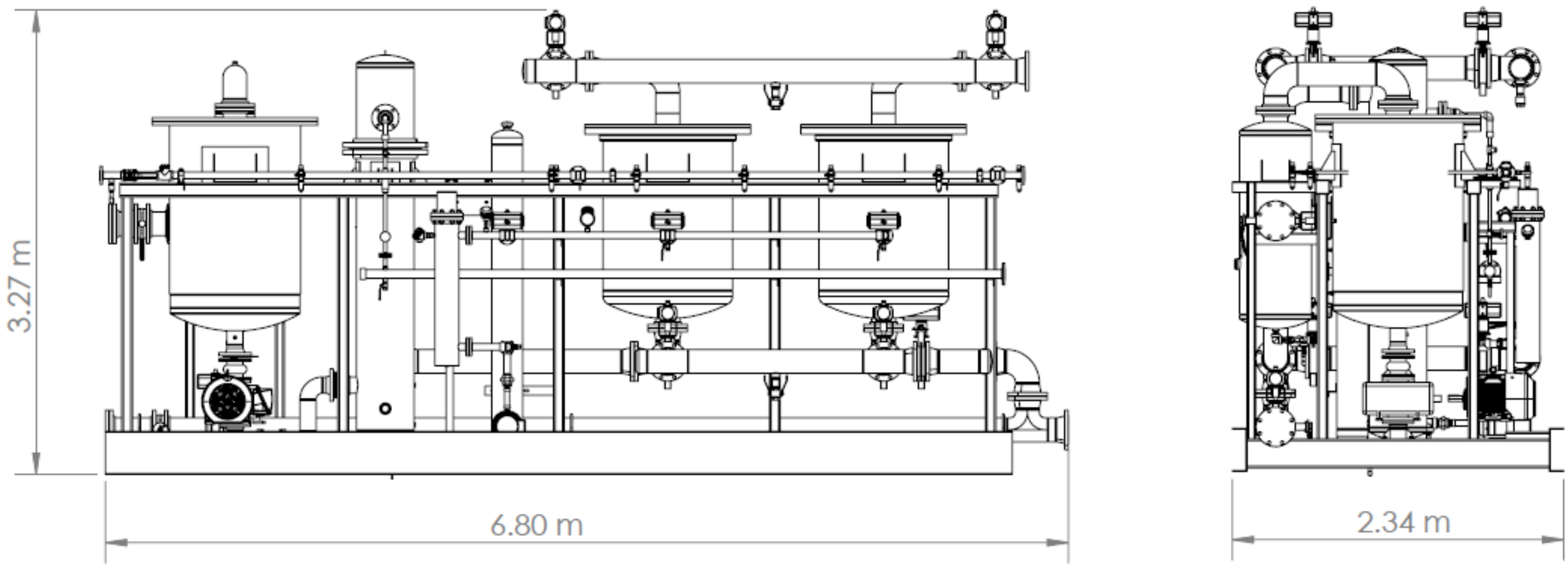
- Skid design and testing, field test report and updated TEA
- Most of the effort focused on bench unit fabrication including lab tests in support of skid design
  - Capable of processing 500 nm^3/hr of flue gas
  - Being designed as three separate skids
  - Skid 1 for feed preparation and drying
  - Skid 2 for CO_2 adsorption and regeneration
  - Skid 3 for regeneration
  - Each skid is about 8’ w x 10’ H and 25’ L, about 12,000 lbs each
  - Very significant challenges due to fabrication resources, engineering resources, supply chain constraints leading to project delays
- Bench Unit Status
  - All the major components procured and sent to the fabricators
  - Skid 1 nearing completion
  - Work started on Skid 2 piping and vessels
  - Detailed design for Skid 3 completed

