21GRD06 MetCCUS

A2.2.8 - REPLICATION OF CO_2 EMISSIONS USING A CONTROLLED RELEASE FACILITY TO EVALUATE MEASUREMENT METHODS AT BOTH THE COMPONENT AND SITE SPATIAL SCALE

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Due date of the deliverable: 31 July 2025

Actual submission date of the deliverable: 02 September 2025

The project has received funding from the European Partnership on Metrology, co-financed by European Union Horizon Europe Research and Innovation Programme and from the Participating States.

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Summary

This report details the results from two controlled release test campaigns conducted as part of activity A2.2.8 of MetCCUS.

The first part of the report covers the execution and results gathered from a controlled release campaign to replicate site scale emissions of CO_2. The work was conducted at the Centre for Dairy Research (CEDAR), Reading, UK in November 2024, and evaluated the performance of the tracer dispersion technique for quantifying large spatial and large emission rate releases.

The second part of this report presents work undertaken in May 2025, at NPL, which involved replicating CO_2 leaks at the component scale. Controlled releases of carbon dioxide were performed on two test rigs to assess the performance of various detectors and to quantify known CO_2 release rates using the Bacharach Hi-Flow sampler in combination with the AERIS analyser. Measurements were conducted using Optical Gas Imaging (FLIR G343), passive handheld detector (Sefram 9825), high flow sampling (Bacharach Hi-Flow with AERIS CO_2/N_2O analyser.

Table of Contents

1 Introduction

This report provides an overview of two separate controlled gas release test campaigns focused on the detection and quantification of CO_2 leaks using various measurement technologies. The work was conducted as part of MetCCUS, Activity 2.2.8.

The first campaign was conducted in November 2024 at the Centre for Dairy Research (CEDAR). This involved a series of large-scale CO_2 release trials, with flow rates ranging from 14.20 kg/h to 22.66 kg/h. These tests were designed to validate the capability of methods which may be applied to measuring total site industrial CO2 emissions.

The second campaign took place in May 2025 at the National Physical Laboratory (NPL). These tests focused on the controlled simulation of CO_2 leaks using NPL's Controlled Release Facility (CRF) and were designed to evaluate the performance of various CO_2 detection instruments. Three detection devices were used: the Sefram 9825, a CO_2 Optical Gas Imaging (OGI) camera, and the AERIS analyser. For quantification purposes, the Bacharach Hi-Flow Sampler (BHFS) was used in conjunction with the AERIS analyser to measure leak rates. Two test rigs were employed to replicate realistic field leak conditions. The objective was to assess the response time, sensitivity, and quantification accuracy of these detection systems under precisely controlled conditions. The CRF enabled safe, repeatable releases of CO_2 at known flow rates, ensuring consistent and reliable performance evaluation. Tracer correlation methods were also applied at multiple field tests to develop a methodology and test the tracer gas correlation method as a tool for quantifying diffuse CO_2 emissions throughout the CCUS process chain.

2 Component Scale Assessment

2.1 Methods

2.1.1 Controlled release facility

For testing at CEDAR involving large CO_2 releases, NPL's Controlled Release Facility (CRF) was used, while for lab-scale testing, the smaller Controlled Release Facility (MidiCRF) was utilised. Both systems are based on arrays of mass flow controllers (MFCs)

The required gas flow rates were achieved using the NPL Controlled Release Facility (CRF) and Midi Controlled Release Facility (MidiCRF, SN:NPL0002954). The CRF and MidiCRF are NPL designed systems for the mixing, dilution and metered delivery of gaseous species to atmosphere, and incorporates a number of thermal mass flow control (MFC) devices. For these tests one MFC on the CRF nominally 500 litre/minute and four MFC on the MidiCRF nominally 0.025 litre/minute, 0.25 litre/minute, 5 litre/minute and 50 litre/minute at full scale flow devices were used for the delivery of the pure carbon dioxide, were calibrated with the pure carbon dioxide using 5 litre/minute to 500 litre/minute, 0.005 to 0.5 litre/minute and 0.5 to 50 litre per minute volumetric flow calibrators DryCal ML 1020, DryCal BIOS ML 800-10 and ML 800- 44 (all MFCs calibrated for gas at T = 0 °C). The gas was supplied by BOC Group plc and was of 'Commercial Product' grade carbon dioxide, with a minimum purity of 99.995%.

2.1.2 Optical gas imaging camera

A FLIR Optical Gas Imaging (OGI) camera was used to ascertain whether leaks of CO_2 are visible at a variety of leak flow rates. The OGI operates by detecting the presence of carbon-hydrogen bonds through their interaction in infrared radiation (IR), whereby for each particular compound can be identified by particular spectral bands. For this particular model (G343), uses High-Sensitivity Mode which makes CO_2 stand out more clearly from the background, by filtering for the 4.2-4.4 µm spectral range.

2.1.3 Sefram 9825

The Sefram 9825 is a handheld carbon dioxide (CO_2) meter based on a dual-wavelength non-dispersive infrared (NDIR) sensor. It is primarily designed as an indoor air-quality and room-monitoring instrument, but in this study it was used as a portable, diffusion-based detector to assess whether localised CO_2 increases from controlled leaks could be detected near the source.

The instrument measures CO_2 concentration over a range of 0–30 000 ppm with a resolution of 1 ppm. According to the manufacturer, the stated accuracy at (23 ± 5) °C is ±(75 ppm + 3 % of reading) between 0 and 5 000 ppm and ±(150 ppm + 5 % of reading) from 5 001 to 30 000 ppm, with a typical response time of 20 s and a sampling interval of 2 s. In addition to CO_2, the probe integrates temperature and relative humidity sensors, and the device includes a built-in audible alarm and an internal datalogger capable of storing up to 32 000 records.

During the component-scale tests at NPL, the Sefram 9825 was operated as a passive handheld detector, without an external sampling pump. The probe was positioned close to suspected leak points

(tube outlet and test-rig components) and moved slowly along the potential leak path while monitoring the CO_2 concentration relative to background. The objective was to determine, for each controlled release condition, whether the instrument provided a clear, repeatable indication of a leak (qualitative "detection") rather than to perform quantitative leak-rate estimation. The relatively long response time means that its performance is more suited to steady or slowly varying leaks; for the smallest flow rates and for short exposures, readings were more strongly affected by local air movement and plume dispersion.

