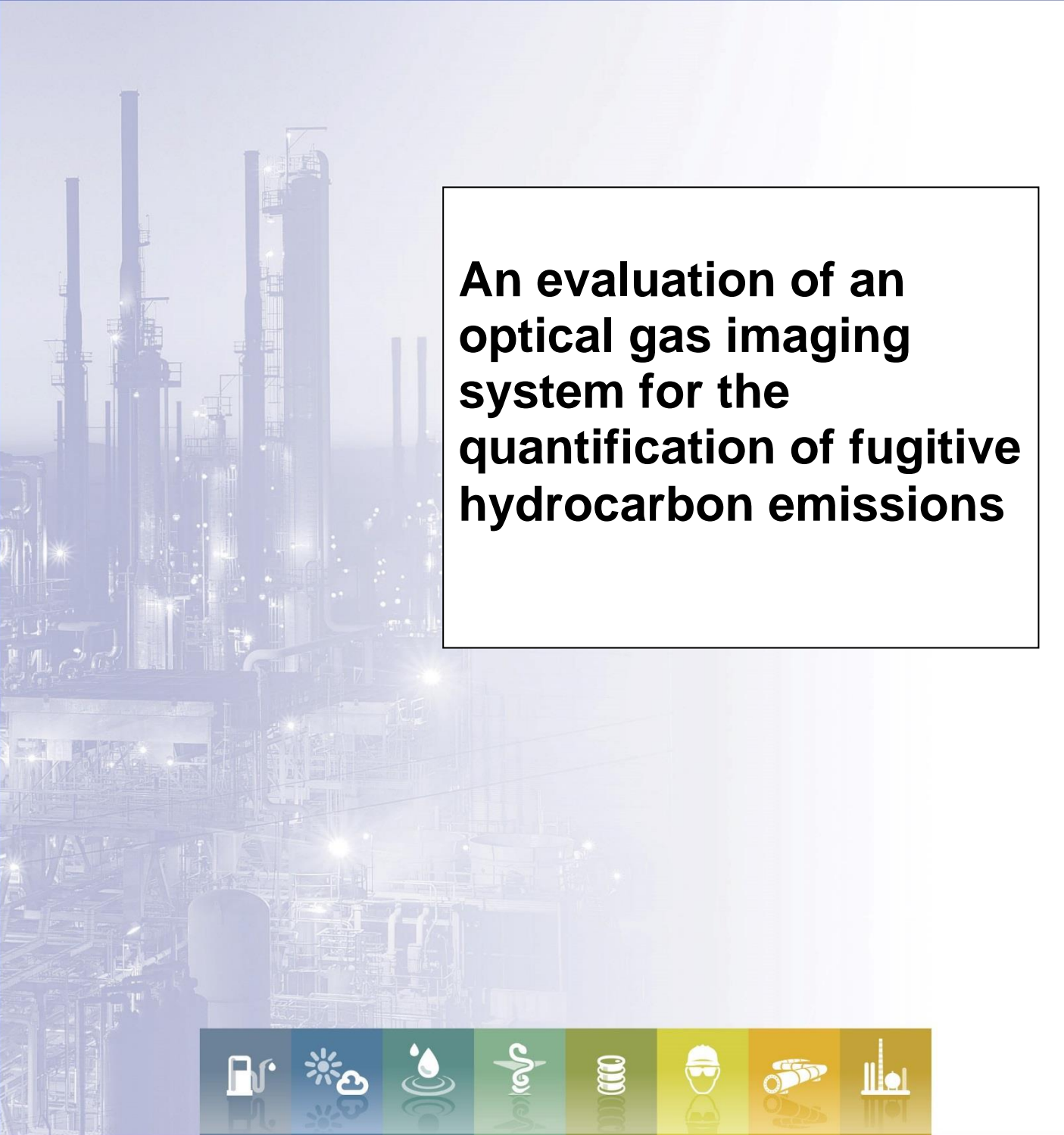


report

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An evaluation of an optical gas imaging system for the quantification of fugitive hydrocarbon emissions



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An evaluation of an optical gas imaging system for the quantification of fugitive hydrocarbon emissions

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ABSTRACT

This report provides the results of a preliminary study undertaken to test the performance of a quantitative optical gas imaging (QOGI) system. This has been developed to measure the mass emission rate of hydrocarbon leaks from industrial process equipment.

Testing was performed using controlled releases in the range 1.7 g/h to 1000 g/h. For comparison purposes a conventional sniffing technique was also used for leak detection with emission estimates determined using the correlation equations from US EPA Method 21.

Sixty one leak tests were performed. The QOGI system detected all of these leaks but it was found that quantification required a differential temperature of $> 5^{\circ}\text{C}$ between the released gas and the background.

Where leak rate quantification was achieved with the QOGI system the differences between the values determined and the known release rates were within a range of -23% to 69%, with an average difference of 6%. By comparison, where the US EPA Method 21 correlations were used to estimate leak rates these differed from the known release rates within a range of -92% to 667%, with an average difference of 31%.

KEYWORDS

Fugitive emissions, quantification, LDAR, optical gas imaging, OGI, quantitative optical gas imaging, QOGI, refinery.

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SUMMARY

This report presents the results from the preliminary testing of a quantitative optical gas imaging (QOGI) system, consisting of an infrared optical gas imaging (OGI) camera and a quantification module. The QOGI system allows an operator to detect and quantify mass emission rates of hydrocarbon gases.

The objective of this study was to assess the ability of the QOGI system to detect fugitive emission sources and to quantify their mass release rates using a number of controlled but realistic releases. The study was conducted at VITO's leak detection and repair (LDAR) training facility in Mol, Belgium in Summer 2015.

OGI cameras allow leaks of hydrocarbon substances to be visualised, which can be very useful when conducting LDAR programs. The operating principle is straightforward and uses the fact that hydrocarbon gases absorb infra-red light. If gas passes between the camera and a reference surface, light is absorbed by the gas and an image will be formed. OGI cameras are very good visual tools, but currently their use in LDAR programs is limited to detection as they are considered to be applicable only for qualitative monitoring.

The QOGI technology used for this study [7] is a patented technology designed to work with the FLIR GF 300/320 series of infra-red (IR) cameras [5]. The QL100 quantification module uses the image information from a OGI camera and supplementary data (distance from camera to leak source, environmental conditions and gas optical properties) to calculate the hydrocarbon mass emission rate. This QOGI system is designed to fulfil the needs of an LDAR program to detect hydrocarbon leak sources and determine their mass rates of release.

The LDAR installation was used to generate controlled hydrocarbon releases simulating leaks of varying sizes from different process plant components (i.e. valves, open-ended pipes and flanges). The release rates ranged from 1.7 to 1000 g/h. All the gas releases took place at ambient temperature. Because the QOGI technique uses naturally occurring infra-red radiation and not a reference source of radiation (an 'illuminant'), a wide range of camera positions, weather conditions and background scenes were explored. For comparison purposes, a conventional sniffing technique (EN 15446:2008) [1] was used for leak detection and the US EPA Method 21 (Correlation Approach) [9] was used to estimate the emissions of the leaking components.

A total of 61 scenarios were explored in two test periods:

The first series of tests (hereafter called the 'pre-test') used the normal backgrounds available at the test facility with the aim of identifying conditions suitable for detection and quantification. A total of 37 releases were carried out.

The second series of tests (hereafter called the 'full test') introduced some artificial backgrounds where necessary to enhance the difference in temperature between the background surface and the ambient air. A total of 24 releases were carried out.

The results showed that all 61 releases could be detected using the camera even though the environmental conditions were such that there was little difference between the temperatures of the gas and the background facility structure which included various built materials. This is fully consistent with experience with the FLIR GF 300/320 camera series that gas can be detected if there is temperature difference as small as 1 to 2 degrees between the gas and the contrasting background.