Process Flow Diagram for the Bench Unit



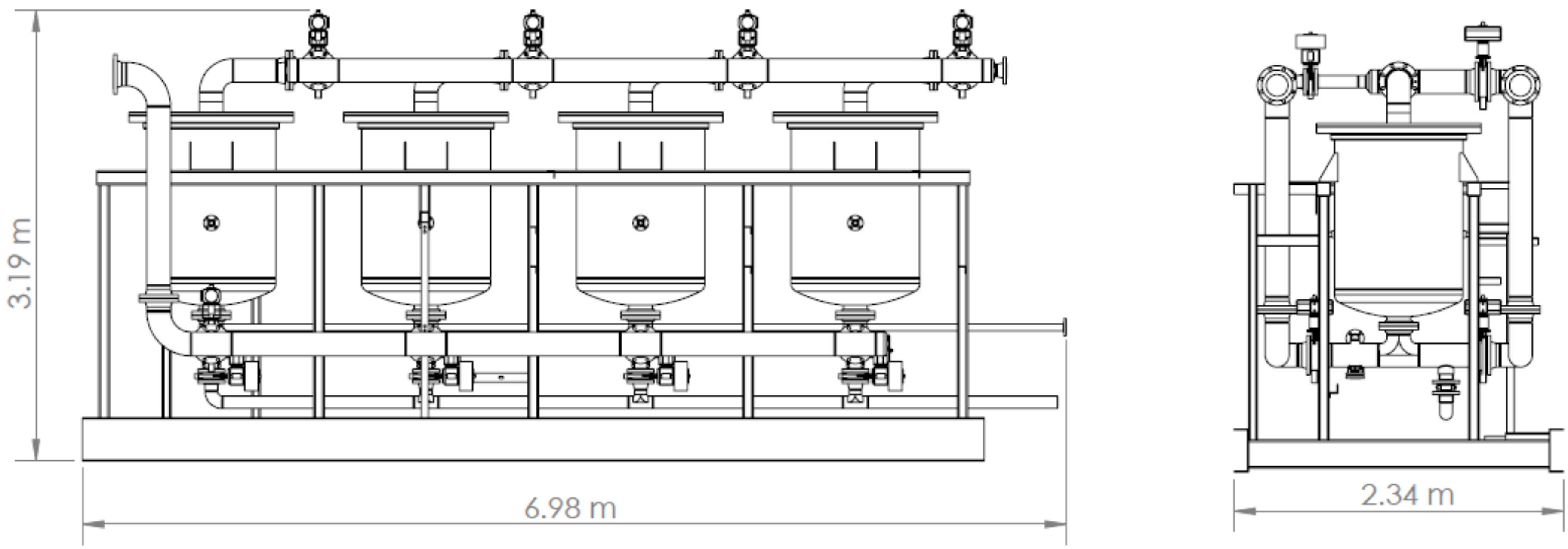
Layout of InnoSepra Skid #1

Purification and drying section

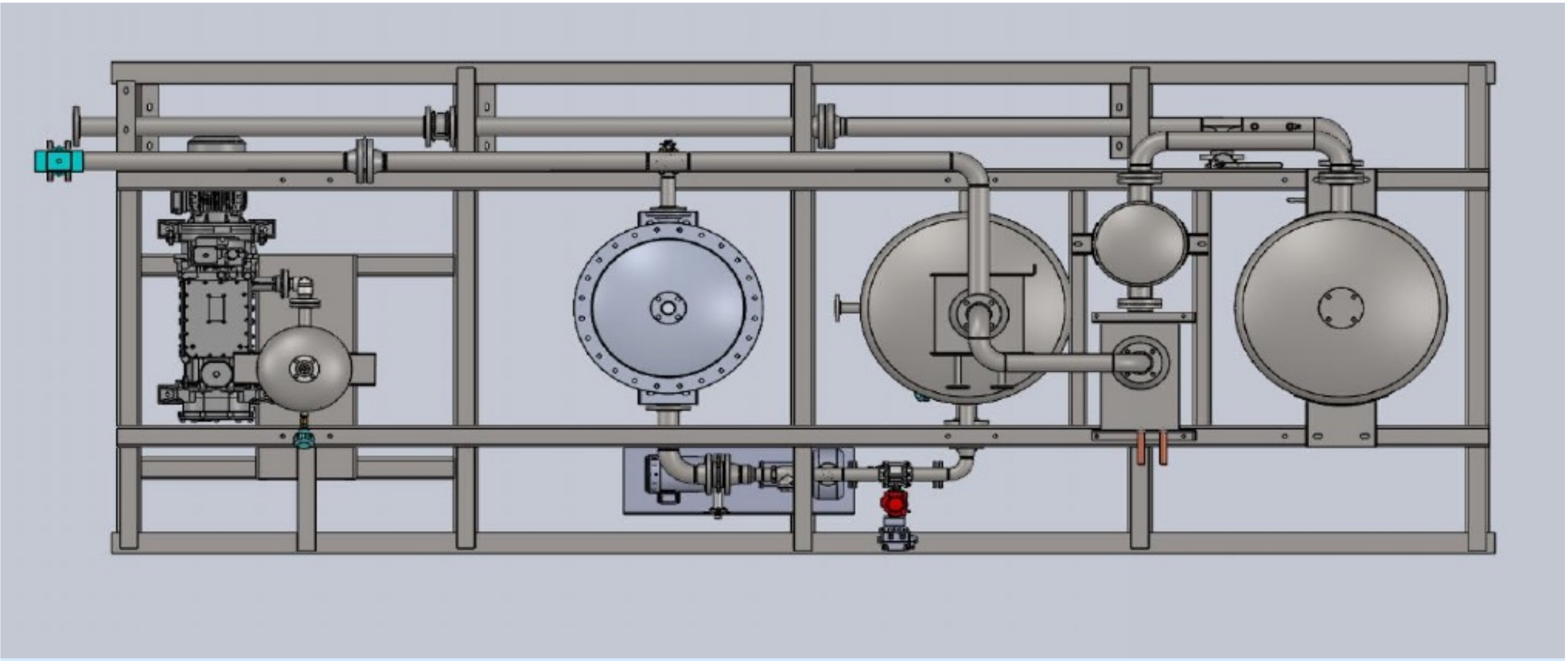


Layout of InnoSepra Skid #2

Adsorption section



Layout of InnoSepra Skid #3



Plan for Future Testing / Commercializations

- Need one intermediate scale up after TCM testing to build commercial scale CO_2 capture plants

Steps toward technology commercialization