2.1.4 Aeris MIRA and Bacharach Hi-Flow Sampler

The Aeris MIRA Series analyser operates in the middle infrared (MIR) region to simultaneously monitor N_2O and CO_2, this absorption region is significantly stronger than in the near-IR region. The Aeris samples from 2 ports and has autonomous built-in calibration and zero cycles. It logs continuously and takes readings every millisecond.

The BHFS (Bacharach Hi-Flow Sampler, hereby known as BHFS or Hi-Flow) has been on the commercial market since 2001 and have been utilised for natural gas (NG) emissions campaigns. The instrument was developed initially for measurement of NG streams with a composition of primarily methane (CH_4). The BHFS operates by drawing in a measured volume of air around a suspected leak using various attachments at an intake of 200-250 L/min. During sampling it is assumed the entire leak is captured and diluted with background air. This sample volume passes across an orifice and the resulting pressure drop is recorded. From this pressure drop the sample flow rate is calculated. A portion of this sampled flow is draw into a concentration sensor. This concentration measurement sensor works in two modes, whereby the first mode operates via catalytic oxidation (CO) up to 5.9% CH4, and the second mode uses thermal conductivity (TC) from this point up to 100%.

This sampling methodology has been translated to the sampling of gases other than CH_4 or NG. The internal plumbing of the Hi-Flow can be altered so that the sampling tube which originally supplied the internal concentration sensor for NG is plumbed into the external port. This reconfiguration ensures the integrity of the instrument and is safety features remain legitimate. Gas detection instruments can then be connected to this external port whereby the detect the selected gas species concentration within the given flow rate.

From previous work (2.2.6), it can be assumed that with a sampling rate of 200 L/min with a leak rate greater than 0.01 L/min will incur uncertainties of <5%. As with previous test bench experimentation, the leak rate was calculated by the below equation, whereby the background concentration of CO_2 was set to 500 ppm and the sample concentration is the largest value indicated by the Aeris when in combination with the Hi-Flow.

$$Leak\ rate = Measured\ total\ flow * (sample\ concentration - background\ concentration)$$

2.2 Equipment specifications

Table 1 displays the equipment used and their uncertainties.

Table 1: Test equipment and relevant specifications.

Equipment	Item	Calibration date	Uncertainty
Flowmeter	BIOS DryCal ML800 10 (SN:178265), ML800 44 (SN:180539) ML 1020	31/1/2025	Expanded Uncertainty: 0.18%
CRF	MFC 04	04/11/2024	± 13.40 L/min, CO_2 gas
MidiCRF	MFC 02	12/05/2025	± 0.001 L/min, CO_2 gas
	MFC 06	12/05/2025	± 0.012 L/min, CO_2 gas
	MFC 09	12/05/2025	± 0.034 L/min, CO_2 gas
	MFC 10	12/05/2025	± 0.777 L/min, CO_2 gas
Sefram	Sefram 9825 SN: 2024100508	12/05/2025	Manufacturer specification ±(75 ppm + 3 % of reading) (0–5 000 ppm), ±(150 ppm + 5 % of reading) (5 001–30 000 ppm)
AERIS Hi Flow sampler			

The expanded uncertainties for the CRF and MidiCRF reported in **Error! Reference source not found.** are based on standard uncertainties multiplied by a coverage factor, *k*, equal to 2, to give a confidence level of approximately 95%.

2.3 Test set up

2.3.1 Controlled release facility

The controlled release experiments were carried out at the Controlled Release Facility (CRF) located at CEDAR. The facility is specifically designed to simulate a wide range of gas emission scenarios under controlled and repeatable conditions.

As shown in Figure 1, the CRF setup at CEDAR allows for large-scale gas releases, providing a realistic environment for testing the performance of various leak detection and quantification technologies. The gas supply for the controlled releases was provided through pressurised cylinders, as illustrated in Figure 2.

The overall configuration of the experiments, including the positioning of the Ring Node relative to the test area, is depicted in Figure 3. The Ring Node, shown in detail in Figure 4, served as a central point for CO_2 release during several of the test runs.

As part of MetCCUS activity 2.28, two experimental setups were used to evaluate the performance of different leak detection instruments. In the first configuration, leak detection was carried out directly

at the outlet of a release tube using an Optical Gas Imaging (OGI) camera and a Sefram device (Figure 5). In the second configuration, the same instruments were deployed to detect leaks from a purpose-built test rig designed to replicate real-world emission sources (Figure 6).

These experimental setups enabled a comprehensive evaluation of detection capabilities under varied flow conditions, providing valuable insights into the effectiveness of each technique in practical field scenarios.

Figure 1: Controlled Release Facility (CRF) setup for conducting large controlled releases at CEDAR.

Figure 2: Controlled release setup with gas cylinders.

Figure 3: Configuration of the controlled release experiments at CEDAR showing location of Ring Node.

Figure 4: Ring node for CO_2 release

Figure 5: Leak detection from a tube outlet using an OGI camera and Sefram device.

Figure 6: Leak detection using an OGI camera and Sefram device on a test rig.

2.3.2 Aeris and Hi-Flow Sampler

In this test series, the midiCRF was used to produce known flow rates (table 3) for CO2 from specified leaking components on NPL's test rig. In this experiment, the leaking components assessed where a compression fitting and a flange (Figure 7 left and right respectively). Target leak rates of 5, 25, 50, 100 and 1000 mL/min were assessed with the Aeris alone and then the Aeris/Hi-Flow configuration. As shown in 2.2.6, the Aeris has demonstrated quick responses to application of target gas species (average response time of 17 s) and records automatically at a frequency of every millisecond.

