InnoCO2Sepra

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^oC
    - Absolute energy requirement is 40% lower than Shell Cansolv and 57% lower than MEA
    - The relative energy requirement, based on lost work analysis, is 64% lower than Shell Cansolv and 71% lower than MEA assuming 160^oC 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

About InnoSepra

- Started in 2007 by a team with 70+ years of experience in industrial gases separation and purification
  - More than 25 commercialized technologies in more than 100 plants for The BOC Group leading to a value creation of >>$100 MM, 30-2,000 tons per day scale
  - Air purification prior to cryogenic distillation, N_2 PSA, O_2 VSA, UHP nitrogen for electronics, merchant CO_2 production and purification (80-800 tpd scale), liquid and gaseous hydrogen, NO_X removal from the flue gas
- Understanding customer needs/pain points is in our DNA
  - Worked very closely with business units (at The BOC Group) to understand business needs and developed technologies to address those needs
- Since its founding InnoSepra's primary focus has been on the development of cost-effective carbon mitigation technologies
  - CO_2 capture from existing point sources (power plants and industrial)
  - Low carbon H_2 from SMRs, renewable H_2 and fuels from biogenic sources
  - Removal of legacy CO_2 from air (Direct Air Capture)
  - Renewable natural gas from waste (landfill gas, biogas from anaerobic digesters)

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. $5.07 million ($4.01 MM DOE, $1.06 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 April 2024) we
  - Constructed a field test unit (500 Nm^3/hr scale)
  - Shipped the test unit to TCM and completed commissioning
  - Will carry out process testing at TCM, do 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 Young)

InnoSepra

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

Process and Equipment Development Corp (PEDCO)

