

Transformational Sorbent-Based Process for Direct Air Capture

primary project goal

InnoSeptra LLC is advancing an adsorption-based direct air capture (DAC) process. The overall goals of the project are to generate data to confirm that the process can provide significant cost and parasitic power savings compared to state-of-the-art DAC processes and to utilize process models to produce a conceptual design of a large-scale DAC system.

In Phase I, the technical and economic feasibility of the technology was demonstrated through laboratory testing, process modeling, and a preliminary techno-economic analysis (TEA). The Phase II objectives are to scale-up and test optimized materials (developed in a separate DOE-funded project) in structured form for CO₂ removal and moisture removal using semi-bench units in the laboratory; design, construct, and test a bench-scale unit at the National Carbon Capture Center (NCCC); and update the process model, process simulation, and TEA to predict performance and cost of commercial-scale systems.

technical goals

- Construction of semi-bench and bench-scale units capable of dehumidifying 10–250 standard cubic feet per minute (scfm) of air.
- Construction of semi-bench and bench-scale units capable of carbon dioxide (CO₂) capture tests for the CO₂ adsorption part of the process.
- Process data collection for the feed dehumidification and the CO₂ capture parts of the process.
- Installation and testing at NCCC, validating the process simulation model for the proposed process.
- Estimation of capital cost (CAPEX), operating cost (OPEX), and CO₂ capture cost for approximately 250-tonne-per-day (tpd) CO₂ capture from air.

technical content

The Phase I project was based on utilizing physical sorbents in particulate form for capturing CO₂ from the air and further upgrading it to purities needed for pipeline transport. In contrast to amine-based systems, the heats of adsorption of CO₂ on physical sorbents range between 30–40 kJ/mole of CO₂—about a fifth of the total energy needed for amine-based absorption systems. Even after adding the heat needed for vessel and sieve heating, and the sensible heat for heating CO₂, the total energy required is significantly lower than that for amine-based solvents and reactive sorbents. This can lead to significantly lower parasitic power consumption. InnoSeptra discusses the use of physical sorbents for CO₂ capture from power plants. The sorbents used in the InnoSeptra process have a much higher surface-to-volume ratio (greater than 1x10⁶ m²/m³) compared to structured packings used in absorption processes (less than 1,000 m²/m³) and membranes (250–5,000 m²/m³ for plate-and-frame, spiral-wound, and hollow fiber modules, respectively), which allows a five-foot tall adsorption bed to provide the same or better separation of CO₂ as a 200-foot tall absorption column.

program area:

Carbon Dioxide Removal

ending scale:

Bench Scale

application:

Direct Air Capture

key technology:

Sorbents

project focus:

Physical Sorbent-Based Process for DAC

participant:

InnoSeptra LLC

project number:

SC0020740

predecessor projects:

N/A

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N/A

start date:

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percent complete:

40%

In the InnoSeptra process, the CO₂ in ambient air, about 400 parts per million (ppm), is concentrated to a stream containing greater than 95% CO₂, which can be transported through a CO₂ pipeline for storage or enhanced oil recovery (EOR). DAC plants can be standalone plants or they can be part of CO₂ capture at a power plant and utilize the power from the plant for capture. This can be particularly advantageous during times when the power demand from the fossil-fuel-based power plant is low and the power prices are very low or even negative during high renewables penetration.

