

A Complete Solution for Upgrading Biogas to Renewable Natural Gas



Taking Sulfur Out of the Equation



Danny Shade, Ph.D.;
Gökhan Alptekin, Ph.D.

3/25/26

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SulfaTrap™-R2GX

Removal of halides, HCN and sulfur polishing

SulfaTrap

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A Complete Solution for Upgrading Biogas to Renewable Natural Gas

Wednesday | March 25
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SulfaTrap Introduction

SulfaTrap™ provides customized purification solutions for treatment of natural gas, biogas, CO₂, LPG and a wide range of gaseous and liquid hydrocarbon feedstocks

- Sorbents (Gas purification and bulk separation)
- Sulfur Sensors/End-of-life Indicators (SulfaTrack™, SulfaSense™)
- Catalysts (COS hydrolysis, NO oxidation, VOC oxidation)

BIOGAS SOLUTIONS



MATERIAL SUPPLY

- Biogas purification, CO₂ purification



TURN-KEY SOLUTIONS

- Full-service engineering, design, and construction
- Modular fabrication
- Field services
- Material and process support

Today's Speakers



Gökhan Alptekin, Ph.D.
SulfaTrap Founder, Managing
Director

- Founder & Managing Director of SulfaTrap
- President of TDA Research, SulfaTrap's parent company
- Managed over \$120 million of R&D efforts for development of new materials and processes for purification and separation applications



Danny Shade, Ph.D.
Senior Chemical Engineer

- B.S. & Ph.D. at Johns Hopkins & Georgia Tech
 - Ph.D. thesis in gas separations by adsorption
- Reaction engineer at Dow Chemical (Houston)
- Chemical engineer at TDA Research
 - Gas separations: NG upgrading, O₂ or N₂ from air, CO₂ removal, etc.

Why Gas Cleanup & Upgrading Matter

Raw Biogas

- Corrosive
- Low quality/ heating value (500–700 BTU/ft³)
- **Not salable**
- **Not transportable via pipeline**
- On-site electricity generation & heating
- Combined Heat & Power
- Equipment modifications:
 - Filtration
 - Acid-neutralizing lubricant
 - Tuned ignition/fuel mixing for variable gas quality

Renewable Natural Gas (RNG)

- High quality (>970 BTU/ft³)
- Salable - \$3.76–3.80/ MMBtu in 2026 per EIA forecast
- Transportable via pipeline
- No special equipment needed at point of use
- Main uses:
 - Grid injection
 - Vehicle fuel
 - Turbines
 - Fuel cells (may need more cleanup)
- Much higher value product (potential further value-add if qualified for subsidies)

Biogas & RNG Contents

Contaminants & Limits

- Acid gases: CO₂, H₂S
 - Highest concentration contaminant by far is CO₂
 - H₂S is toxic, highly corrosive and its emissions are highly restricted
- Permanent gases: O₂, N₂
 - Diluents
 - O₂ is restricted in pipelines
- Trace contaminants
 - Organic sulfur compounds
 - Siloxanes
 - Ammonia
 - Volatile organic compounds (VOCs)
- *Northern Natural Gas spec
https://www.northernnaturalgas.com/Document%20Postings/Biomethane_Gas_Guidelines.pdf

Component	Landfill Gas	Digester Gas	NG Pipeline Spec*
Methane	45-60%	50-75%	-
Carbon dioxide	40-60%	20-50%	<2%
Oxygen	0-2%	0-1%	<0.2%
Nitrogen	0-15%	0-1%	N ₂ + O ₂ + CO ₂ <4%
Water	Saturated	Saturated	<6 lb/MMscf
Hydrogen	0-1%	0-1%	<0.1%
Hydrogen sulfide	0-100 ppmv	0-30,000 ppmv	<0.25 grains/100 scf (~4 ppmv)
Total sulfur	0-20,000 ppmv	0-20,000 ppmv	<20 grains/100 scf (~340 ppmv)
Siloxanes	0.1-50+ mg Si/m ³	0.1-50+ mg Si/m ³	<0.5 mg Si/m ³
Heating value	-	-	>950 BTU/scf

Typical Cleanup & Upgrading Process

Bulk H₂S Removal

- Prevent corrosion
- Adsorption (iron oxide, carbon)
- Scrubbing (caustic soda)

Water KO & Drying

- Prevent freezing/corrosion
- Compression & cooling
- Silica gel/ mol sieve
- Absorption (glycol)

Siloxane & VOC Removal

- Avoid forming abrasive SiO₂ & organic deposits
- Adsorption (carbon, alumina)

Metal & Halogen Removal

- Hg, HCl, HF, halocarbons
- Hg incompatible with aluminum & alloys
- Adsorption (carbon, sulfurized carbon)

N₂/O₂ (Polishing)

- Increase heating value (N₂)
- Safety, corrosion (O₂)
- Pressure Swing Adsorption
- Membrane or cryogenic

CO₂ Removal (Upgrading)

- CO₂ up to 50% by volume!
- Increase heating value
- Physical absorption (water, Selexol) or adsorption (carbon, zeolite)

Opportunities for Combined Purifications

Combined Scrubbing

- Remove H₂S and CO₂ (and NH₃) together using water scrub
 - Or MEA, Selexol, etc.
- Introduces water to the gas that must be removed later
- H₂S must be removed from CO₂ product before use of CO₂
- 40% market share for CO₂ removal (but shrinking)

Activated Carbon PSA

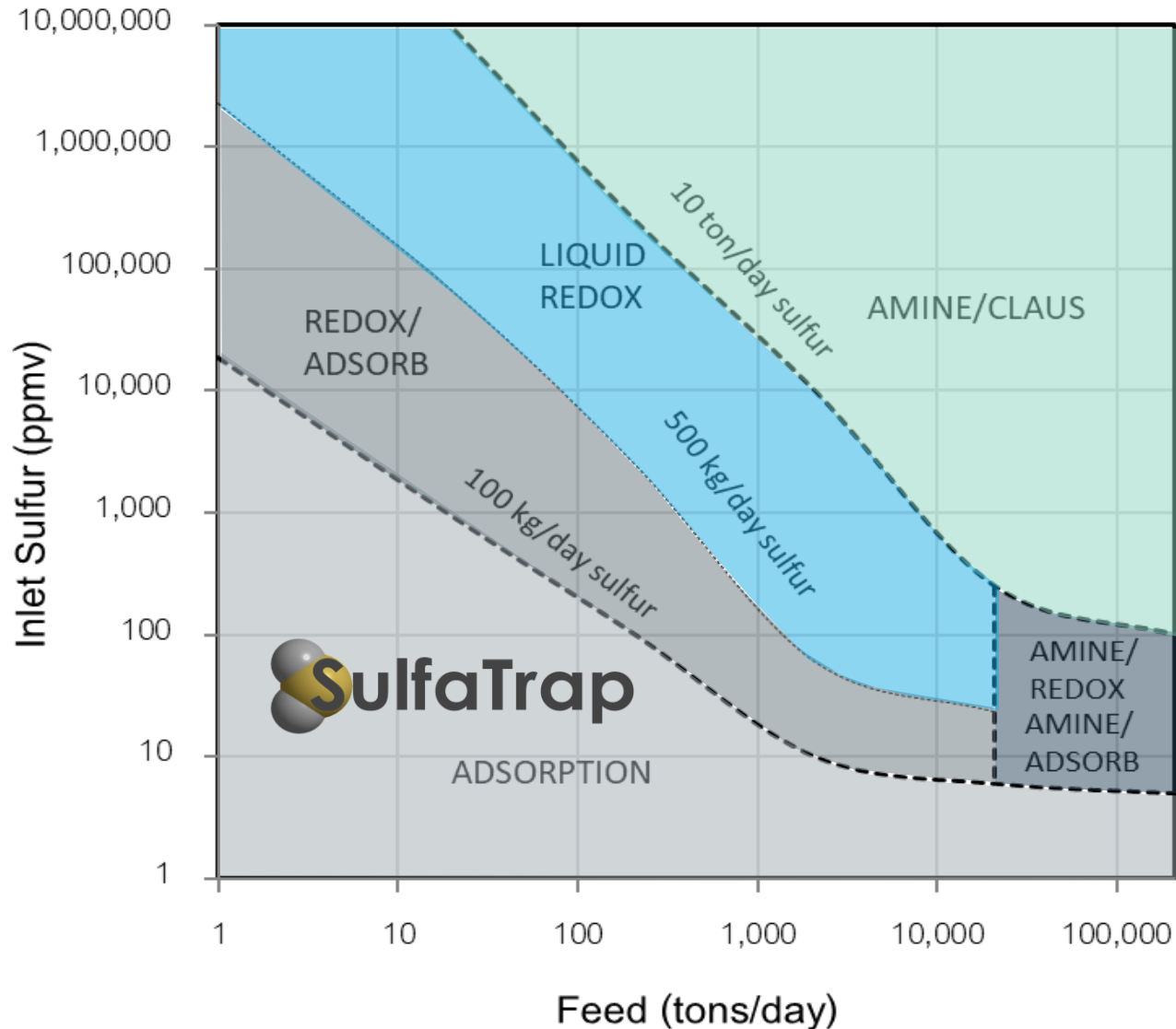
- Pressure Swing Adsorption (PSA) removes H₂S, VOCs, and moisture



Cryogenic Distillation

- Economics favored only at large scale
- Remove CO₂, N₂, and O₂ after pretreatments remove other contaminants