- Detailed techno-economic analysis, cost share

TCM

- Field testing, commercial feedback, and cost share

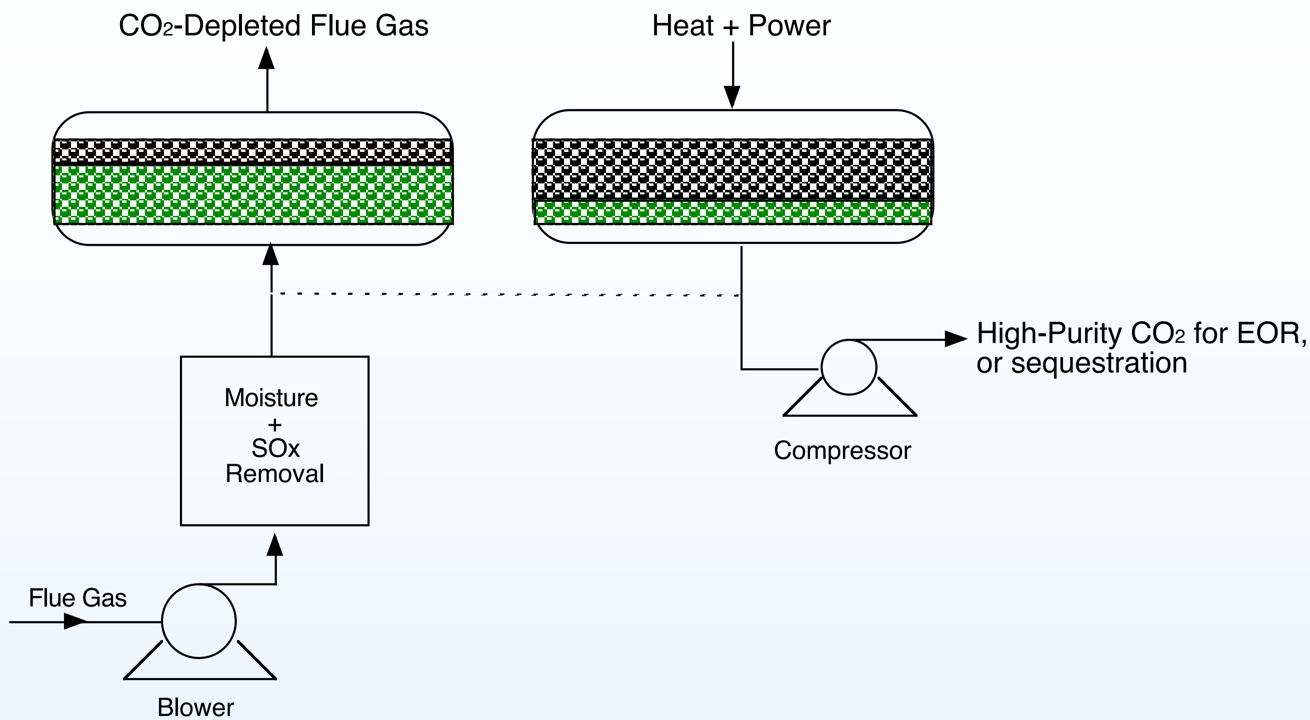
Adroitech

- Monte Carlo Simulation, fabrication of structured sorbents

Adsorptech / Fabrication Partners

- Bench unit design and fabrication, cost share

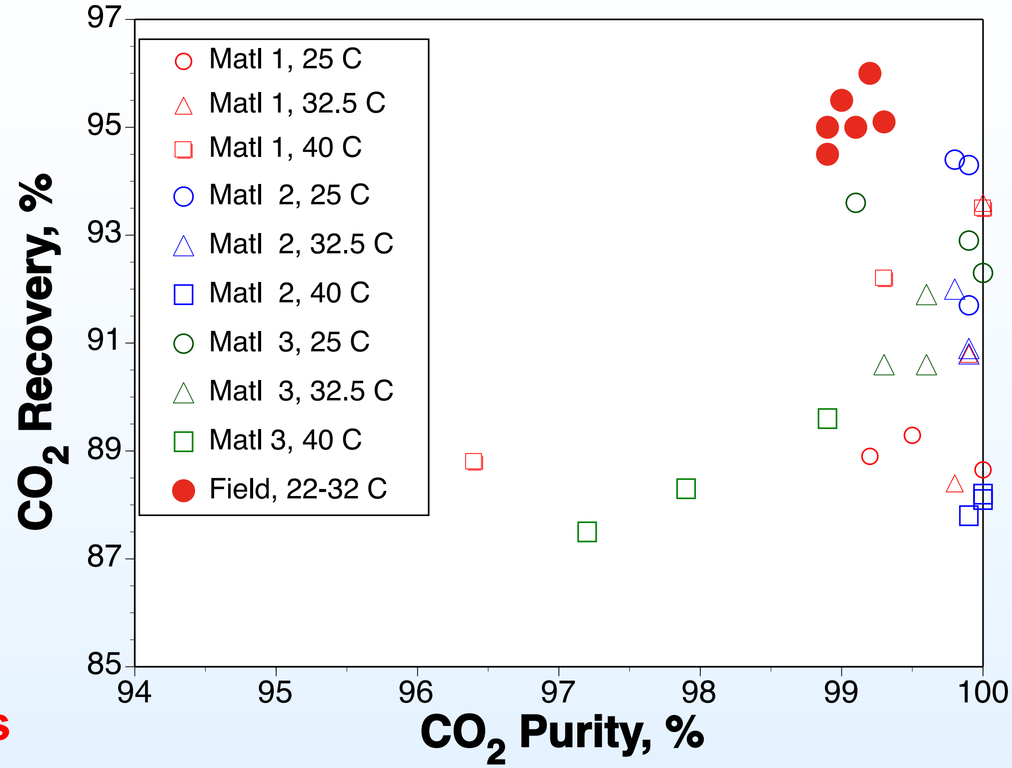
Technology Background



- **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