The QOGI system provided quantified leak rates for 31 of the 61 detected releases. This is because quantification requires a greater temperature difference, ΔT , between the gas and the background than for detection. From these tests it was found that the current technology required a $\Delta T > 5^{\circ}\text{C}$ in order to successfully quantify emissions.

In the pre-test period, 7 out of the 37 release scenarios were quantified by the QOGI system and for each of these scenarios the ΔT was in excess of 5°C .

In the full test period all 24 release scenarios were quantified by the QOGI system with the backgrounds being adjusted when necessary, using a temperature enhancement device, to ensure $\Delta T > 5^{\circ}\text{C}$.

It is foreseen that ΔT will be an important criterion or Data Quality Indicator (DQI) for any QOGI method. Furthermore, when a specific test method is developed for QOGI, a refined criterion for ΔT must be considered.

Where leak rate quantification was achieved with the QOGI system, the differences between the values determined and the known release rates were within a range of -23% to 69%, with an average difference of 6%. By comparison, where the US EPA Method 21 correlations were used to estimate leak rates these differed from the known release rates within a range of -92% to 667%, with an average difference of 31%.

Overall the QOGI results from this evaluation were very promising. This was a demanding test of the technique because there was no operational heat release on the test facility and hence both the released gas and all surfaces were close to ambient temperature. Work needs to be done to refine the criterion that ΔT has to be $> 5^{\circ}\text{C}$ to achieve quantification and also to identify quick and effective means of providing an enhanced background to increase ΔT when needed. On an operational site with heat release and fluids at process temperatures the likelihood of needing such action is less than during the controlled release conditions. This should be considered as a factor in future investigations.

The QOGI technology evaluated in this study was still in the development stage at the time of these tests in June of 2015. It is recommended that further testing using the latest version of the technology is undertaken in field conditions. .

1. INTRODUCTION

1.1. CURRENT USE OF OPTICAL GAS IMAGING (OGI)

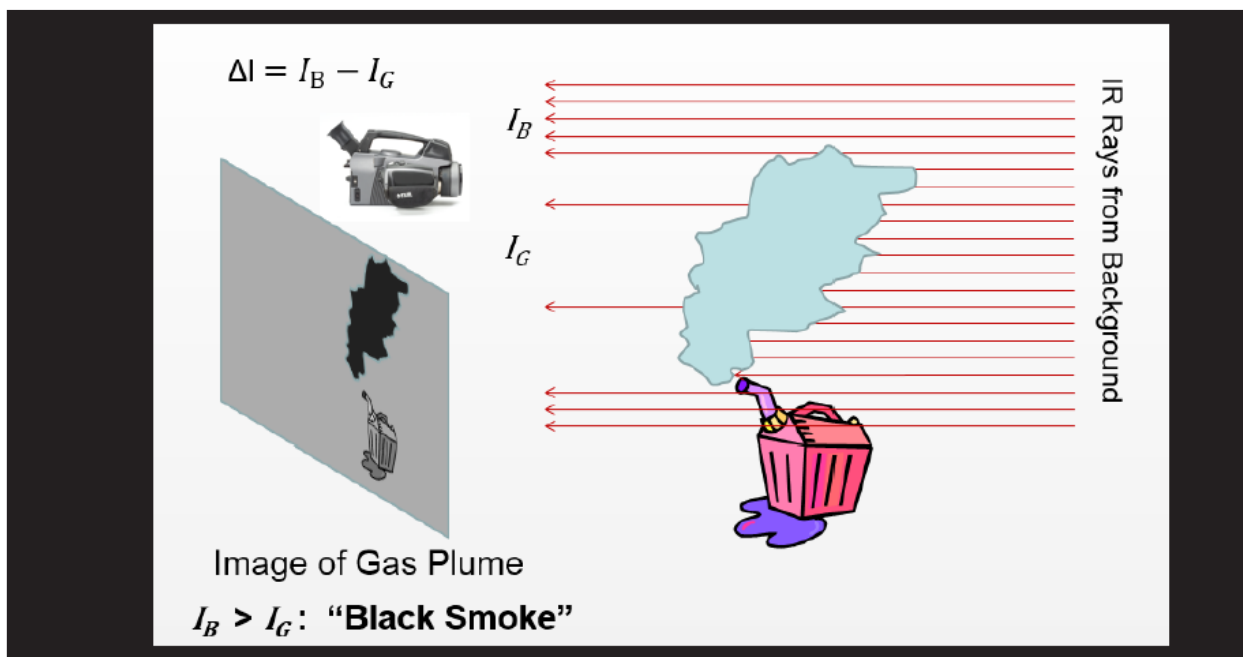
Infrared cameras have gained increasing application in recent years in the oil and gas (O&G) industry for their ability to rapidly detect leaking equipment. As well as their use in LDAR programmes, OGI inspections are typically performed after maintenance activities, to investigate odour sources, follow up on alarms from other sensors, etc. OGI therefore now plays an important role in the safety and environmental programs in both upstream and downstream oil refining and also petrochemical facilities.

In the petrochemical sector, the US EPA has promulgated an Alternative Work Practice (AWP) [10] which allows operators to use OGI as part of an LDAR program. However, the productivity advantage of using OGI in US LDAR programs is negated by the requirement to also perform Method 21 at least once annually. Hence, there are no facilities in the US currently utilizing OGI in LDAR programs. In Europe, OGI is considered as a Best Available Technique (BAT) for LDAR (in the refining BREF [4] and in the common waste water and gas treatment/management BREF [3]). There are some European countries that accept OGI as a stand-alone method for LDAR.

1.2. OGI OPERATING PRINCIPLES

The operating principle of the OGI camera is to detect the absorption of infra-red light by a gas plume. The base infra-red signal originates from a background, shown uniform in **Figure 1** below. Infra-red (IR) radiation flux is related to temperature. If the background is warmer than the released gas ($I_B > I_G$) then the gas appears dark; if it is cooler the gas appears white.

Figure 1 Impact of gas plume on infra-red signal from background (I_B = background Intensity, I_G = Gas Intensity) [12] (Courtesy of Providence Photonics)



The OGI camera differs from other instruments that use light absorption to detect VOC emissions in that it uses background radiation as the source of radiance. Therefore, for an image to be recorded there must be a temperature difference (ΔT) between the gas and the background. Other techniques, e.g. differential infra-red absorption (DIRA), use a controlled radiant source and at least two wavelengths, one absorbed and one not absorbed, to make an absolute measurement of the amount of light absorbed by the molecules in the light path between the camera and background. Such systems either use a fixed radiation source and sensor or, for more easy alignment, a retro-reflector and co-aligned sensor and source.

Another feature of the OGI camera is its narrow bandpass filter. A given gas is only detected if its infra-red absorption spectrum overlaps the absorption band of the camera. The minimum detection limit for a given gas depends on the number of molecules between the camera and the background.

For more details of the OGI camera used for these tests, see reference [5].

