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Results of a comparative pilot field test study of a first generation Quantitative Optical Gas Imaging (QOGI) system

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Results of a comparative pilot field test study of a first generation Quantitative Optical Gas Imaging (QOGI) system

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ABSTRACT

Quantitative optical gas imaging (QOGI) is a new system to detect fugitive emission sources and quantify their mass release rates. This report presents an evaluation of QOGI technology compared to other techniques (Sniffing/EPA Method 21 and high flow sampling (HFS)), during a field study in a European petro-chemical manufacturing site. A sample of 33 leaks from those detected during a Leak Detection and Repair (LDAR) campaign were surveyed during the field study. The QOGI system was able to quantify 18 in the field. A further 10 leaks were quantified following the field test after processing of the leak images by the system manufacturer. Unstable imaging of the background was the main reason for not being able to quantify emissions from the other 5 leaks.

For the portion of the leaks that could not be quantified, there is no procedure envisaged which can overcome this limitation with the generation of QOGI system tested at the time of this field study (2016). When comparing the quantification between HFS and QOGI, the most accurate QOGI results were obtained with leak rates > 60 g/h. QOGI was shown to be as accurate as using Sniffing/Method 21 to estimate total VOC fugitive emissions.

The results from the evaluation of the QOGI technology, showed that QOGI is a promising technology for detecting fugitive emission sources and quantifying the mass release rate for each individual leak. Sniffing/Method 21 also provide emissions quantification but only at the level of the facility, using statistical-derived factors.

This field trial has identified issues with the use of the first generation of QOGI system in a refinery process plant environment which should be further assessed before any recommendation for using it in such an environment can be made. A second generation has been developed and the vendors state that some of the issues have been overcome. However, further field testing is required to evaluate these developments.

KEYWORDS

Fugitive emissions, Optical Gas Imaging, OGI, Quantitative Optical Gas Imaging, QOGI, Sniffing, US EPA Method 21, High Flow Sampling

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SUMMARY

Infra-red cameras have been used more often in recent years in the oil and gas industry for their ability to rapidly detect leaking equipment, which can be very useful when conducting Leak Detection and Repair (LDAR) programmes. For this application these cameras are known as optical gas imaging (OGI) cameras. As well as their use in LDAR programmes these cameras are also used, for example, in OGI inspections (which are typically performed after maintenance activities), to investigate odour sources, follow up on alarms from sensors, etc. Quantitative Optical Gas Imaging (QOGI) is a new system designed to both detect hydrocarbon leak sources and determine their mass rates of release. Currently there is only one commercial supplier of such a system. Results from previous laboratory studies have shown it to be able to provide accurate quantification for individual leaks.

After promising results under controlled test conditions [7], a first generation commercial model QOGI has been used for the first time in a European petro-chemical manufacturing context during a pilot field test study in 2016. This report presents the results from that study and evaluates the ability of the QOGI system to quantify emissions from leaking components in comparison with other techniques (i.e., Sniffing/EPA Method 21 (M21) and high flow sampling (HFS)), the latter being used as the reference method.

Prior to the field testing of the QOGI system, a site-wide LDAR-OGI campaign was undertaken which focused on leak detection. 114 accessible leaks were detected on typical LDAR components (e.g. pumps, valves, flanges, etc.). A subset of 37 leaks were selected[1] to be surveyed during the following QOGI field test. Four of these leaks were eventually not used in the comparative testing due to issues with sampling them with HFS. Of the remaining 33 tested with QOGI, the system was able to quantify 18 in the field. A further 10 leaks were later quantified by post-processing of the images by the system manufacturer. Although these 33 leaks represented just under one third of the total leaks detected at the site, this subset can be considered representative based on the location and type of leaking components selected. The flow rate of the leaks surveyed with QOGI varied between 2 and 2200 g/h with a median of approximately 120 g/h.

Four criteria were set to assess the performance of QOGI in quantifying emissions from leaking components: survey time duration, cost-effectiveness, consistency and accuracy.

At the time of the testing, the QOGI system was commercialised as a rigid tablet which is connected to the OGI camera by a USB cable. A tripod is also supplied on which to mount the OGI camera to ensure a stable image. Analysis of the results indicated that about 15 minutes were needed to install the system at the best possible location and to record a stable image of a leak. This typically involved selecting a position for the QOGI measurement based on observation of the leak with the camera, choosing an appropriate background and maximising the signal (see **Appendix 2**). In many cases it was not possible to position the camera at the distance considered optimal by the manufacturer due to the congested nature of the areas surveyed. For an average EU refinery with 110,000 LDAR points, a complete LDAR-OGI campaign generally lasts for 6 weeks[2]. The additional 15 minutes required to set up a QOGI system for each leak, therefore, imposes about

[1] The selection of the leaks used for the QOGI field test is described in **Section 3.1**.
[2] One can assume that typically 110 leaks would be detected (0.1% of potential leak points) and that QOGI can be operated for 6 hours per day.

a 15% increase in the total survey time compared to using just an OGI camera for leak detection. If LDAR with Sniffing/Method 21 was applied to 100% of the site components, the duration of the campaign would be about 4 times longer (i.e. ~6 months), assuming the same number of test personnel in both cases. To undertake a survey with sniffing/M21 in 6 weeks, it would require four times more test personnel. The total time required in the field to undertake an LDAR-OGI campaign, as well as the cost associated, would therefore still remain significantly less than that required for Sniffing/Method 21. However, in this field test, images for about a third of the leaks detected required image post-processing. The time required and the cost for doing this, if undertaken on a commercial basis, is not known. It has not therefore been possible to obtain a direct comparison of the total time and cost required to obtain emissions quantification with QOGI versus Sniffing/Method 21 in field use.

The field test identified several problems. For example, as the scene is fixed, interferences cannot always be avoided. These interferences add “noise” to the plume infra-red (IR) radiation signal which can lead to either over-prediction or under-prediction of the leak rate. Taking specific measures to improve the image signal, e.g. providing an artificial background or modifying the algorithm, did not always produce the expected improvements in quantification.

Five of the 33 leaks surveyed could not be quantified. Reasons for this included failure to fully capture large plumes, excessive interference and insufficient difference in temperature between the plume and the background. With the first generation of QOGI system tested at the time of these field trials no procedures were identified to overcome these limitations.

From the comparison with the HFS reference method it was shown that QOGI results were in good agreement for those leaks which could be quantified and which had leak rates > 60 g/h[3]. At the moment, due to the limited data set available, there is no means to assign an uncertainty to an individual QOGI measurement. However, after gaining more field experience, it is believed that QOGI would be able to quantify the majority of large leaks, and provide a reasonable accuracy prediction.

With a much larger measurement data base, it may be feasible to assign a default mass emission rate where the OGI camera, operating in high sensitivity mode, detects a leak but quantification with the QOGI system is not possible.

Because of the statistical methods used to derive the Method 21 correlations, the accuracy of quantification with this method is very poor for individual leaks or the sum of the leaks from a small number of components. QOGI was found to be comparable to Sniffing/Method 21 in estimating the total VOC fugitive emissions from 27 leaks.

[3] The 60 g/h is the criterion above which the OGI camera should detect leaks with a very high probability [2].

1. INTRODUCTION

1.1. CURRENT USE OF OPTICAL GAS IMAGING (OGI)

Infra-red cameras have been used more often in recent years in the oil and gas (O&G) industry for their ability to rapidly detect leaking equipment. For that application the cameras are known as optical gas imaging (OGI) cameras. As well as their use in leak detection and repair (LDAR) programmes, they are also employed for OGI inspections (which are typically performed after maintenance activities), to investigate odour sources, follow up on alarms from sensors, etc. The use of OGI cameras, therefore, now plays an important role in the safety and environmental programmes in both upstream and downstream operations and also in petrochemical facilities.

