





Novel CO_2 Liquefaction for Small-Scale AD

March 2026

GNI Innovation Grant - CO2 Liquefaction System Final Report

Biogas, or renewable natural gas, produced from anaerobic digestion (AD), contains a mix of biomethane and CO_2. Unfortunately, most of the CO_2 is released into the atmosphere, either during combustion or during the upgrading of biogas to biomethane. Whilst there is a trend to capturing this CO_2, this has so far been restricted to very large projects.

The CO_2 produced by AD is particularly valuable because it is 100% biogenic. Biogenic refers to emissions from organic sources and, unlike fossil CO_2, does not accumulate in the atmosphere. Furthermore, when biogenic CO_2 is recovered, it is a form of carbon capture.

The challenge for this grant was to develop a technology that, in a cost-effective manner, captures biogenic CO2 from small-scale AD plants, thereby creating additional value in both financial and carbon accounting.

Bringing together **Innovatium's** knowledge in gas compression and liquefaction with the Hydrus Smart Biogas Upgrader was an opportunity to achieve this, as the CO2 from the upgrader was expected to be of very high quality, ready to be turned into liquid immediately without extra steps.

The project, led by **Innovatium,** designed a new, affordable machine to turn this gas into a liquid. By using simple, mass-produced parts, the system remains low-cost. This allows small plants to store their CO_2 and sell it to local users, turning a byproduct into a valuable resource.

Biogenic CO_2 Commercial Overview:

The market for biogenic CO_2 is shifting toward a period of significant growth, driven largely by the rise of e-fuel production and Carbon Capture and Storage (CCS). According to the Biomethane Industrial Partnership, Anaerobic Digestion (AD) will be essential in meeting this demand. Unlike the current market, which is dominated by high-purity food-grade CO_2, these emerging industrial sectors do not require the same rigorous certification, opening the door for a new, more accessible commercial grade of CO_2

Technically, biomethane plants have a distinct advantage because carbon capture is already integral to their production process, resulting in capture costs that are much lower than those of Direct Air Capture (DAC) technologies. However, the commercial challenge lies in logistics. Because AD plants are often small and geographically dispersed, transporting liquid CO_2 by truck is the most viable option, but this adds complexity and cost compared to centralised industrial hubs.

The industry's commercial viability currently faces two main hurdles: legislation and biogenic CO_2 certification. The market for non-food-grade CO_2 has been slow to develop because the necessary regulations for a "commercial grade" commodity are being implemented slowly. Furthermore, biogenic CO_2 certification, whether voluntary or otherwise, was expected to be well established by now, but it is still some way from adoption.

Despite these delays, the negative carbon footprint of AD-derived CO_2represents an untapped revenue stream, as its environmental value is expected to become a tradable asset in the evolving green economy.

Feature	**AD-Derived Biogenic CO2**	**Direct Air Capture (DAC)**
Capture Cost (per tonne)	$40 – $150 (Highly competitive)	$300 – $800+ (Early commercial stage)
Energy Intensity	Low: CO2 separation is already part of the biogas upgrading process.	High: Requires massive energy to pull dilute CO2 (420 ppm) from ambient air.
Purity & Grade	Naturally high purity; currently "Food Grade" but shifting to "Commercial."	High purity, but requires significant processing and stable renewable power.
Scalability	Limited by feedstock (organic waste) and diffuse, smaller-scale sites.	Theoretically unlimited; can be built anywhere with low-cost renewable energy.
Logistics	Challenging: Smaller volumes often require truck transport over long distances.	Optimized: Plants can be co-located with storage or e-fuel production hubs.
Primary End Use (2026)	E-fuels, regional industrial use, and horticulture.	Permanent geological storage (Carbon Removal Credits) and e-SAF.

System Overview:

The CO2 liquefaction system, intended for liquefying CO2 from the Hydrus Biogas upgrading system, was designed and built at the Innovatium East Kilbride site. The Hydrus system, designed during this project, was intended to deliver a significantly purer CO2 stream than systems typically available, thereby reducing capital and operating costs and increasing liquefaction efficiency, particularly for small- to medium-scale AD.

The project timeline and the scope of what could be tested were, however, materially reshaped by two external factors outside the team's control:

1. Delays caused by design changes in the associated Hydrus system, and
2. The intended demonstration site in Co Meath introduced commercially driven changes to the liquefaction system's specification. The most significant of these was a late requirement, originating from the site's own CO_2 off-take contract negotiations, to accommodate a much larger pressurised vertical storage tank in place of the compact trailer-mounted tank Innovatium had specified (see Addendum). Innovatium accommodated these client-driven changes and completed and built the modified system.