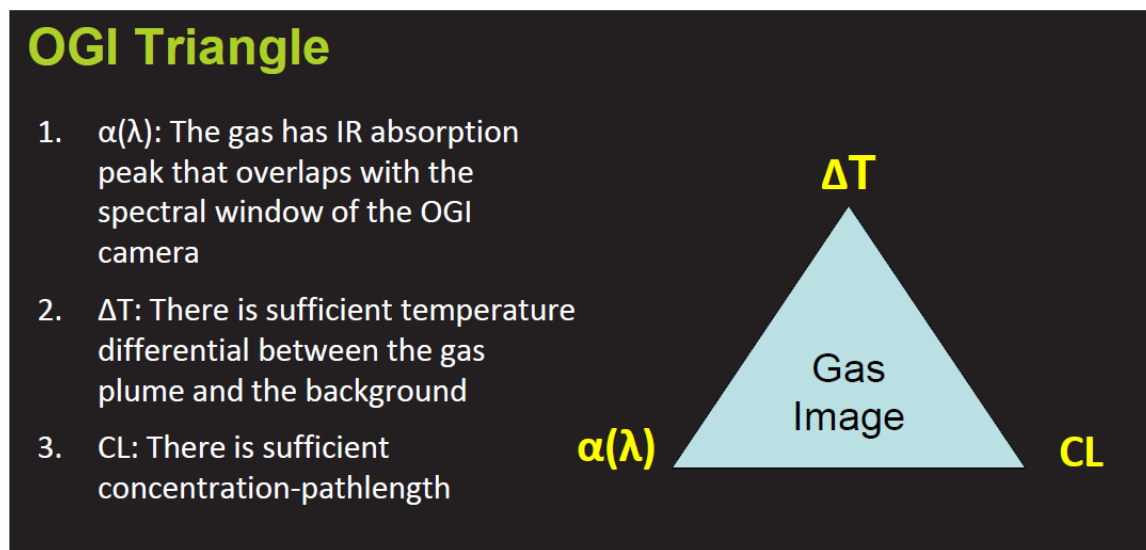
1.3. QOGI METHOD: FROM QUALITATIVE TO QUANTITATIVE

In a step beyond using OGI for detection purposes only, a new methodology for deriving an emission rate from an OGI camera image has been developed [7]. This Quantitative Optical Gas Imaging (QOGI) system uses a conventional OGI camera coupled to an external device that runs analysis software. Prior to QOGI, OGI techniques were effective visual tools but had limited application for LDAR compliance since they were only qualitative. Consequently the American Petroleum Institute (API) developed OGI leak/no-leak factors [6] to permit the quantification of VOC emissions rates from leaks detected by an OGI camera.

Two parameters affecting the performance of the QOGI system to detect and quantify releases (see **Figure 2**) are the temperature difference between the released gas and the background (ΔT) and the total number of molecules in a line of sight through the plume to the background, referred to as concentration-path length (CL). This path-integrated concentration is measured using the brightness of each pixel in the image. The system will have detection/quantification limits represented by a minimum value of CL and this minimum value can be expected to decrease as ΔT increases.

A further parameter, considered fixed in this work, is the sensitivity of the camera to the wavelength that is absorbed. This is set using a specific wavelength filter on the camera matched to the target gas. Because many hydrocarbons have similar absorption spectra, response factors can be used to account for different target gas compositions.

Figure 2. The parameters that can affect the performance of the QOGI system [12] (Courtesy of Providence Photonics)



1.4. STUDY OBJECTIVE AND OVERVIEW

This Concaawe report describes the first evaluation trials of QOGI in a European context. A series of controlled releases, comprising realistic simulations of emissions from process plant leaks, were carried out at the VITO LDAR training facility. A QOGI system was used to detect and quantify the releases found and the results compared to the known release rates. Additionally, a traditional sniffing method was used to detect the emissions and the Method 21 correlations were used to provide calculation-based leak estimates for comparison purposes.

The parameters in **Table 1** were explored to determine how the technology performs under a variety of conditions. Similar conditions were used in earlier controlled tests performed by Concaawe [2] and are believed to be representative of field LDAR.

Table 1 Key parameters and variables explored during testing

Key Parameters	Types / Ranges
Background scene	brick wall, concrete, metal, sky
Leaking component	flange, valve, open-ended pipe
Volatile organic gas	methane, propane, propylene, a mixture of the three (~33% each)
Leak rate	1.7 – 1000 g/h
Camera distance from leak source (meters)	2, 3, 5 and 10

Test matrices were developed to encompass a combination of the aforementioned parameters resulting in a total of 61 testing scenarios. Backgrounds similar to those found in refineries, such as concrete and pipe/metalwork, were used. The range of leak rates generated reflected the range of emissions that might be observed in the field. Propane, propylene, methane and a mixture of these 3 gases were used to generate the leaks.

For each test release the OGI camera was used to scan for and detect the source of emission. When a leak was detected, images of the leak were recorded by the OGI camera (attached to a tripod to steady the image) and the QL100 device was connected via a USB cable to the OGI camera to analyse the IR camera images and to calculate the emission rate of the leaking gas in g/h (see **Figure 3**). For each leak, three scans of 30 seconds each were recorded and the average leak rate determined.

Meteorological conditions, i.e. wind direction and speed, ambient air temperature, relative humidity and the barometric pressure, were measured using an All-in-One Compact Weather Station. Using a common date/time reference the data were logged every 10 seconds to allow for synchronisation with the recorded plume images.

Figure 3 Set-up of QOGL system used during the study (Courtesy of Providence Photonics)

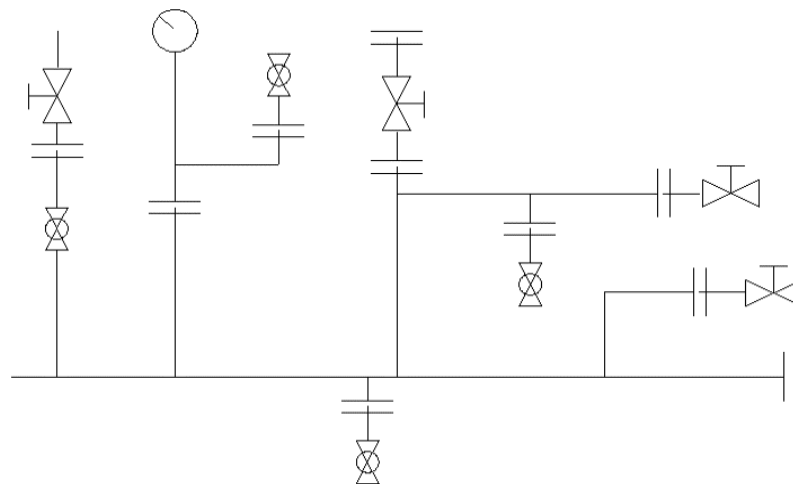


2. LEAK GENERATION EQUIPMENT & METHODS

2.1. VITO LDAR INSTALLATION

The LDAR installation at the VITO facility is designed to generate releases simulating leaks from various equipment pieces (e.g. flanges, valve stems, valve bonnets, and open-ended pipes). All of the controlled leak tests using one of the three pure gases (propane, methane, propylene) or an approximately equal mixture of the three were performed using this installation. A schematic overview of the LDAR installation at the VITO site in Mol is presented in **Figure 4**.

Figure 4 Schematic overview of the LDAR installation



2.2. GENERATION OF KNOWN LEAK RATES

A mass flow controller (MFC) was used to generate the mass flow rate. A MFC is a self-regulating device that can generate a stable flow rate by comparing the input signal provided by the operator (set-point) to the value from the mass flow sensor and adjusting the proportional valve accordingly to achieve the required flow. Any back pressure that might be caused by the LDAR installation does not influence the flow rate of the MFC.

MFCs with the following ranges were used to generate known leak rates:

- Propane:
 - 0 - 10 g/h
 - 0 - 300 g/h
 - 0 - 1200 g/h
- Propylene:
 - 0 - 5 g/h
 - 0 - 200 g/h
- Methane:
 - 0 - 200 g/h.

2.2.1. MFC Calibration

VITO calibrated the MFCs using a mercury sealed piston prover. This is subjected to VITO's ISO 17025 accreditation and allows them to calibrate MFCs with an uncertainty of 0.3%. The results of these calibrations are reported in **Annex A**.