H₂S Removal



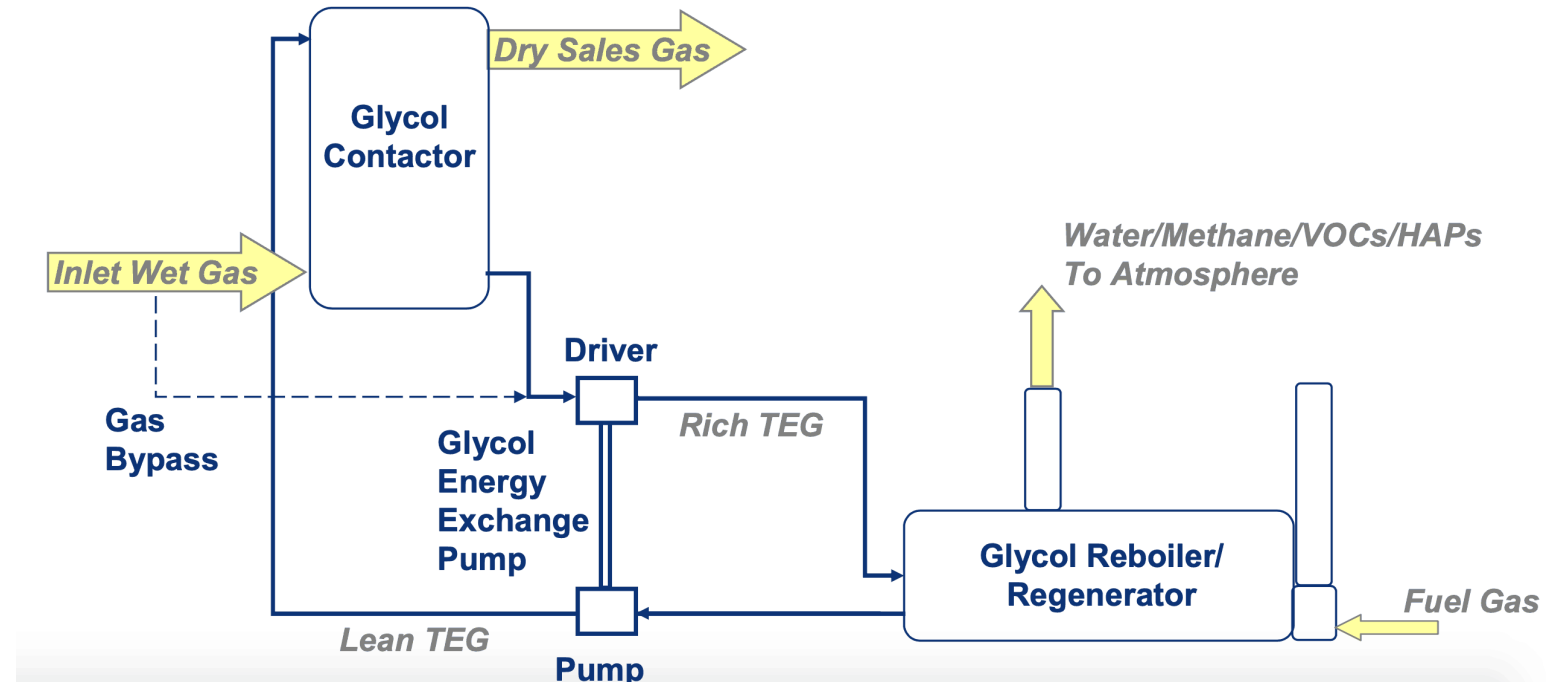
H₂S Removal Options

- Concentration & flow rate determine best technology fit
- Absorbent (liquid) or adsorbent (solid) materials
 - Amine scrubbing
 - Iron sponge
 - Activated carbon (requires O₂ presence)
 - Other metal oxides
- Pipeline spec: <0.25 grains/ 100 scf (~4 ppmv)
- Cost: \$0.05–0.35/ MMBtu

Moisture Removal

Dehydration Overview

- Raw biogas is saturated with water
- 80 °F = 3.5% water
- Remove to protect compressors, sorbents, prevent condensation
- Common approaches
 - Glycol dehydration
 - Cooling & condensation
 - Refrigeration dryer
- Pipeline spec: <6 lb/MMscf
- Cost: \$0.3–0.8/ MMBtu

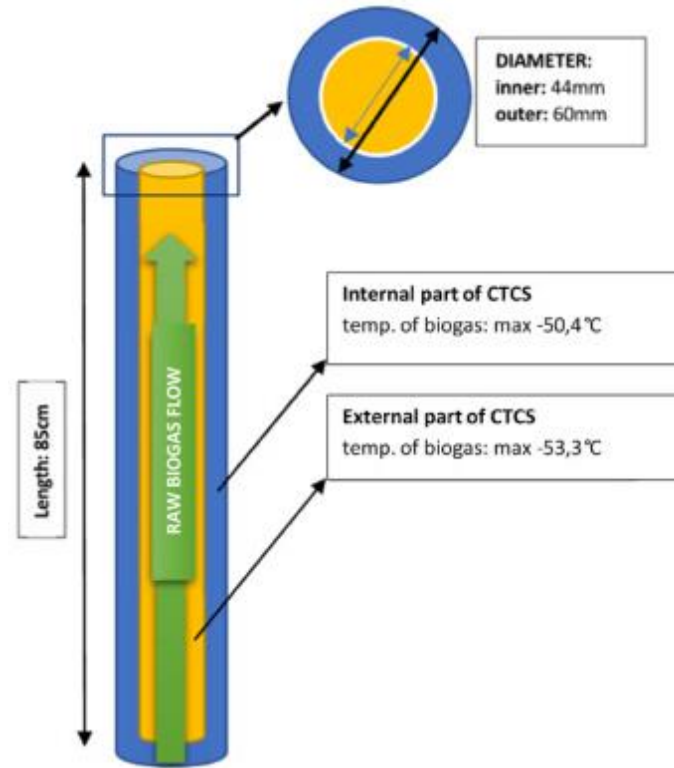


Tetraethylene glycol (TEG) dehydrator process diagram from Van Air Systems.
<https://www.vanairsystems.com/eliminate-teg-emissions-with-van-air-systems-gas-plds/>

Siloxane & VOC Removal

Why Remove?

- Combusting siloxanes (R_2SiO) creates SiO_2 deposits
- VOCs cause corrosion & clogging
- Remove via activated carbon adsorption, cooling, or combination
- Pipeline spec: $<0.5 \text{ mg Si/m}^3$
 - Fuel cells may require $<1 \text{ ppm VOCs}$ to prevent damage from trace sulfur & chlorine
- Cost: $\$0.3\text{--}1.3/ \text{ MMBtu}$



Cryogenic temperature condensation system (CTCS) column. (1)

Category	Typical Concentration in Landfill Gas
BTEX	50-500 ppmv (2)
Halocarbons	100-400 ppmv (3)
Siloxanes	0.1–50 mg Si/m ³ (4)
Alkanes C ₂₊	up to 1,500 ppmv (3)
NMOC*	0.1-0.6% (3)

*NMOC = non-methane organic carbon

¹Piechota, G. (2021). Removal of siloxanes from biogas upgraded to biomethane by Cryogenic Temperature Condensation System. *Journal of Cleaner Production*, 308, 127404. <https://doi.org/10.1016/j.jclepro.2021.127404>

²Cabral, A. R., Moreira, J. F. V., & Jugnia, L. B. (2014). Evaluation of the efficiency of an experimental biocover to reduce BTEX emissions from landfill biogas. *Chemosphere*, 95. <https://doi.org/10.1016/j.chemosphere.2013.XX.XXX>

³Environmental Protection Agency. (1998, November). *AP-42: Compilation of air pollutant emissions factors: Vol. 1. Stationary point and area sources* (5th ed). https://gaftp.epa.gov/ap42/ch02/s04/final/c02s04_aug1998.pdf

⁴Kong, Q., He, J., Chen, H., Zhou, D., Yu, C., Zhang, Z., Yao, J., & Shen, D. (2024). Dynamic release of siloxanes in the form of biogas from simulated municipal-solid-waste landfill and the corresponding driving mechanism. *Waste Management*, 184, 101–108. <https://doi.org/10.1016/j.wasman.2024.05.038>