As set out below, it was these externally-mandated modifications, rather than the underlying design, that prevented the factory trial from being concluded.

Details of the system design and subsequent modifications are found in the addendum to this report.

System Factory Testing

To conduct a suitable factory-testing program, the control system was placed in manual mode. The liquefaction system was connected to the flow loop, pressurised to the initial condition, and the compressor pressurised the pressure reservoir, while bottled CO2 was controlled to maintain the compressor inlet pressure at ambient. Once the system pressures had been increased to those suitable for liquefaction, the refrigeration system was started to initiate CO2 liquefaction.

Unfortunately, before the refrigeration system reached the liquefaction temperature, it shut off due to a low compressor inlet temperature. This has since been interpreted as resulting from system modifications to move away from the liquid CO2 gravity feed. The pressure-feed system, which employed a liquid trap, prevented CO2 recirculation before liquefaction commenced and reduced the refrigeration system load to below its design capacity.

The built-in Panasonic chiller control system is set to protect against the return of liquid refrigerant to the compressor, as this would cause significant damage. In the initial system design, the flow of CO2 through the heat exchanger would provide the required load to exit this self-protection mode and enable the system to liquefy.

Modifications to the system to resolve this issue were considered; however, a comprehensive solution that enables automatic system startup without manual intervention would require further design and fabrication. A number of workarounds to enable testing were considered but deemed impractical.

It is important to record what was achieved: a complete liquefaction system was designed, fabricated, and commissioned for testing on a purpose-built closed-loop flow system, and a full factory test sequence was executed up to the point of shutdown. The shutdown was attributed to a single, well-understood cause: the loss of the CO_2 recirculation load following the client-mandated move away from the original gravity-feed arrangement to a pressure-feed system with a liquid trap, which reduced the refrigeration load below the chiller's self-protection threshold. The original gravity-feed design would not have been expected to encounter this behaviour (see the redesign documented in the Addendum). The fix is understood (restoring an adequate start-up load or an automated start-up sequence) and requires further design and fabrication rather than any change to the core concept. The technology is therefore de-risked to the point where the remaining work is well-defined engineering rather than open research.

Feasibility of Operational Testing in Ireland

An operational trial of the CO_2 liquefaction system in Ireland is not feasible in the short- to medium-term (the next 18 months). This is not a consequence of technical readiness but of two independent barriers, one commercial and regulatory and the other infrastructural, each outside the project's control and neither resolvable within the window. What remains outstanding is a technical operational trial in Ireland; the two barriers are set out below:

Barrier 1: The commercial and regulatory environment. A market for biogenic CO_2 cannot commence in Ireland until the EU regulatory framework for commercial-grade CO_2 and a biogenic CO_2 certification scheme are enacted. Both remain materially delayed at the EU level, with debate centred on whether a voluntary or an EU-prescribed market should prevail. In the absence of an addressable market, there is no commercial off-taker, and therefore no commercial party with reason to invest in hosting an operational plant.

Barrier 2: The absence of a commissioned feedstock source and host site. A trial requires CO_2 from a commissioned Hydrus Smart Upgrader operating at a willing Irish host, and neither is currently in place. The intended demonstration site in Co Meath has not been able to bring the biogas upgrader into operation and so has no source of CO_2 with which to facilitate the trial, and no other AD operator on the island of Ireland is presently in a position to host one. The upgrader itself is not yet commissioned: although it has operated at low flow on a manual basis, it is due to return to the UK next month for engineering changes, with no agreement or timeline for its next deployment. Even were an alternative host and a commissioned upgrader available, the CO_2 quality could not be assured, since impurities above the design specification demand lower temperatures and higher pressures than this unit was built for, which would invalidate the trial results.

These two barriers are independent, and neither can realistically be resolved within the 18-month window; nor would resolving one alone enable a trial, since a market-driven host and a commissioned, suitable feedstock source are both required. This is precisely why the project's value in this period lies in the completed design, build and de-risking of the technology, positioning it for rapid operational deployment once the enabling conditions arise.

Innovation Objectives Delivered:

The innovation at the heart of this project was substantially advanced, independent of the operational pilot:

- **A novel low-cost liquefaction system** was designed and physically realised, using mass-produced, standard-grade components (detailed in the addendum) in place of the costly specialised equipment such systems normally require. This was the central cost-reduction innovation of the proposal, and the platform from which a food-grade unit for suitable feedstocks would be built.
- **Waste-heat integration** was designed in, recovering up to 16.7 kW of usable heat for AD digester heating, materially improving whole-system economics and carbon performance.
- **Variable-rate modulation** to match the intermittent, variable CO_2 output of small-scale AD (compressor VSD control plus buffer/ride-over) was designed and built, meaning a specific technical barrier to small-scale application that this project addressed.