The calibration of the MFCs was performed before the first test day and at the end of the final test day. Each set point that was used was calibrated with propane. The stability of the mass flow controller was monitored during each test. The flow was required to be constant within 1% within the elapsed time of the test or it had to be repeated. In practice, during the tests all releases met the stability condition. The system was calibrated to deliver fixed flow rates of propane, methane, propylene or a mixture of these three gases in approximately equal proportions. **Figure 5** shows a picture of the MFCs used during the study.

Figure 5 Mass flow controllers used during the study (Courtesy of Providence Photonics)



3. LEAK DETECTION METHODS

3.1. OPTICAL GAS IMAGING (OGI) CAMERA

The FLIR GF320 camera was used to survey the controlled leaks. The camera utilised a 38 mm optical lens and was equipped with the latest firmware version. Prior to the study, the camera was synchronized to the quantification module. This accounts for any differences between individual OGI camera responses and is a required step for the QOGI method. The process takes place the first time a camera is used with a module. The synchronization took a couple of hours and was conducted at the VITO test facility.

3.1.1. OGI camera sensitivity check

Prior to each day of testing, the camera's ability to detect a 5 g/h leak of propylene was verified in the field. Propylene was selected for verification purpose because it is one of the gases having the highest detection limit for the camera used in the study. This approach is consistent with the suggested method in the US EPA LDAR Alternate Work Practice (AWP) [10].

3.2. TVA 1000B AND DILUTION KIT

The Toxic Vapour Analyser (TVA 1000B) applied in the sniffing method was used in flame ionisation detector (FID) mode to record the screening value (gas concentration in ppmv) of the leaking components before and after testing, consistent with EN 15446:2008 [1]. This screening value, corrected for the response factor of the actual gas, was used to estimate the leak rate with the EPA Method 21 correlations (see **Section 4.2**).

The working principle of the flame ionization detector (FID) is to ionize the hydrocarbons in a combustion chamber utilising a flame produced by the combustion of hydrogen and air. The ions are subsequently attracted to a collector electrode, and quantified based on the current produced. When there is not enough air in the vicinity of the leak (e.g. at elevated hydrocarbon concentration), the combustion cannot take place and the FID provides no response. This is referred to as 'flame-out'.

A dilution probe can be used to enrich oxygen deficient samples by adding ambient air to the combustion chamber. The use of a dilution probe allows flame-out to be avoided and this enables the recording of screening value for the larger leaks, which permits their mass estimation with the Method 21 correlations. A dilution probe (Century Dilutor Kit; part No. CR010MR) was applied during some of the tests (i.e. those with the highest leak rates).

The analyser (TVA 1000B) was calibrated each day prior to use and drift checked throughout the day to evaluate the bias and accuracy of the screening measurements used for the EPA Correlation Approach (Method 21) - see **Section 4.2**. Zero air and 500 and 10,000 ppmv methane-in-air were used for daily analyser calibration. The 500 ppm standard was used for analyser drift checks throughout the day and at the end of testing each day.

4. LEAK QUANTIFICATION METHODS

4.1. QUANTIFICATION MODULE

The quantification module utilizes proprietary algorithms to automatically calculate mass leak rates in g/hr and analyses IR images of a leak to determine the intensity on a pixel-by-pixel basis. Each pixel represents a column of hydrocarbon vapour between the camera and the background. Pixel contrast intensity is a function of temperature difference (ΔT) between the background and the plume. At a given ΔT , the contrast intensity is proportional to the number of hydrocarbon molecules in the vapour column. The leak rate drives the pixel intensity and the number of pixels covering the plume. US Patent 9225915 B2 [11] provides a more detailed description of the method.

4.1.1. OGI camera and quantification module synchronisation

The quantification module must be synchronised to the specific OGI camera being used. This is needed to account for variations between OGI cameras and must be performed for the temperature range setting to be used and the lens.

All of the data captured during the study utilised the 38mm lens and the 10 - 60°C temperature range. It is important to note that temperature range is the only camera setting which has an effect on the QOGI method used in the study. The user is free to change the polarity of the camera or switch to manual or high sensitivity modes if desired, but the temperature range must match the synchronisation. It is possible to synchronise a single quantification module to multiple lenses or temperature ranges. For this study, only one combination of lens and temperature range was selected. **Figure 6** shows a FLIR GF320 and a black body set up for synchronisation.

Figure 6 Synchronisation of the OGI camera with the quantification module used for the study (Courtesy of Providence Photonics)



4.1.2. Response factors

The OGI camera used for the study is a single spectrum camera. This means that it is not able to distinguish between different compounds; instead it measures the response to different compounds in the same mid-wave IR spectral window (3.3 μ m to 3.4 μ m). The QOGI system has been calibrated to propane, but if the operator knows the specific compound (or composition) a response factor (RF) can be applied to adjust the result. The response factor takes into account the relative sensitivity of the compound (or compounds) within the spectral window of the OGI camera, as well as the molecular weight of the compound, for mass emission calculations. The QOGI system has built in RF values for many common compounds. In this study, releases of propane, propylene, methane, and a mixture of all three compounds were quantified. The propane results were directly measured and the rest used compound specific response factors.

4.1.3. Temperature and distance parameters

The QOGI system requires the user to provide the ambient temperature and the distance from the OGI camera to the leak. The ambient temperature was measured with a National Institute of Standards and Technology (NIST) traceable version of the ThermoWorks Thermanen. The ambient temperature is generally taken at the location of the OGI camera but should be representative of the conditions at the site of the leak. Distance measurements were obtained with a tape measure.

4.1.4. Use of enhanced backgrounds

In cases where ΔT is not sufficient to apply the QL100 method, the background can be enhanced to generate the needed temperature differential. Enhancing the background can be typically accomplished by applying a heated or cooled surface behind the leak. During this study cold towels were used to lower the background temperature when ΔT was insufficient for quantification. In practice, enhanced backgrounds will probably not be necessary depending on the environmental conditions.

4.2. EPA CORRELATION APPROACH (METHOD 21)

The EPA correlation approach, commonly referred to as Method 21, was applied to derive mass emissions for the TVA screening values (SV). The methodology for Method 21 is described in US EPA Report 453/R95-017 [8]. The Method 21 correlations were originally derived by vacuum bagging leaks of several equipment pieces (e.g. valves) under different service conditions such as light or heavy liquid. The resulting correlations allow mass leak rate to be determined from a screening value for the equipment types and services in the database. A large degree of variation was found during the derivation of the correlations for Method 21 including the fact that several screening values of the same magnitude could have represented mass emission rates with several orders of magnitude difference. The accuracy of the correlation for predicting the emission from a single source is therefore poor. In LDAR surveys this can result in so called 'false negatives' (large leak with low screening value) and 'false positives' (very small leak with high screening value). However, as the correlations are applied to all leaks marked for repair the individual uncertainty is less important and averaging means that the total mass emissions determined from an LDAR campaign should be in reasonable agreement with the real emissions. Therefore, the Method 21 correlations are only statistically meaningful if applied to a very large number of leaks [2].

Examples of the equations applied, in this case for a valve, using the TVA screening values (SV) and the Method 21 correlation and pegged factors are:

For SV between 1 - 100,000 ppmv: Leak rate (kg/h) = $2.29 \times 10^{-6} \times \text{Screening Value}^{0.746}$

For SV above 100,000 ppmv: Leak rate (kg/h) = pegged value emission factor (kg/h)

When the leak concentration was high and caused the FID instrument to flame-out, a dilution probe with a dilution factor (DF) = 10 was used to obtain a screening value. The screening values measured with a dilution probe were used in the same equations above to get a "diluted" leak rate, which was then multiplied by the dilution factor to get the real leak rate. If the TVA screening gave a 'flame-out' reading even with the dilution probe being used, the pegged value emission factor was used. When the generated gas was not methane, the TVA 1000B response factors for the gas were used to correct the methane equivalent screening value recorded by the instrument.