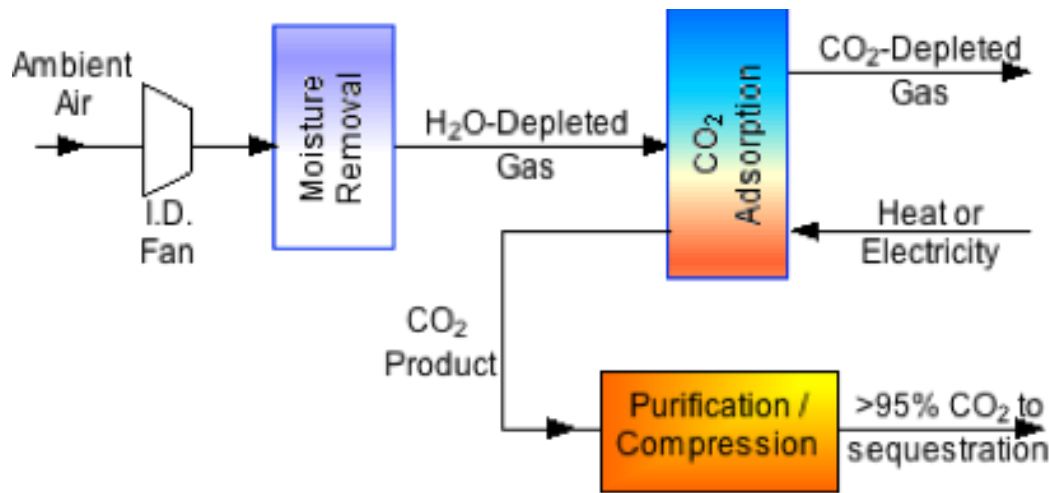


Figure 1. Process schematic for the InnoSeptra process.

The process schematic in Figure 1 shows the proposed process for DAC. The pressure of ambient air is raised by 0.1–0.2 pounds per square inch (psi) in an induced draft (ID) fan and the compressed air is sent to a rotating bed moisture adsorption unit for removing moisture and a CO₂ adsorption unit in sequence. Because of the very large gas volumes involved with DAC, the system pressure drop for CO₂ capture needs to be minimized and structured sorbents are used in both stages for this to be accomplished. The pressure drop in each of these stages is expected to be less than 0.05 psi. Depending on the fabrication method, the costs of the structured sorbents are not significantly higher than the cost of particulate sorbents.

The purpose of the moisture adsorption system is to reduce the relative humidity of the feed gas to below 1% to minimize the moisture adsorption on the CO₂ sorbent. The rotating bed configuration for moisture removal is shown in Figure 2. The entire structure is housed inside a duct. The typical wheel depth is eight to 16 inches. Short bed height coupled with a large open area, greater than 75%, leads to a very low pressure drop. One rotation of the wheel takes six to 12 minutes, during which time the entire wheel undergoes adsorption (in the adsorption zone) and regeneration (in the regeneration zone). A rotating seal is used to separate the adsorption and regeneration zones. The wheel areas used for adsorption and desorption steps are nearly equal. For this dehumidification process, the adsorbent volumes needed are reduced by a factor of more than 10 compared to the particulate sorbents. Flue gas dehumidification using rotating wheel adsorbents provides very significant process intensification and is very important for DAC.

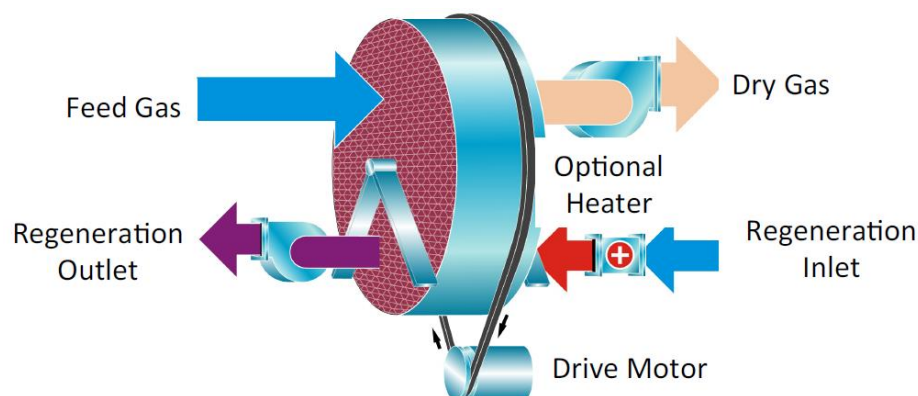


Figure 2. Rotating wheel dryer for feed dehumidification.

The moisture-depleted gas is sent to a CO₂ adsorber containing a sorbent that has a high CO₂ capacity at low CO₂ partial pressures. These sorbents can be thermally regenerated to produce a first CO₂ product stream that can be further purified and compressed to produce a CO₂ stream suitable for pipeline transport (Figure 1). The process operates continuously and does not require any switching valves, unlike the fixed bed adsorption processes.

The CO₂ adsorber is a rotating bed (similar to that in Figure 2) or a parallel passage contactor. Again, the pressure drop in this step is less than 0.03 psi. The regeneration of CO₂ sorbents is done at 100–110°C and typically requires low pressure steam. Where possible, the steam for regeneration is generated by solar heating and is stored during non-daylight hours. The dry, CO₂-product stream is further concentrated to a purity (greater than 95% CO₂) suitable for pipeline transport in another stage. If the DAC system is sited at a power plant, synergies between post-combustion capture and DAC can be utilized to significantly reduce the cost of CO₂ capture using DAC. The power plant can be utilized to provide steam and electrical power needed for capture.