OGI techniques are effective visual tools but initially had limited application for LDAR compliance since they were only qualitative. Consequently, the American Petroleum Institute (API) developed OGI leak/no-leak factors [1] to permit the quantification of VOC emissions rates from leaks detected by an OGI camera.

In the petrochemical sector, the United States Environmental Protection Agency (US EPA) has promulgated an Alternative Work Practice (AWP) [2] 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 Sniffing/Method 21 at least once annually. Hence, there are no facilities in the US currently utilising OGI in LDAR programs. In Europe, OGI is considered as a Best Available Technique (BAT) for LDAR [3, 4]. There are some European countries that accept OGI as a stand-alone method for LDAR.

1.2. OGI CAMERA OPERATING PRINCIPLES

The operating principle of the OGI camera is to detect the absorption of infra-red (IR) light by a gas plume. The base infra-red signal originates from a background. Infra-red radiation flux is related to temperature. If the background is warmer than the released gas ($I_B > I_G$)[4] then the gas appears dark; if it is cooler the gas appears white. OGI uses a narrow band pass 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.

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.

For more details on the OGI camera used as part of the QOGI system in these tests, see reference [5].

[4] I_B: Background Intensity; I_G: Gas Intensity

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 flowrate from an OGI camera image has been developed [6]. This Quantitative Optical Gas Imaging (QOGI) system uses a conventional OGI camera coupled to an external device that runs analysis software. Currently there is only one commercial supplier of a QOGI system

1.4. STUDY OBJECTIVE AND OVERVIEW

This report describes the first evaluation of QOGI in a European petro-chemical manufacturing site context. After some promising testing in a research set-up in 2015 (documented in Concawe report No. 2/17 [7]), piloting this technology in an operating facility was the logical next step. The contractor selected to perform QOGI during this field test was the same company who developed the technology.

The difficulty in assessing the performance of a new technology in a real case scenario is that the observed emissions are not controlled. A reference method is needed against which the new system can be assessed. In this field test a well-established independent emission monitoring method was deployed alongside the QOGI system being tested. Concawe used the high flow sampling (HFS) method as the reference for determining the leak rate. The mass emission estimated by HFS was considered to be the "true" emission to allow the evaluation of the QOGI performance. More information about HFS and its validation during earlier Concawe work is provided in **Section 2.2.1**.

The objective of the study was to assess whether QOGI could be applied in field LDAR surveys in a *fast*, *cost-effective* and *consistent* way, and provide *accurate* leak quantification. The criteria against which the QOGI system was judged in this study are set out below:

i. Survey time duration: What is the increase in survey time relative to using OGI with the addition of QOGI versus a Sniffing/Method 21 survey?

ii. Cost-effectiveness: Is the cost benefit of an OGI survey versus a Sniffing/Method 21 survey (if applied at similar time intervals) significantly affected by QOGI addition to OGI? Experience has shown that OGI is at least 4 times faster, and hence cheaper in terms of man-power, than Sniffing/Method 21.This factor is based on the typical average number of leaks surveyed per day by one operator i.e. 500 leaks for Sniffing/Method 21 and 2000 to 2500 leaks for OGI.

iii. Consistency: Are the effects of environmental factors[5] understood and could a protocol for OGI surveys including QOGI quantification be written?

iv. Accuracy: Is the total VOC mass leak estimation with QOGI at least as accurate as Method 21?

In the weeks prior to the field testing of the QOGI system, a full site LDAR-OGI survey had taken place. The identified leaking components ("leakers") were tagged in the field, and video recordings of each leak were made. This is consistent with the way QOGI is expected to be deployed as part of a site LDAR survey. However, due to the limited duration of the study (10 working days) only a portion of the detected leaks could be evaluated, but their number and variety were considered sufficient to extrapolate the results to a site-wide QOGI deployment.

[5] Environmental factors are e.g. wind, glint, image contrast, obstruction, etc.

As this was a validation study, it required the deployment of additional techniques alongside the QOGI system. These techniques were provided by independent contractors, specialised in each area:

- HFS method for bagging the leaking equipment and estimating the emission flow rate (as CH_4 equivalent).
- Mobile GC installation for analysing the composition of a gas sample taken at each leak point being studied.

The information provided by these two techniques allowed the total volatile organic compound (VOC) mass leak rate to be independently estimated. These results were only communicated to Concawe and not disclosed to the QOGI contractor before the latter determined their own estimate of the mass leak rate.

2. TECHNICAL METHODS DEPLOYED IN THIS STUDY

2.1. QOGI SYSTEM

The QOGI system consists of the same OGI camera used for leak detection in LDAR surveys, combined with a tablet computer running proprietary software. The quantification module analyses IR images of a leak to determine the intensity on a pixel-by-pixel basis and utilises proprietary algorithms to derive the mass leak rates in g/h.

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 [8] provides a more detailed description of the method.

2.1.1. QOGI principle

Two parameters affecting the performance of the QOGI system to detect and quantify releases 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.

2.1.2. OGI camera verification

The OGI camera used for this test was a FLIR GF320 with a 23 or 38 mm lens [5].

Prior to each day of testing, the camera's ability to detect a 5 g/h leak of propane was verified in the field. Propylene gas was initially requested, because it is one of the gases having the highest detection limit for the camera used in the study, but could not be made available. However, leak detection has not been an issue for this field study.

2.1.3. Camera and quantification module synchronisation

At the time of the testing, the first commercially available QOGI model module (QL100) was used. This quantification module had to be synchronised to the specific OGI camera being used. This is needed to account for variations between OGI cameras and had to be performed for the temperature range setting to be used and the lens.

As the QOGI contractor provided both the camera and the quantification module, the synchronisation was done at their facility ahead of the field testing[6].

2.1.4. 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 µm to 3.4 µm). The QOGI system had been calibrated to propane and methane. When the detected leak is made of other gas or gas mixtures, a response factor (RF) can be used to adjust the result. The response factor takes into account the relative sensitivity of the leaking compound (or compounds) within the spectral window of the OGI camera, as well as the molecular weight of the compound.

The QOGI system has built-in RF values for many common compounds. For complex blends an on-line tool providing data for a large number of hydrocarbons is freely available to calculate the volume weighted response factor based on the composition [9].

2.1.5. 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 Thermapen. 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 in this field test were obtained with a tape measure.

2.1.6. Use of enhanced backgrounds

As explained above in the operating principles, OGI and QOGI only work when there is an adequate contrast between the background and the leak, created by a temperature difference. For leak detection, a ΔT of 0.2ºC is sufficient. For quantification, a higher ΔT is required (a minimum of 3ºC for the QOGI method evaluated in this study).

During the earlier testing in a laboratory set-up [7], there were cases where the ΔT was not sufficient to apply the QL100 module. In such cases 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. Cold towels were used successfully to lower the background temperature in some of the earlier laboratory testing.

During the field testing, the temperature difference was sufficient in most cases. A hot background (heated blanket) was used for a few leaks where the image showed a poor contrast. These results are discussed later in this report.

[6] At the time of writing of this report, a new version is available (QL320), which uses a different QOGI method and does not require synchronisation to the specific OGI camera used in conjunction with it.

2.2. HIGH FLOW SAMPLING

2.2.1. High Flow Sampling principle

High flow sampling (HFS) is a "bagging method" which allows VOC leaks to be measured directly. A source is bagged by enclosing it in order to collect leaking vapours but a small flow of air is allowed to flow into and through the bag to the main sampling hose of the high flow sampler.

The volumetric flow rate through the bag induced by the pump in the high flow sampler is calculated from the pressure differential across an orifice plate. The leak rate is then calculated as the product of the concentration and flow rate, corrected to standard conditions.