5. TEST RESULTS

5.1. PRE-TEST SUMMARY

The purpose of the pre-test was to learn more about the application and limitations of the QOGI system to permit the finalisation of the test protocol for the full testing. The environmental conditions during the pre-test were challenging with cold temperatures and rain. In practice, LDAR surveys are not generally performed during periods of high wind speed or rainy weather, despite the fact that no normative guidelines on recommended environmental conditions have been developed to-date.

37 tests were undertaken during the pre-test and all of the generated leaks were detected by the OGI camera, regardless of background, leak rate, gas composition or weather conditions.

When there was sufficient IR radiance between the background and a leaked plume, the QOGI system provided measured leak rates. However, for most tests the background was a brick wall and there was insufficient ΔT to apply the QL100 module. During the second test day, no data were recorded that met the ΔT threshold of $> 5^{\circ}\text{C}$. No enhanced backgrounds were attempted during the pre-test, but it is reasonable to expect that results could have been obtained for most of the leak scenarios with the use of enhanced backgrounds.

The results for propylene were obtained through the use of a response factor based on its IR spectrum and molecular weight, as described in **Section 4.1.2**, and provided accuracy similar to the propane results. The manufacturers advise that the Response Factor approach can be used for many other compounds, with similar measurement accuracy expected.

The pre-test could not evaluate the effects of distance because all of the quantifiable scenarios coincidentally occurred at 3 meters. Testing was undertaken in the full tests to evaluate changes in distance (see **Section 5.2**).

The sniffing method was applied to 14 leaks and quantified using Method 21 correlations and pegged factors. For the other 23 scenarios, the sniffing method was not applied because flame-out was expected, given the high release rate.

The pre-test parameters and results for QOGI and Method 21 are summarized below in **Table 2** and **Table 3**.

Table 2. Pre-test results for May 4, 2015

Test / Ambient conditions							Leak generation			Method 21			QOGI system				
No.	Time	Temp (°C)	Humidity (%)	Wind speed (m/s)	Wind direction		Leak component type/ID	Mass release rate (g/h)	Gas used	TVA-1000B screening value (ppm CH4) (Note 1)	Calculated emission rate with Method 21 using RF (g/h)	Diff. (2) %	Background scene	Distance from camera to leak source (m)	Δ T °C	Calculated emission rate from QL100 (g/h)	Diff. (2) %
					°	Direction											
1	10:45	16.4	-	1.15	189	SSW	Open end: 1	10.3	Propane	F.O.	79	667%	Brick wall	3 m	< 5	No result	
2	10:57	16.4	-	1.11	189	SSW	Open end: 1	50.6	Propane	(Note 3)	79	56%	Brick wall	3 m	< 5	No result	
3	11:14	16.7	-	1.09	189	SSW	Open end: 1	16.9	Propane	(Note 3)	79	367%	Brick wall	3 m	< 5	No result	
4	11:19	16.3	-	0.95	196	SSW	Open end: 1	198.6	Propane	(Note 3)	79	-60%	Brick wall	3 m	< 5	No result	
5	11:27	16.5	-	1.00	145	SSE	Open end: 1	198.6	Propane	(Note 3)	79	-60%	Brick wall	5m	< 5	No result	
6	11:35	16.6	-	0.84	145	SSE	Open end: 1	198.6	Propane	(Note 3)	79	-60%	Brick wall	10m	< 5	No result	
7	11:40	16.6	-	1.01	164	SSE	Open end: 1	49.5	Propane	(Note 3)	79	60%	Brick wall	10m	< 5	No result	
8	11:46	16.8	-	1.19	156	SSE	Open end: 1	49.5	Propane	(Note 3)	79	60%	Brick wall	5m	< 5	No result	
9	13:40	19.9	52.0	1.73	138	SE	Flange: 5	49.5	Propane	F.O.	84	70%	Concrete	3 m	9.4	54.4	10%
10	13:55	19.4	52.0	1.58	209	SSW	Flange: 5	16.6	Propane	50 000	25.3	53%	Concrete	3 m	10.9	14.1	-15%
11	14:00	19.6	52.0	1.53	212	SSW	Flange: 5	10.1	Propane	30 000	17.7	75%	Concrete	3 m	7.7	14.5	44%
12	14:15	20.6	51.4	1.50	198	SSW	Flange: 5	10.1	Propane	(Note 4)			Concrete	2 m	< 5	No result	
13	14:25	20.2	51.5	1.60	198	SSW	Flange: 5	198.6	Propane	F.O.	84	-58%	Concrete	3 m	7.3	335.9	69%
14	14:45	20.1	51.7	1.43	178	S	Valve: 4	49.5	Propane	No data			Metal door	3 m	6.0	55.3	12%
15	14:50	20.3	51.2	1.35	160	SSE	Valve: 4	16.6	Propane	35 000	16.3	-2%	Metal door	3 m	< 5	No result	
16	15:05	20.3	51.2	1.61	159	SSE	Valve: 4	49.6	Propylene	110 000	38.0	-23%	Concrete	3 m	< 5	No result	
17	15:15	20.3	51.5	1.92	267	W	Valve: 4	16.7	Propylene	30 000	14.4	-14%	Concrete	3 m	11.5	20.4	22%
18	15:25	20.7	50.7	1.39	238	WSW	Valve: 4	10	Propylene	25 000	12.6	26%	Concrete	3 m	5.1	16.5	65%
19	15:40	20.5	51.0	1.27	105	ESE	Valve: 4	175.4	Propylene	F.O.	140	-20%	Concrete	3 m	< 5	No result	

Table notes:

1. Unless indicated otherwise, all Method 21 screening values were measured with a dilution probe (dilution factor 1:10)
2. Difference = (determined leak rate – release rate) / release rate (%)
3. For this component and type of gas a flame-out reading was recorded at a lower leak rate. Method 21 was not performed. A flame-out reading was assumed for all similar scenarios with higher leak rates.
4. In tests 11 and 12 the same gas, leak rate and leaking component were used. Only one Method 21 screening was performed.

Table 3 Pre-test results for May 5, 2015

Test / Ambient conditions							Leak generation			Method 21			QOGI system				
No	Time	Temp (°C)	Humidity (%)	Wind speed (m/s)	Wind direction		Leak component type/ID	Mass release rate (g/h)	Gas used	TVA-1000B screening value (ppm CH4) (Note 1)	Calculated emission rate with Method 21 using RF (g/h)	Diff. (2) %	Background scene	Distance from camera to leak source (m)	Δ T °C	Calculated emission rate from QL100 (g/h)	Diff. (2) %
					.	Direction											
20	15:15	15.4	-	2.61	234	SW	Open end: 2	1000	Propane	F.O.	79	-92%	Brick wall	3	< 5	No result	
21	15:35	16.3	-	3.93	231	SW	Flange 3	49.5	Propane	No data			Brick wall	3	< 5	No result	
22	15:39	16.3	-	2.93	223	SW	Flange 3	198.6	Propane	No data			Brick wall	3	< 5	No result	
23	15:44	16.9	-	2.65	221	SW	Flange 3	1.7	Propane	7300 ⁽³⁾	1.4	-17%	Brick wall	2	< 5	No result	
24	15:57	17.1	48.6	4.08	225	SW	Valve 4	198.6	Propane	No data			Brick wall	3	< 5	No result	
25	16:07	17.3	49.2	2.71	236	WSW	Valve 4	1.7	Propane	22 000 ⁽³⁾	2.1	24%	Brick wall	3	< 5	No result	
26	16:15	17.3	48.9	2.47	227	SW	Open end: 1	1.7	Propane	55 000 ⁽³⁾	2.6	52%	Brick wall	3	< 5	No result	
27	16:25	17.3	50.2	2.26	231	SW	Open end: 1	49.5	Propane	No data			Metal door	3	< 5	No result	
28	16:32	17.2	50.1	2.67	231	SW	Flange 3	49.5	Propane	No data			Metal door	3	< 5	No result	
29	16:39	17.2	50.0	2.30	239	WSW	Valve 4	49.5	Propane	No data			Metal door	3	< 5	No result	
30	16:45	17.4	49.9	2.67	240	WSW	Valve 4	49.5	Propane	No data			Metal door	2	< 5	No result	
31	16:51	17.6	48.8	2.83	237	WSW	Valve 4	49.5	Propane	No data			Metal door	5	< 5	No result	
32	16:55	17.8	48.2	2.59	232	SW	Valve 4	49.5	Propane	No data			Metal door	9	< 5	No result	
33	17:10	17.6	44.7	3.35	242	WSW	Valve 4	167.2	Methane	No data			Metal door	3	< 5	No result	
34	17:24	18.1	44.2	1.73	212	SW	Valve 4	49.8	Methane	No data			Metal door	3	< 5	No result	
35	17:30	18.1	43.3	2.20	222	SW	Valve 4	148.9	Mixture	No data			Metal door	3	< 5	No result	
36	17:37	17.7	41.9	2.50	224	SW	Valve 4	49.8	Mixture	No data			Metal door	3	< 5	No result	
37	17:42	17.9	41.5	2.32	234	SW	Valve 4	30.1	Mixture	No data			Metal door	3	< 5	No result	