- **A purpose-built flow-loop test facility** was designed and built, and generated the operating knowledge that identified the start-up load issue and its solution.

Specifically regarding the grant's food-grade objective, the pilot demonstrates the liquefaction pathway on which food-grade production depends, and the food-grade capability for suitable feedstocks is an incremental, non-novel step (food-grade lubricants and product certification) rather than an unsolved problem. As detailed in the Addendum, the pilot-grade specification was adopted during the project with GNI's involvement, reflecting both the evolving nature of an innovation project and a linked change of scope at the GNI-funded Teagasc Grange demonstration facility.

The result is validated design knowledge and a physical, de-risked system (the innovation deliverables the grant was intended to produce) with only the external physical operational trial outstanding.

Conclusion:

The core objective of this grant, to design and build a novel, low-cost system capable of liquefying biogenic CO_2 from small-to medium-scale AD, was delivered. A complete system was designed, built and factory-tested, and the single cause of the incomplete trial has been identified and is resolvable through further engineering.

An operational trialling phase is not feasible in Ireland in the short- to medium-term for reasons that are external to the technology and cumulative: the absence of an enacted EU regulatory framework and biogenic-CO_2 certification scheme means no commercial market, and therefore no operational host can exist in Ireland in this period; no Irish or UK AD operator is currently able or willing to host an interim trial or guarantee suitable CO_2 quality; and the upstream Hydrus upgrader that supplies the feedstock is not yet commissioned at appropriate scale. The combination of these will not realistically be resolved within 18 months, and no single resolution would be sufficient on its own.

The concept and core technology hold strong promise for carbon capture at small- to medium-scale AD plants. The appropriate outcome for this phase of funding was therefore a de-risked, built and tested design ready for rapid operational deployment once the enabling regulatory and commercial conditions are in place, which is what has been achieved.

Addendum

System Design and Build:

To realise a low-cost system suitable for the capture of commercial-grade CO2, several steps were taken to reduce costs, and low-cost equipment was specified that is suited only to this CO2 grade. At project initiation, the system used gravity-fed liquid CO2 delivery to an external storage tank, enabling a simple, compact design. The P&ID of this system is shown in Figure 1.

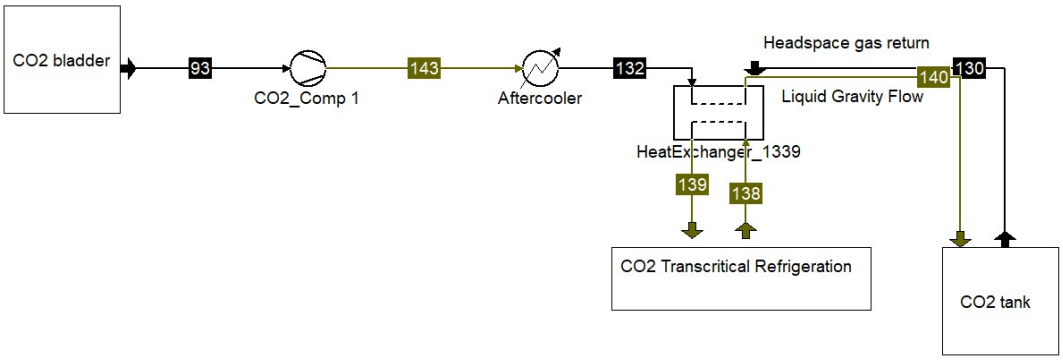


Figure 1 – Initial System P&ID

The relationship between CO2 liquefaction pressure and temperature is such that a standard compressor capable of compressing to 13 barg would require a refrigeration system capable of cooling the compressed CO2 to between -35 °C and -40 °C, depending on the CO2 purity.

A transcritical CO2 refrigeration system appeared to be the optimal choice; however, none were commercially available at the required size for this temperature range. A higher-pressure-ratio compressor able to work with available refrigeration systems was therefore required, and an oil-injected screw compressor was found to be available at the size required from Renner. Although this was a fixed-speed unit, a variable-speed drive was fitted to enable modulation that matched the liquefaction rate to that of the CO2 supplied by the biogas upgrader.

The pilot system was not designed to provide food-grade liquid CO2, so the requirements for oil-free compression were not in place. It was therefore appropriate to use an oil-injected screw and filtration system to reduce costs and increase efficiency.