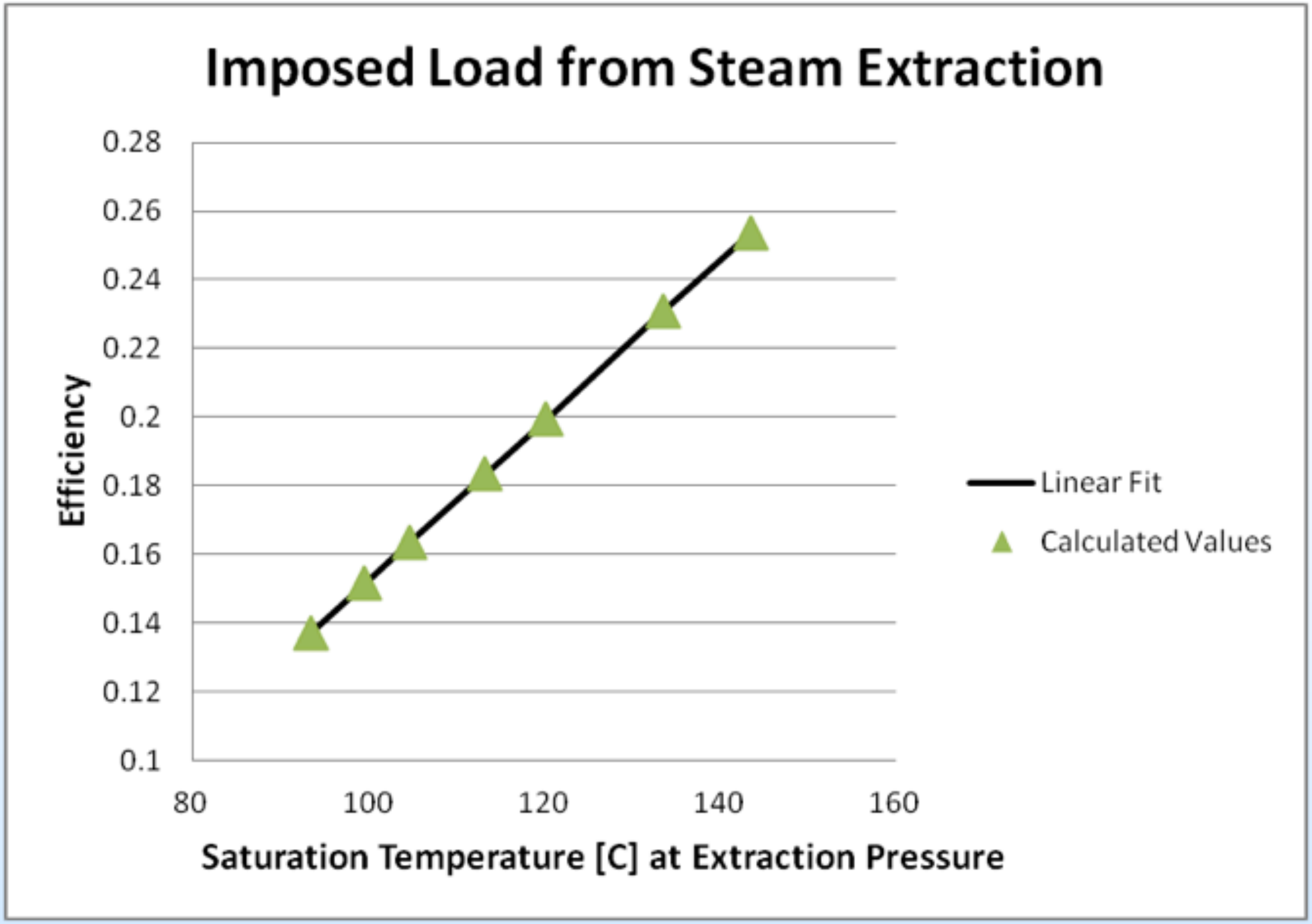
Field Demonstration of First Generation CO_2 Capture Process

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, IL power plant (500 scfm)

Impact of Steam Extraction Temperature on Power Generation Efficiency



- 40% lower efficiency for saturated steam extracted at 160^{o}C vs. 105^{o}C
- 40% lower power (work) lost due to lower extraction temperature for the same absolute amount of steam extracted