- FEED study for a 550-650 MW SCPC plant after the completion and analysis of field test results
- Further process demonstration at ~100 tonnes per day scale
  - 25X scale up over the TCM pilot
- Once the process has been demonstrated at 100 tonnes per day scale
  - 1,000-2,500 tonnes per day CO_2 capture plants can be built with high degree of confidence

InnoSepra – TCM interface and utilities

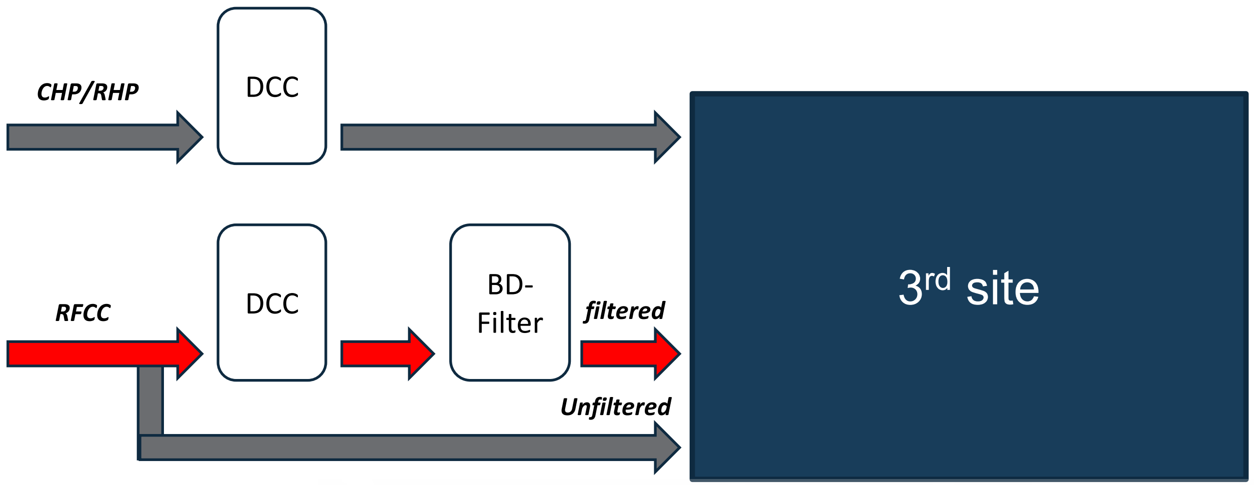
Image of TCM test bay for emerging technologies