The decision to build the pilot to a commercial rather than food-grade specification was taken during the project, in consultation with GNI, once several factors became clear that were not apparent at the outset. Food-grade production would require food-grade compressor lubricants together with certified food-grade testing of the product CO_2, both of which are prohibitively expensive at pilot scale while adding no technical learning. The intended end use, supply to a meat-processing client using the CO_2 in animal-slaughter operations, did not require a food-grade specification. In addition, CO_2 derived from cattle-slurry anaerobic digestion, as at the Teagasc Grange facility, is unlikely to achieve food-grade acceptance in any case. Food-grade capability is not, however, a technical barrier for suitable feedstocks. It is reached through simple, well-understood modifications, namely food-grade lubricants and product certification, that a future commercial unit can incorporate, and the pilot demonstrates the liquefaction pathway on which that capability depends.

Additionally, an expensive process compressor with double seals would not be required, as air screw compressor seals have improved to the state where leakage is minimal, and seal degradation is low. CO2 monitoring is in place, and ventilation is adequate under normal operating conditions. Inlet modifications were required to remove the standard inlet tract and filtration system and replace it with a manifold that provides a sealed connection to the CO2 inlet pipe, preventing air ingress and CO2 egress.

CO2 Comp 1 is the modified for the CO2 Renner RS-H 15 air compressor; this is speed-controlled based on the inlet CO2 flow rate. There will be an output pressure

control which will override the bladder inflation level control, with the compressor going off load if at minimum speed, and turning off after a predetermined wait time. The CO2 transcritical refrigeration package is a Panasonic OCU-CR1000VF8A-PRV; this will have a separate recirculating CO2 loop. This is set to a temperature able to be set in the controller and will control itself to achieve this temperature, causing the CO2 flow from the second stage to condense at just above this temperature, controlling the pressure from the Renner compressor and maintaining the CO2 liquid pressure in the liquid CO2 tank via condensation of the tank headspace gas via the headspace gas return line. Liquid CO2 feed to the liquid CO2 tank will be by gravity; this necessitates the use of a horizontal CO2 tank which, at its highest point is lower than the bottom of the liquefaction heat exchanger .

The system (not including the liquid CO2 tank) is housed in a 20ft container, which will have the liquid CO2 tank (not provided) situated in close proximity, ideally within 2 metres of the container. The system can be attached to a heated water system with cooling water provided at up to 30C and a CO2 feed will be required at atmospheric pressure.

The proposed flow rate of gaseous CO2 to be liquefied was based on the 80Nm^3/h biogas flow rate expected from the AD plant at the Teagasc research centre and the 45% by volume expected proportions of CO2 and Methane. The refrigeration power necessary to liquefy the calculated CO2 flowrate of 18g/s at 7kW would therefore be below the 8kW capability at -35ºC of the Panasonic OCU-CR1000VF8A-PRV. The Renner RS-H 15 compressor has the capacity to compress between 24 and 80m3/min at minimum and maximum speed, so was well suited to the duty.

The system volume was to be provided by the headspace in the liquid CO2 tank, obviating the need for a pressure reservoir which would add to the cost and size of the system. This was made possible by the gravity feed system which allowed a direct communication path between the CO2 compressor and the liquid CO2 tank.

A non-condensables purge system would be required, but was not detailed in the initial proposal and is therefore not shown on the initial system P&ID of figure 1.

The transcritical CO2 refrigeration unit was specified over systems using more common refrigerants due to its high-quality heat rejection, which could be efficiently captured and used to reduce heating gas use for the necessary heating of the biogas AD system. Though slightly more expensive and marginally lower in efficiency than other potential refrigeration systems, the overall commercial and environmental benefits accruing would be very significant over the life of the unit, and though it was beyond the remit of this project to investigate this thoroughly, it is expected that payback time associated with this equipment choice would be short. The use of

waste heat would require that the CO2 liquefaction system be situated close to the AD digestor to allow the water piping system to be acceptably low in cost.

Thermodynamic design of the system was carried out with the assistance of Dr Gábor Böszörmény of Clade Engineering Systems (https://clade-es.com/), who were manufacturers of CO2 refrigeration systems which would be suitable for commercial-scale CO2 liquefaction systems and were providing assistance to gain market and operational knowledge with a view to entering the market as the partners of Innovatium. The document - SWEP B185_78 THERMO CALCS.docx can be seen as an addendum to this report.

The Panasonic chiller unit is able to provide a significant quantity of hot water to the site for various uses including AD digestor heating, with up to 16.7kW of heat available when operating at the units 8kW refrigeration capacity. When no hot water provision is required, to operate the refrigeration unit, an alternative source of cooling is required, and this is provided by the unit's internal CO2 to air radiator. This requires substantial airflow, necessitating large ventilation panels installed in the container housing the chiller and ducting to vent the air from the container and prevent recirculation. The CO2 feed compressor is also air-cooled and requires air to be supplied via the ventilation panels and ducting to extract the heated air. Both the chiller and compressor have internal fans, so no additional fans are required. The ventilation panel sizing was specified to provide the maximum airflow required by the chiller and the CO2 compressor with minimal pressure drop.