Regeneration Energy Requirements (First Generation Process)

- Estimates for the InnoSepra process based on the field tests and EPRI evaluation:
  - Heat of desorption 0.80 GJ/MT
  - **Vessel + sieve heating** 0.60 GJ/MT
  - Miscellaneous **0.70 GJ/MT**
  - **Dehydration** 0.00 GJ/MT
  - Total (excluding compression) 2.10 GJ/MT
- The absolute energy requirement is about 40% lower than MEA
- Regeneration energy is needed at about 105^{o}C compared to >160^{o}C for amines
  - About 40% lower power loss due to steam extraction for the same absolute amount of steam extracted
- Lower absolute amount of regeneration energy and lower regeneration temperature leads to 74% lower power loss vs. MEA

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 1.0 GJ/MT based on a steam extraction temperature of 160^{o}C (74 psia) for MEA and Cansolv
  - **About 64% lower than Cansolv, and about 71% 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 2023

Regeneration Energy Requirement for the Second Generation Process

- Estimates for the second generation InnoSepra process:
  - Heat of desorption 0.80 GJ/MT
  - **Vessel + sieve heating** 0.60 GJ/MT
  - Miscellaneous **0.15 GJ/MT**
  - **Dehydration** 0.00 GJ/MT
  - Total (excluding compression) 1.55 GJ/MT