The second key element of the proposed system is the adsorption of CO₂ on structured sorbents with very high capacities at low CO₂ partial pressures. Whereas typical physical sorbents have CO₂ capacities below 1 wt% for typical CO₂ concentrations in air, the InnoSeptra materials have a CO₂ capacity of more than 4.0 wt% for 400-ppm CO₂ in air. These materials also have low heats of adsorption (less than 42 kJ/mol of CO₂). These high CO₂ capacities and low heats of adsorption significantly reduce the regeneration energy needed for DAC. The regeneration energy requirement for this system is significantly lower compared to other DAC technologies. The use of structured sorbents for moisture removal and CO₂ capture allows the equipment to be shop-fabricated and field-assembled, significantly reducing fabrication and transportation costs.

The third key element of the proposed system is the regeneration of the CO₂-containing sorbent to produce a pipeline-quality CO₂ product in two stages. The final CO₂ product is compressed to a pressure of approximately 2,200 pounds per square inch gauge (psig) for pipeline transport. A cooling water stream is heated to 50–70°C in the CO₂ compressor train, utilizing the CO₂ heat of compression, and provides some of the process heating needs. The estimated energy required for the CO₂ capture for an air feed containing 400-ppm CO₂ is given in Table 1. This assumes feed compression to 0.1 psig, a heat of adsorption of 42 kJ/mol of CO₂, and a net adsorption capacity of 3.5 wt%. The energy consumption to capture CO₂ at a pressure of 1 bara is approximately 550 kJ/mol of CO₂ (4.6 GJ/tonne). This number is significantly lower than the 1,000 kJ/mol of CO₂ (less than 8.5 kJ/mol) needed for amine-based sorbents for DAC.

TABLE 1: ENERGY REQUIRED FOR CO₂ AND MOISTURE REMOVAL SECTIONS

Heat of Desorption	1.0 GJ/tonne of CO ₂
Sensible Heat for CO ₂	0.1 GJ/tonne of CO ₂
Sensible Heat for the Sorbent	3.0 GJ/tonne of CO ₂
Dehydration Energy	0.1 GJ/tonne of CO ₂
Mechanical Energy	0.4 GJ/tonne of CO ₂
TOTAL	4.6 GJ/tonne of CO₂

TABLE 2: DAC SORBENT PROCESS PARAMETERS

Sorbent	Units	Current R&D Value	Target R&D Value
True Density @ STP	kg/m ³	1,600	1,600
Bulk Density	kg/m ³	690	690
Average Particle Diameter	mm	<0.1	<0.01
Particle Void Fraction	m ³ /m ³	0.45	0.45
Packing Density	m ² /m ³	1e+8	1e+8
Solid Heat Capacity @ STP	kJ/kg-K	1.00	1.00
Crush Strength	kg _f	>10	>10
Attrition Index	-	<0.01%	<0.01%
Thermal Conductivity	W/(m-K)	—	—
Manufacturing Cost for Sorbent	\$/kg	15	10
Adsorption			
Pressure	bar	1.01	1.005
Temperature	°C	25-35	25-35
Equilibrium Loading	g mol CO ₂ /kg	0.9	1.2
Heat of Adsorption	kJ/mol CO ₂	44	44
CO ₂ Adsorption Kinetics	gmol/time	0.2	0.5
Desorption			
Pressure	bar	0.2-1.0	0.2-1.0
Temperature	°C	100-150	90-105
Equilibrium CO ₂ Loading	g mol CO ₂ /kg	0.2	0.1
Heat of Desorption	kJ/mol CO ₂	44	44
CO ₂ Desorption Kinetics	gmol/time	0.4	0.6
Proposed Module Design		<i>(for equipment developers)</i>	
Flow Arrangement/Operation	—	—	—
Flue Gas Flowrate	kg/hr	—	—
Space Velocity	hr ⁻¹	—	—
Volumetric Productivity	gmolCO ₂ /(hr lab sorber bed)	—	—
CO ₂ Recovery, Purity, and Pressure	% / % / bar	—	—
Adsorber Pressure Drop	bar	—	—
Degradation	% capacity fade/cycle	—	—
Estimated Adsorber/Stripper Cost of Manufacturing and Installation	$\frac{\$}{\text{kg/hr}}$	—	—

Definitions:

STP – Standard Temperature and Pressure (15°C, 1 atm).