For each leak rate, the leak was approach with the Aeris, and readings allowed to stabilise. The Aeris was then removed and allowed to stabilise to ambient air conditions. The Aeris was then connected to the Hi-Flow exhaust, and the leak was approached with the Hi-Flow's hose with slanted pipe attachment and Aeris readings were allowed to stabilise. Once stabilised, the measurement was saved on the Hi-Flow so that the flow rate was recorded appropriately. This was then repeated for all target leak rates. The methodology used for how to suitably sample from leaking components has been adapted from that outlined in BS-EN 15446. While outside the scope of this scope, for the highest leak rate (30000 mL/min), an assessment of the capture of the leak with a selection of Hi-Flow attachments was undertaken. Whereby both the plunger and then bag, in addition to the slanted pip attachment, were used during the Aeris/Hi-Flow configuration measurements.

Figure 7: Leak detection Aeris and Aeris/Hi-Flow combination on a test rig. Aeris/Hi-Flow measurement of leaking compression fitting (left) and Aeris measurement of leaking flange (right)

2.3.3 OGI camera

Before measurements with the OGI camera was taken, meteorological information such as weather and temperature where recorded and wind speed data was collected through the use of a portable monitor. For each leak type, the camera was set at a set distance and a video taken, and it was noted if the leak was visible.

2.4 Critical orifice

NOVA FCT METROVAC (Laboratory for Vacuum Technology and Metrology) provided a calibrated orifice which simulates low flow leak rates of carbon dioxide. The orifice (CO2_SC_20240315) contained a stainless-steel capillary within a stainless-steel tube to restrict flow and was fitted with a dust filer on either end.

Two different tests with the capillary were performed, one with the orifice freestanding and the leak measured directly from the capillary (figure 8), the second test had the orifice connected to the fugitive emissions rig, to simulate a leak found at a potential gas transmission facility (figure 9).

For both tests a digital pressure gauge was connected upstream of the capillary to measure the pressure differential and therefore determine the flow rate.

Figure 8 (left): Set up of the calibrated orifice in test 1 sampling directly from the source & figure 9 (right) sampling with the fugitive emissions leak rig

2.5 Results

2.5.1 Controlled release data from Cedar

Table 2 shows the results of three controlled CO_2 release tests using Ring Node at CEDAR under varying conditions to assess the response of different measuring instruments. The release rates differed across the tests, with the highest at 192.35 l/min, followed by a lower rate of 120.54 l/min, and a moderate rate of 145.81 l/min.

Table 2: Controlled gas release data with expanded uncertainty

Date	Test #	Start time (UTC)	End time (UTC)	Release rates					
				Ring Node - CO2					
				CO2 (l/min)	Std U. (l/min)	Exp. U. (l/min)	CO2 (kg/h)	Std U. (kg/h)	Exp. U. (kg/h)
19/11/2024	1	10:44:57	12:13:04	192.35	5.98	13.40	22.66	0.70	1.58
	2	12:36:56	14:14:12	120.54	4.39	9.44	14.20	0.52	1.11
	3	14:19:05	15:49:42	145.81	4.92	10.74	17.18	0.58	1.27

The expanded uncertainties reported in Table 2 are based on standard uncertainties multiplied by a coverage factor, k, equal to 2, to give a confidence level of approximately 95%. The reported uncertainty takes into account the uncertainty in the purity of the source gas, the repeatability of MFCs, and the volumetric calibration of MFCs.

2.5.2 Controlled release data using test rigs

A series of experiments were conducted at the controlled release facility using two different test rigs to simulate real-world leak scenarios. Measurements were taken both from the test rigs and directly from the outlet of the release point when not connected to any rig, allowing assessment of instrument sensitivity under various conditions. The objective was to evaluate the performance of different detection techniques, including Optical Gas Imaging (OGI), Sefram, and AERIS. CO_2 flow rates were varied between 0.005 L/min and 42 L/min to represent a range of emission scenarios. Emission quantification was subsequently carried out using the Hi-Flow sampler. Table 3 summarises all the controlled releases conducted during these tests.

Table 3: Controlled gas release data with expanded uncertainty

Date	Release #	Start time (BST)	End time (BST)	Release rates CO_2		
				Emission rate (l/min)	Std U. (l/min)	Exp. U. (l/min)
20/05/2025	1	11:03:53	11:24:58	0.0054	0.0004	0.0010
	2	11:40:22	12:00:45	0.0494	0.0005	0.0012
	3	12:00:59	12:08:08	0.0244	0.0005	0.0012
	4	12:08:23	12:15:36	0.0993	0.0006	0.0013
	5	13:21:41	13:44:35	1.017	0.0143	0.034
	6	13:46:40	13:51:09	5.04	0.3201	0.78
	7	13:52:14	13:52:36	42.2	0.5575	1.2
	8	13:57:57	14:12:44	0.0054	0.0004	0.0010
	9	14:12:58	14:22:26	0.0244	0.0007	0.0015
	10	14:25:09	14:42:08	0.0993	0.0006	0.0013
	11	14:44:36	14:50:54	5.04	0.3201	0.78
	12	14:54:18	14:59:23	27.54	0.4329	0.94
	13	15:01:44	15:14:47	0.2463	0.0009	0.0020
	14	15:15:01	15:18:25	0.0993	0.0006	0.0013
	15	15:18:47	15:22:11	0.0244	0.0005	0.0012
	16	15:24:44	15:28:00	0.0054	0.0004	0.0010
21/05/2025	1	10:14:57	10:24:01	0.0054	0.0004	0.0010
	2	10:26:04	10:35:34	0.0242	0.0005	0.0012
	3	10:35:51	10:43:34	0.0992	0.0006	0.0013
	4	10:46:18	10:55:08	1.017	0.0143	0.034
	5	10:58:32	11:05:27	Nominal flow (5000) not achieved due to restrictions		
	6	11:08:34	11:15:38	0.0054	0.0004	0.0010