The CO2 compressor does not have heat recovery as standard, but on commercially sized units, this would be feasible, and would add a significant extra site heating availability.

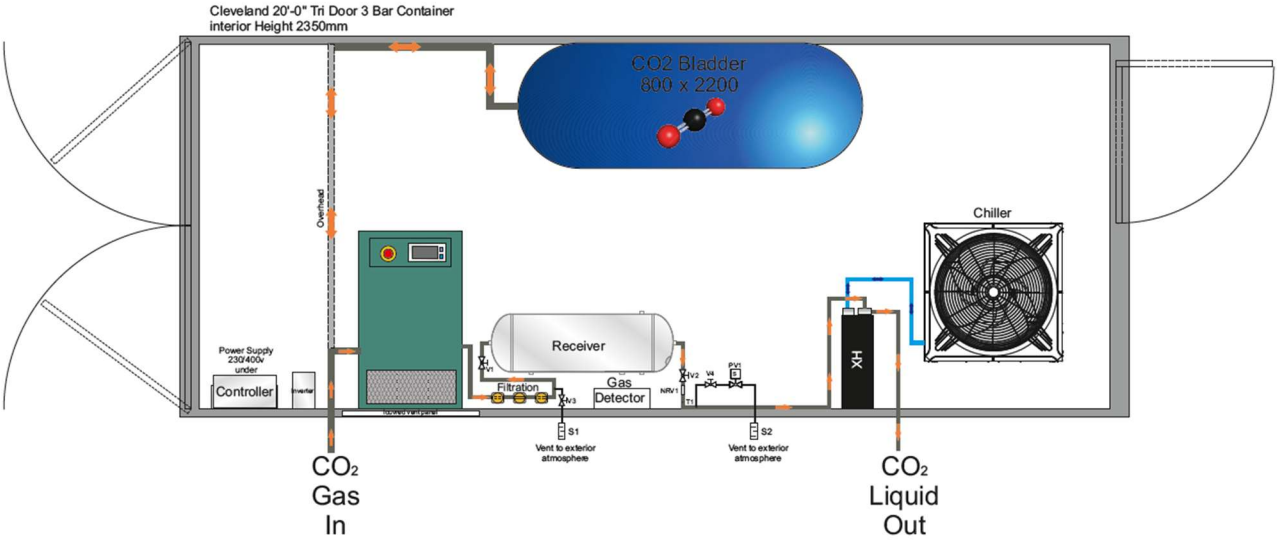


Figure 2 – Package Initial Internal Layout

During the build process, a change in design was requested to allow the use of a significantly larger CO2 tank, as the management of the Teagasc trial site was negotiating for a CO2 contract to deliver to a local stakeholder using a carrier who recommended a large vertical tank in place of the small trailer-mounted tank recommended by Innovatium. This entailed the redesign of the system with the addition of a number of functional items, including a large ambient temperature CO2 gas pressure reservoir, a liquid CO2 separation system including a liquid CO2 trap shown in figure 4, and a modified non-condensables purge system. This modified system is shown in P&ID form in Figure 3.