The device used for high flow sampling was primarily developed for methane emissions. In such applications, it not only provides a volumetric flow rate but also a mass emission. Methane concentration can be measured using the built-in sensors (Catalytic Oxidation Detector (0-5% volume CH_4) and a Thermal Conductivity Detector (5-100% volume CH_4)). For heavier gases than methane, a correction is required. While a simple correction factor can be applied for other light gases, this approach does not work for complex mixtures observed in refineries.

A variation of this method was initially proposed by a European LDAR contractor and was adopted and successfully validated by Concawe [10, 11]. This method was also used in earlier Concawe studies (Concawe report No. 6/15 [12]).

In the method variation an FID[7] or PID[8] instrument is placed at the exhaust of the high flow sampling device. The emissions mass flow is calculated by multiplying the recorded HFS volumetric flow rate by the hydrocarbon concentration measured by the FID or PID.

The FID detectors used in this study to obtain the emission concentrations are most commonly calibrated with methane and consequently measure emissions as methane equivalent. Therefore, a response factor needs to be applied to adjust the instrument reading from ppmv of methane equivalent to ppmv of total organic compound(s). For a blend, the response factor is calculated based on the gas composition. Each instrument manufacturer provides response factors for various gases, which are valid within a given concentration range (which can be achieved, if necessary, by sufficient dilution).

This correction is well known and applied in Sniffing LDAR surveys, where similar PID/FID instruments are used. In such surveys, it is not practical to take a sample of each leak to determine the gas composition, and the average composition of the leak is estimated based on process knowledge (e.g. the site holds a database of the potential leak points and the associated average composition).

For this study, in order to increase the accuracy of the high flow sampling technique as it was going to be used to provide the "true" leak rate, gas samples were taken from each leak and analysed by GC.

Appendix 1 and the appendices of Concawe report 6/15 [12] can be consulted for additional information on the HFS technique.

[7] Flame Ionisation Detector
[8] Photoionization Detector

2.2.2. Instruments used to perform High Flow Sampling

The instruments used in this study were the Hi Flow® Sampler from Bacharach [13] and the Toxic Vapour Analyser (TVA) 1000B by Thermo Environmental Instruments [14].

The Hi-Flow® Sampler had a valid certificate from the manufacturer, having been checked for correct flow measurement.

The TVA 1000B was used in FID mode. It was calibrated each day prior to use and drift checked throughout the day to evaluate the bias and accuracy of the screening measurements. 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.

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 values for the larger leaks, which permits their mass estimation with the Method 21 correlations. A dilution probe (Century Dilutor Kit; part No. CR010MR) was used during the tests.

2.3. GC ANALYSIS

A micro-GC/MS was used in this study [15]. On-site analysis was performed on 33 samples taken in Tedlar bags from the vent of the Hi Flow® Sampler.

Micro-chromatography allows the analysis of a complex mixture to be performed in less than 3 minutes. The detector is a non-destructive thermal conductivity detector. The coupling with a mass spectrometer, downstream of the micro-GC, enables the accurate identification of each compound, after their separation on the chromatographic column. This coupling combines two different detectors, each of them working very differently, but only requires one gas sample.

This coupling is composed of two separate elements, each of which has its own function during the analysis:

- Micro-chromatography allows the separation of different compounds of a gas mixture. Each compound is detected by the thermal conductivity detector, which can provide an initial chromatogram allowing the quantification of certain compounds.
- Quadrupolar mass spectrometry enables a second chromatogram to be obtained, based on the variation of the total ionic current (TIC), and a mass spectrum allowing the identification of each compound.

Sulphur containing VOCs were identified and quantified by mass spectrometry. Other gases permanently present were quantified by the thermal conductivity detector. Most compounds to be analysed were calibrated one by one. The errors and uncertainty from calibration, analysis and integration can either be added or compensated for. Consequently the final concentration sum can be slightly different to 100%.

More information regarding the specification of the micro-GC/MS system, the concentration uncertainty of the analytical device, as well as a summary of the results regarding the composition of the detected compounds in analysed samples can be found in reference [15].

2.4. EPA METHOD 21

The EPA methodology, referred to as Method 21, is still the most commonly used method to estimate VOC mass emissions from LDAR surveys. The detection is performed by drawing an air sample past a hydrocarbon ionisation detector to detect the VOC concentration in the vicinity of the leak sources The methodology is described in US EPA Report 453/R95-017 [16], key elements of which are adopted in the European Standard EN 15446:2008 (i.e., Sniffing, a modified version of Method 21) [17]. The accuracy of the method for predicting the emission of a single source is poor (inherent in the way the correlations were developed) but when it is applied to all screened components during an LDAR survey, the resulting emissions are expected to be in reasonable agreement with the real emissions [12].

Method 21 was applied to derive the mass emission from the TVA screening values (SV) measured for each of the leak points. By chance, all leaks studied in this field test caused a 'flame-out' of the FID. The components chosen for this study were selected for their type and/or location (for ease of using HFS) and not their leak size determined during the preceding LDAR survey. A flame-out occurs when there is not enough air in the vicinity of the leak for the hydrocarbons to be combusted by the instrument. The FID provides no numerical response in such cases and the screening values are reported as ">100,000 ppmv CH_4" or "pegged values" and the estimated mass emission with Method 21 is not derived from a correlation but is a fixed value, depending only on the type of equipment [12, 16]. However, previous experience [12] has shown that the actual emission rates measured using HFS for apparently large leaks designated by Method 21 with "pegged" values can have a significant spread of values. This over-estimation by Method 21 is the result of so-called "false positives" which are due to leaks having small leak rates but a high concentration in the vicinity of the leak.

3. TEST RESULTS

3.1. SELECTION OF THE LEAKS FOR THE QOGI FIELD TEST

Given the number of techniques which were to be applied for each leak during this field study, it was estimated that 5 to 10 leaks could be surveyed per working day. During planning, timing and resources were made available for studying around 50 leaks (7 working days).

The site-wide OGI-LDAR campaign, which took place in the weeks before the study, detected more leaks (262) than the number which could be studied and a selection had to be made. The site LDAR component count is 148,387, of which the number found to leak represent 0.18%.

A significant portion of these leaks (134) were plugs of air-cooled heat exchangers, which are not the typical components surveyed in LDAR campaigns and they were not considered further. Moreover, such components would have been very difficult to bag individually (component size 5-10 cm; spacing between components 5-10 cm). 14 other leaks were not accessible and were also left out as they could not be bagged with HFS, bringing the number down to 114.

A total of 37 leaks were finally surveyed during the QOGI field test. Although fewer than planned[9] (50), these represented about one third of the 114 leaks but they were considered representative, by location and type, of typical LDAR components exhibiting leaks. Four of these 37 leaks were eventually not used in the comparative testing due to issues with sampling them with HFS (see **Section 3.3**).

The majority of the 114 leaking components were concentrated in two areas: the reformer (73%) and the light ends storage and loading area (16%). The QOGI field test also focused on these two areas: from the leaks quantified, 70% were in the reformer area and 30% in the light ends storage and loading.

Leak sources were stems of block valves (58%) followed by flanges (12%) and potential open-end connections in block valve arrangements (10%). In the QOGI field test, evaluated leaks were from stems of block valves (51%) and potential open-end connections in block valve arrangements (21%). A few components from the other types were bagged as well (see **Table 1**).

3.2. SUCCESSIVE TECHNIQUES DEPLOYED AT EACH SELECTED LEAK

All techniques described in **Section 2** were applied successively at each selected leaking component:

1. The presence of a leak, during the day of the QOGI field test, was confirmed by means of OGI (hand-held camera).
2. Sniffing was applied on the leak using the TVA 1000B detector to record a CH_4 equivalent concentration measurement (ppmv). Remark: as stated earlier, all leaks studied in this field test caused a 'flame-out' of the FID detector. In such cases, the mass emissions estimated with Method 21 are fixed, "pegged" values, depending only on the type of equipment.