	7	11:17:18	11:24:21	0.0242	0.0005	0.0012
	8	11:24:37	11:34:57	0.0492	0.0005	0.0012
	9	11:35:13	11:41:03	0.0992	0.0006	0.0013
	10	11:42:26	11:49:13	1.017	0.0143	0.034
	11	13:27:35	13:38:09	0.0054	0.0004	0.0010
	12	13:39:49	13:48:54	0.0242	0.0005	0.0012
	13	13:49:19	14:00:19	0.0492	0.0005	0.0012
	14	14:00:35	14:10:06	0.0992	0.0006	0.0013
	15	14:11:44	14:19:03	1.0172	0.0143	0.0337
	16	14:22:03	14:30:12	5.05	0.3201	0.78
	17	14:31:43	14:41:21	29.2	0.7310	1.5
	18	14:45:34	14:49:14	29.2	0.7310	1.5
	19	14:49:30	14:50:35	5.05	0.3201	0.78
	20	14:53:04	14:53:44	1.017	0.0143	0.034

The expanded uncertainties reported in Table 3 are based on standard uncertainties multiplied by a coverage factor, *k*, equal to 2, to give a confidence level of approximately 95%. The reported uncertainty considers the uncertainty in the purity of the source gas, the repeatability of MFCs, and the volumetric calibration of MFCs.

2.5.3 OGI camera

Table 4 indicates whether the leaks were detectable via the OGI camera at certain nominal leak rates and distances from leak. Figure _ depicts how the leaks are visualised through the camera, at high leak rates the leaking gas is clearly visible as a plume rising upwards and being dispersed by wind. However, at lower leak rates (5 mL/min), leaks can easily be missed or are indecipherable from thermal currents in the image background.

Table 4: OGI imaging results

Diameter of release orifice (mm)	Wind Speed (m/s)	Nominal Leak Rate (mL/min)	Distance from Leak (m)	Leak Detectable?
4.03	<1	5	1	×
4.03	2	50	1	✓
4.03	1.5	25	1	✓

4.03	<0.5	100	1	✓
4.03	<0.5	1000	1	✓
4.03	0	5000	1	✓
4.03	<1	50000	1	✓
4.03	0	5	1	✓
2.5	1	30000	2.5	✓
2.5	1	5000	2.5	✓
2.5	1	1000	2.5	✓

Figure 10: Still images of CO_2 controlled releases taken with G320 OGI camera for: a high leak rate (left, 5000 mL/min) and at low leak rate (right, 5 mL/min)

2.5.4 Sefram

The behaviour of the Sefram 9825 handheld CO_2 indicator was assessed during all component-scale trials at NPL, including tests directly at the tube outlet and on the two leak-replicating rigs (compression fitting and flange). The intention of this assessment was not to quantify leaks but to determine how reliably the device can signal their presence across the range of controlled release rates used in this campaign.

At very short distances from the source (typically within a few centimetres), the Sefram responded consistently to leaks down to 5 mL/min. Although the rise above background was small at the lowest flows, the device showed a discernible signal when the probe passed directly through the plume, especially under low-ventilation conditions. As the imposed flow increased (≥25–50 mL/min), the detector produced progressively clearer and more stable responses, with obvious peaks as the probe crossed the main gas jet. For the highest leak rates tested (≥1 000 mL/min), the instrument often reached the upper part of its range at close proximity, confirming strong sensitivity to moderate and large emissions.

When used on the test rigs, the Sefram reliably flagged leaks from the loose compression fitting for all releases of 25 mL/min and above. The signal increased qualitatively with the release rate, and the plume could be repeatedly located by scanning around the fitting. The flange presented a more challenging geometry: for very small leaks (5 mL/min), the detector showed no consistent indication above ambient. Between 25 and 100 mL/min the leak was detectable, but the signal varied more with probe position, reflecting the more diffuse plume structure at the flange compared with the compression fitting.

Distance had a strong influence on the Sefram's performance. Beyond roughly 10–15 cm from the source, only the larger flows produced clear responses. Smaller leaks were rapidly diluted and became indistinguishable from background fluctuations. This trend matches previous laboratory observations for passive handheld detectors, which rely on the operator physically sweeping the probe through the plume.

In summary, the Sefram 9825 is well suited for qualitative leak localisation at the component level when the operator can scan close to the potential source. Under the controlled conditions of this activity, it consistently identified CO_2 releases of approximately 10–30 mL/min and above. However, because the reading depends strongly on probe placement, airflow and plume shape, the instrument cannot support quantitative leak-rate estimation. Instead, it serves as a practical and low-complexity tool for routine screening and pinpointing of leaks, complementing the more accurate quantification techniques (Aeris and Hi-Flow) and the visual detection provided by OGI imaging.

2.5.5 Aeris and Hi-Flow Sampler

The table below indicates the reference leak rate from the MidiCRF, the expanded uncertainty associated with that reference leak rate and the measure volumetric leak rate calculated from the Hi-Flow sampler and Aeris combination. For the measurements of leak rates of 5 mL/min, no increase above background CO2 levels were detected, indicating that the flow rates are too small to be measured through this method. Agreement between the target reference leak rate and the measured volumetric leak rate is better for leak rates of 100 mL/min and below. There is poor agreement at leak rates greater than this, particularly for 5000 mL/min and 30000 mL/min where calculated leak rates are half of that of the reference leak rate. This can likely be attributed to the inability to achieve full capture at higher leak rates, whereby the flow rate of the Hi-Flow is insufficient in its ability to capture a true representation of the leaking gas.

Agreement, particularly at 1000 mL/min and below, appears to be greater for measurements of leaks from the loose compression fitting compared to the leaking flange (figure 11 and 12). This again can be attributed to the sampling methods, and the difficulty in achieving full capture on leak from components with difficult geometries.