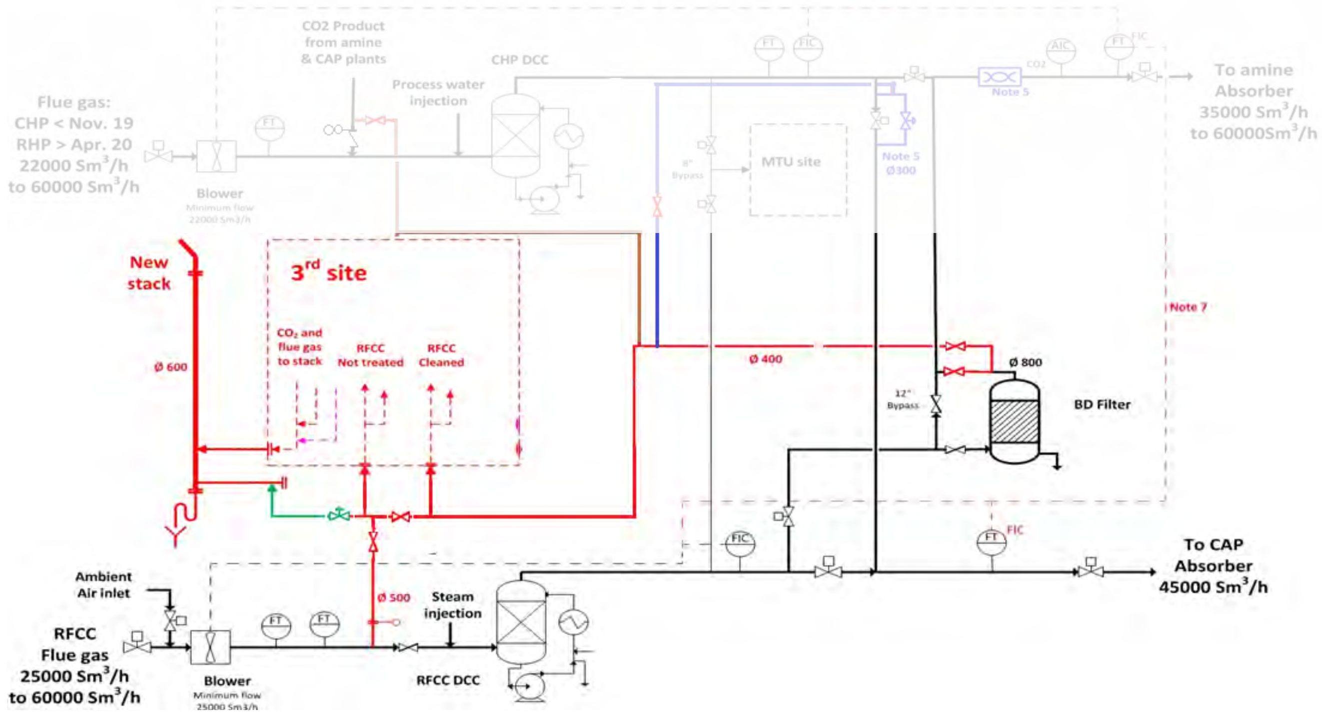
TECHNOLOGY CENTRE MONGSTAD

– *catching our future*

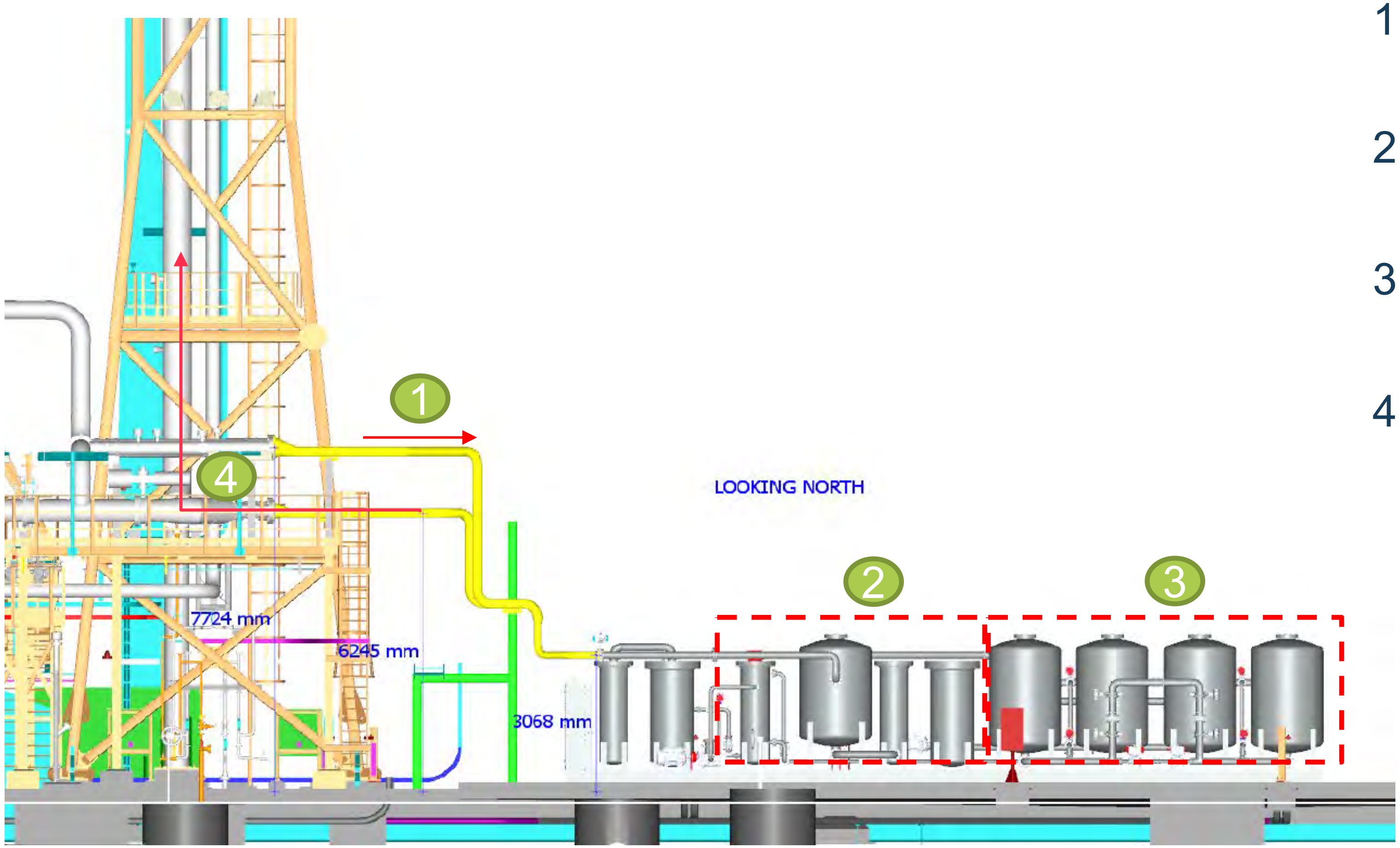
The flue gas - RFCC

Component	unit	Value
CO_2	mol%	13-14.5
SO_x	ppmv	5
NO_x	ppmv	100
Particles	mg/Sm^3	<0.5