Metal & Halogen Removal

Metal & Halogen Removal

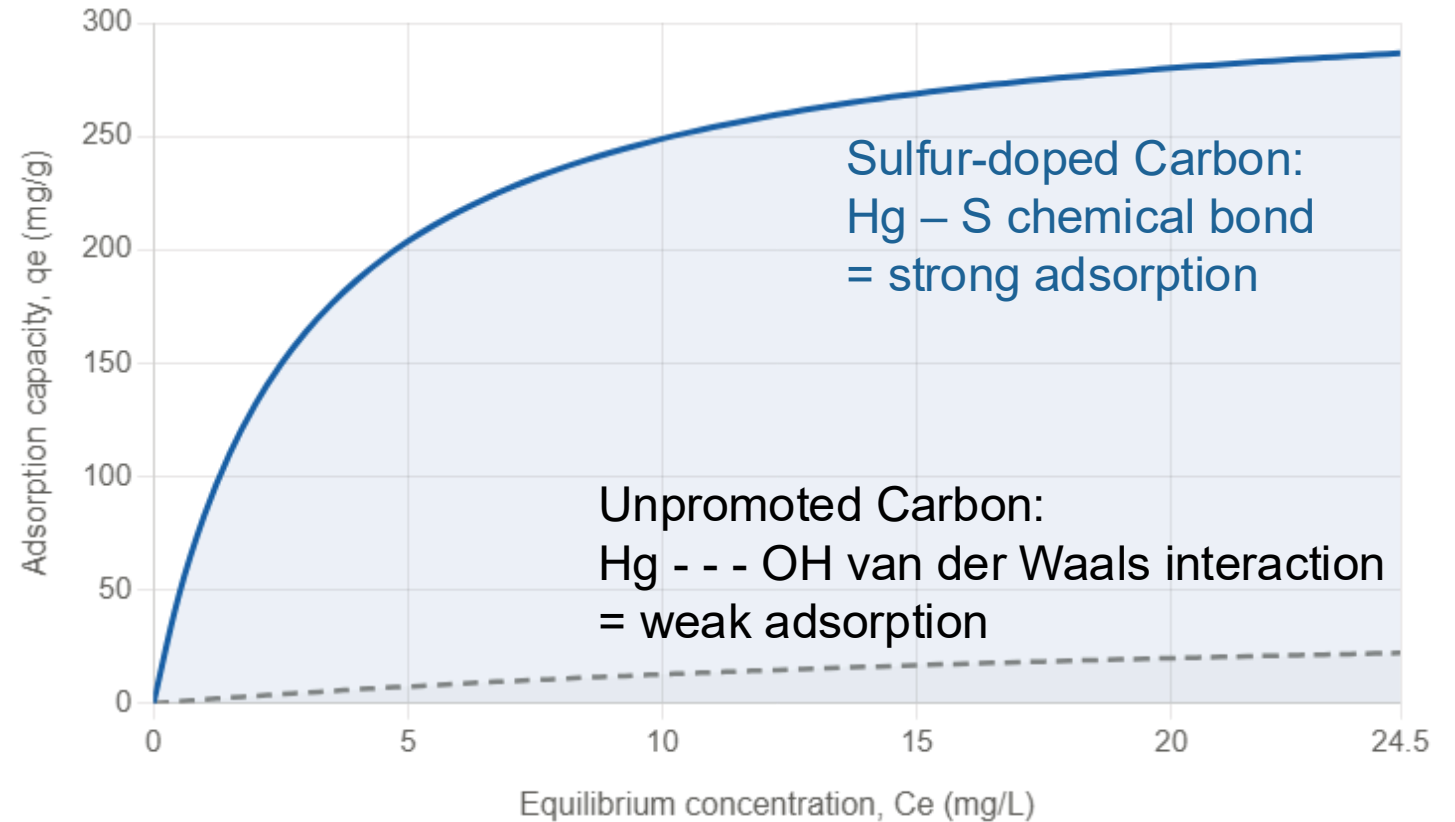
- Sulfurized carbon common for mercury (Hg) & halogen/halocarbon removal
- Hg embrittles aluminum heat exchangers & cryogenic equipment

[1] Granite, E.J. et al. (2000). Novel sorbents for mercury removal from flue gas. *Ind. Eng. Chem. Res.*, 39(4), 1020–1029. <https://doi.org/10.1021/ie990758p>

[2] Liu, W. et al. (2010). Sulfur-impregnated activated carbon for mercury removal from aqueous solutions. *J. Hazard. Mater.*, 181(1–3), 802–808. <https://doi.org/10.1016/j.jhazmat.2010.05.082>

[3] Hsi, H.-C. et al. (2001). Mercury adsorption properties of sulfur-impregnated porous carbons. *J. Environ. Eng.*, 127(8), 699–708. [https://doi.org/10.1061/\(ASCE\)0733-9372\(2001\)127:8\(699\)](https://doi.org/10.1061/(ASCE)0733-9372(2001)127:8(699))

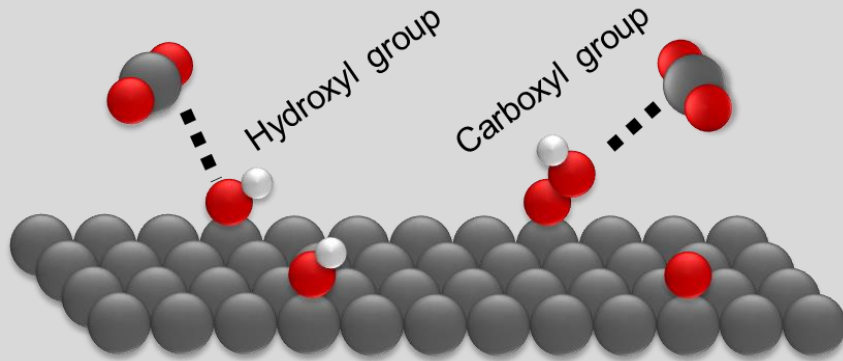
Mercury Adsorption Sulfur-doped vs Unpromoted Carbon



Physical vs Chemical Adsorption

Physical Adsorption

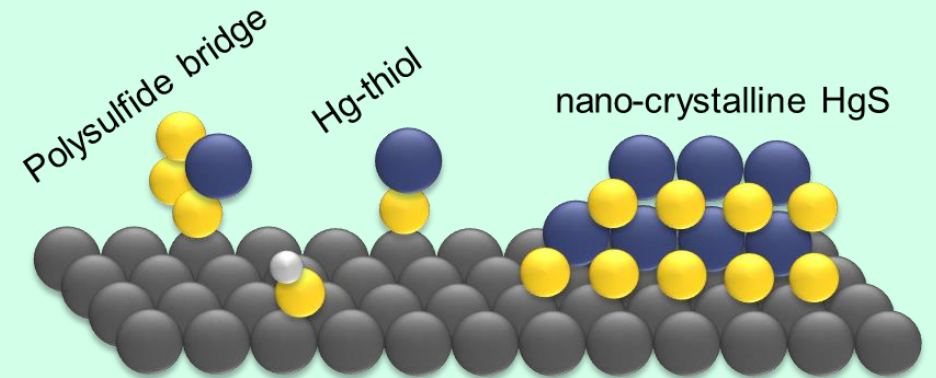
- **Example: CO₂ on activated carbon**
- Does not form chemical bonds
 - Instead, weaker electrostatic or van der Waals forces between CO₂ and solid at ~8 kcal/mol



- Sorbents regenerable for 1000s of cycles at low energy cost (pressure swing), no capacity loss
- CO₂ removal usually to % or high ppm levels

Chemical Adsorption

- **Example: Hg on S-doped carbon**
- Form chemical bonds during adsorption
 - Hg-S thiol bond at ~70 kcal/mol

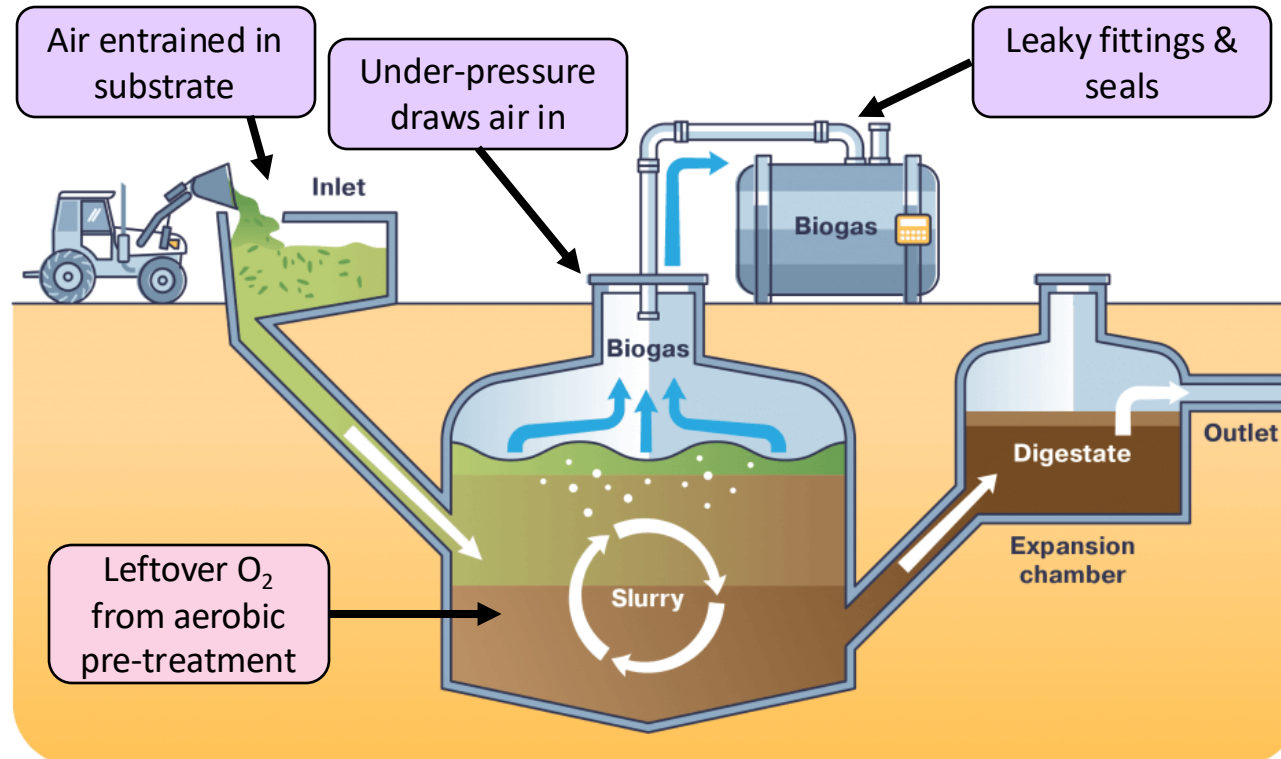


- Sorbents less regenerable, need Temp swing
 - Hg sorbent regenerable 3-5 times. Capacity loss each time
- Hg removal into ppb range