Table 5: Results of Aeris/Hi-Flow configuration leak detection at component spatial scale

Leak ID	Reference Leak Rate (L/min)	Expanded uncertainty (L/min)	Measured Volumetric Leak Rate (L/min)
Leaking flange	0.024	0.001	0.024
Leaking flange	0.049	0.001	0.054
Leaking flange	0.099	0.001	0.085
Leaking flange	1.017	0.034	0.696
Leaking flange	5.046	0.777	2.473
Leaking flange	29.220	1.462	14.966
Loose compression fitting	0.024	0.001	0.022
Loose compression fitting	0.049	0.001	0.049
Loose compression fitting	0.099	0.001	0.104
Loose compression fitting	1.017	0.034	0.945

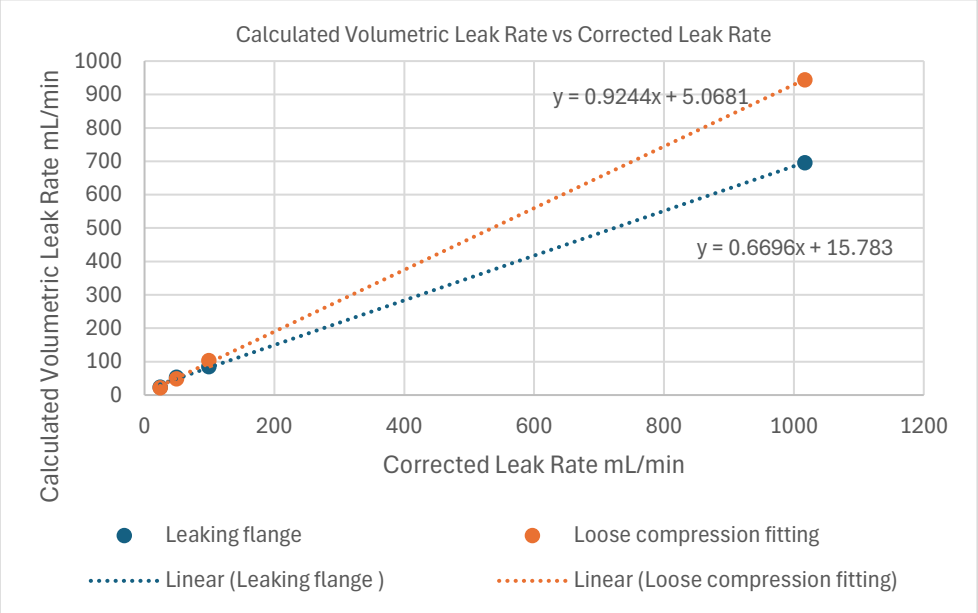


Figure 11 calculated volumetric leak rate plotted against corrected leak rate for leak rates of nominal value 25, 50, 100 and 1000 mL/min for each leaking component

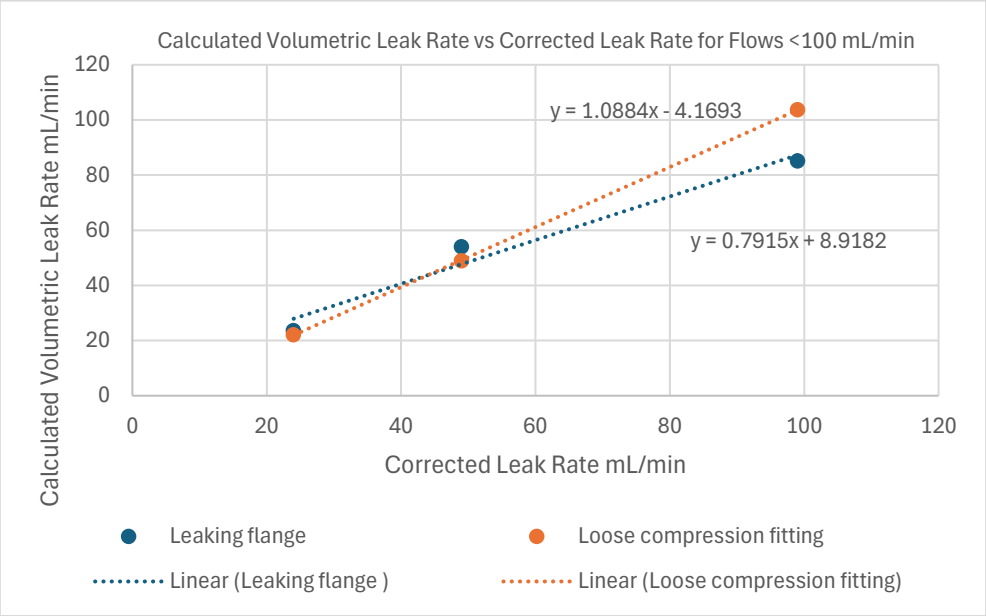


Figure 12 calculated volumetric leak rate plotted against corrected leak rate for leak rates of nominal value 25, 50 and 100 mL/min for each leaking component

2.5.6 Critical orifice

Figure 13 shows the measured leak rate using the Aeris and Hi-Flow sampling system against the calibrated flow rate produced by NOVA FCT.