InnoSepra - Solid Sorbent CO_2 Capture



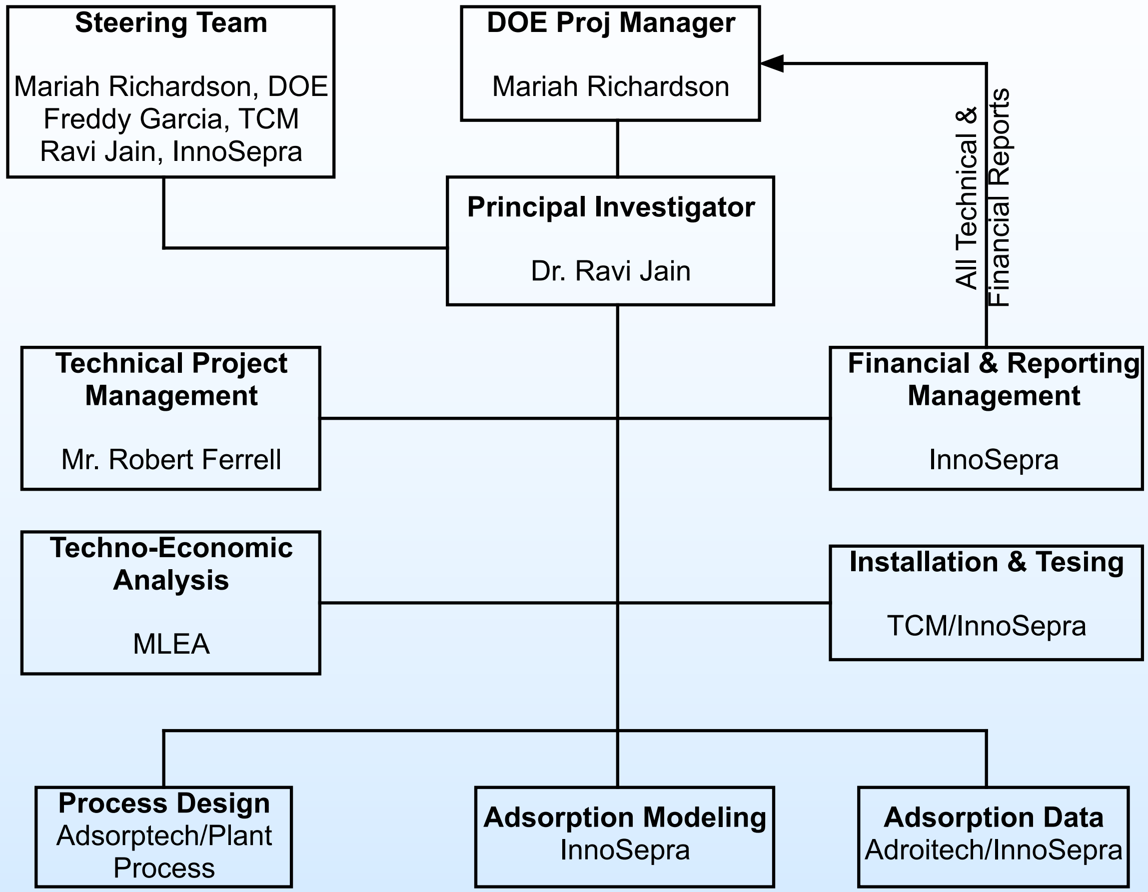
3D model of temporary linear design at TCM

1. Filtered RFCC flue gas enters the InnoSepra unit
2. Pre-treatment
   – NO_2 & SO_x removal
3. Capture
   – Drying and capture
4. Depleted flue gas and CO_2 product is combined and transported to stack