[9] Main reasons were: a) logistical limitations (time to bring the sample from the process area to the area were the GC was located, and time to apply all the techniques one after the other for each leak), as well as b) the impossibility to bag some leaks initially selected.

3. The HFS technique was applied on the component following the methodology described in **Appendix 1**. Remarks:
   i. The TVA 1000B response factor was set at 1 (=CH_4), as the correction for molecular weight was done afterwards, using the results of the sample GC analysis.
   ii. For all cases, the TVA 1000B was used in combination with a calibrated dilution probe (dilution factor 10). This allowed it to stay within its linear range (< 20 000 ppm CH_4 equivalent).
   iii. For all cases (except 2) the concentration was stable (< 30% variation) during the recording time of approximately 3 minutes. The two cases with high variable concentration were repeated during the last day of the test and valid readings were recorded.
   iv. Two volume and concentration readings were recorded for each component (one at high pumping speed, one at low speed). All pairs of readings met the stability criterion (<30% variation). The reported leak rate for the component is the average of those two measurements.
4. After the component was bagged with HFS, two leak samples were collected in plastic bags using a small vacuum pump. The bags were brought to the location of the portable GC for analysis. The analysis was done within the hour following the sample collection.
5. The QOGI technique was applied to the component, following the methodology described in **Appendix 2**. Remarks:
   i. On many occasions, the camera (connected to the QOGI module by USB cable) mounted on the tripod had to be repositioned in order to achieve a stable reading. A reading is considered stable when 3 recordings of one minute duration give a leak mass estimation within 30%.
   ii. In congested areas (e.g. large equipment surrounding the leaking component) it was not possible to find the ideal position recommended by the system manufacturer of between 1.5 to 6 meters from the leak (see **Appendix 2**). A tripod is needed to have a stable image and with a tripod in all cases it was not possible to go closer than 1.5 meters.
   iii. On some occasions the background was recorded as a “moving image” due to glint, steam plume, moving clouds, etc. In such cases no stable reading was possible in the field (e.g. in real time) and the image had to be post-processed to remove the biases. This was partially successful but it brings a higher uncertainty of the estimated leak rate. The manufacturer advises that the version of the QOGI module (QL320) marketed at the time of publication of this report has additional software features which provide the operator with the ability to address these types of interferences in the field.
6. Before moving to the next component, Sniffing was applied again to verify that the leak rate did not significantly change from the initial recording. All leaks studied in this field test caused a ‘flame-out’ of the FID, also during the second reading.

In order to gain time, as they were done be different teams, the order of steps (3) + (4) and (5) were swapped for some components (i.e. QOGI was done for point “x” first, while the other team was doing HFS for point “y” first). Applying all steps (1) to (6) of the comparative testing took on average one hour per component.

3.3. REVIEW OF RESULTS

A total of 37 leaks were surveyed during this QOGI testing. It was not possible to quantify four of these leaks with HFS. Of the remaining 33 leaks, 28 were quantified with QOGI.

The reasons for not quantifying 4 leaks with HFS were:

- Flame-out of the TVA analyser, even when using the dilution probe (due to too high a hydrocarbon concentration). This occurred in two cases.
- Too difficult to bag one component, which was a large control valve.
- Decision to skip one component to save time, as it was similar to two other components (pumps) which were bagged successfully.

QOGI was not applied to the 4 components which could not be quantified by HFS.

Of the 33 tested with QOGI, the system was able to quantify 18 in the field. A further 10 leaks were quantified following the field test after processing of the images by the system manufacturer. This post-processing requires an in-depth knowledge of the technology.

The reasons for QOGI not being able to quantify the leaks from the remaining 5 components were:

- Unstable background due to glint, moving clouds or steam (for 2 components).
- Insufficient delta temperature. Hot blanket was used but it did not allow a stable image of the background to be created (for 1 component).
- Diffuse plume: moving pixels in the video recording were spread all over the field of view, making it difficult to identify and count the pixels belonging to the plume (large flange, unstable background) (for 1 component).
- Plume not visible on the QOGI tablet (only visible using camera in High Sensitivity Mode*) (for 1 component).

  * Remark: The High Sensitivity Mode is an enhanced viewing mode available in the new IR camera models: short-term image captures are overlaid with continuous (averaging) images, allowing movements to be better seen. QOGI uses the raw image data to select the pixels representing the leak, which only depend on the camera resolution.

The results of high flow sampling are presented in **Table 1**, which also includes the leak estimation using Method 21 (pegged values for Petroleum Industry). The results of QOGI are presented in **Table 2**. For completeness, this Table includes details of 6 tests undertaken with QOGI which were initially unsuccessful but quantification was achieved when, for example, the camera was moved to a different location, test undertaken at a later time, etc.

Table 3 provides a comparison of the leak estimations given by the various methods as well as the delta between QOGI and HFS. A comparison of the leak rates determined for each component using HFS and QOGI is presented graphically in **Figure 1**. The comparison is done for leak mass rate (g/h).

Table 1 Summary results using Method 21 and High Flow Sampling (HFS) method during the field study

Identification					Measurement	M21 Correlation Method		HFS with TVA	
Console	Leak ID	Equipment	Subtype	Source	Concentration TVA (ppm) LDAR	PI (Petroleum Industry)		Emission (m^3/h)	Emission (g/h)
						g/h	m^3/h	Average	Average
Console C[1]	17399	Valve	Gate	Potential Open End Connection	101,000	30	0.012	0.108[2]	267
Console C	17212	Valve	Gate	Stem valve	101,000	140	0.057	0.088	217
Console C	17194	Valve	Gate	Flange	101,000	220	0.089	0.098	242
Console C	17070	Valve	Gate	Stem valve	101,000	140	0.057	0.135	334
Console C	14143	Valve	Gate	Stem valve	101,000	140	0.085	0.113	186
Console C	11192	Control valve	Globe	Stem control valve	101,000	140	0.097	0.012	17
Console C	37616	Valve	Gate	Potential Open End Connection	101,000	30	0.011	0.058	159
Console C	12973	Valve	Gate	Potential Open End Connection	101,000	30	0.030	0.063	64
Console C	15566	Valve	Gate	Potential Open End Connection	101,000	30	0.010	0.013	39
Console C	36054	Valve	Gate	Stem valve	101,000	140	0.346	0.286	116
Console C	36094	Valve	Gate	Stem valve	101,000	140	0.354	0.293	116
Console C	37620	Valve	Needle	Sample point	101,000	220	0.577	0.158	60
Console C	36050	Valve	Gate	Stem valve	101,000	140	0.368	0.115	44
Console C	17249	Control valve	3-way	Flange	101,000	220	0.088	0.040	101
Console C	17300	Valve	Gate	Stem valve	101,000	140	0.056	0.029	72
Console C	17014	Valve	Gate	Potential Open End Connection	101,000	30	0.012	0.054	135
Console F	33098	Valve	Gate	Potential Open End Connection	101,000	30	0.017	0.030	54
Console F	31184	Pump	Not Recognised	Open End	101,000	220	0.111	0.167	332