N₂ & O₂ in Biogas

N₂ and O₂ Pathways into Biogas from Anaerobic Digester

- N₂ sources
- Air sources (N₂ and O₂)
- O₂ sources



Sources

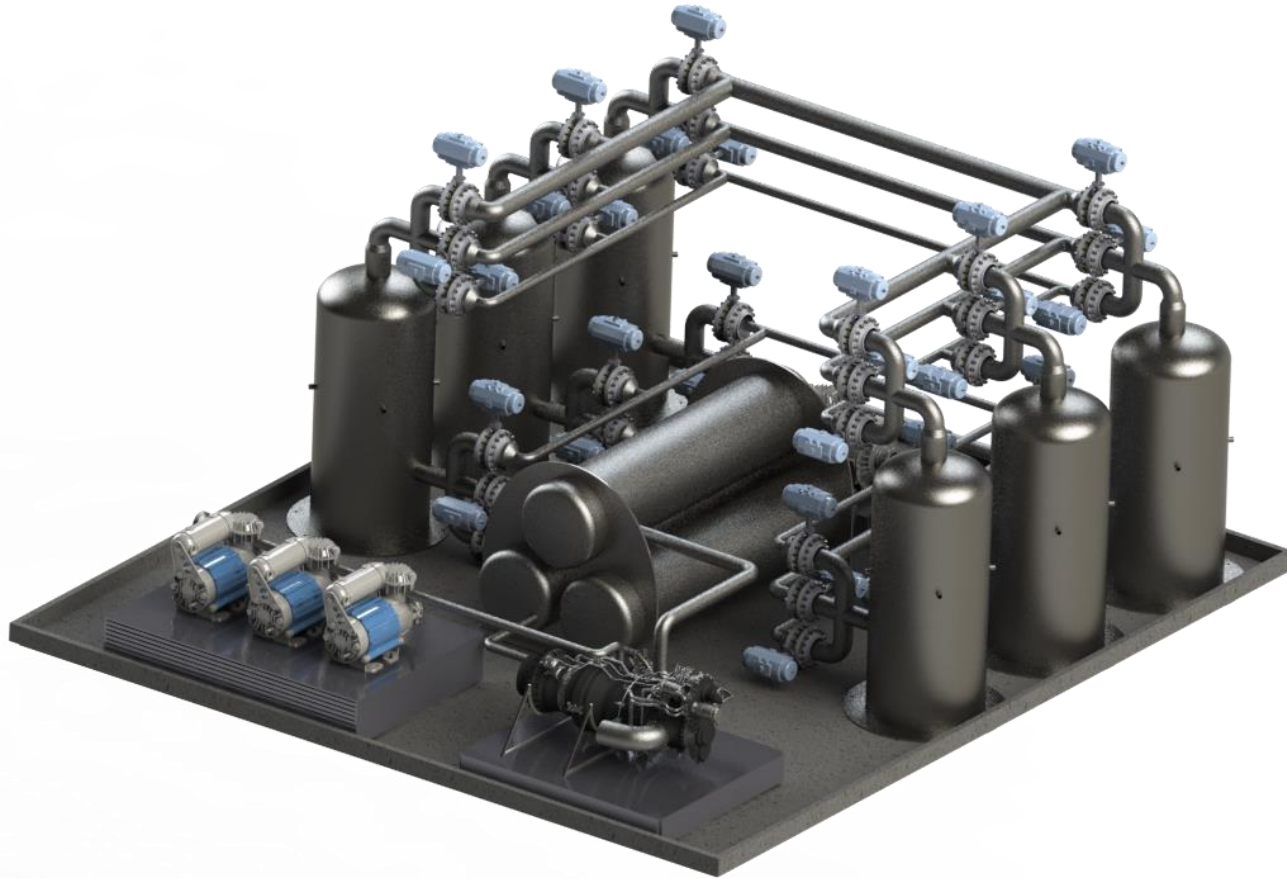
- N₂: 0–5% v/v
- O₂: 0–2% v/v
- N₂ reduces heating value
- O₂ can be explosion risk

N₂ slip from PSA or membrane

Digester cartoon from Power Knot.

<https://powerknot.com/2023/10/09/are-biodigesters-really-feasible-solutions-for-small-farms/>

N₂ Removal Technologies



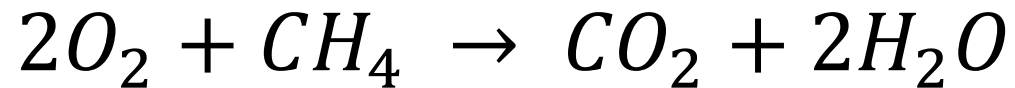
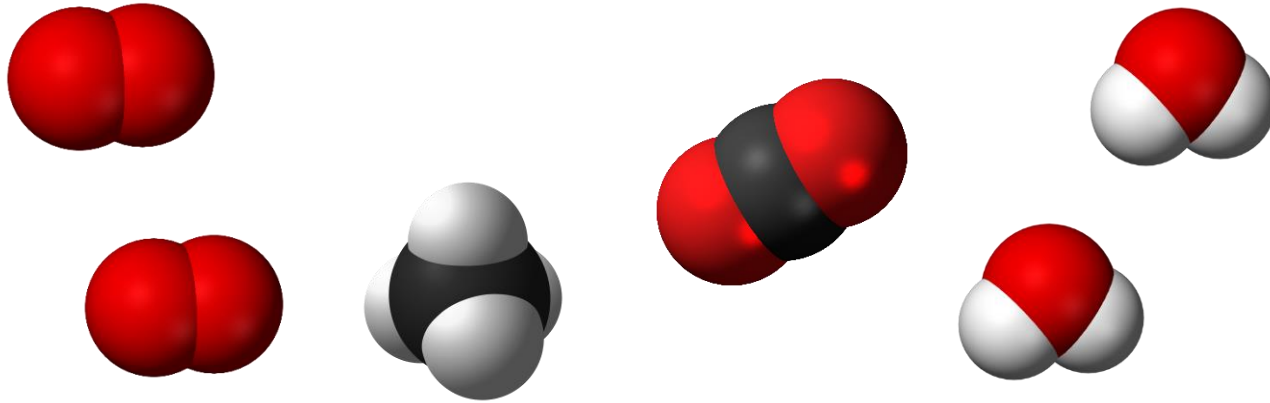
SulfaTrap N₂ rejection unit with 18%-v N₂ feed
Capacity: 12 MMSCFD CNG

Challenges

- N₂ is **inert** and difficult to remove
- PSA (kinetic separation with molecular sieve) can remove N₂ with CO₂ and O₂
- PSA (equilibrium separation with zeolite) can remove N₂ with higher CH₄ recovery
- Polyimide/ cellulose acetate membranes let N₂ through while retaining CH₄
- Cost: \$2–4 per MMBtu by conventional means but can be <\$1/MMBtu with new sorbents

¹<https://www.epa.gov/sites/default/files/2016-06/documents/smyth.pdf>

O₂ Removal Technologies



- 170 – 370 °C, <75 psig, reach <1 ppmv O₂
- Catalysts sensitive to sulfur, chlorine, C_{>2} (must remove first!)
- Produce water & CO₂ (must remove later if out of spec!)

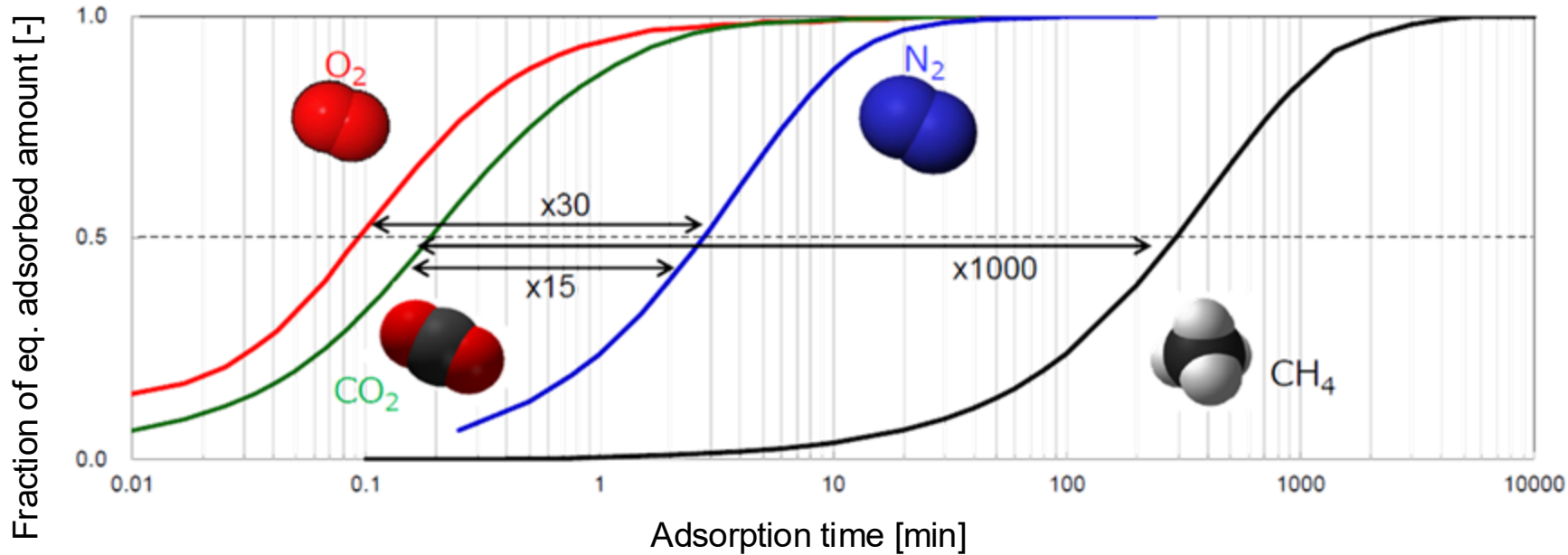
¹<https://www.epa.gov/sites/default/files/2016-06/documents/smyth.pdf>