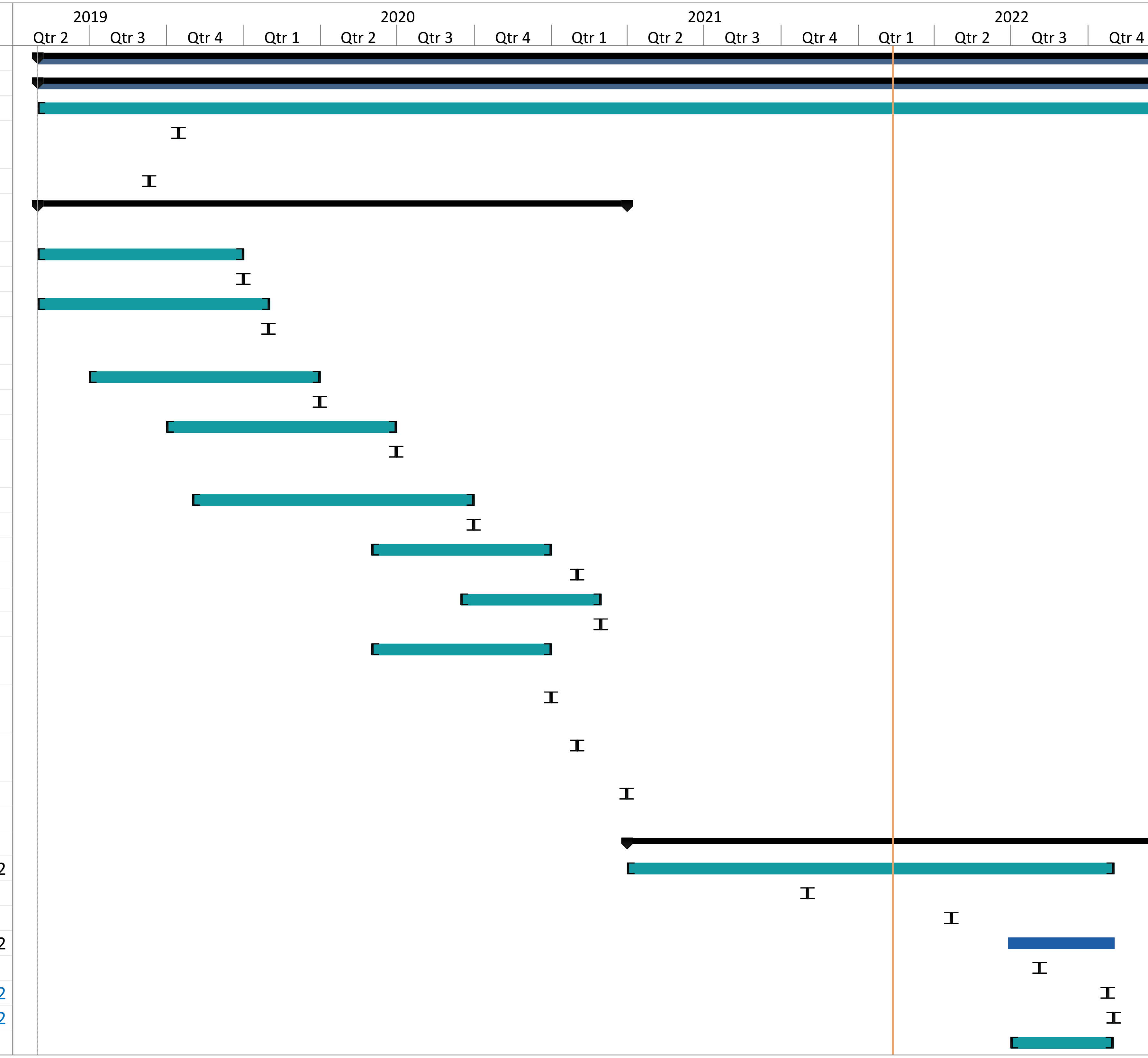
Summary

- The InnoSepra CO_2 capture technology, based on physical sorbents, has the potential for a significant reduction in the CO_2 capture cost for the power plant and industrial flue gases.
- During BP1 (based on lab testing & process simulation), InnoSepra demonstrated the potential of the technology to obtain 90-95% recovery and >98% purity CO_2 with >45% lower capture cost compared to solvent-based processes.
- During BP2, InnoSepra will demonstrate the technology at the Technology Centre Mongstad and use the test data along with process simulation and a TEA to evaluate the technology's potential for the reduction in parasitic power and capture cost.
- If the lab results are validated during field testing the InnoSepra technology would represent a viable pathway for decarbonizing power and industrial sectors with a significantly lower green premium compared to solvent-based technologies.