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

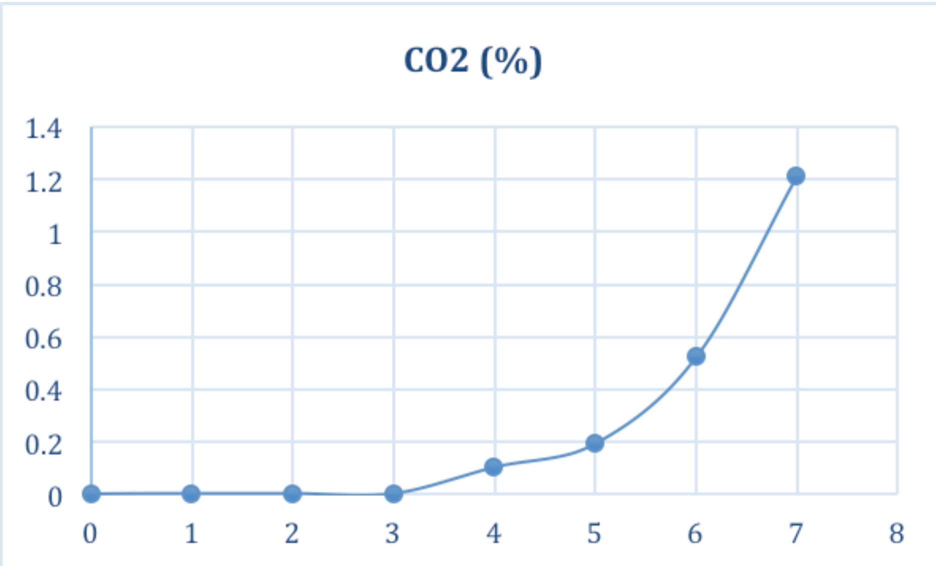
Project Risks and Mitigation Strategies

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

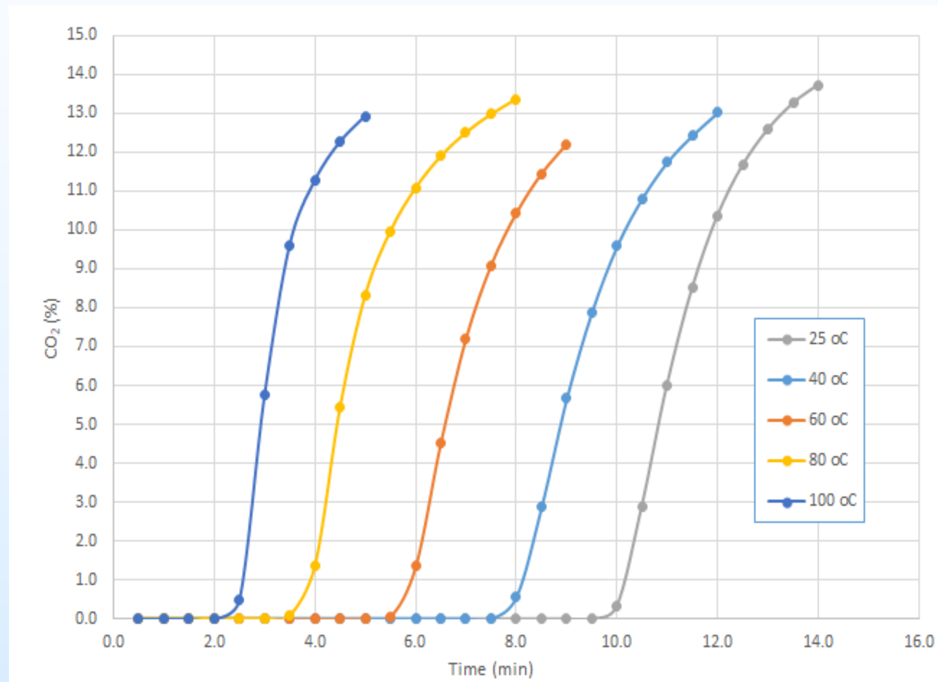
Key Activities for BP1

- Monte Carlo simulations to identify the suitable sorbents
  - **Sorbent structure variation can provide absolute CO_2 capacities (15% CO_2 at 25°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**

Breakthrough and Cyclic Testing



Typical Breakthrough Curve (25^{o}C)