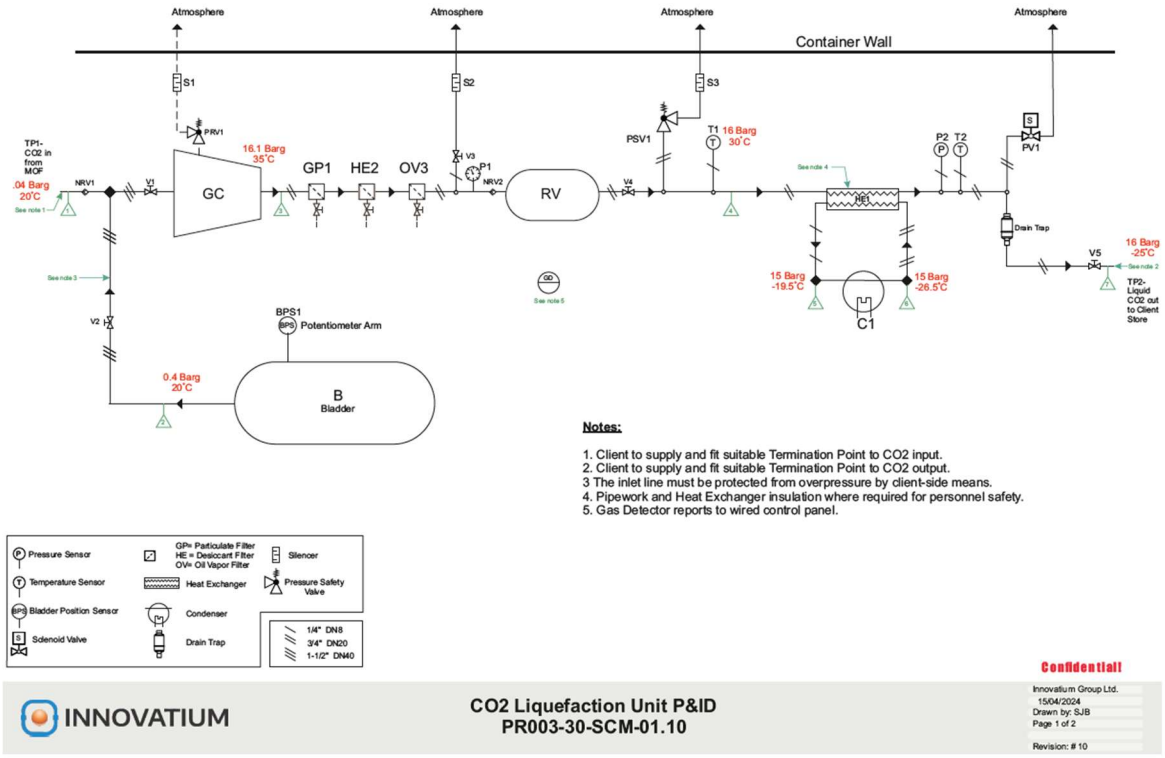


Figure 3 – Final System P&ID

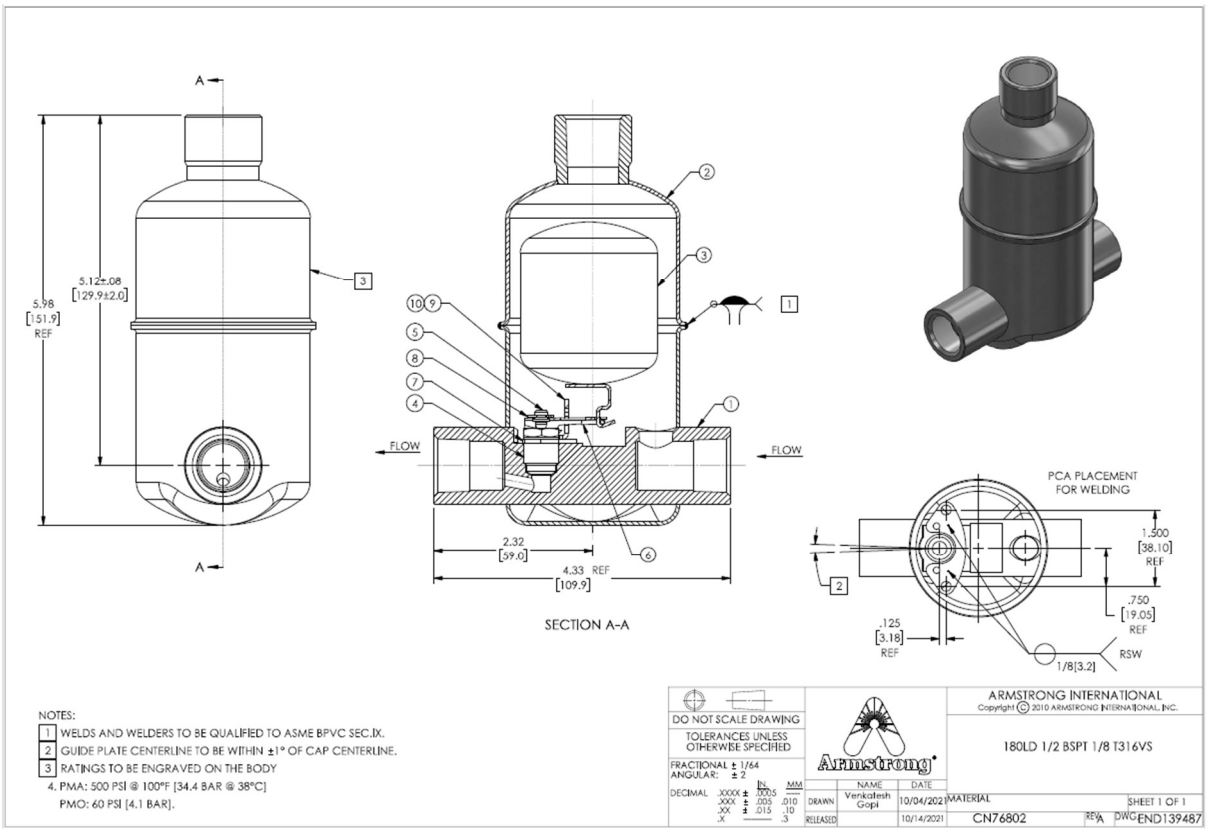


Figure 4 – Armstrong Cryogenic Liquid Trap

System Control:

