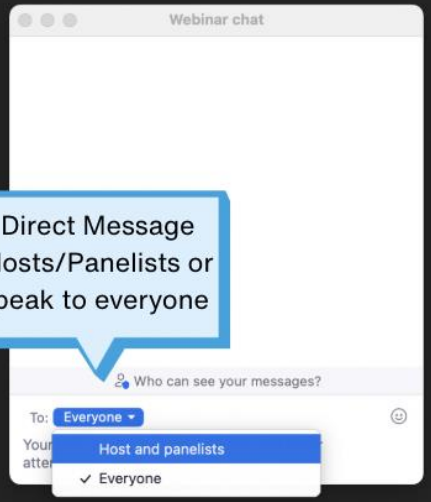
Nitrogen Rejection via Membrane Technology

Gregory Myrick
Technical Director, Air Liquide Advanced Separations

ABC Webinar • August 27, 2025

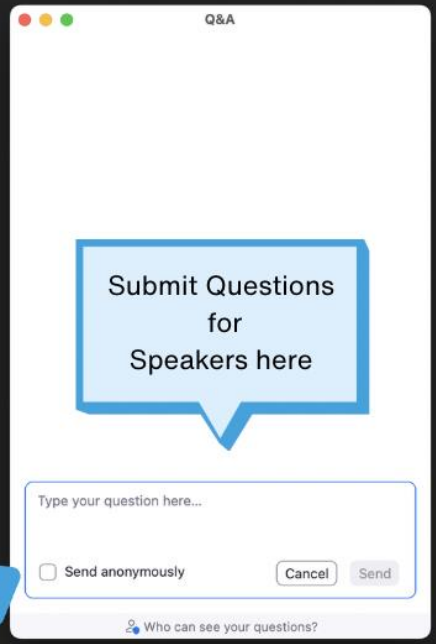
zoom



Free ABC Sponsored Webinar

Nitrogen Rejection via Membrane Technology

Today | August 27
2:00-3:00PM ET



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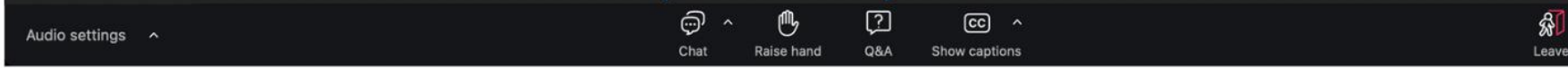