Identification					Measurement	M21 Correlation Method		HFS with TVA	
Console	Leak ID	Equipment	Subtype	Source	Concentration TVA (ppm) LDAR	PI (Petroleum Industry)		Emission (m^3/h)	Emission (g/h)
						g/h	m^3/h	Average	Average
Console F	31334	Pump	Not Recognised	Open End	101,000	220	0.112	0.151	299
Console F	33099	Control valve	Gate	Stem control valve	101,000	140	0.082	0.018	31
Console F	33635	Valve	Gate	Stem valve	101,000	140	0.077	0.085	154
Console F	33642	Valve	Gate	Stem valve	101,000	140	0.073	0.006	11
Console F	33871	Valve	Gate	Stem valve	101,000	140	0.065	0.086	185
Console F	33877	Valve	Gate	Stem valve	101,000	140	0.067	0.011	22
Console F	33796	Valve	Gate	Stem valve	101,000	140	0.056	0.001	2
Console F	33671	Valve	Needle	Stem valve	101,000	140	0.075	0.154	287
Console C	17272	Valve	Gate	Stem valve	101,000	140	0.055	0.088	222
Console C	17454	Valve	Gate	Stem valve	101,000	140	0.055	0.017	42
Console C	17424	Valve	Gate	Potential Open End Connection	101,000	30	0.012	0.019	48
Console C	17205	Valve	Gate	Stem valve	101,000	140	0.055	0.034	86
Console D	37614	Level instrument	Welding	Connection	101,000	30	0.045	3.294	2,197
Console C	15519	Valve	Gate	connection	101,000	30	0.016	0.079	145
Console C	17026	Valve	Gate	Stem valve	101,000	140	0.055	0.069	174

[1] *Console C refers to a reformer. Console F refers to a storage area (LPG, Gas)*

[2] *The equations used to calculate the emissions leak rates and loss using HFS can be found in* ***Appendix 1****.*

Table 2 Summary results using the QOGI method during the field study

Leak ID	Location	Lens	Distance (m)	Ambient temp (°C)	Measured Intensity[1]	QL100 Leak Rate (as propane) scc/min	QL100 Leak Rate (as propane) m^3/h	Response Factor[2] (RF)	RF Adjusted Leak Rate (m^3/h)	RF Adjusted Leak Rate (g/h)	Comments
17399				*Note 4*	40 406	1200	0.072	0.872	0.086	218.1	
17212		23mm	1.5	12.8	26 085	641	0.038	1.009	0.038	93.8	
17194	17194-1	23mm	1.5	11.7	35 778	1019	0.061	1.008	0.060	150.1	
17070		23mm	1.5	16.1	39 287	1156	0.069	0.968	0.072	177.0	Post-process quantification
14143									0.039	64.2	Value calculated from density derived from HFS data.
11192		23mm	1.5	10.6	25 154	605	0.036	1.062	0.033	47.2	
37616		23mm	1.5	11.1	28 261	726	0.044	0.995	0.044	121.4	
12973		23mm	1.5		26 707	665	0.040	1.015	0.039	39.6	
15566		23mm	1.5	11.1	23 222	529	0.032	1.021	0.031	96.5	
15566		23mm	2.1	8.9					0.000	0.0	Attempt with heated blanket; not successful
36054		23mm	1.5	15.6	33 291	922	0.055	0.952	0.059	23.8	
36094		23mm	1.5	12.2	46 518	1438	0.086	0.939	0.093	36.9	
37620		23mm	1.5	15.0	22 320	494	0.030	0.947	0.033	12.3	Post process quantification
36050		23mm	1.5	16.1	25 504	618	0.037	0.965	0.039	14.8	
17249		23mm	1.5	7.2					0.000	0.0	Large flange, diffuse leak, not clearly visible (no plume extraction)
17300		23mm	1.5	8.9					0.000	0.0	Leak not observable; a lot of heat sources in the background
17014		38mm	7.3	7.8					0.000	0.0	No result, glint, clouds/steam

Leak ID	Location	Lens	Distance (m)	Ambient temp (°C)	Measured Intensity[1]	QL100 Leak Rate (as propane) scc/min	QL100 Leak Rate (as propane) m^3/h	Response Factor[2] (RF)	RF Adjusted Leak Rate (m^3/h)	RF Adjusted Leak Rate (g/h)	Comments
33098		23mm	1.5	11.7					0.000	0.0	Plume not visible; small leak based on HFS (22 g/h)
31184		38mm	2.7	6.7	40 846	1217	0.073	0.997	0.073	146.4	
31334		38mm	2.7	6.7	31 726	861	0.052	0.999	0.052	102.4	
33099		23mm	1.5	10.6	32 111	876	0.053	1.026	0.051	86.1	
33635		38mm	2.4	5.0	65 765	2189	0.131	1.002	0.131	240.4	
33642		23mm	2.3	5.6	42 367	1276	0.077	1.001	0.076	147.8	Post process quantification
33871		38mm	3.4	8.9	35 491	1008	0.060	1.011	0.060	127.4	
33877		23mm	1.5	13.9	121 564	4365	0.262	1.011	0.259	530.2	Post process quantification
33796									0.000	0.0	No plume visible
33796				*Note 4*	25 102	603	0.036	1.011	0.036	72.0	Post process quantification
33671		23mm	1.5	10.0	63 902	2116	0.127	1.005	0.126	235.6	
17272		23mm	1.8	8.3					0.000	0.0	Steam all around. Did not work better with heat blanket
17272				*Note 4*	159 863	5858	0.352	1.011	0.347	856.3	Post process quantification
17454		38mm	2.1	10.6	49 489	1554	0.093	0.870	0.111	275.4	Post process quantification
17424									0.000	0.0	Could not see gas leak; not better with heated blanket
17424				*Note 4*	60 137	1969	0.118	0.870	0.139	347.4	Post process quantification

Leak ID	Location	Lens	Distance (m)	Ambient temp (ºC)	Measured Intensity[1]	QL100 Leak Rate (as propane) scc/min	QL100 Leak Rate (as propane) m^3/h	Response Factor[2] (RF)	RF Adjusted Leak Rate (m^3/h)	RF Adjusted Leak Rate (g/h)	Comments
17205		23mm	1.8	10.6					0.000	0.0	Attempt with heated blanket; not successful
37614		23mm	1.8	7.8	299 333	11 298	0.678	0.996	0.681	453.1	Trial day 1
37614		23mm	1.5	11.7	547 919	20 993	1.260	0.996	1.264	830.3	Trial day 2
37614									0.000	0.0	Heated blanket ineffective on day 2
15519[3]		23mm	1.5	10.0	29 778	785	0.047	0.999	0.047	85.9	
15519									0.000	0.0	Attempt with heated blanket; not successful
17026			1.5	13.3	24 479	578	0.035	0.976	0.036	89.1	

[1] IR images of a leak are analysed for intensity on a pixel-by-pixel basis. Each pixel represents a column of hydrocarbon vapour between the camera and the background. Leak rate drives both pixel intensity and number of pixels.

*[2] Response factor refers to the IR response factor (correction for gas composition different from propane). More details in **Section 2.1.4**.*

[3] Two different flows were used during the measurement, being high and low flow. In some cases when the deviation on the loss at high vs. low flow was >10%, the measurements were repeated.