Sorbent – Adsorbate-free (i.e., CO₂-free) and dry material as used in adsorption/desorption cycle.

Manufacturing Cost for Sorbent – “Current” is the market price of material, if applicable; “Target” is the estimated manufacturing cost for new materials, or the estimated cost of bulk manufacturing for existing materials.

Adsorption – The conditions of interest for adsorption are those that prevail at maximum sorbent loading. Measured data are preferable to estimated data.

Desorption – The conditions of interest for desorption are those that prevail at minimum sorbent loading. Operating pressure and temperature for the desorber/stripper are process-dependent. Measured data are preferable to estimated data.

Pressure – The pressure of CO₂ in equilibrium with the sorbent. If the vapor phase is pure CO₂, this is the total pressure; if it is a mixture of gases, this is the partial pressure of CO₂.

Packing Density – Ratio of the active sorbent area to the bulk sorbent volume.

Loading – The basis for CO₂ loadings is mass of dry, adsorbate-free sorbent.

Kinetics – A characterization of the CO₂ adsorption/desorption trend with respect to time, as complete in the range of time as possible.

Flow Arrangement/Operation – Gas-solid module designs include fixed, fluidized, and moving bed, which result in either continuous, cyclic, or semi-regenerative operation.

Estimated Cost – Basis is kg/hr of CO₂ in CO₂-rich product gas; assuming targets are met.

Atmospheric Air Feed-Gas Assumptions – Update values below to describe the air feed-gas pressure, temperature, and composition entering the capture system:

Pressure	Composition						SO _x	NO _x
	CO ₂	H ₂ O	vol% N ₂	O ₂	Ar		ppmv trace	trace
14.7 psia	0.04	variable	78.09	20.95	0.93			

Other Parameter Descriptions:

Chemical/Physical Sorbent Mechanism – Physical.

Sorbent Contaminant Resistance – No impact of oxygen and moisture in feed air, acid gas impurities are not relevant to DAC.

Sorbent Attrition and Thermal/Hydrothermal Stability – Very stable.

Flue Gas Pretreatment Requirements – N/A.

Sorbent Make-Up Requirements – At least five-year life before any make-up is needed.

Waste Streams Generated – N/A.

Proposed Module Design – N/A.

TABLE 3: DIRECT AIR CAPTURE ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Carbon Captured	\$/tonne CO ₂	175-200	150-175
Cost of Carbon Avoided	\$/tonne CO ₂	—	—
Capital Expenditures	\$/tonne CO ₂	100-115	80-100
Operating Expenditures	\$/tonne CO ₂	75-85	70-75

Definitions:

Cost of Carbon Captured – Projected cost of capture per mass of CO₂ captured under expected operating conditions.

Cost of Carbon Avoided – Projected cost of capture per mass of CO₂ avoided under expected operating conditions.

Capital Expenditures – Projected capital expenditures in dollars per tonne of CO₂ captured.

Operating Expenditures – Projected operating expenditures in dollars per tonne of CO₂ captured.

Calculations Basis – No U.S. Department of Energy (DOE) reference case for DAC.

Scale of Validation of Technology Used in TEA – Lab-scale.

Qualifying Information or Assumptions – N/A.

technology advantages

- Very low pressure drops (typically one-fifth to one-tenth used for particulate sorbents for the same flow rate).
- Not subject to fluidization constraints or attrition issues.
- Very small effective particle size (less than 80 μm), leading to very short mass transfer zones.
- Can process significantly higher flows for a given bed volume.
- The materials are low cost and can be produced in very large quantities fairly quickly.
- Can be fabricated with virtually any sorbent.
- Equipment is commercially available up to 10 feet in diameter.

R&D challenges

- Identifying pathways for materials fabrication at large scale and further process scale-up.

status

InnoSeptra LLC is currently working on the design, engineering, and manufacturing of the 250-tpd DAC system. Model development for the DAC system and process simulation are also going on concurrently. Work has been initiated on a bench-scale system for testing at NCCC.

available reports/technical papers/presentations

Ravi Jain, Norberto Lemcoff, “Transformational Sorbent-Based Process for Direct Air Capture,” Project kickoff meeting presentation, Pittsburgh, PA, October 2021. <https://www.netl.doe.gov/projects/plp-download.aspx?id=12451&filename=Transformational+Sorbent-Based+Process+for+Direct+Air+Capture.pdf>.