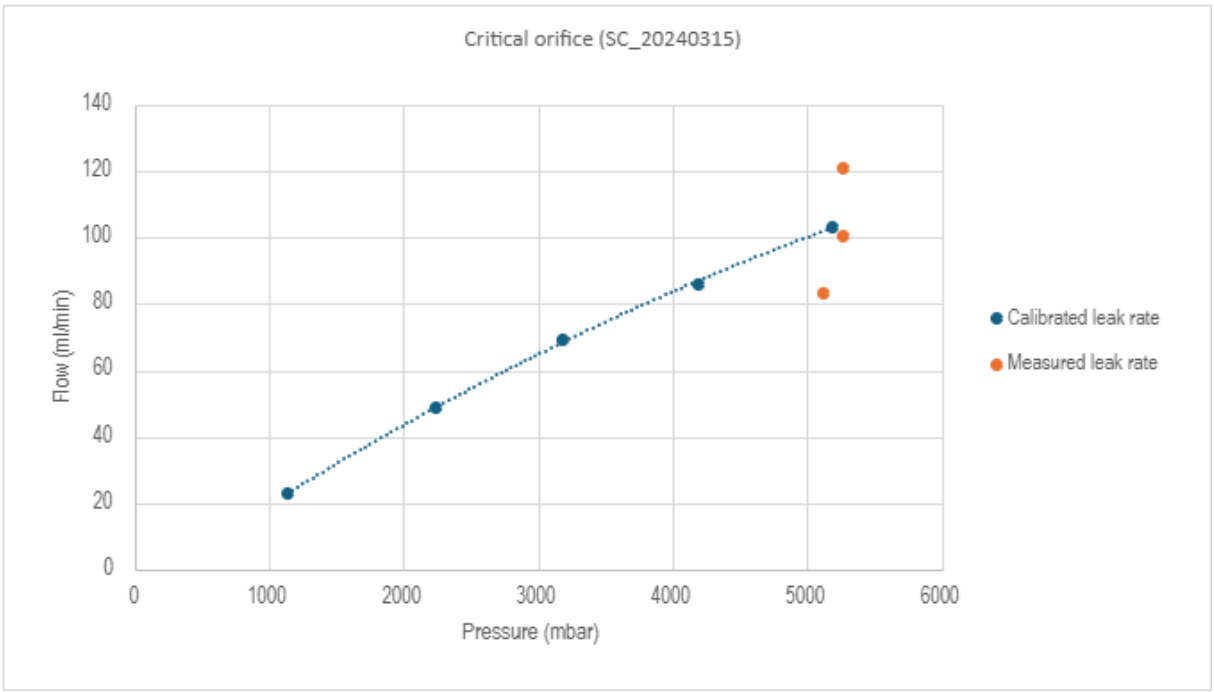


Figure 13. Calibrated leak rate against the measured leak rate derived from the critical orifice.

As the leaking gas passes through the leaking component, this will cause an increase in the pressure inside a close volume. The leak rate Q is calculated by the pressure rise using the equation:

$$Qt = -\Delta p_0 V ln(1 - \frac{\Delta p(t)}{\Delta p_0})$$

Where V is the volume, t is the time, Δp_0 is the initial pressure difference and $\Delta p(t)$is the pressure recorded through the reporting period.

2.6 Conclusions

3 Site level assessment

3.1 Methods

The tracer correlation method involves co-releasing a known tracer gas alongside CO_2 and measuring their concentrations downwind. By comparing the measured ratio of CO_2 to the tracer and knowing the tracer's release rate, the CO_2 emission rate can be calculated:

$$Q_{CO_2} = Q_{tracer} * \frac{[CO_2]}{[tracer]}$$

Where Q_{CO_2} is the emission rate of CO_2 in g/s, Q_{tracer} is emission rate of known tracer release gas in g/s and $[CO_2]$ and $[tracer]$ are the measured concentrations downwind adjusted for their molar masses.

3.2 Equipment specifications

The instrumentation used during this test series for quantifying diffuse CO_2 emissions utilising the tracer gas method. The best available instrument for the continuous and remote measurements of CO_2 and N_2O and an instrument for measurement of very low concentrations of the chosen tracer gas acetylene (C_2H_2).

3.2.1 Aeris MIRA

As previously outlined within 2.2.6, the Aeris MIRA CO_2/N_2O analyser is a compact, high precision gas analyser designed for the simultaneous measurements of both carbon dioxide and nitrous oxide by deploying mid-infrared laser absorption spectroscopy, alongside water vapour (H_2O). As seen in 2.2.6, this instrument offers fast response times and has shown excellent stability in field campaigns.

The instruments compact design and low power draw make it an ideal candidate for mobile and field-based campaigns such as diffused emissions quantification. In the tracer gas correlation setup, the Aeris was used to measure CO_2 and N_2O simultaneously, allowing for direct estimation of both CO_2 and N_2O when used as the tracer gas.

Table 6. Instrument specification for Aeris MIRA CO_2/N_2O analyser

Measurement principle	Mid-infrared laser absorption spectroscopy
Gas species specificity	Carbon dioxide (CO_2), nitrous oxide (N_2O) and water vapour (H_2O)
Precision	Typically 200 ppb for CO_2 and 200 ppt for N_2O (1 s integration); improves to ~20 ppb/ppt over 5 min
Species measurement ranges	N_2O from a few ppb to hundreds of ppm; CO_2 from ppm to percentage levels

Power consumption	Approximately 20–25 W, suitable for portable operation
Start up time	Approximately 1 minute after power-on
Features	Internal data logging, Wi-Fi/USB connectivity, automatic dry-mole fraction reporting (humidity correction)

3.2.2 Picarro G2203

The Picarro G2203 (Picarro, Inc.) is a high precision gas analyser based on Cavity Ring-Down Spectroscopy (CRDS) designed to specifically for simultaneous measurements of methane (CH_4) and acetylene (C_2H_2)., along with water vapour (H_2O). It is widely used in tracer gas correlation experiments where C_2H_2 is released as a known tracer, used to quantify diffuse emissions of CO_2 and CH_4.

In field tests, the G2203 was deployed to detect C_2H_2 as the tracer gas. The instruments sensitivity and stability enabled clear differentition between the background and plume concentrations to be seen. This allowed for accurate tracer-to- CO_2 ration calculations for emission rate estimation.

Together with the Aeris, the G2203 provided complementary measurements covering CO_2, N_2O, CH_4, and C_2H_2. This configuration is optimised for multi-species tracer correlation studies of diffuse CO_2 emissions.

Table 7 instrument specification of Picarro G2203 analyser

Measurement principle	Cavity Ring-Down Spectroscopy (CRDS)
Gas species specificity	Methane (CH_4), acetylyene (C_2H_2), and water vapour (H_2O)
Precision	CH_4 <3 ppb (5 s average); C_2H_2 <1 ppb (5 s average)
Response time	<5 s
Power requirements	~120 W (steady-state) plus external pump (~150 W)
Dimensions	≈ 43 × 18 × 45 cm; weight ≈ 27 kg
Features	Integrated water-vapor correction; outputs dry mole fractions