Challenges

- O₂ is reactive but not soluble in scrubbing liquids
- Catalytic deoxo (ZerO2) reacts O₂ with CH₄
 - Often Pd or Pt on alumina
- Chemical scavengers:
 - Sodium sulfite (Na₂SO₃) or bisulfite solution plus nickel or cobalt catalyst
 - Organic (carbohydrazine, citrate) solution
- Pipeline spec: <0.2%
- Cost: \$0.16–1.00/ MMBtu¹

Alternate O₂ Removal Technologies

Diffusion Rates in Size-Selective Sorbent



Molecule	Kinetic Diameter [nm]	Time to 50% Saturation [min]
Oxygen	0.346	0.09
Carbon Dioxide	0.330	0.18
Nitrogen	0.364	2.6
Methane	0.380	300

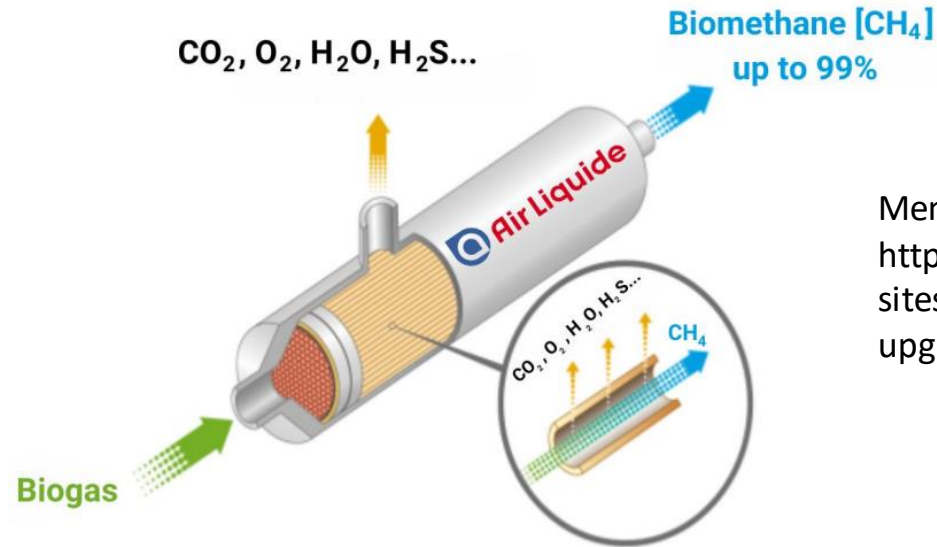
Kinetic Separation PSA

- Size-selective sorbents can pick up N₂ and O₂ much faster than CH₄
- Lower cost vs O₂ scavengers
- Combine with removal of N₂ and/or CO₂
- Multiple stages could be needed to minimize CH₄ slip

CO₂ Removal (Upgrading)

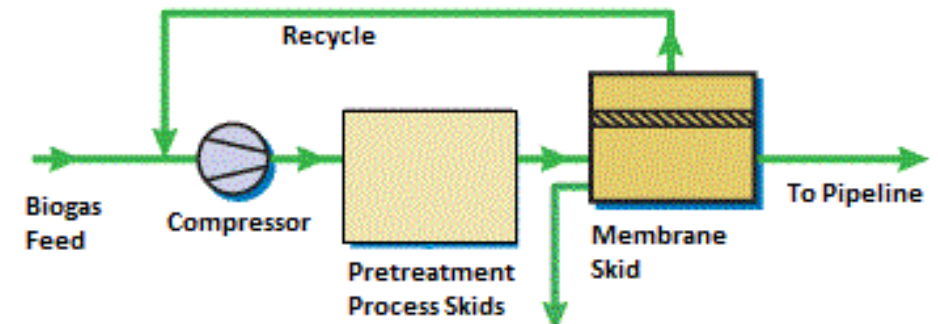
Available Technologies

- Membranes (polyimide, polyetherimide, cellulose acetate, polysulfone, etc.)
- Pressure swing adsorption (PSA): only option to simultaneously remove CO₂ and N₂ + O₂
- Water scrubbing
- Amine scrubbing (large scale)
- Pipeline spec: <2% CO₂
- Cost: \$0.5–1.60/ MMBtu



Membrane module cartoon from Air Liquide.
<https://advancedseparations.airliquide.com/sites/alas/files/2024-10/air-liquide-biogas-upgrading-systems-09-24.pdf>

Membrane process cartoon from MTR.
<https://www.mtrinc.com/natural-gas/biogas-co2-removal/>