Table Notes

- 1: Unless indicated otherwise, all Method 21 screening values were measured with the dilution probe (dilution factor 1:10)
- 2: Difference = (calculated emission rate – release rate) / release rate (%)
- 3: Measurements were performed without dilution probe

5.2. FULL TEST RESULTS

24 tests were undertaken and, as with the pre-testing, leaks were detected by the OGI camera for all of these tests regardless of the background, leak rate, gas composition or weather conditions.

For all 24 test conditions, the background (either naturally occurring or enhanced as required) provided sufficient IR radiance, making quantification possible. On the second day, the naturally occurring background - a brick wall with north orientation - did not provide sufficient ΔT to allow leak quantification with the QOGI system. Hence, a towel which has previously been placed in a bucket of ice water was used as an 'enhanced background'. It was positioned in front of the brick wall and provided a sufficient temperature difference (negative ΔT in this case) between the background and the plume to make leak quantification with the QL100 possible for each of these leaks. The accuracy of the QOGI results using the enhanced background scenarios was comparable to those using natural backgrounds.

The results for propylene, methane and the mixture (a blend of propylene, propane and methane in equal volumes) were obtained through the use of a response factor based on IR spectra of the gases using QOGI propane calibration curves. For the other gases and the blend, the accuracy of leak quantification by QOGI was similar to the propane results. The Response Factor approach can be used for many other compounds, with similar measurement accuracy expected.

Changes in distances were explored during the full testing for different gases and leak rates. The QOGI system was set in distances of 2 - 8 meters from the leak source. The results showed that the accuracy of QOGI leak quantification was not significantly affected by changes in distance.

The sniffing method was applied to 6 leaks and quantification was provided using Method 21 correlations and pegged factors. For the other 18 scenarios, the sniffing method was not applied because flame-out was expected, given the high release rate. The full testing parameters and results for the QOGI system and Method 21 are summarized in **Table 4** and **Table 5**.

Table 4 Test Results for June 15, 2015

Test / Ambient conditions							Leak generation			Method 21			QOGI system				
No.	Time	Temp (°C)	Humidity (%)	Wind speed (m/s)	Wind direction		Leak component type/ID	Mass release rate (g/h)	Gas used	TVA-1000B screening value (ppm CH4) (Note 1)	Calculated emission rate with Method 21 using RF (g/h)	Diff. (2) %	Background scene	Distance from camera to leak source (m)	Δ T °C	Calculated emission rate from QL100 (g/h)	Diff. (2) %
					°	Direction											
1	14:03	20.5	36.0	0.80	81	E	Lower Flange 5	16.5	Propane	30 000	17.7	7%	Concrete pad	2.74	16.1	21.3	29%
2	14:15	20.8	35.7	0.68	91	E	Lower Flange 5	49.7	Propane	40 000	21.7	-56%	Concrete pad	2.74	15.1	43.5	-12%
3	14:31	20.9	36.0	0.78	100	E	Lower Flange 5	200.5	Propane	No data			Concrete pad	2.74	19.7	224.9	12%
4	14:45	20.6	36.2	1.11	76	ENE	Lower Flange 5	998.70	Propane	No data			Concrete pad	2.74	19.3	1118.6	12%
5	15:01	21.0	34.3	0.70	213	SSW	Lower Flange 5	49.8	Methane	F.O.	84.0	69%	Concrete pad	2.74	13.1	45.3	-9%
6	15:06	21.2	33.3	0.94	93	ENE	Lower Flange 5	169.7	Methane	(Note 3)	84.0	69%	Concrete pad	2.74	19.4	168.6	-1%
7	15:14	21.0	33.9	0.56	149	SSE	Lower Flange 5	49.7	Mix	No data			Concrete pad	2.74	20.3	43.7	-12%
8	15:20	21.4	33.3	1.10	75	ENE	Lower Flange 5	149.4	Mix	No data			Concrete pad	2.74	21.5	148.8	0%
9	15:26	20.8	33.7	1.15	76	ENE	Lower Flange 5	16.7	Propylene	13 000	9.7	-42%	Concrete pad	2.74	15.3	14.5	-13%
10	15:31	20.4	35.1	0.63	79	ENE	Lower Flange 5	49.9	Propylene	44 000	23.0	-54%	Concrete pad	2.74	20.2	42.5	-15%
11	15:35	20.3	35.4	0.30	174	S	Lower Flange 5	204.7	Propylene	No data			Concrete pad	2.74	20.6	237.7	16%
12	16:08	20.4	34.8	1.03	73	ENE	Open end 1	49.7	Propane	No data			Sky	2.74	-11.0	58.5	18%
13	16:42	20.8	34.7	0.57	159	SSE	Open end 1	49.7	Propane	No data			Brick Wall	2.74	9.3	54.5	10%
14	16:51	20.2	35.7	0.51	113	ESE	Open end 1	49.7	Propane	No data			Brick Wall 2	2.74	30.7	46.4	-7%

Test / Ambient conditions							Leak generation			Method 21			QOGI system				
No.	Time	Temp (°C)	Humidity (%)	Wind speed (m/s)	Wind direction		Leak component type/ID	Mass release rate (g/h)	Gas used	TVA-1000B screening value (ppm CH4) (Note 1)	Calculated emission rate with Method 21 using RF (g/h)	Diff. (2) %	Background scene	Distance from camera to leak source (m)	Δ T °C	Calculated emission rate from QL100 (g/h)	Diff. (2) %
					°	Direction											
15	17:00	20.1	34.4	0.56	189	S	Open end 1	200.5	Propane	No data			Brick Wall 2	2.74	33.0	238.5	19%
16	17:12	20.0	35.5	0.71	158	SSE	Valve 4	49.7	Propane	No data			Brick Wall 2	2.74	34.0	53.3	7%
17	17:17	19.7	36.1	0.67	128	SE	Valve 4	200.5	Propane	No data			Brick Wall 2	2.74	33.9	207.1	3%
18	17:24	19.6	35.4	0.58	111	ESE	Valve 4	200.5	Propane	No data			Brick Wall 2	4.57	23.7	237.3	18%

Table Notes:

1: Unless indicated otherwise, all Method 21 screening values were measured with the dilution probe (dilution factor 1:10)

2: Difference = (calculated emission rate – release rate) / release rate (%)

3: For this component, a flame-out reading was recorded at a lower leak rate. Method 21 was not performed for this scenario. A flame-out reading was assumed.