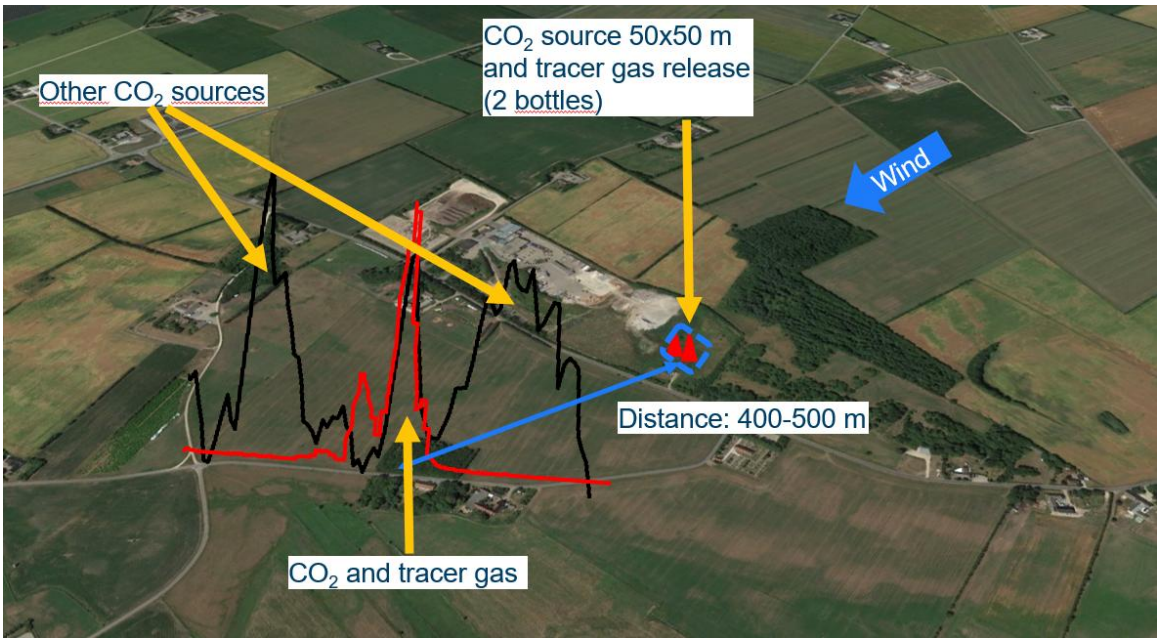
3.3 Test set up

This methodology was tested at two facilities with diffuse CO_2 emissions and at a controlled release setup, including release of multiple gases.

First facility was a wastewater treatment plant, where CO_2 was emitted from the aeriation tanks during aeriation. The emission area was approx. 140 x 160 m.

Figure 14: The measured wastewater treatment plant (left) including the measurement road (red line) and the tracer gas placement (orange marks).

The second facility measured was a biocover at a landfill. The biocover was receiving landfill gas with the purpose to oxidize the methane in the landfill gas to CO_2. The flow of landfill gas to the biocover was known and the methane slip through the biocover was measured using the tracer correlation



method. The CO_2 release area (biocover) was approx. 50 × 50 m and the diffuse emission of CO_2 was calculated to approx. 60 kg/h. The distance to the measurement road was 400-500 m. Figure 15 shows the downwind plume of CO_2 the tracer gas.

Figure 15. Tracer release at biocover and the CO_2 and tracer gas downwind plumes 400-500 m. from the release/emission.

The third test was conducted as a controlled release, performed in Reading, UK in November 2024. Controlled release of CO_2, N_2O, CH_4, C_2H_6 and C_2H_2 were done, but only CO_2, N_2O and C_2H_2 were relevant for this study. CO_2 and C_2H_2 were used for testing the tracer correlation method for quantifying CO_2, while N_2O was used for identifying the downwind plumes when the CO_2 release were not high enough for the instrumentation to measure the concentration increase in the downwind plume. The gases were released on a field and the closest road for measuring the downwind plume was approx. 500 meters away.

3.4 Results

The measurements at the wastewater treatment plant showed a good agreement between the CO_2 and the tracer gas plumes and showing a CO_2 emission about 1500 kg/h. The measurements were done 200-300 meter downwind from the emission area. The limiting factor for quantifying lower emission rates is the CO_2 analyser, needing approx. 1 ppm of CO_2 to quantify the CO_2 peak. Under the conditions at the wastewater plant, the CO_2 peaks were around 20 ppm and thus, the quantification limit was about 20 times lower than the measured emission: 1500 kg/h / 20 = 75 kg/h.

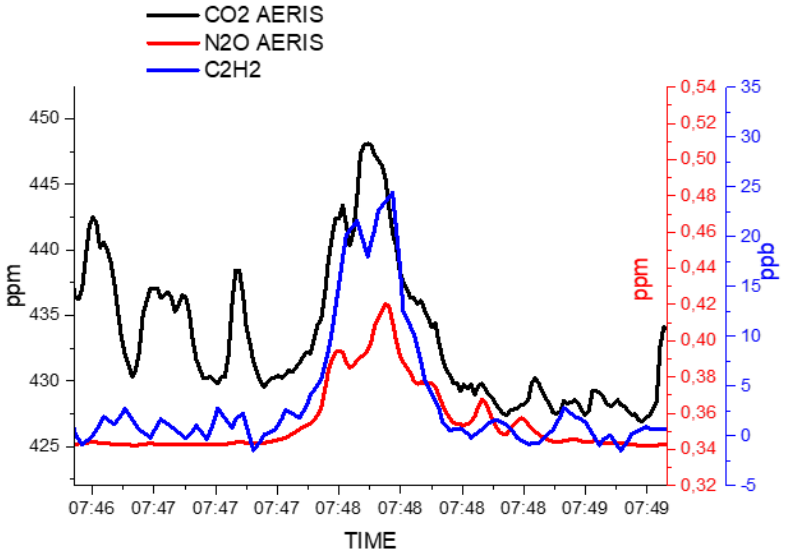


Figure 16. Example measured concentrations of CO_2, N_2O and the tracer gas (C_2H_2) in the downwind plume at first test facility.

The CO_2 release area at the biocover site was approximately 50x50 m and the diffuse emissions of CO_2 were calculated to be approximately 60 kg/h with the measurement distance of 400-500m from the plume. As seen in figure 17, the emission was measured to be approximately 65 kg/h. Under the conditions at the measurement day, the limit of quantification was approx. 5 times lower than the measured emission, thus about 12 kg/h.