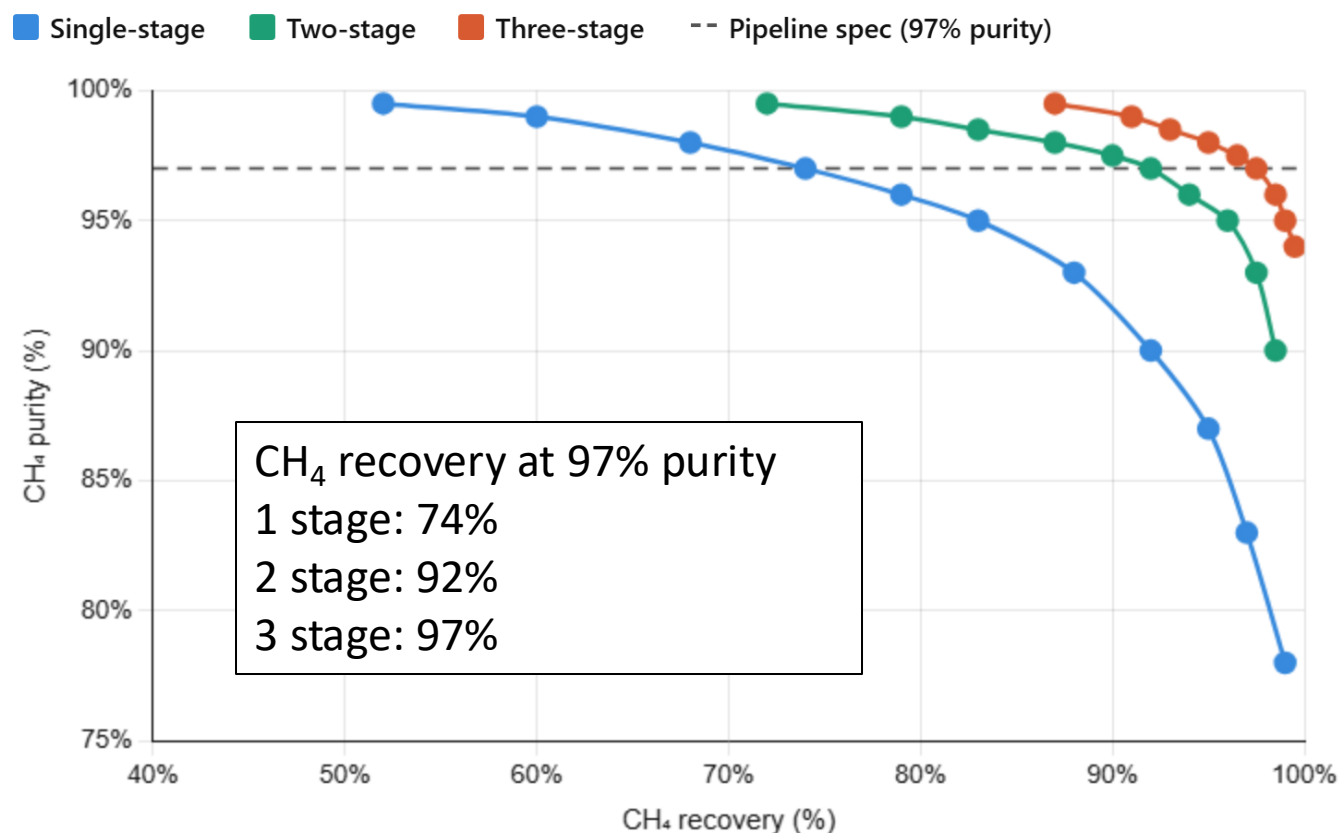


Challenges for Membranes in CO₂ Removal

Bulk CO₂ Remover

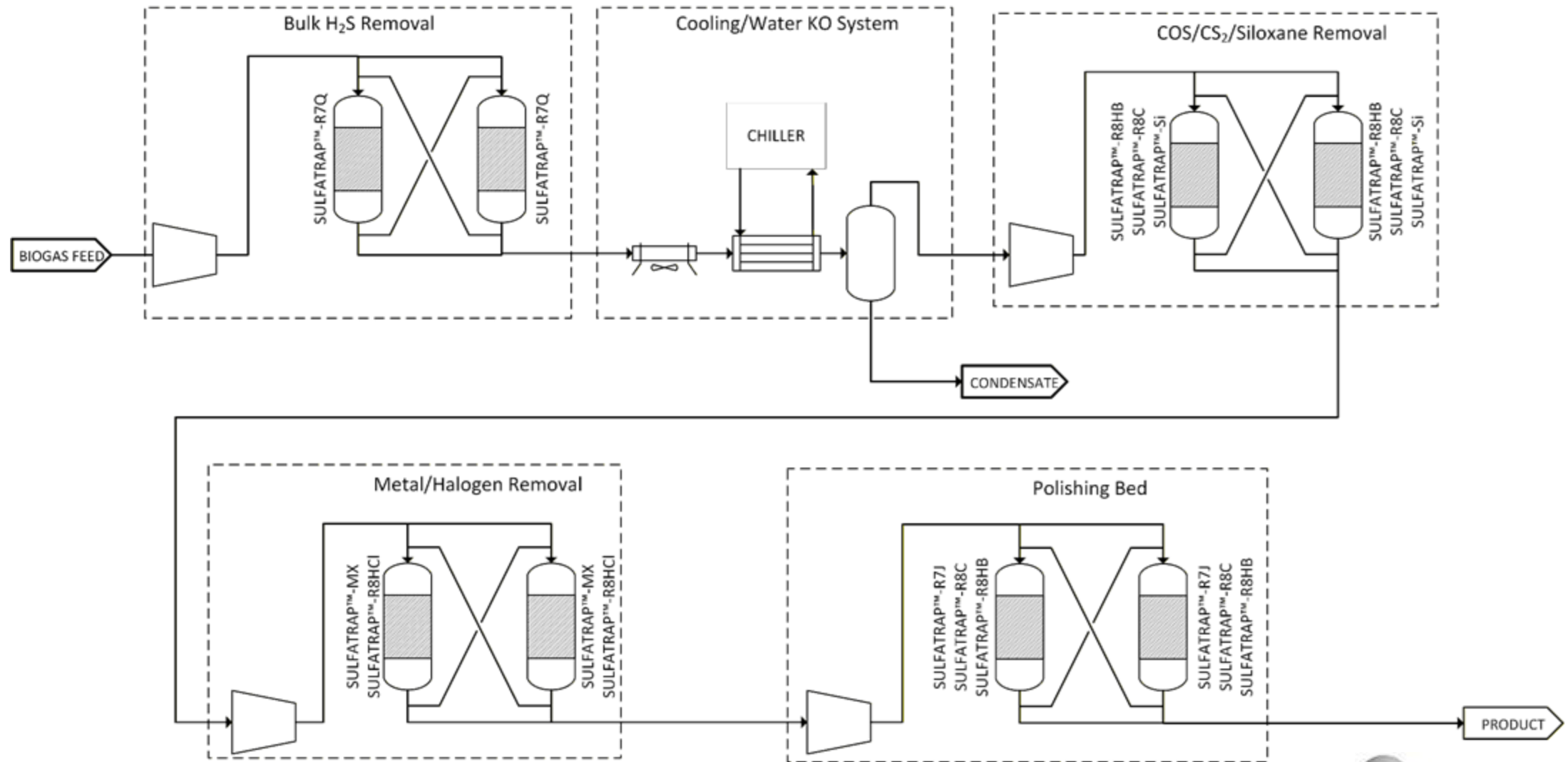
- Membranes are good at cutting CO₂ content from “high” to “medium” at low energy cost
- Membranes struggle to reach high purity (>97%) on CH₄ and CO₂ sides
- Methane slip burdens later stages (e.g., CO₂ liquefaction)
- CO₂ slip could require multiple stages to meet pipeline spec

Methane Recovery – Purity Tradeoff for Typical Membrane System

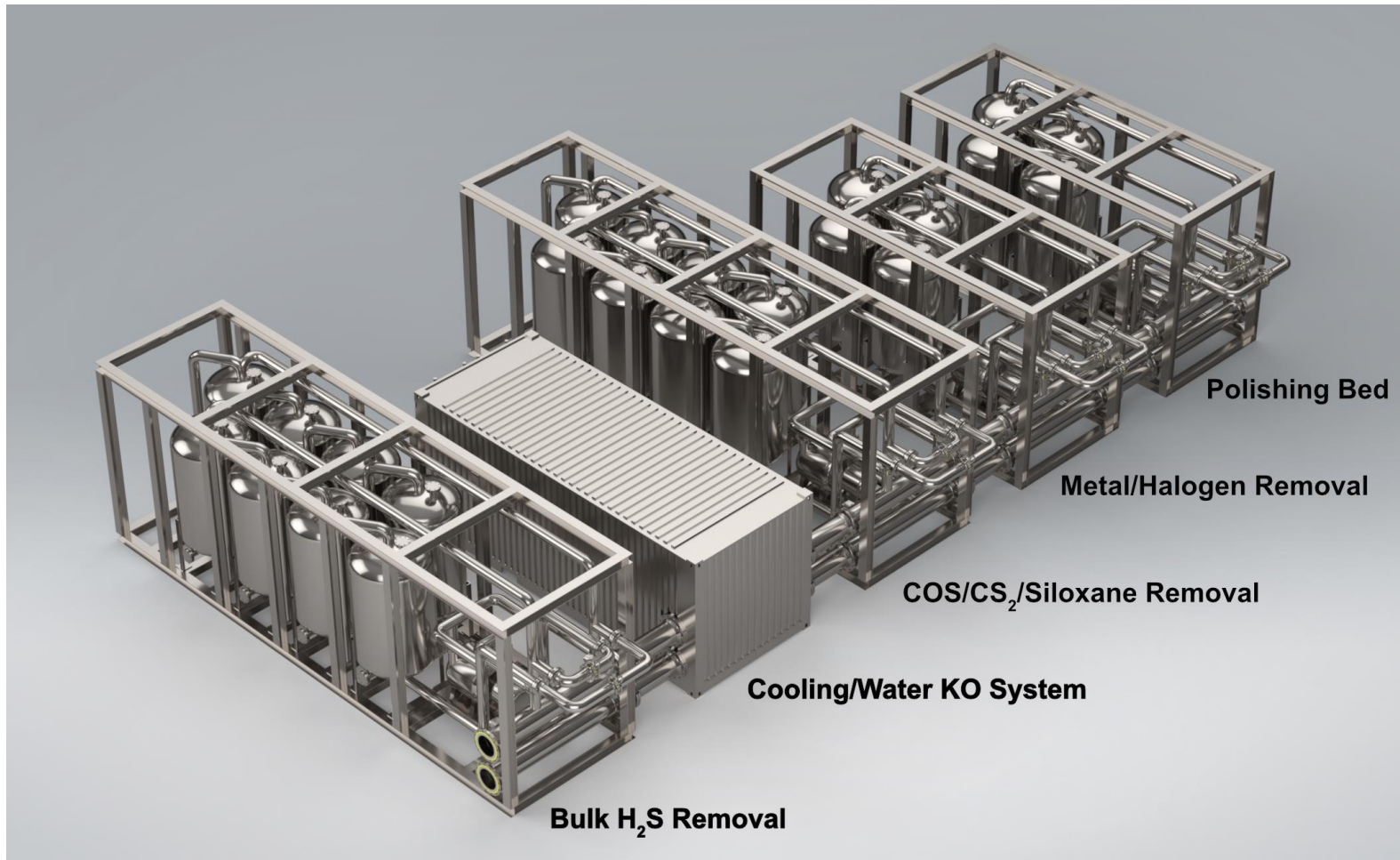


Feed: 50% CH₄ / 50% CO₂. Data from Scholz et al. 2013; Baena-Moreno et al. 2020; Sunarso et al. 2018; Pak et al. 2021; Wojnarova et al. 2022.
Selectivity $\alpha(\text{CO}_2/\text{CH}_4) = 20\text{--}30$.

SulfaTrap Technology Offering for Biogas Purification



SulfaTrap Technology Offering for Biogas Purification



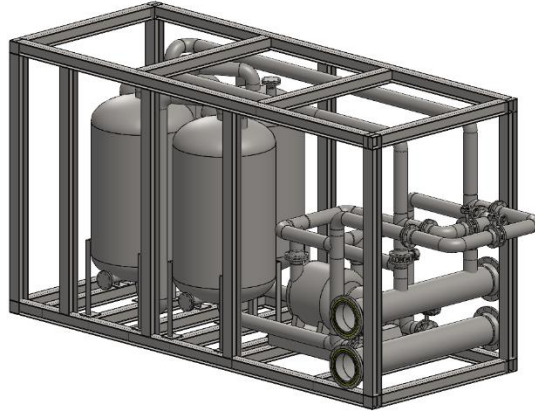
Modular System

- 5-stage modular design is expandable for larger streams
- Flexible for gases with different contaminants
- Scale up or add skids for streams with other species
 - Ammonia
 - NO_x