For the system to modulate its capacity to match the CO2 output from the biogas upgrader, a detection method is required to adjust the liquefaction rate of the unit. The CO2 flow rate will vary with both the biogas generation rate and the CO2 content from the AD digester, and with the operation of the upgrader unit, which will have discontinuous flow during periods when the media become saturated in one contactor and the unit switches flow to the other contactor. Although this was likely to be a short period, it was unknown at the time that the liquefaction unit was in design, so the decision was made to provide a significant buffer to allow these periods to be weathered without taking the liquefaction unit offline.

The modulation and ride-over capabilities were intended to be provided by the use of an approximately 1m^3 bladder which would remain at a mostly inflated condition and have a monitoring and control system to maintain it in this condition. This took the form of a control arm that rested on the top of the bladder and measured its inflation using a potentiometer connected to the controller. When the bladder exceeded the desired inflation level, the CO2 compressor would increase its speed to match the

incoming CO2 flow, and vice versa. When the flow from the upgrader was periodically interrupted by contactor switching, the compressor flow could be supplied by the bladder for approximately 1 minute. It was not known whether this would be adequate in all scenarios; however, increasing the bladder size could extend the time period if required, though the bladder and control arm would then likely need to be mounted outside the container.

The refrigeration system is self-regulating to maintain the required liquefaction temperature and automatically adjusts to match the CO2 flow rate to the heat exchanger.

Although the CO2 supplied to the liquefier will be relatively pure, with trace amounts of nitrogen and methane (predicted to be below 0.2%), which do not liquefy at the CO2 liquefaction temperature, these gases will tend to accumulate in the heat exchanger. The relative concentration of these gases in the heat exchanger will increase over time, which will decrease the condensation temperature of the CO2, leading to greater power input requirement from the refrigeration system.

If no action is taken to remove these non-condensable gases, once the maximum capacity of the refrigeration system has been reached, the pressure within the heat exchanger will begin to rise due to the flow provided to it from the CO2 compressor being modulated based on the flow able to be provided by the biogas upgrading system.

At higher pressures, condensation can be sustained until the system is unable to liquefy all incoming CO2, at which point the CO2 compressor will shut down due to reaching its maximum operating pressure.

In order to maintain system operation, it is necessary to periodically vent these non-condensable gases – the system pressure and temperature within the heat exchanger is continually monitored. When the temperature falls below a set value for the current pressure, a purge valve will open and vent these non-condensable gases and a small amount of CO2 to the atmosphere.

Flow Loop Test Facility

To facilitate system testing at the Innovatium East Kilbride site, a dedicated flow loop was designed and constructed. This took the liquid CO2 from the liquefaction system, heated it to ambient temperature at 16 barg storage pressure, depressurised it to approximately 3 barg (causing further cooling), and then reheated it to ambient temperature. This was routed via a buffer tank to a depressurisation valve, which

reduced the pressure to ambient, after which it was reintroduced to the liquefaction system.

The heating of the CO2 before and after pressure reduction from 16Barg to 3Barg took place using approximately 5 metre long flexible hoses immersed in a heated water bath. Before the system was filled with CO2 from bottles, it was evacuated with a vacuum pump to remove non-condensable gases. It was ensured that, during evacuation, all parts of the system remained in communication to prevent any pockets of non-condensables. A hand valve was installed in parallel with the pressure-reduction valve between the two heating flexibles to enable this, and the valve was closed before testing.