Figure 17. represents the measured downwind plumes (4) of N_2O and the corresponding CO_2 concentration at the third facility. The first N_2O plume seems to have a matching CO_2 plume, but this is by chance that another CO_2 source gave a plume at the same time. A zoom on plume number two is shown in Figure 18, revealing a possible CO_2 plume with a peak height of about 1 ppm.

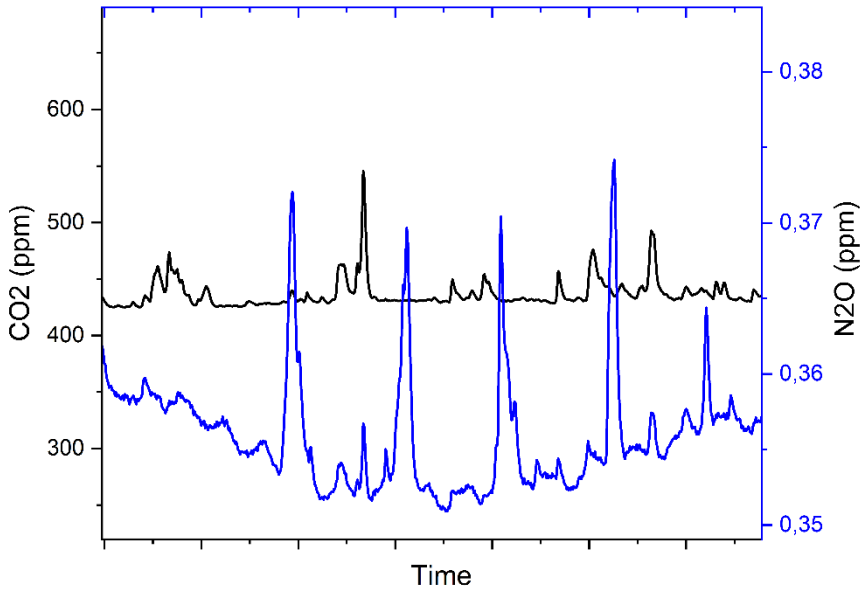


Figure 17. Downwind concentrations of N_2O and CO_2 approx. 500 meters from the controlled release area near Reading in Nov. 2024. Four plumes of N_2O but limited/no matching CO_2 plumes.

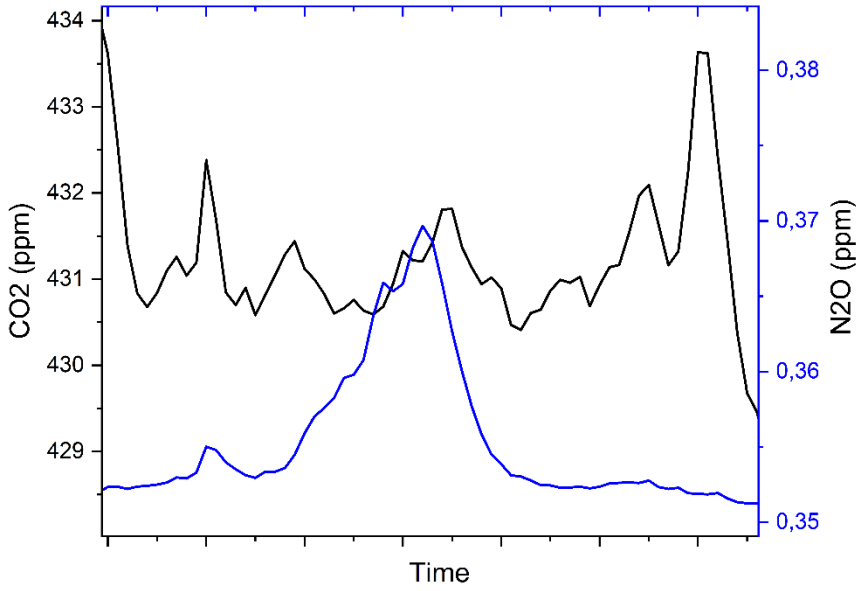


Figure 18. A zoom on the second peak in Figure 3, showing a possible matching CO_2 concentration to the N_2O concentration.

3.5 Conclusions

The first two field tests demonstrated the feasibility of the use of tracer correlation for diffuse CO_2 emissions quantification. However, emissions from large areas, such as the wastewater treatment plant, require high emission rates (upwards of 75 kg/h) to reach the quantification limit. The approximately 10 times smaller biocover site, showed a quantification limit of around 12 kg/h at the slightly further distance. The controlled relase test showed that the relwased amount of CO_2 was not nearly large enough to reach the lower limit of quantification. It is also seen that atmospheric stability and distance from the source strongly influence the detection sensitivity.

The key to generating reliable quantification of emissions rate are emissions rates exceeding 100 kg/h, measurements must be performed close to the source and should be conducted during atmospherically stable periods such as at night.

The main limiting factor is the CO_2 concentration resolution of available instrumentation relative to ambient CO_2 variability. Additionally, wind turbulence and background sources can obscure weak diffuse emissions. Electric vehicles (EVs) and UAVs offer advantages in minimizing contamination and improving mobility around sources. However, traffic on the measurement road is the main source of "noise" in the CO_2 signal and this traffic is difficult to control.

The tracer gas correlation method is a robust technique for quantifying large amount of diffuse CO_2 emissions when properly optimized. Tests confirm its viability and sensitivity under specific atmospheric conditions. For better quantification limits, enhancing the instrument resolution for CO_2 would give the biggest improvement, thus future available instrumentation might enable even better measurement possibilities for the tracer correlation method and CO_2 emissions.

4 Sustainability

As part of NPLs ambition to improve its sustainability, several initiatives are being undertaken to improve the accuracy of greenhouse gas reporting. As the work detailed in this report involved the direct or indirect release of greenhouse gases to atmosphere, the species, quantity, date location and purpose will be reported to the corporate sustainability team.

Table 4: Record of greenhouse gases released to atmosphere

Greenhouse gas species	Total mass released (kg)	Date(s) releases were made	General location of releases	Purpose
Carbon dioxide	81.96	19/11/2024	CEDAR	MetCCUS
Carbon dioxide	1.37	20/05/2025, 21/05/2025	NPL	MetCCUS