Table 5 Test Results for June 16, 2015

Test / Ambient conditions							Leak generation			Method 21 Results			QOGI system				
No.	Time	Temp (°C)	Humidity (%)	Wind speed (m/s)	Wind direction		Leak component type/ID	Mass release rate (g/h)	Gas used	TVA-1000B screening value (ppm CH4) (Note 1)	Calculated emission rate with Method 21 using RF (g/h)	Diff. (2) %	Background scene	Distance from camera to leak source (m)	Δ T °C	Calculated emission rate from QL100 (g/h) average	Diff. (2) %
					°	Direction											
20	10:17	15.3	44.5	0.53	109	ESE	Valve 4	49.7	Propane	(Note 3)	19.7	-60%	Cool Towel	3.05	-9.8	41.2	-17%
21	10:33	14.9	45.9	0.38	171	S	Valve 4	49.7	Propane	45,000	19.7	-60%	Cool Towel	1.83	-7.8	43.8	-12%
22	10:43	14.9	45.9	0.38	171	S	Valve 4	49.7	Propane	(Note 3)	19.7	-60%	Cool Towel	4.57	-6.8	38.5	-23%
23	10:52	15.5	47.4	0.37	145	SE	Valve 4	49.7	Propane	(Note 3)	19.7	-60%	Cool Towel	8.23	-8.0	45.0	-9%
24	11:19	16.2	45.2	0.51	247	WSW	Middle Flange	49.7	Propylene	No data			Cool Towel	3.05	-8.3	46.6	-6%

Table Notes:

1: Unless indicated otherwise, all Method 21 screening values were measured with the dilution probe (dilution factor 1:10).

2: Difference = (calculated emission rate – release rate) / release rate (%)

3: These tests were all the same as test number 21. The same gas, leak rate and leaking component were used. Only one Method 21 screening was performed.

5.3. CALCULATED EMISSION RATES

5.3.1. Method 21 vs. Generated leak rate

For 31 out of 61 leak scenarios, a Method 21 screening value was recorded (or assumed similar to an earlier recorded value) - see **Tables 2 to 5**. Due to the high leak rates generated during the tests, many scenarios gave flame-out, even after using the dilution probe. If a flame-out reading occurred at a given flow rate for a given component and gas, no Method 21 measurement was performed for the higher flow rates. It was assumed that a flame-out reading would have resulted. Pegged values for the flame-out scenarios are included in the data analysis results in **Table 6**, as these values are used for leak mass estimation when applying Method 21.

For scenarios with identical leak rates, component and gas, only one Method 21 screening was performed. These scenarios are marked in **Tables 2 to 5** (See table footnotes).

Table 6 Method 21 - Comparison between calculated emission data and known release rates

Method 21 - Difference between calculated emissions and known release rates ¹	
Minimum	-92%
Average	31%
Standard deviation	155%
Median	-4%
Maximum	667%

Table note 1: Difference = (calculated emission rate – release rate) / release rate (%)

The Method 21 results obtained in this study were better than observed in previous Concaawe field operations [2]. One explanation is that a TVA specific response factor was used in the calculation of emission rates. In addition, the dilution probe was used to the maximum extent so that higher leak rates could be better quantified. If the dilution probe had not been used, a pegged value would have been assigned to more leak rates, resulting in a more conservative estimation.

5.3.2. QOGI vs. Generated leak rate

For the leak scenarios where quantification was possible (31 out of 61), a comparison of the differences between the calculated emissions and the known release rates for both the pre-test and full test is provided in **Table 7**.

Table 7 QOGI system - Comparison between calculated emission data and known release rates

QOGI - Difference between calculated emissions and known release rates ¹	
Minimum	-23%
Average	6%
Standard deviation	22%
Median	2%
Maximum	69%

Table note 1: Difference = (calculated emission rate – release rate) / release rate (%)

5.3.3. QOGI vs. Method 21

To permit a direct comparison of the accuracy of the emission estimates derived using Method 21 and the quantified leak rates provided by the QOGI system, **Tables 6 and 7** have been combined in **Table 8**. This shows that despite the good quantitative results obtained by Method 21 in this study compared to other Concaawe studies [2], the QOGI system out-performed Method 21.

Table 8 Comparison of QOGI vs. Method 21

QOGI vs. Method 21 – Comparison of differences between calculated emissions and known release rates		
Difference ¹	QOGI	Method 21
Minimum	-23%	-92%
Average	6%	31%
Standard deviation	22%	155%
Median	2%	-4%
Maximum	69%	667%

Table note 1: Difference = (calculated emission rate – release rate) / release rate (%)

However, the number of quantifiable scenarios used to derive the results in **Table 8** are not the same for QOGI and Method 21. In order to allow for a better comparison, the results of both methods for the most commonly generated leak rate (i.e. 50 g/h) are illustrated in **Figure 7**. This analysis also shows that QOGI out-performed Method 21.

Seven release rates were used during the pre-test and full test campaigns; 1.7, 10, 16.5, 50, 175, 200 and 1000 g/h. **Figure 8** provides the average values for the M21 and QOGI calculated emission rates for the tests at each of the flow rates. This shows that the QOGI system provided good agreement with the set release rates over the entire range of mass flows whereas the M21 methodology significantly under-estimated the emissions at the higher flow rates. This is because pegged

values had to be used to estimate the mass flows at the higher hydrocarbon concentrations due to flame-out of the TOC monitor used for sniffing (see **Section 4.2**).

Figure 7 Comparison box whisker plot for Method 21 and QOGI at a generated leak rate of approximately 50 g/h

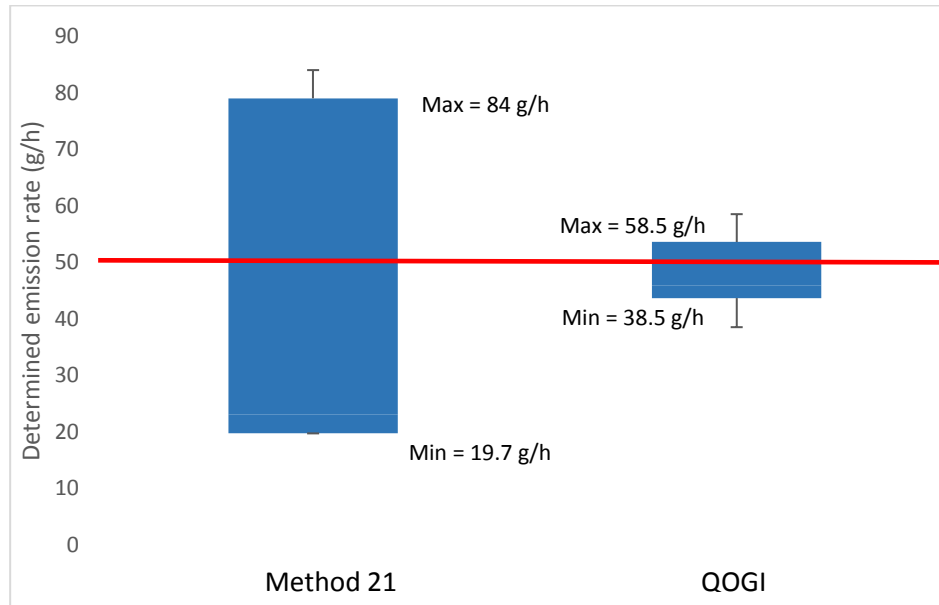
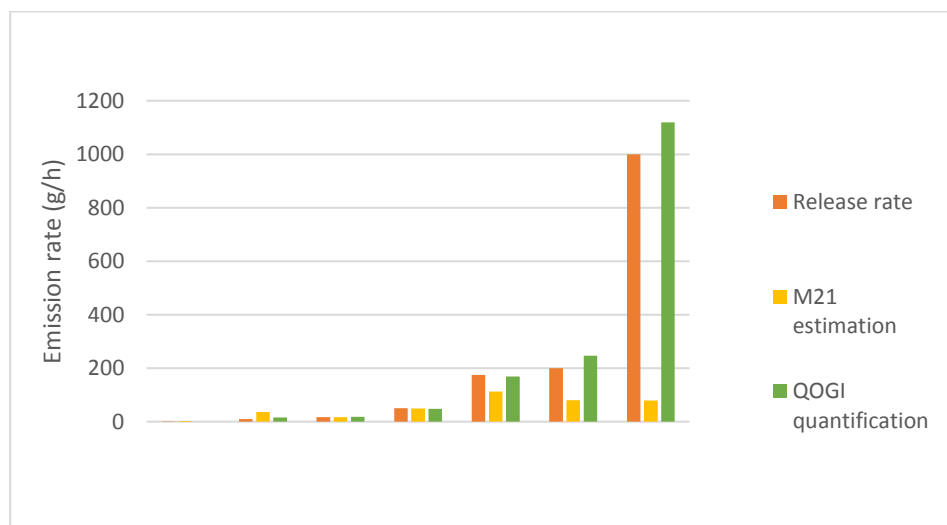