Modular Design for Biogas Purification

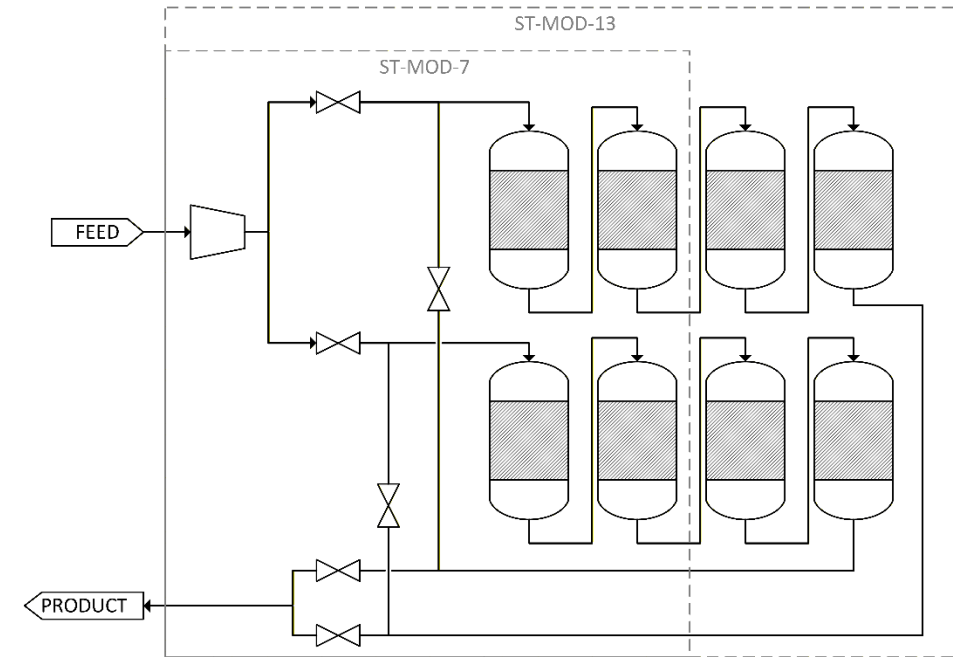
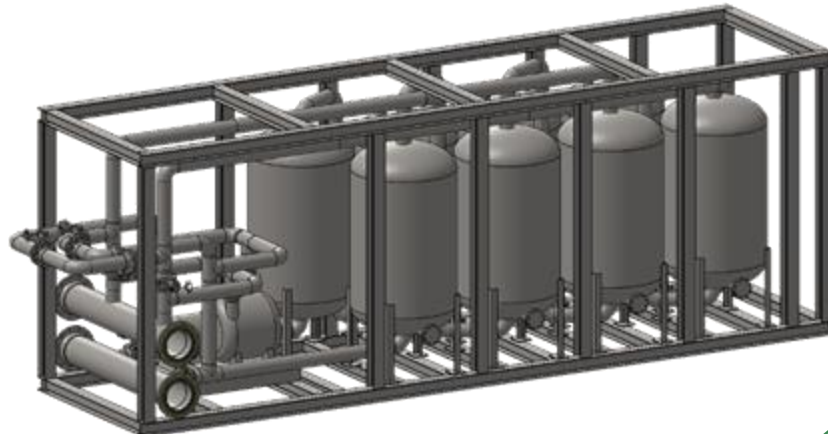
ST-MOD-7 (Small Skid)

Vessel Size: 48" OD x 64" T/T
Inlet Pipe Size: 6" NPT
Sorbent Volume: 6,650 L/System
Booster Blower P Increase: ≤ 5 psi
Frame Dimensions: 20' x 8' x 11'
Total Weight: Approx 16,500 lbs



ST-MOD-13 (Large Skid)

Vessel Size: 48" OD x 64" T/T
Inlet Pipe Size: 6" NPT
Sorbent Volume: 13,300 L/System
Booster Blower P Increase: ≤ 5 psi
Frame Dimensions: 30' x 8' x 11'
Total Weight: Approx 25,000 lbs



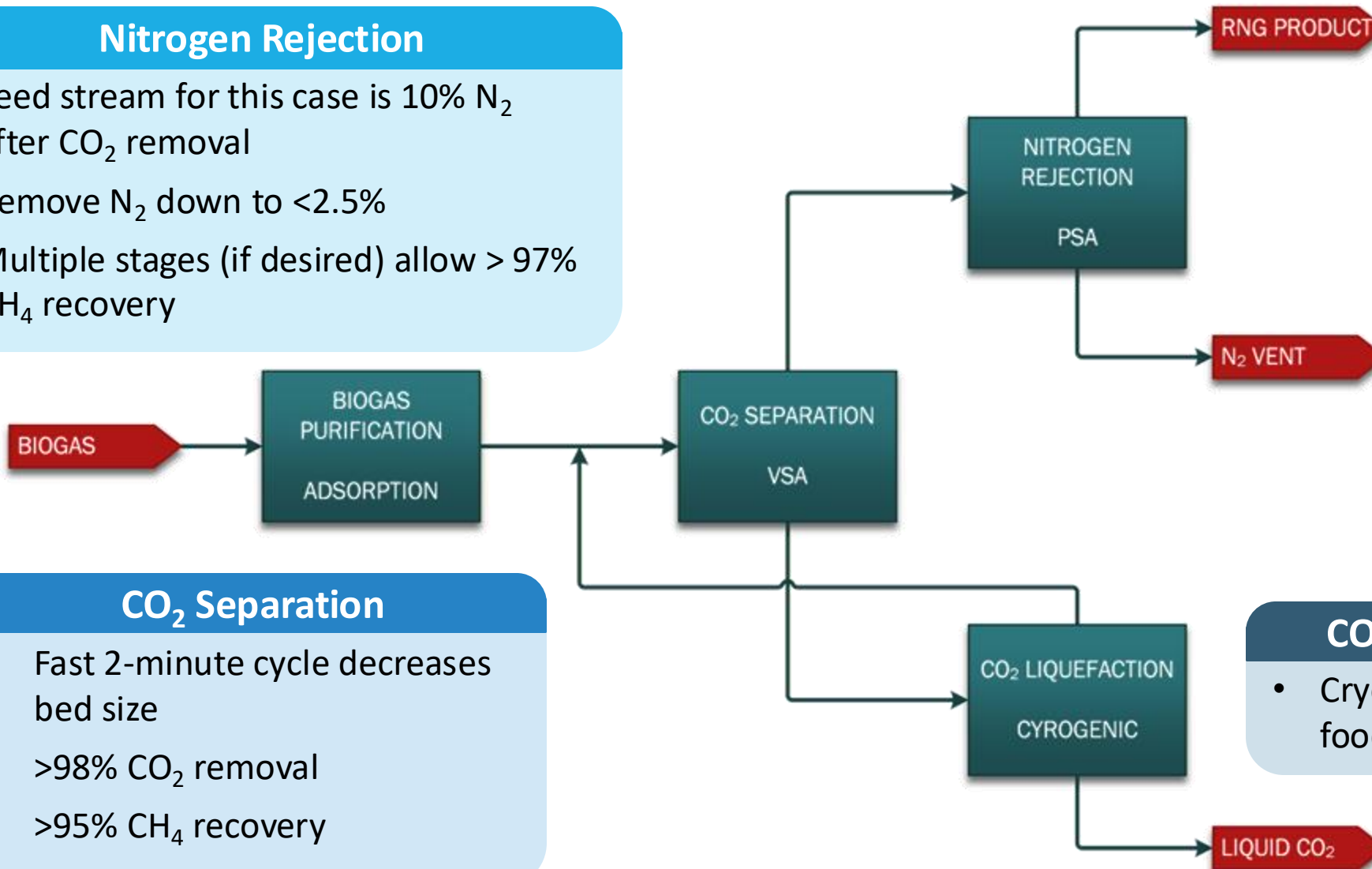
Benefits

- Modular system minimizes capital cost
- Multiple systems combined in parallel to increase treat capacity

SulfaTrap Technology Offering for Biogas Upgrading

Nitrogen Rejection

- Feed stream for this case is 10% N₂ after CO₂ removal
- Remove N₂ down to <2.5%
- Multiple stages (if desired) allow > 97% CH₄ recovery