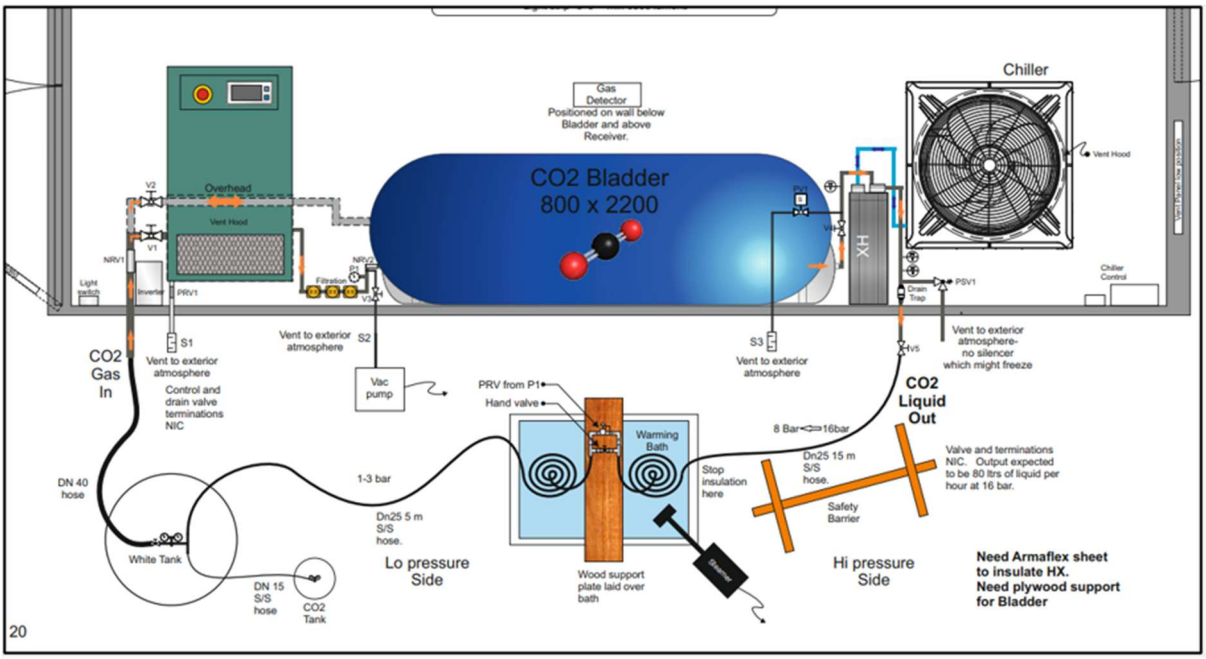


Figure 5 – Flow Loop

NOVA Q

INNOVATIUM

SWEP

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CASCADE - DESIGN
HEAT EXCHANGER: B185Hx78/1P

SWEP DThermX
Date: 21/08/2023

SSP Alias: B185H

DUTY REQUIREMENTS		Side 1		Side 2
Fluid		R744 (Carbon Dioxide)		R744 (Carbon Dioxide)
Flow type				
Circuit		Inner		Outer
Heat load	kW		8.100	
Subcooled liq. temp.				
Inlet vapor quality		0.570		1.000
Outlet vapor quality		1.000		0.000
Inlet temperature	°C	-26.46		30.00
Evaporation temperature (dew)	°C	-26.50		
Superheating	K	7.00		
Condensation temperature (dew)	°C			-24.70
Subcooling	K			0.00
Outlet temperature	°C	-19.50		-24.72
Flow rate	kg/s	0.05978		0.02312
• Inlet vapor	kg/s	0.03407		
Fluid vaporized	kg/s	0.02570		
Fluid condensed	kg/s			0.02312
Pressure drop (Design PD)	kPa	2.21 (30.00)		1.20 (30.00)

PLATE HEAT EXCHANGER		Side 1		Side 2
Total heat transfer area	m²		5.75	
Heat flux	kW/m²		1.41	
O.H.T.C. (available/required)	W/m²,°C		1180/685	
Pressure drop - total*	kPa	2.21		1.20
- in ports (Inlet/Outlet)	kPa	-0.0194/0.0756		-1.21e-3/427e-6
Pressure drop in fluid distribution	kPa	0.000 - 0.000		
Operating pressure (outlet)	kPa	1600		1700
Number of channels per pass		38		39
Number of plates			78	
Oversurfacing	%		72	
Port diameter (up/down)	mm	33.0/33.0		50.0/50.0
Recommended inlet connection diameter	mm	6.54 - 10.3		5.15 - 11.5
Recommended outlet connection diameter	mm	8.53 - 19.1		3.74 - 7.48
Outlet Port velocity	m/s	1.76		
Port velocity	m/s			0.362
Channel velocity	m/s	0.133		0.0610
Largest wall temperature difference	K		0.14	
Min./Max. wall temperature	°C	-26.34/-3.44		-26.33/-3.34

*Excluding pressure drop in connections.

NOTES

! *Vapor velocity is lower than recommended, this can have impact on oil transport.*
! *SWEP does not recommend to select B-type evaporator with large number of plates.*

PHYSICAL PROPERTIES		Side 1	Side 2
Reference temperature	°C	-26.49	-24.70
Liquid • Dynamic viscosity	cP	0.155	0.151
• Density	kg/m³	1061	1053
• Heat capacity	kJ/kg,°C	2.101	2.117

Photographs



Package external view



CO2 feed compressor and inverter



Panasonic Transcritical CO2 Refrigeration Unit



View showing liquefaction heat exchanger, reservoir, deflated butyl bladder



System controller

Attachments - control system documentation.