Figure 8 Comparison of emission rates determined by M21 and QOGI for each of the set release rates (1.7, 10, 16.5, 50, 175, 200 and 1000 g/h)



6. CONCLUSIONS

The aim of this study was to evaluate the emerging field of Quantitative Optical Gas Imaging and assess its applications in the oil and gas (O&G) industry and in particular the refining sector. Leak Detection and Repair (LDAR) is one application that seems promising for QOGI. As the US EPA Method 21 (M21) is the most commonly used methodology for LDAR monitoring, it was included in the study for a side-by-side comparison.

The test data confirm that the M21 correlations cannot be used to accurately estimate individual leak rates because of the statistical method used in their development. The QOGI system, on the other hand, has been shown to be able to provide accurate quantification for individual leaks over the range 1.7 to 1000 g/h. Even where estimation is made for the total emissions from a number of leak sources (for example as would occur in an LDAR survey), the QOGI system provided a more accurate total flux value than M21. This suggests that QOGI could indeed be used for numerous applications in the O&G industry, including demonstration of LDAR compliance.

One important finding of the study was the application of response factors (RFs) for QOGI. The study demonstrated that RFs can be used to calibrate a QOGI module to one gas and then use that module to measure another gas (similar to the use of the TOC monitor in Method 21). This makes the application of QOGI very practical and eliminates the need to calibrate the module to each compound. It also allows the quantification of fugitive emissions from process streams composed of multiple compounds.

Another important finding was the importance of ΔT as a data quality indicator for QOGI methods. Though there was only one QOGI technology evaluated in this study, the ΔT requirement is fundamental to the infrared imaging technology and would apply to any optical imaging based quantitative method. If QOGI is to be used as a standard and prescribed method in the O&G industry, ΔT must be measured and validated as part of the method. The QOGI system used in this study, for example, provides the operator with a screening tool which allows for immediate assessment of ΔT .

The study used a ΔT threshold of 5°C to define the applicability of the QOGI system. Further study completed by the technology supplier indicates that this limit could be reduced to as low as 2 to 3°C, even though accuracy and precision may be lower. As previously mentioned, this needs to be confirmed through additional testing. Future test studies would be best performed in field conditions rather than with controlled leak scenarios to ensure that the method is exposed to a variety of environments and to evaluate the practical application of enhanced backgrounds in the field. Another area for further study is the effects of wind speed and temperature as data quality indicators for QOGI methods.

The QOGI technology evaluated in this study was still in the development stage at the time of these tests in June of 2015. It is recommended that testing of the latest version of the technology be undertaken in field conditions.

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ANNEX A – MASS FLOW CONTROLLER (MFC) CALIBRATION DATA

Table 9 MFC calibration data – tests on May 4th and 5th

Gas	MFC flow range g/h	Setpoint %	Temp °C	Barometric pressure mbar	Volume flow		Mass flow g/h
					ml/min	Nml/min	
Propane	0 - 5	10.5	22.5	1021.1	9.12	8.49	1.0
		17.0	22.4	1021.1	15.2	14.08	1.7
	0 - 300	2.8	22.3	1021.1	91.55	85.30	10.1
		5.0	22.2	1021.2	150.80	140.56	16.6
		16.1	22.2	1021.2	450.60	420.00	49.5
		33.3	22.0	1021.2	903.40	842.62	99.3
	67.7	21.8	1021.2	1805.00	1684.71	198.6	
0 - 1200	51.0	13.2	1003.9	9008.00	8513.46	1003.4	
Propylene	0 - 5	3.3	22.0	1021.3	9.47	8.83	1.0
		3.6	21.8	1021.4	15.36	14.34	1.6
		5.0	22.3	1003.9	48.68	44.59	5.0
	0 - 200	7.9	21.5	1021.4	94.70	88.50	10.0
		11.4	21.3	1021.4	158.40	148.12	16.7
		29.4	21.9	1021.3	472.50	440.90	49.6
		57.3	21.8	1021.3	942.90	880.15	99.0
100.0	21.7	1021.3	1670.00	1559.38	175.4		
Methane	0 - 200	1.4	21.2	1021.3	25.35	23.71	1.0
		1.8	21.0	1021.3	41.50	38.84	1.7
		6.9	20.8	1021.3	248.10	232.38	10.0
		11.0	21.1	1021.3	412.70	386.15	16.5
		31.0	21.2	1021.3	1243.00	1162.64	49.8
		60.0	21.1	1021.3	2463.00	2304.55	98.8
100.0	20.8	1021.3	4165.00	3901.03	167.2		

Table 10 MFC calibration data – tests on June 15th and 16th

Gas	MFC flow range g/h	Setpoint %	Temp °C	Barometric pressure mbar	Volume flow		Mass flow g/h
					ml/min	Nml/min	
Propane	0 - 10	10.5	23.3	1020.1	9.17	8.51	1.0
		17.0	23.3	1020.1	15.08	13.99	1.6
	0 - 300	3.3	24.4	1020.7	91.48	84.60	10.0
		5.5	24.3	1020.7	151.80	140.42	16.5
		16.7	24.2	1020.7	456.00	421.97	49.7
		34.0	24.2	1020.7	915.50	847.17	99.8
		69.0	24.1	1020.7	1838.00	1701.40	200.5
	0 - 1200	52.5	23.6	1020.7	9139.00	8474.04	998.7
Propylene	0 - 5	24.2	22.0	1025.0	9.52	8.91	1.0
		39.3	22.0	1025.0	15.88	14.87	1.7
	0 - 200	2.2	21.4	1025.2	48.21	45.23	5.1
		4.4	22.1	1025.0	95.50	89.38	10.1
		7.5	22.0	1025.0	158.30	148.20	16.7
		23.5	22.0	1025.0	474.10	443.85	49.9
		48.0	22.0	1025.0	949.40	888.82	100.0
		100.0	21.9	1025.0	1943.00	1819.64	204.7
Methane	0 - 200	1.5	24.1	1020.6	23.09	21.37	0.9
		1.9	24.0	1020.6	40.65	37.64	1.6
		7.0	24.0	1020.6	251.60	232.96	10.0
		11.0	24.0	1020.5	416.10	385.23	16.5
		31.0	24.1	1020.5	1256.00	1162.43	49.8
		60.0	24.0	1020.5	2501.00	2315.45	99.2
		100.0	24.0	1020.5	4278.00	3960.62	169.7

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