Project Organization Chart



ID		Task Name	Duration	Start	Finish
1		**Breakthrough CO2 Capture Technology**	**960 days**	**Wed 5/1/19**	**Sat 12/31/22**
2		**Project Management**	**960 days**	**Wed 5/1/19**	**Sat 12/31/22**
3		Project Management & Planning	960 days	Wed 5/1/19	Sat 12/31/22
4		Milestone 1: Complete Update of Project Management Plan	1 day	Tue 10/15/19	Tue 10/15/19
5		Milestone 2: Project Kickoff Meeting	1 day	**Tue 9/10/19**	**Tue 9/10/19**
6		**BP 1: Materials Selection, Lab Testing, Initial TEA, Bench Unit Design**	**502 days**	**Wed 5/1/19**	**Wed 3/31/21**
7		Develop Technology Maturation Plan	175 days	Wed 5/1/19	Tue 12/31/19
8		Milestone 3: Submit Technology Maturation P	1 day	Tue 12/31/19	Tue 12/31/19
9		Identification of Suitable Materials for Lab Tes	198 days	Wed 5/1/19	Fri 1/31/20
10		Milestone 4: Suitable materials with >6-wt% capacity	1 day	Thu 1/30/20	Thu 1/30/20
11		Construction of Lab Test Unit	197 days	Mon 7/1/19	Tue 3/31/20
12		Milestone 5: Finish construction of lab unit	1 day	Tue 3/31/20	Tue 3/31/20
13		Breakthrough & Cyclic Testing	196 days	Tue 10/1/19	Tue 6/30/20
14		Milestone 6: Sorbent downselection based on lab testing	1 day	Tue 6/30/20	Tue 6/30/20
15		Process Simulation	239 days	Fri 11/1/19	Wed 9/30/20
16		Milestone 7: Process model completion	1 day	Wed 9/30/20	Wed 9/30/20
17		Initial Techno-Economic Analysis	154 days	Mon 6/1/20	Thu 12/31/20
18		Milestone 8: Complete and present initial TEA	1 day	Sun 1/31/21	Sun 1/31/21
19		Lab Testing for Process Intensification	121 days	Tue 9/15/20	Sun 2/28/21
20		Milestone 9: Structured Sorbent Testing	1 day	Sun 2/28/21	Sun 2/28/21
21		Bench Scale Unit Process Design and Fabrication Costing	154 days	Mon 6/1/20	Thu 12/31/20
22		Milestone 10: Preliminary bench unit costing to determine size	1 day	Thu 12/31/20	Thu 12/31/20
23		Milestone 11: Detailed bench unit design including HAZOP	1 day	Sun 1/31/21	Sun 1/31/21
24		Milestone 12: TCM test site agreement	1 day	Wed 3/31/21	Wed 3/31/21
25					
26		**BP 2: Bench Unit Fabrication & Testing**	**457 days**	**Thu 4/1/21**	**Sat 12/31/22**
27		Bench Unit Fabrication, Shipping & Installatior	413 days	Thu 4/1/21	Mon 10/31/22
28		Milestone 13: Bench unit procurement schedu	1 day	Mon 11/1/21	Mon 11/1/21
29		Milestone 14: Bench unit fabrication complete	1 day	Thu 4/21/22	Thu 4/21/22
30		Bench Unit Testing	90 days	Tue 6/28/22	Mon 10/31/22
31		Milestone 15: Bench unit installation at TCM	1 day	Thu 8/4/22	Thu 8/4/22
32		Milestone 16: Bench Unit Test Report	1 day	Mon 10/24/22	Mon 10/24/22
33		Milestone 17: Bench Unit decommissioning	1 day	Mon 10/31/22	Mon 10/31/22
34		Engg Design and TEA of the Full Scale Plant	87 days	Fri 7/1/22	Sun 10/30/22



Project: Release 9.0
Date: Fri 2/11/22

Task	Project Summary	Inactive Milestone	Manual Summary Rollup	Deadline
Split	External Tasks	Inactive Summary	Manual Summary	Progress
Milestone	External Milestone	Manual Task	Start-only	
Summary	Inactive Task	Duration-only	Finish-only	

ID		Task Name	Duration	Start	Finish
35		Milestone 18: Detailed engineering of full scale plant	1 day	Mon 10/31/22	Mon 10/31/22
36		Milestone 19: Complete final TEA	1 day	Wed 11/30/22	Wed 11/30/22
37		State Point Data Table	65 days	Thu 9/1/22	Wed 11/30/22
38		Milestone 20: Complete state data point table	1 day	Wed 11/30/22	Wed 11/30/22
39		Technology Gap Analysis	65 days	Thu 9/1/22	Wed 11/30/22
40		Milestone 21: Report on Technology Gap Anal	1 day	Wed 11/30/22	Wed 11/30/22
41		EH&S Risk Assessment	65 days	Thu 9/1/22	Wed 11/30/22
42		Milestone 22: Complete EH&S risk assessment	1 day	Wed 11/30/22	Wed 11/30/22
43		Final Project Report	111 days	Mon 8/1/22	Sat 12/31/22
44		Milestone 23: Present Closeout Report Incl. Final TEA	1 day	Sat 12/31/22	Sat 12/31/22

2019: Qtr 2, Qtr 3, Qtr 4 | 2020: Qtr 1, Qtr 2, Qtr 3, Qtr 4 | 2021: Qtr 1, Qtr 2, Qtr 3, Qtr 4 | 2022: Qtr 1, Qtr 2, Qtr 3, Qtr 4

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