Contents

Safety Moment

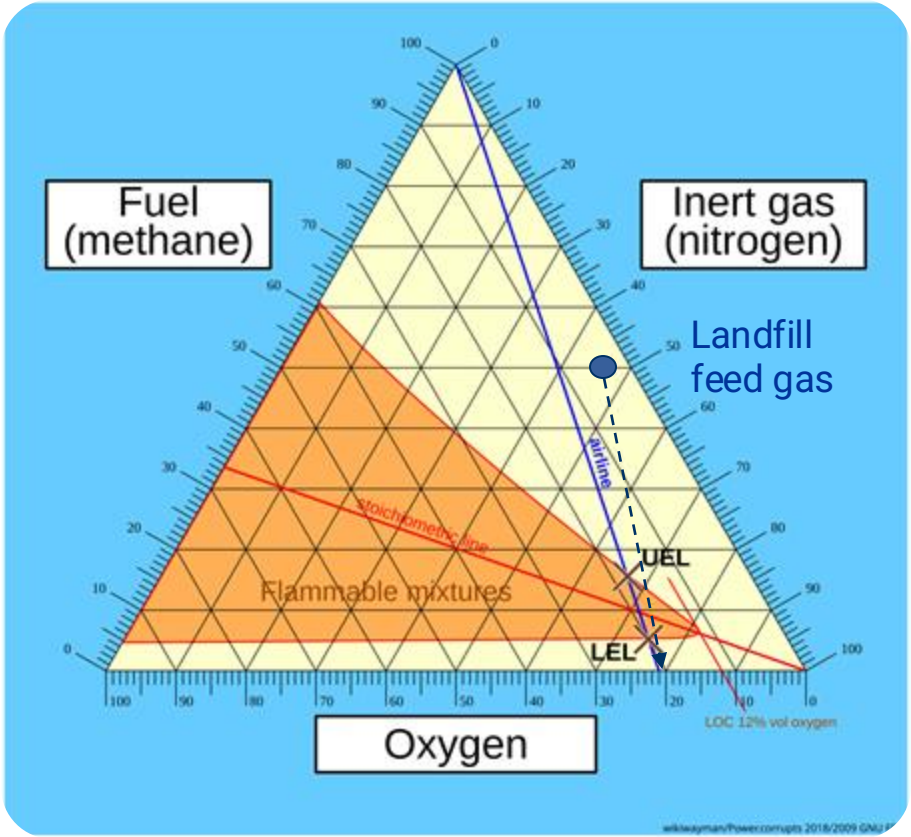
With N_2... comes O_2

Fuel Source + Heat Source + O_2

Biogas upgrading technologies concentrate CH_4 through removal of CO_2 and O_2.

- O_2 builds in the waste stream.
- Air intrusion has the potential to pass through the flammable mixture window.

Flammability Triangle



UEL = upper explosive limit, LEL = lower explosive limit, LOC = limiting oxygen concentration

Air Liquide's Biogas Experience

Advanced Separations

- Unique hollow fiber **membrane purification** and **gas recovery** technology
- **In-house development** of **new fibers, membrane modules**, and **applications** at Air Liquide's Innovation Campus Delaware

37+ years
in membrane production

Manufactured in USA
for Air Liquide's global customer base

10,000+ purification units
equipped with membrane technology

Air Liquide membranes: accelerating innovation

Membranes are being deployed everywhere: land, air & sea.

Air Liquide innovation to deliver results for new and mature technologies:

- Manufacturing with AI
- Step changes in technology
- New polymers
- Standardization initiatives

Concrete achievements in 2024 & 2025

Natural Gas: Lowest methane slip on operating FPSO as of 2025

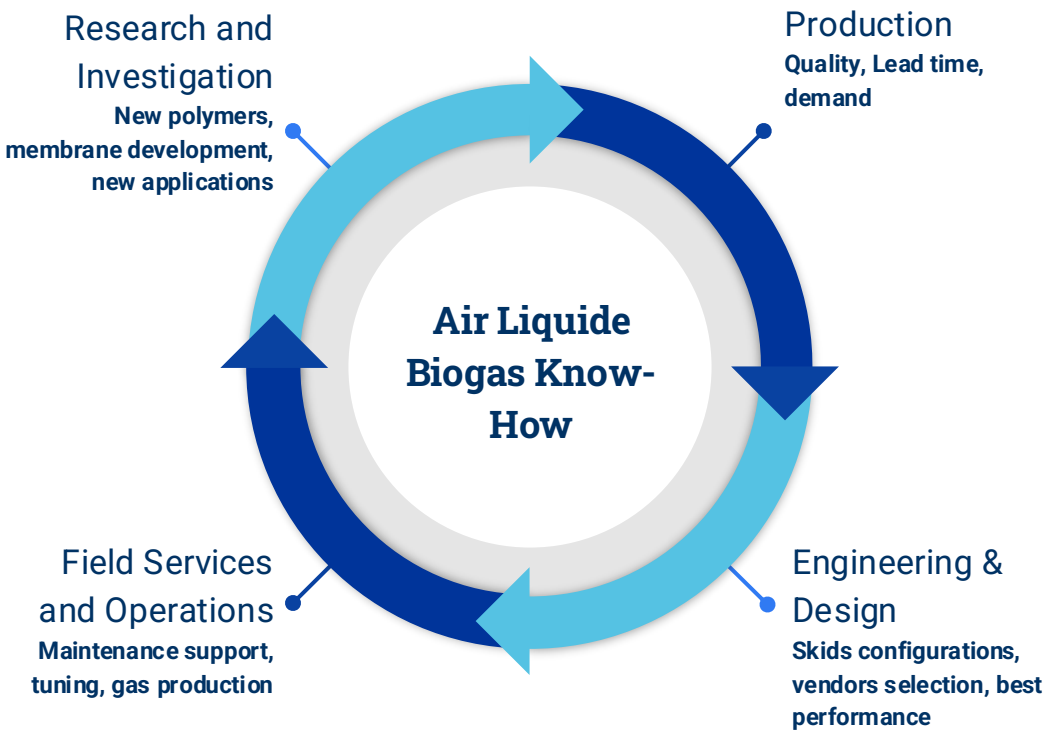
Hydrogen: Since 2024 drastic hydrogen recovery improvement (+ 7% hydrogen recovery in some cases)