[4] When no temperature was recorded, an approximation was done based on the ratio volume/mass for the equivalent HFS measurement, as the same temperature correction was applied

Table 3 Comparison of results during the field study

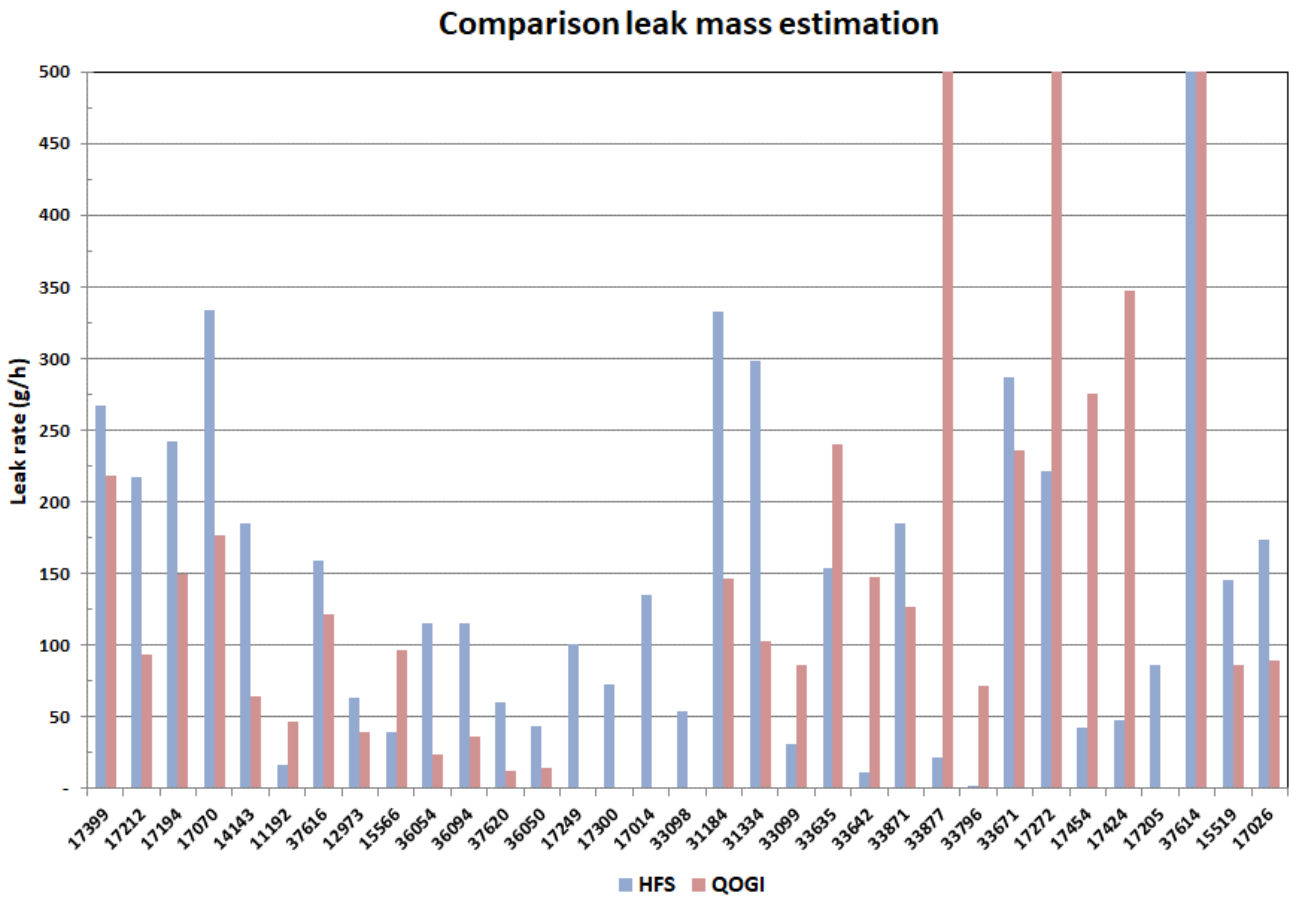
Identification		Measurement	M21-PI		HFS with TVA		QOGI		Delta % QOGI/HFS
Console	LEC	Concentration TVA (ppm) LDAR	Emission (m^3/h)	Emission (g/h)	Emission (m^3/h)	Emission (g/h)	Emission (m^3/h)	Emission (g//h)	
	ID				Average				
Console C	17399	101,000	0.012	30	0.108	267	0.086	218.1	-19
Console C	17212	101,000	0.057	140	0.088	217	0.038	93.8	-57
Console C	17194	101,000	0.089	220	0.098	242	0.060	150.1	-38
Console C	17070	101,000	0.057	140	0.135	334	0.072	177.0	-47
Console C	14143	101,000	0.085	140	0.113	186	0.039	64.2	-65
Console C	11192	101,000	0.097	140	0.012	17	0.033	47.2	181
Console C	37616	101,000	0.011	30	0.058	159	0.044	121.4	-24
Console C	12973	101,000	0.030	30	0.063	64	0.039	39.6	-38
Console C	15566	101,000	0.010	30	0.013	39	0.031	96.5	146
Console C	36054	101,000	0.346	140	0.286	116	0.059	23.8	-79
Console C	36094	101,000	0.354	140	0.293	116	0.093	36.9	-68
Console C	37620	101,000	0.577	220	0.158	60	0.033	12.3	-80
Console C	36050	101,000	0.368	140	0.115	44	0.039	14.8	-66
Console C	17249	101,000	0.088	220	0.040	101	0	0.0	
Console C	17300	101,000	0.056	140	0.029	72	0	0.0	
Console C	17014	101,000	0.012	30	0.054	135	0	0.0	
Console F	33098	101,000	0.017	30	0.030	54	0	0.0	

Identification		Measurement	M21-PI		HFS with TVA		QOGI		Delta % QOGI/HFS
Console	LEC	Concentration TVA (ppm) LDAR	Emission (m^3/h)	Emission (g/h)	Emission (m^3/h)	Emission (g/h)	Emission (m^3/h)	Emission (g//h)	
	ID				Average				
Console F	31184	101,000	0.111	220	0.167	332	0.073	146.4	-56
Console F	31334	101,000	0.112	220	0.151	299	0.052	102.4	-66
Console F	33099	101,000	0.082	140	0.018	31	0.051	86.1	179
Console F	33635	101,000	0.077	140	0.085	154	0.131	240.4	56
Console F	33642	101,000	0.073	140	0.006	11	0.076	147.8	1250
Console F	33871	101,000	0.065	140	0.086	185	0.060	127.4	-31
Console F	33877	101,000	0.067	140	0.011	22	0.259	530.2	2301
Console F	33796	101,000	0.056	140	0.001	2	0.036	72.0	3648
Console F	33671	101,000	0.075	140	0.154	287	0.126	235.6	-18
Console C	17272	101,000	0.055	140	0.088	222	0.347	856.3	287
Console C	17454	101,000	0.055	140	0.017	42	0.111	275.4	555
Console C	17424	101,000	0.012	30	0.019	48	0.139	347.4	622
Console C	17205	101,000	0.055	140	0.034	86	0	0.0	
Console D	37614	101,000	0.045	30	3.294	2,197	0.972	642.7[1]	-70
Console C	15519	101,000	0.016	30	0.079	145	0.047	85.9	-41
Console C	17026	101,000	0.055	140	0.069	174	0.036	89.1	-48
Totals [2]			**3.232**	**4,000**	**2.678**	**4,263**	**2.210**	**4,438**	**4**

[1] Average value of 2 readings.

[2] In order to draw conclusions more representative of a "normal" LDAR campaign, the totals exclude LEC 37614 which was on an "atypical" LDAR component: recent integrity failure of a glass level-reading instrument, resulting in a very significant leak. This leak was detected by visual observation before the LDAR campaign, but was not fixed at the time of the QOGI test.

Figure 1 Comparison of the leak mass rate (g/h) determined by QOGI and HFS during the field study



The high flow sampler (HFS) provides the most accurate emission determination and is used as the reference method to provide the "true" emissions for the 33 components surveyed. Review of the individual component mass emission rates indicates that component # 37614 emitted 34% of the total emissions. This size leak is not typical of those found during LDAR surveys and can be considered as an outlier and, as such, would skew the comparison of the methods used to quantify total emissions. The following analysis of the measurement data, therefore, excludes those for component # 37614.

The following conclusions can be drawn from the comparison:

Looking first at the total mass of emissions from 32 of the leaks surveyed (i.e. excluding component # 37614). Estimates have been made using the EPA M21 factors. Due to the statistical methods used to derive these factors, estimates are only representative for the total emissions of a large number of components and individual leak estimation is poor. The total of the individual quantified emissions using QOGI has also been compared to the HFS measurements for 27 of the leaks. The range of leaks determined with HFS was from 2 g/h to 334 g/h (excluding component # 37614) with a mean of 133 g/h and median of 116 g/h.