Breakthrough Curves at Different Temperatures

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

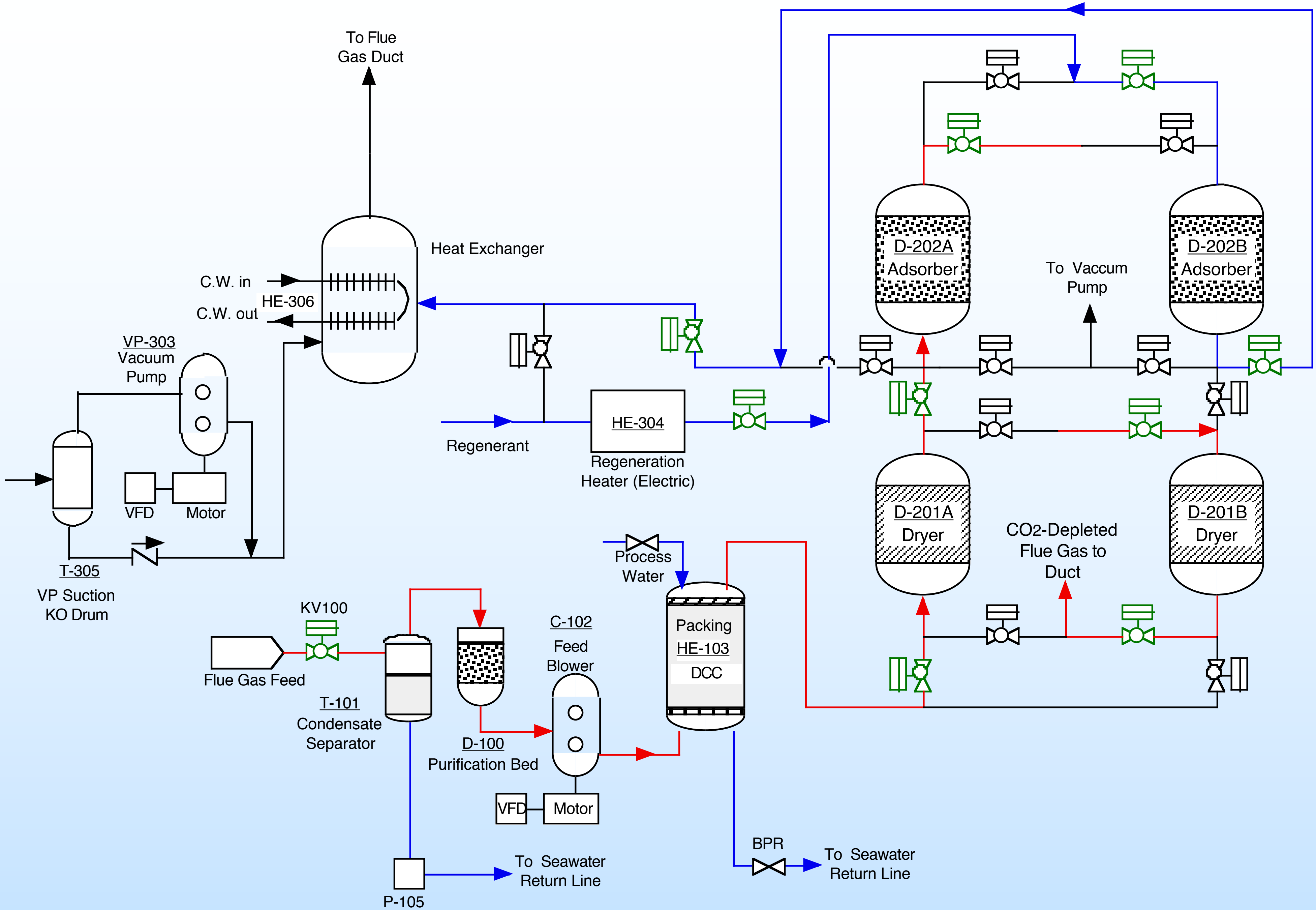
	Shell Cansolv	1st Generation InnoSepra Process	2nd Generation InnoSepra Process
Indicative TOC, U.S.$MM	891	561	482
Power Loss Due to Steam Extraction, MW	70	32	**24**
Electrical Power (compression, auxiliaries), MW	67	67	**55**
Total Power Loss, MW	137	99	**79**
Power Loss as % of Base Output	25	18	**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
  - Designed as three separate skids
  - 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
  - All the skids completed and initial testing done at the fabrication site
  - All the skids shipped to TCM
  - The skids have been installed and the commissioning is underway

Process Flow Diagram for the Bench Unit



Bench Unit Design

- The bench unit was designed as three separate skids
- Skid 1 consists of the following
  - Feed purification: Removal of condensate as well as NO_2, SO_X, and aerosols
  - Feed compression and cooling
  - Feed drying
- Skid 2 consists of the following
  - Four adsorption beds for CO_2 separation from the flue gas
  - The process cycle consists of: adsorption, regeneration, cooling and repressurization
  - The four bed cycle allows continuous operation
- Skid 3 consists of the following
  - Vacuum pump for evacuation
  - Heating of regeneration medium
  - Cooling of CO_2 product

Photo of Skid 1 Prior to Shipment

Photo of Skid 2 Prior to Shipment

Photo of Skid 3 Prior to Shipment

InnoSepra Test Unit at TCM

InnoSepra Test Unit at TCM

Test Plan

- A series of parametric tests are planned
  - CO_2 concentration: 4-12%
  - Flue gas flow rate: 300-500 nm^3/hr
  - Dryer bed half cycle: 12-20 minutes
  - CO_2 adsorption time: 6-10 minutes
  - A total of over 20 tests at different process conditions
- A continuous test for about 200 hours is also planned

Remaining Project Tasks

- Updated detailed engineering design, capital and operating cost estimates
  - An engineering design for a 300 tpd capture unit using this technology was done for a customer and will form the basis for the updated design
- State Point Data Table
- Technology Gap Analysis
- EH&S Risk Assessment
- Final Technical Report

Plan for Future Testing / Commercialization

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

Steps towards 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 current 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

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.