Nitrogen: Improvement of +30% productivity starting in 2025

Biogas: Breakthrough in N2 RemovAL in 2025, much more coming in 2026

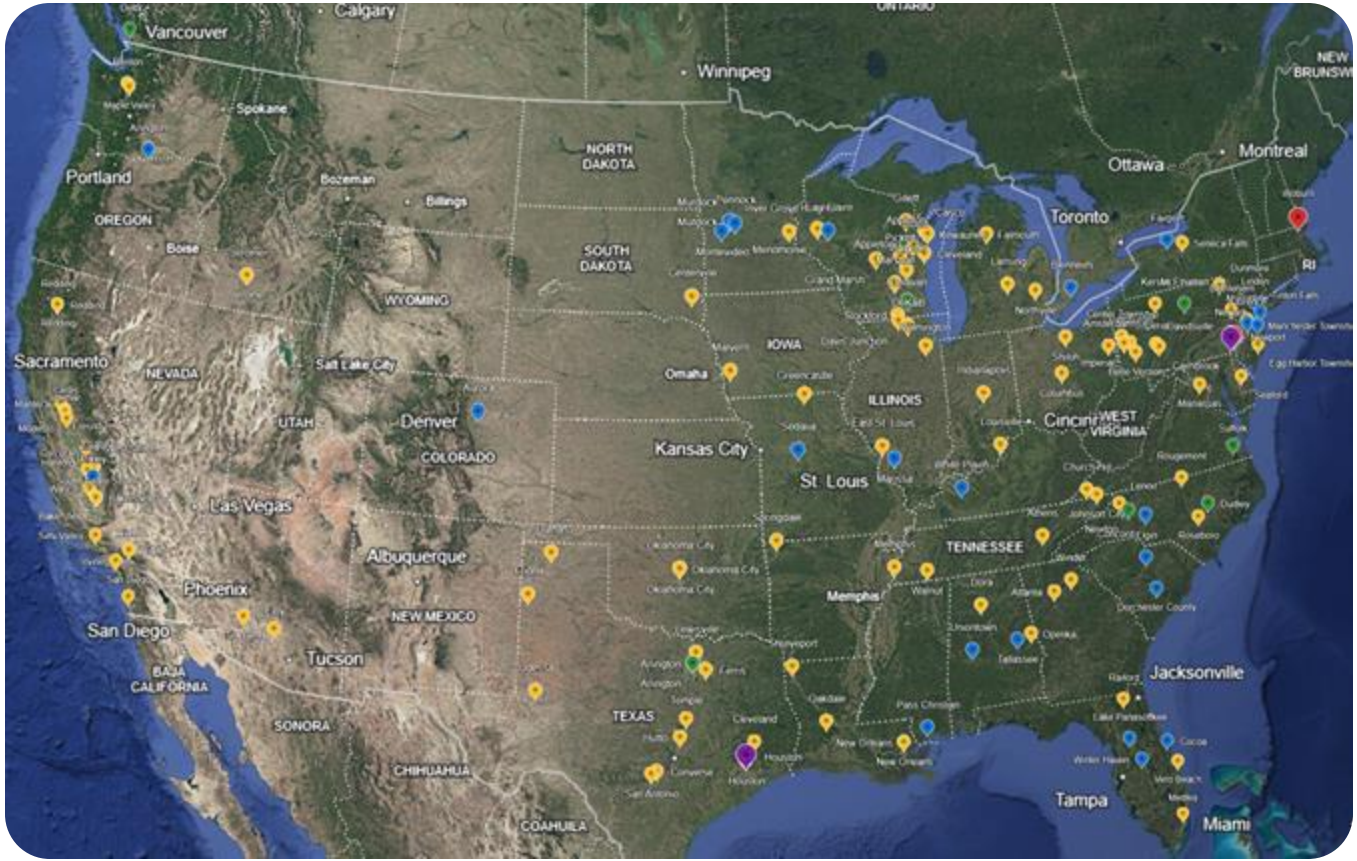
Helium: -23% CAPEX in Modular Helium Purifiers in 2025