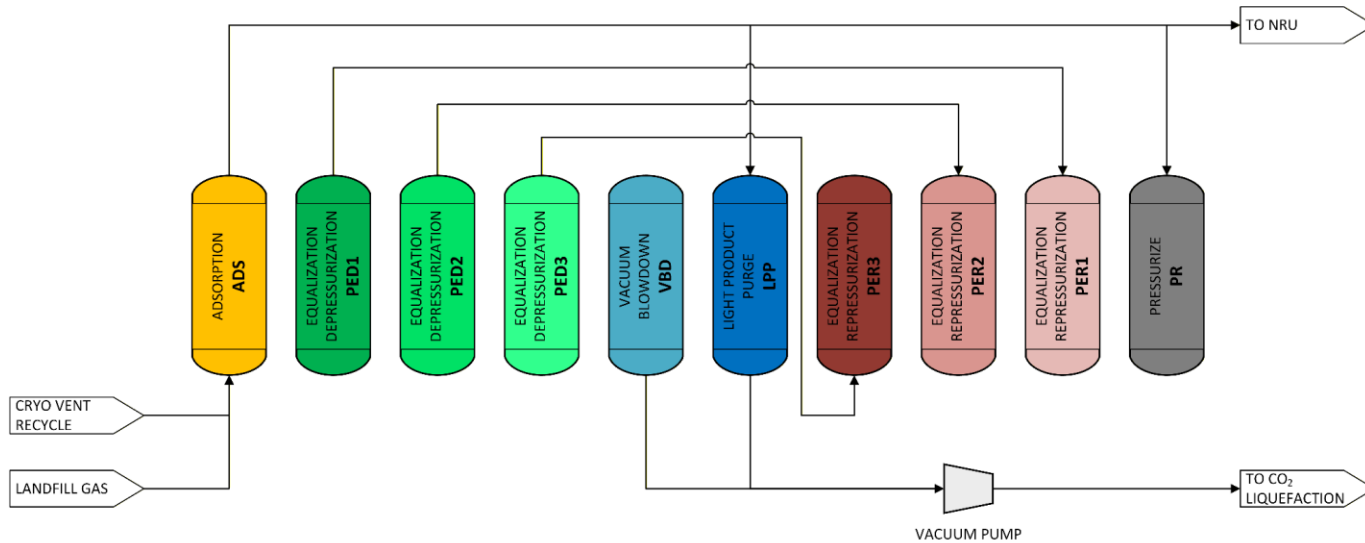
CO₂ Separation

- Fast 2-minute cycle decreases bed size
- >98% CO₂ removal
- >95% CH₄ recovery

CO₂ Liquefaction

- Cryogenic process for food-grade CO₂ purity

SulfaTrap Technology Offering – CO₂ Rejection



CO₂ Separation

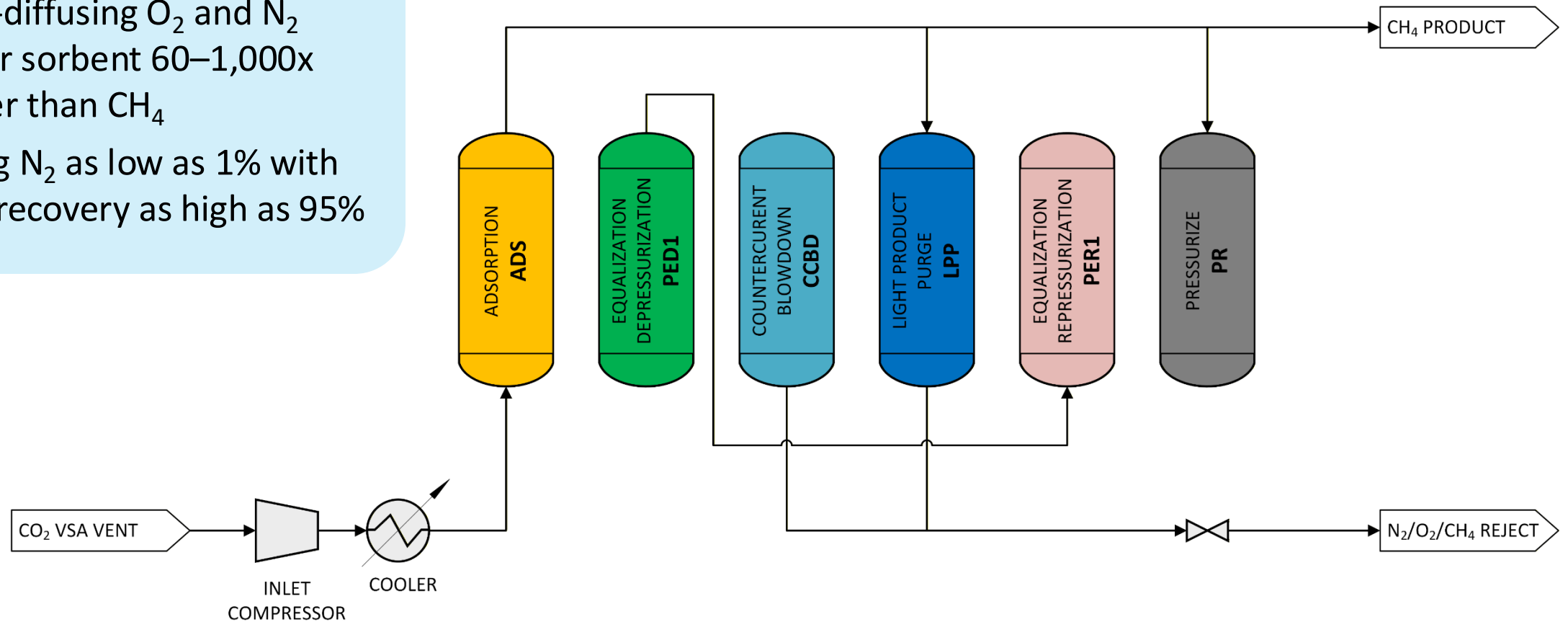
- CO₂-selective sorbent runs with low CH₄ loss
- Vacuum swing with pressure equalizations minimizes bed size & CH₄ loss
- Sorbent regeneration with purge under vacuum



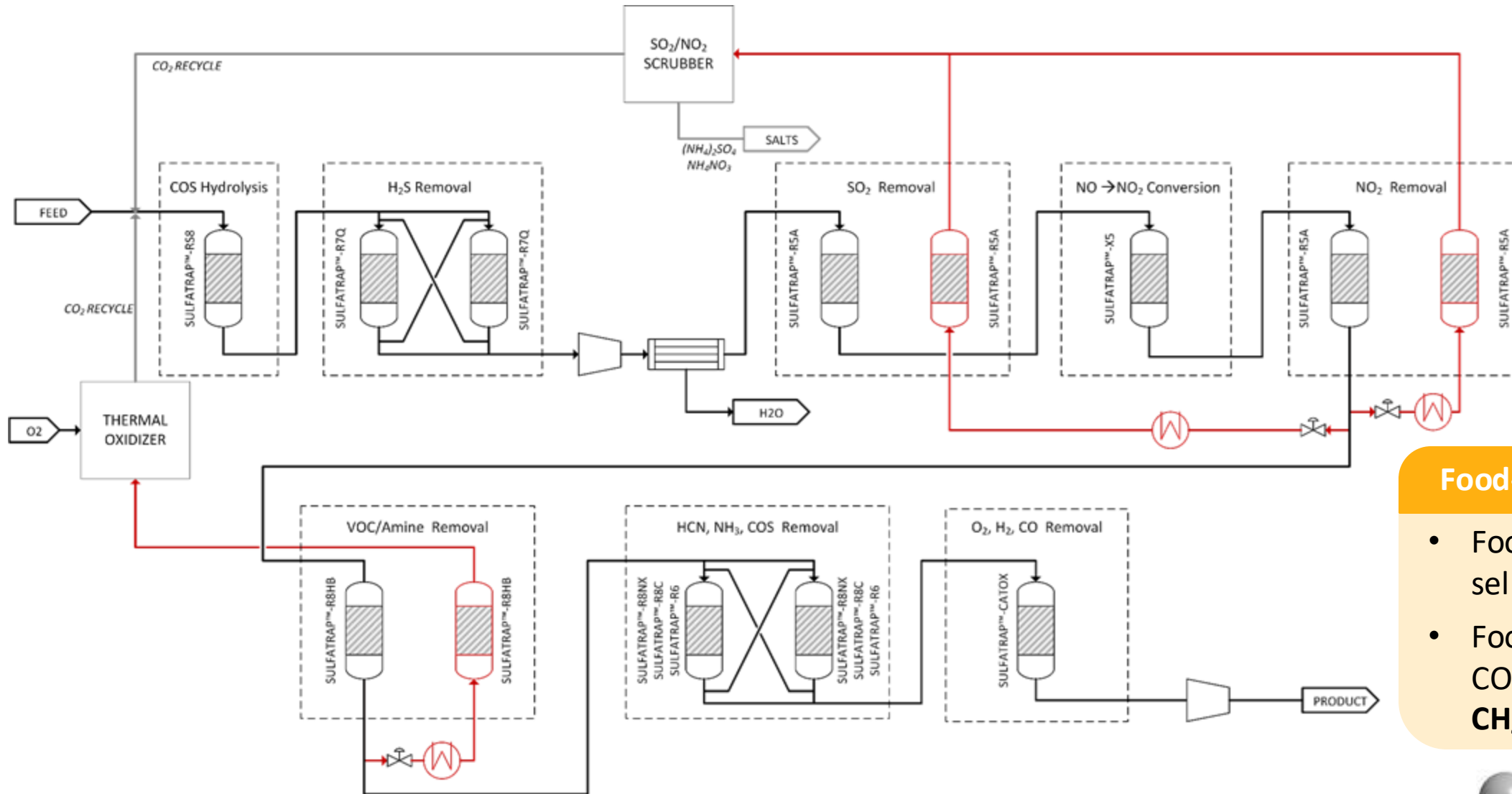
SulfaTrap Technology Offering – N₂/O₂ Rejection

Kinetically Selective Sorbent

- Fast-diffusing O₂ and N₂ enter sorbent 60–1,000x faster than CH₄
- Bring N₂ as low as 1% with CH₄ recovery as high as 95%



CO₂ Purification for Food/Beverage Grade and Pipeline Injection



Food-grade CO₂ Sale

- Food-grade CO₂ sells ~\$130+/ton
- Food grade >99.5% CO₂ by volume; CH₄ <50 ppmv



SulfaTrap Biogas Upgrading – Techno-economic Assessment

Sorbent Fill	\$1,965,434
Eng Design	\$1,250,000
System Cost	\$21,090,116
Total CAPEX	\$24,305,551

Fixed Operating	\$760,091
Variable Operating	\$1,010,301
Power	\$1,733,821
Total OPEX	\$3,504,213

	Unit	Landfill Gas Feed	N ₂ /O ₂ Vent	RNG Product	CO ₂ Product
VAPOR FRACTION	-	1.00	1.00	1.00	0.00
TEMPERATURE	deg C	20.00	30.00	29.82	30.00
PRESSURE	bara	10.00	1.00	54.33	151.97
MOLE FLOW	kmol/hr	444.1	28.3	247.5	166.5
MASS FLOW	kg/hr	12,170	561	4,265	7,288
VOLUME FLOW	m ³ /hr	1,048.8	712.9	104.2	8.9
STD VOL FLOW	SFCM	6,000	394	3,134	748
CH₄	mol%	55.50%	69.49%	91.05%	0.88%
CO₂	mol%	37.66%	0.00%	0.53%	99.12%
N₂	mol%	5.95%	27.33%	7.54%	0.00%
O₂	mol%	0.69%	3.19%	0.88%	0.00%

Assumptions

- CO₂ Sale Price: \$85/tonne
- CH₄ Sale Price: \$4/MMBTU
- Electricity Cost: \$80/MWh

Capital Investment	\$24,305,551
Operating Cost	\$3,504,213
Yearly Cash Flow CH ₄	\$6,032,517
Yearly Cash Flow CO ₂	\$5,412,528
Yearly Profit	\$7,940,832
Payback Period, years	3.66

Plant Life, years	15
Interest Rate, %	8%
Levelized Cost	
Capital, \$/MMBTU	\$1.88
Operating, \$/MMBTU	\$2.32
Total, \$/MMBTU	\$4.21