- The estimate of the total emissions derived using M21 for the 32 leaks was in good agreement (94%) of that determined by HFS. This was despite the fact that all of the M21 measurements resulted in “flame-out” and fixed “pegged” values were used for the emission estimates for the individual components.
- The QOGI system provided total quantification in good agreement (116%) with the HFS measurements for the 27 leaks surveyed for which QOGI provided emission values (i.e. excluding leak # 37614). Looking at the QOGI performance on estimating the leak rate of individual components (mass basis):
  - the deviation in the estimation of the individual mass leak rates between QOGI and HFS is: minimum -80%, average 297%, median -34% and maximum 3648%
  - For the largest leak rates measured with HFS (> 60 g/h), the deviation between the QOGI and HFS individual values was much lower: minimum -79% and maximum 287%. If one leak (leak # 17272) is excluded for which an estimate was provided despite the strong interference with steam, the maximum positive deviation for QOGI was 56%

4. CONCLUSIONS OF THE QOGI FIELD TESTING

This testing allowed the evaluation of the performance of a first generation QOGI system in quantifying emissions from leaking components in a refinery environment.

In the study, the QOGI system was used to survey 33 leaks, ranging in flow rate from approximately 2 to 2200 g/h with a median of approximately 120 g/h. It was able to quantify 18 of these in the field and 10 could be quantified after post-processing of the images by the system manufacturer. The system was not able to quantify the remaining five leaks.

In earlier tests [7] undertaken under controlled conditions, there was difficulty estimating emission rates with QOGI when the difference between ambient temperature and apparent background temperature was insufficient. This was not a dominant issue in these field tests. “Unstable” imaging of the background was the most common reason for the system not being able to quantify leaks. Unstable background imaging can be due to steam, glint, clouds, congestion and insufficient contrast (low temperature difference or small leak).

Only 18 of the leaks were quantified by QOGI when the components were surveyed. The remaining 10 leaks could be quantified after post-processing by the QOGI contractor to “clean-up” the background (e.g. removing moving pixels which did not belong to the leak plume). Such post-processing requires in-depth knowledge of the technology. To eliminate this delay in providing leak quantification data, the image “clean-up” would need to be automated.

The evaluation criteria used in this study to judge if QOGI adds value to an OGI survey are given below (in italics) with the findings of the field testing for each:

1. *Survey time duration: What is the increase in survey time relative to using OGI with the addition of QOGI versus a Sniffing/Method 21 survey?*

This could not be fully assessed because:

i) Of the 33 leaks measured with HFS, 28 were quantified with the QOGI system. However, 10 of these required image post-processing. The time required by the manufacturer to complete this work, if it had been undertaken on a commercial basis, is not known. It was not possible, therefore, to obtain a direct comparison of the time required to obtain quantification of all emissions with QOGI versus using Sniffing/Method 21.

ii) Other techniques (HFS and GC analysis of the gas samples) were used which disrupted the normal chain of operations involved in undertaking a survey.

The test results indicated that it took, on average, about 15 minutes to install the QOGI system at the optimum location near a leaking component and record a stable image of the leak. However, only accessible leaks had been chosen for this study to permit bagging for HFS. It could be expected, therefore, that a longer time may be required to set up and use the QOGI system for components which were more difficult to survey. Taking an average EU refinery with 110,000 LDAR points, a site-wide LDAR-OGI campaign generally lasts for 6 weeks[10]. The additional 15 minutes required to set up a QOGI system for each leak, therefore, imposes about a 15% increase in the total survey time compared to using just an OGI camera for leak detection. If LDAR with Sniffing/Method 21 was applied to 100% of the site

[10] One can assume that typically 110 leaks would be detected (0.1% of potential leak points) and that QOGI can be operated for 6 hours per day.

components, the duration of the campaign, would be about 4 times longer (i.e. ~6 months), assuming the same number of test personnel in both cases. To undertake a survey with sniffing/M21 in 6 weeks, it would require four times more test personnel.

Subsequent to this study, the camera manufacturer has released a new quantification mode (Q-Mode) which allows the operator to record images within the camera which are suitable for QOGI methods. While Q-Mode does not provide a result in the field, it does allow the operator to record QOGI images during the initial leak detection survey without the need to bring the QOGI module into the field. Although Q-Mode was not evaluated in this study, it appears to have the potential to reduce the time required to provide a quantitative result.

2. *Cost-effectiveness: Is the cost benefit of an OGI survey versus a Sniffing/Method 21 survey (if carried out at similar time intervals) significantly affected by the addition of QOGI?*

The main cost benefit from using OGI versus Sniffing/Method 21 is the reduced time taken to undertake a survey. The addition of QOGI would reduce this benefit due to the increased time in the field taken by the personnel relative to an OGI survey. Moreover, post-processing of the leak images, if required, could result in additional costs. It was not possible, therefore, to determine the relative cost-effectiveness of using QOGI to determine total emissions from leaks compared to using Sniffing/Method 21.

3. *Consistency: Are the effects of environmental parameters understood and could a protocol for OGI surveys including QOGI quantification be written?*

The tests carried out so-far have proven that estimating leak rates by analysing IR video images is a sound technique. However, field tests have identified several problems.

The main problem is that interferences cannot always be avoided as the scene is fixed. These add “noise” to the plume IR signal, which can result in both over-prediction and under-prediction of the leak rate. Taking specific measures to improve the image signal, e.g. providing an artificial background or modifying the algorithm, did not always produce the expected improvements in quantification. Moreover, the use of artificial backgrounds (e.g. a heated blanket) did not increase the number of quantifiable leaks nor were they very practical in a refinery environment. Another issue was that it was not always possible to fully capture large plumes, mainly due to congestion caused by adjacent equipment.

The QOGI field testing also indicated that a proportion of the leaks cannot be quantified with the first generation design of system used for the survey, and no procedure was identified to overcome this limitation. Subsequent to this study, a new QOGI module (QL320) has been released by the same vendor. The vendor reports that the new method has additional features which allow the user to address certain types of interferences in the field.

4. *Accuracy: Is the total VOC mass leak estimation with QOGI at least as good as Method 21?*

This criterion was met, as illustrated in **Section 3.3**, where leaks could be quantified.

In this study, HFS was used to provide an accurate estimation of the leak rate. When comparing the quantification between HFS and QOGI, the most accurate QOGI results were obtained with leak rates > 60 g/h (see **Section 3.3**). At the moment, due to the limited data set available, there is no means to assign an uncertainty to an individual QOGI measurement. It is believed that, after gaining more field experience, QOGI would be able to provide quantification of the large leaks with a reasonable accuracy.

Some other observations from the pilot study are:

- Some leaks could not be quantified. In one instance the leak was visible with the OGI camera in the High Sensitivity Mode (see **Section 3.3**) but quantification with the QOGI module was not possible. With a much larger measurement data base it may be feasible to assign a default mass emission rate for these instances.
- Steam plumes posed a problem as steam plume pixels can interfere with leak plume pixels. For a few leaks it was not possible to select a viewing angle without steam in the background.
- Insufficient "Delta T" between the plume and the background, which was the major problem found in previous testing in a laboratory set-up [7], was not an issue during this study. In the vast majority of tests either the sky or running equipment provided enough contrast.
- Capturing the entire plume was not always possible, mainly where there were large plumes in congested areas.
- Background contrast changes (e.g. due to glint) can interfere with plume pixels.
- The correction obtained using the QOGI response factor of between 0.872 and 1.062 (see **Section 2.1.4**) is small compared to the other causes of error in the QOGI estimation. Using the approximate stream composition from the LDAR database is a reasonable approach for any future routine OGI or QOGI campaign.