Presence at all development stages



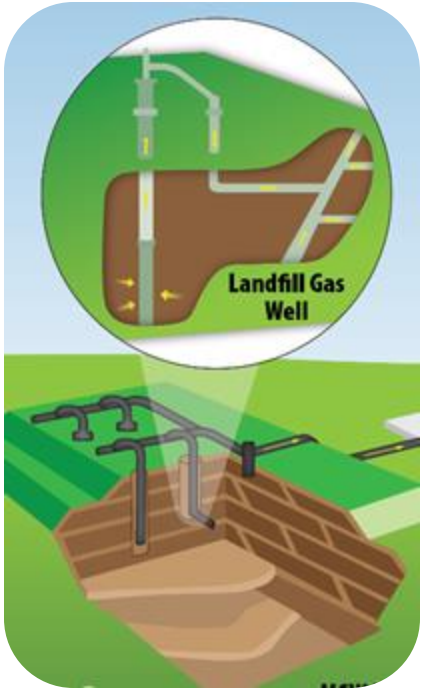
250+ Air Liquide biogas references worldwide, 20 years

- Operating Facilities
- Facilities with NRU Systems
- Projects in Development
- Corporate Offices & Manufacturing



Nitrogen Source

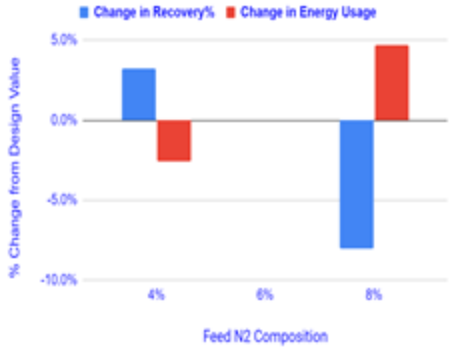
The source of Nitrogen in Landfills



Nitrogen is introduced by pulling vacuum on the wellfield

N_2 feed from a landfill can range from: [3/4]

- < 6% = under stressed / closed
- 6 - 12% = normal
- 16 - 20% = excessive, migration control
- 20+% = overstressed



Composition sensitivity study for Membrane based NRU

- Higher recovery and less energy usage if wellfield N_2 can be managed to 4%

Commercially Available Technologies

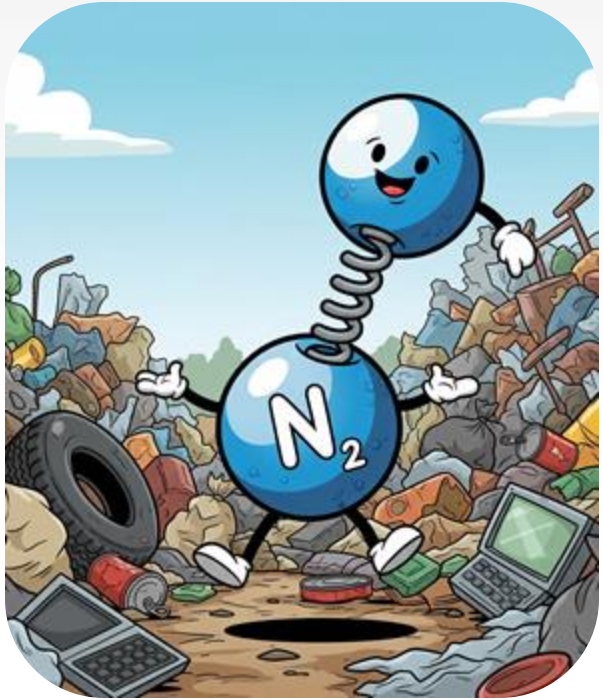
Commercially Available Technologies

Type	Feed Pressure	Product Pressure	CH4 Recovery	Benefits	Drawbacks
Kinetic PSA [5]	Moderate (150 – 200 psig)	Moderate (150 – 200 psig)	90%	• High Feed N_2 • CO_2 co-adsorption	• Adsorption capacity impacted by impurities • Low Recovery
Equilibrium PSA [6]	Moderate (150 – 200 psig)	Low (< 25 psig)	96%	• High Feed N_2 • Rejects O_2	• Adsorption capacity impacted by impurities • Multiple compression stages (vacuum pumps)
Membrane	High (500 psig)	Low (< 25 psig)	96+%	• Small footprint, • Wide flow range • Robust Membranes • No moving parts	• Multiple compression stages • Higher N_2 leads to higher compression costs
Cryogenic [7]	Moderate (150 – 200 psig)	Low (< 25 psig)	96%* *contingent on O_2 content	• High flow range • Rejects CO_2, O_2 & N_2	• Impurities freezing potential • Liquid Nitrogen required