The results from the evaluation of the QOGI technology in a petro-chemical manufacturing context, for the first time, showed that QOGI is a promising technology for detecting fugitive emission sources and quantifying the mass release rate for each individual leak. Sniffing/Method 21 also provide emissions quantification but only at the level of the facility, using statistical-derived factors.

This field trial has identified issues with the use of the first generation of QOGI system in a refinery process plant environment which should be further assessed before any recommendation for using it in such an environment can be made. A second generation has been developed and the vendors state that some of the issues have been overcome. However, further field testing is required to evaluate these developments.

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APPENDICES

APPENDIX 1 – PROTOCOL USED FOR HIGH FLOW SAMPLING

The high flow sampling (HFS) technique described below is a method for mass leak rate estimation developed and validated by Concawe in 2014-2015. It uses two (or three) instruments:

- The Hi Flow Sampler® by manufacturer Bacharach. This device is only used to monitor volumetric flow. The concentration monitors installed on the device are not used.
- The TV1000B, with similar requirements to those when deployed in the Sniffing technique (Method 21).
- A dilution probe, with similar requirements to those when deployed in the Sniffing technique (Method 21).

Equipment used on-site:

- Hi Flow Sampler® (with recent (< 30 days) flow calibration records, per procedure from Bacharach, see HFS manual **Section 5.7**).
- TVA1000B and calibration cylinders.
- Dilution probe for TVA1000B (with calibration certificate).
- Cylinder with propane; cylinder with propylene (for daily OGI sensitivity test).

For each selected equipment leak, the HFS contractor performed the following activities:

1. Select the most appropriate "bagging device" from the Hi Flow Sampler® kit. Usually the Tedlar sheet fits easily over most equipment components. Bag the leak as tightly as possible; use duct tape if needed.
   - The OGI camera can be used to check that the leak is fully captured.
   - If the camera is not available, screening with the TVA 1000B in the vicinity of the bagged component can be used to verify that the leak is fully captured.
2. Start the Hi Flow Sampler® pump at maximum speed, and connect the hose to the bag.
3. Set the TVA100B in "CH_4" measuring mode (response factor = 1). The correction for the stream molecular weight to be done later by calculation (using the results of the sample GC analysis).
4. Observe the VOC concentration at the exhaust of the Hi Flow Sampler® device with the TVA 1000B. The concentration should stay below the lower explosive limit. Log the VOC concentration over approximately 3 minutes.
   - If the TVA 1000B gives a reading > 20 000 ppmv, use the dilution probe (to stay in the linearity range of the FID detector).
   - If the TVA1000B + the dilution probe give a pegged value reading (> 50 000 ppmv), note the leak concentration as "pegged value with dilution probe".

- If the concentration recorded during 3 minutes is stable (variations < 30%), calculate the average concentration of the logged measurements; this average concentration will be used in the emission calculation.
- If the concentration profile is not stable (e.g. variations > 30%), repeat the logging for a longer period (5 to 10 minutes). Note this variation to the standard procedure.
- If time permits, this leak could be redone at another time/day.

5. Two samples taken of the gas at the exhaust of the Hi Flow Sampler pump. Samples taken to the laboratory for GC analysis.
6. Hi Flow Sampler® pump set at a lower speed (30% of maximum speed or lower), and repeat step 4. The new associated VOC concentration calculated (average of logged data for 3 minutes)
   - Taking two different measurements for the leak provides a quality check of the high flow sampling procedure.
   - The leak rate calculated by both modes should not differ by more than 10% to have a valid measurement. Leaks not satisfying this criterion will be noted and, if time permits, could be redone at another time/day.
7. The bag was purged after use until recording < 10 ppmv VOC concentration.

By accurately measuring the flow rate of the sampling stream and the gas concentration within that stream, the emission loss (in volume units) can be calculated as follows:

$$\text{Leak rate gas (lpm)} = Total\ flow\ (lpm) \times \frac{Concentration\ gas\ (ppm)}{10^6} \qquad \text{Eq. 1}$$

Where:

- Leak rate gas (lpm) = quantity of leaking gas in volume units (litres per minute)
- Total flow = total flow (lpm) set on the HFS by the operator
- Concentration gas = average concentration of the gas, determined from the logged concentrations, measured with the TVA at the outlet of the HFS (ppm)

Using the density, the loss in mass units can be calculated as follows:

$$Mass\ loss\ \left(\frac{g}{h}\right) = Total\ flow\ (lpm) \times \frac{Concentration\ gas\ (ppm)}{10^6} \times 60\ \left(\frac{min}{h}\right) \times density\ gas\ \left(\frac{g}{l}\right) \qquad \text{Eq. 2}$$

Where

- Mass loss = loss of leaking gas (g/h)
- Total flow = total flow (lpm) set on the HFS by the operator
- Concentration = average concentration of the gas, determined from the logged concentrations, measured with the TVA at the outlet of the HFS (ppm)

Density = density of the gas, determined based on ideal gas law (Eq.3):

$$Density\ \left(\frac{g}{L}\right) = \frac{MW \times P}{R \times T}$$ Eq. 3

Where

- MW = Molecular weight (g/mol) of the composition of the product
- P = atmospheric pressure (1 atm)
- R = Gas constant (0.0820578 L atm/mol K)
- T = Temperature (K)

APPENDIX 2 - QOGI PROTOCOL

The Quantitative Optical Gas Imaging (QOGI) technique described below is a method for mass leak rate estimation developed and validated by Providence Photonics. The method uses radiometrically calibrated images from a FLIR GF320 camera to extract a signal which is correlated to the absorption of hydrocarbon gases. That signal is then compared to empirically derived calibration equations to produce an emission rate. The method used in this study was deployed to a QL100, which is a tablet based software application. The QOGI method in the QL100 requires the operator to stabilise the camera image, which requires mounting the camera on a tripod. In addition, the operator must provide a measurement of ambient temperature and the distance between the camera and the leak. Note that the method described here is specific to the QL100 module used in this study. The manufacturer has advised that at the date of publication of this report their QOGI method has additional features which are not described here, such as a temperature screening tool and a background masking tool. These additional tools are designed to address poor backgrounds and interferences such as those encountered during this study.

Equipment used on-site:

- QL100 tablet (connected via USB cable)
- Benro Mach3 Tripod.
- Thermoworks Thermopen
- Tape measurer

For each selected equipment leak, the QOGI contractor performed the following activities:

1. Select the most appropriate position for the camera, considering distance and background.
   - The QOGI method has distance limits for each lens. The camera location must fall within these distance limits. For a 38mm lens used in this study, the distance can range from 2.5 to 27 meters.
   - The QOGI method requires a minimum of 3°C of ΔT, where ΔT is defined as the difference between the gas temperature and the apparent temperature of the background.
2. Place the GF320 camera on the tripod and adjust it until the source of the leak is in the centre of the field of view.
3. Connect the QL100 tablet to the GF320 via USB cable and launch the QL100 application.
4. Measure ambient temperature and enter result into the QL100 application.
5. Measure distance from camera to leak source and enter into the QL100 application.
6. Enter the type of gas to be measured. For this study, all measurements were performed as propane and a response factor was applied to correct the result to the actual speciation.

7. Press capture button. QL100 application captures three videos (100 consecutive frames in each video) and immediately processes them to provide a quantitative result.
    - Assess the level of interference in the image. Interference is indicated by any areas highlighted as plume which are not associated with the leak (steam, glint, moving equipment, reflections, etc.). If excessive interference exists, adjust position as needed and repeat the measurement.
    - Assess the delta temperature reported by the QL100. If delta temperature is below 3°C then adjust the background (if possible) and repeat the measurement.
    - Assess the relative standard deviation (RSD) reported for the three measurements. If the RSD exceeds 30%, repeat the measurement.

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