Check In

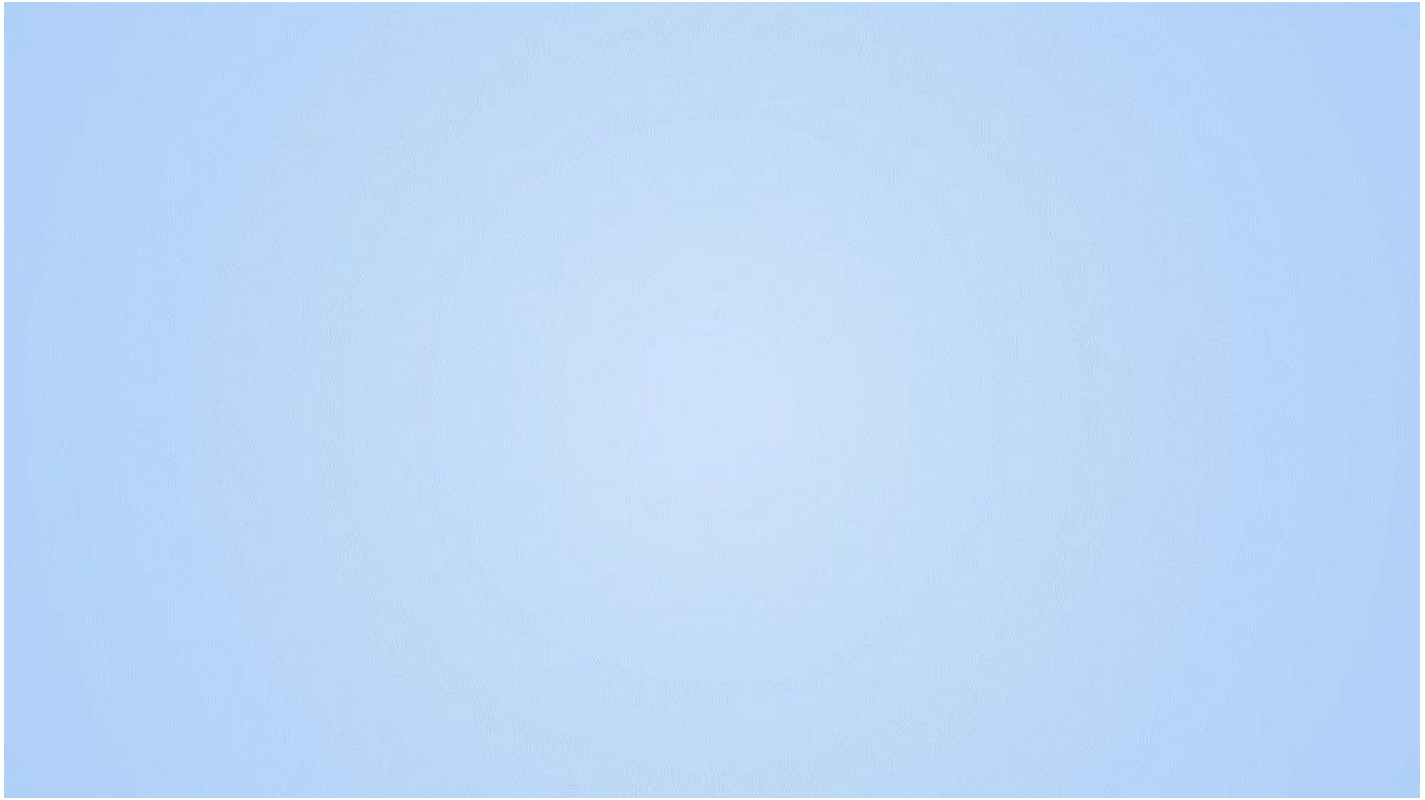
What treatment technology do you use to solve your nitrogen problems?

A. Wellfield Management
B. PSA / Adsorption
C. Cryogenic
D. Membrane
E. Dilution
F. Biological (wastewater)
G. Other
H. None



Membranes 101

Membranes 101: Hollow Fiber Membrane



Membranes 101: N_2 Removal

Polyether Ether Ketone (PEEK): Best in class thermo-mechanical properties and chemical resistance [8]

- Not affected by solvents and chemicals present in natural gas or compressor oil
- Allows membrane to operate with minimal pretreatment

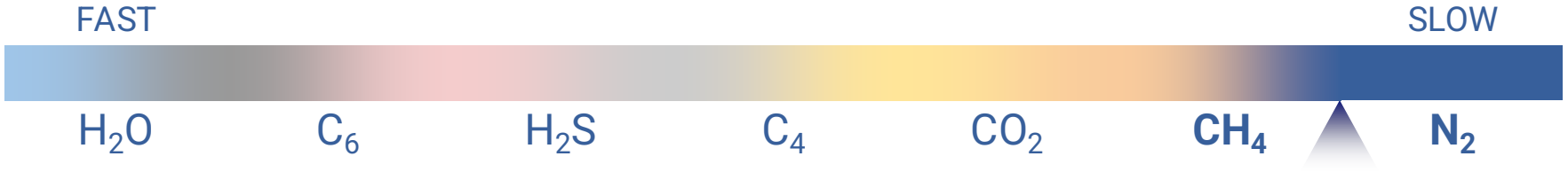
PEEK-Sep™ Membrane

- Porous PEEK Material
- Air Liquide acquisition in 2016
- Proprietary coating process to improve CH_4/N_2 selectivity

Membrane 101: Comparison

CONVENTIONAL MEMBRANES — CO_2 Removal

PEEK-SEP MEMBRANE — N_2 Removal



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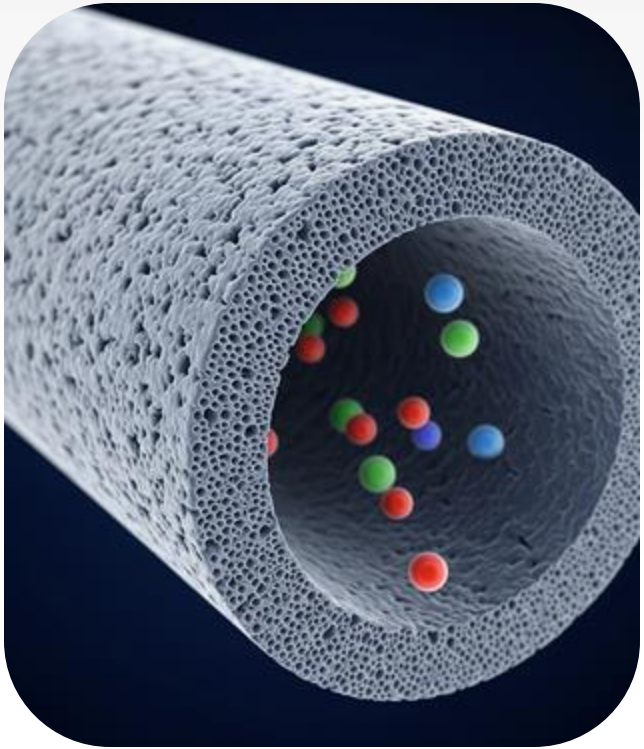


How many fibers can be found in a 12” diameter bundle?

A. 5
B. 500
C. 1,000
D. 10,000
E. 100,000
F. 1,000,000
G. 10,000,000

Process Overview

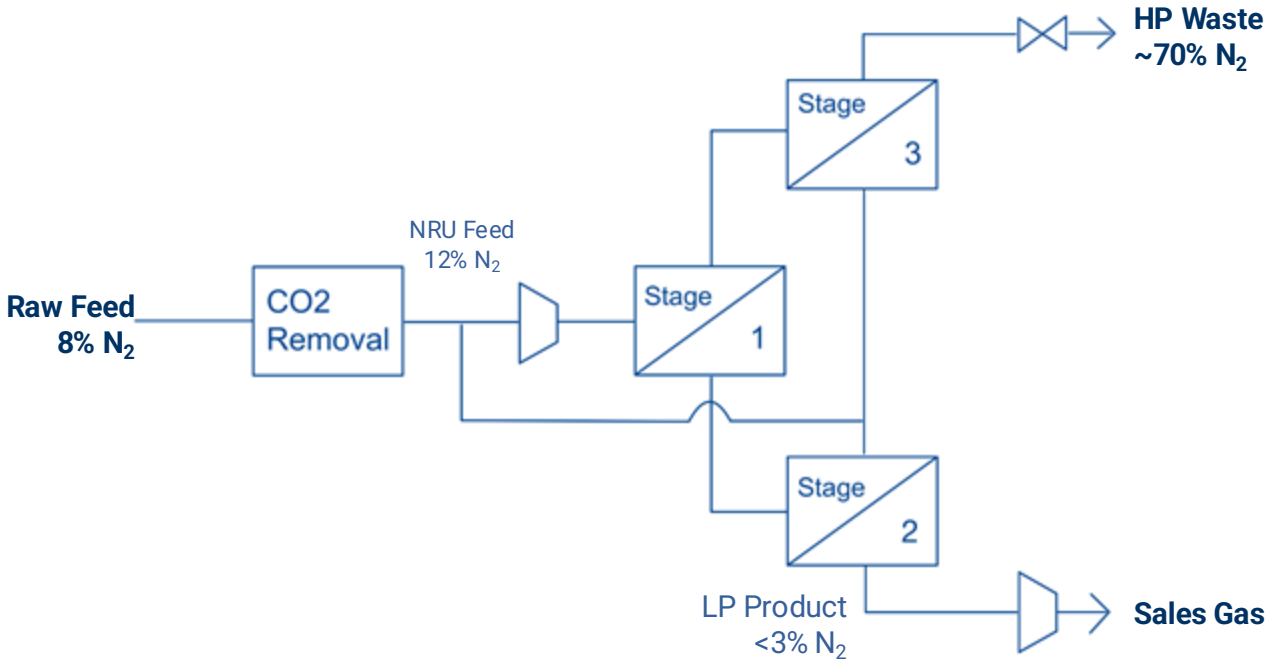
Nitrogen Rejection Unit (NRU)

Membrane NRU Process Overview

Technology developed and patented by Air Liquide (US Patent – 10,780,392) [9]

Scope

- Single stage compression (screw or reciprocating)
- Membrane skid
- Multi-stage compression for product



Cold NRU Process Improvement

Technology developed and patented by Air Liquide (US Patent – 11,318,411) [10]

Scope

- Single stage compression (screw or reciprocating)
- Membrane skid
- Multi-stream cross exchanger
  - no external chiller needed
  - -20 F feed temperatures
- Multi-stage compression for product

	AL NRU Gen 1	AL Cold NRU		
Landfill Gas, %	6	6	6	**12**
Inlet N_2 Composition, %	10	10	10	20
Outlet N_2 Composition, %	3.0	3.0	**2.0**	3.0
CH_4 Recovery, %	96	96	96	96
Recycle Ratio	3.9*	**2.5**	3.9	3.9

* Comparable compression requirement to PSA at similar size

Cold NRU Process Advantages

Footprint savings

- ~80% less than standard PSA
- Modular single skid design
  - Improves space efficiency
  - Simple integration
  - Reduced installation costs

Wide Operating Range

- Consistent performance across range of flows and compositions
  - Expansion capability with significant turndown
- Cool stream utilization to eliminates need for additional equipment

1500 SCFM capacity NRU skid to process 5% N2 from the landfill (8% to the NRU)

Contaminant Resistance

- Ability to tolerate compressor oil and landfill contaminants with no loss of performance

Applications

Case Study: Glacier Ridge Landfill

Horicon, WI

- 2600+ SCFM feed (scalable to 3100 SCFM)
- In operation since Jan 2020
  - Uptime = 98%
    - overall plant for last 3 years
- 8% N_2 in the feed
  - 13% N_2 to the NRU
- 96+% CH_4 purity
- 96% CH_4 Recovery

Customer Applications

8 biogas upgrading plants operating

- 1 facility in operation on Natural Gas feed since October 2020 using Cold NRU concept

Arlington, TX

- In operation since 2019
- ABC Innovation of the Year in 2019 [11]
  - Mixed Feed (Multiple landfills and digester sources)
- 4000 SCFM feed (scalable to 5100 SCFM)
- 6% N_2 in the feed
  - 10% N_2 to the NRU
- 95+% CH_4 Recovery

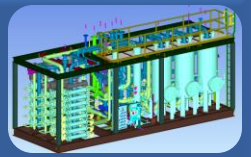
Thank you

Questions?

biogas-solutions@airliquide.com

Don't miss it at the next conference!

1) New Standard Low Flow Landfill Upgrader Introduction



2) Air Liquide talk about nitrogen rejection in conference panel

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