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Case Report

Optical Gas Imaging (OGI) as a Moderator for Interdisciplinary Cooperation, Reduced Emissions and Increased Safety

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Abstract: Optical Gas Imaging (OGI) cameras represent an interesting tool for identifying leaking components in hydrocarbon processing and transport systems. They make it possible to see exactly where a leak originates, thereby enabling efficient leak detection and repair (LDAR) programs. The present paper reports on an OGI test campaign initiated by the Norwegian Environmental Agency (NEA), and how this campaign stimulated cross-disciplinary cooperation at an LNG plant for better control of both fugitive hydrocarbon emissions and safety-related leaks. A surprising potentially severe leak detected in the NEA campaign triggered the introduction of in-house OGI cameras at plants and refineries, and an inter-disciplinary cooperation between specialists in the environment, technical safety and operations. Some benefits of in-house OGI cameras, as well as some concerns regarding their use are presented and discussed. The general experience is that an Ex safe, i.e., rated for safe use in a combustible hydrocarbon gas atmosphere, OGI camera, represents a very valuable tool for detecting fugitive emissions as the start point for LDAR programs. An OGI camera did, however, also turn out to be a valuable tool for fire and explosion risk management, and has led to reduced downtime after leak incidents. The concerns relate to leaks seen through the OGI camera that may look overwhelming, even with concentrations well below the ignitable limits of the released gas. Based on the LNG plant experiences, it is generally recommended that specialists in the environment, technical safety, operations and teaching fields cooperate regarding the introduction and use of OGI cameras. Suggestions for training courses are also discussed.

Keywords: methane emissions; hydrocarbon leaks; Optical Gas Imaging (OGI); interdisciplinary cooperation; leak detection and repair (LDAR)

1. Introduction

Natural gas plays a central role in the global energy supply due to its availability and environmental benefits, compared to heavier hydrocarbons and coal, especially in the process of reducing the consumption of heavier hydrocarbons towards a future of renewable energy sources. The flexibility of, e.g., Liquefied Natural Gas (LNG) in complementing temporarily varying renewable energy sources, is of great value for this transition. Handling natural gas and LNG requires operations at high pressures, where even very small openings in e.g., flanges and valve stems, may release quite large quantities of methane (CH_4) if the leaks remain undetected. Methane is especially in focus due to a significant Global Warming Potential (GWP). It is estimated that the GWP for methane over a 100 years' time span is 34 times the GWP value of CO_2, and over a 20 years' time span, it is 86 times the GWP value of CO_2 [1].

There is therefore an increasing focus in containing the gas due to the environmental impact of leaks, as well as preventing losses of a valuable product. Leakages are, however, a major issue.

Loss of energy is experienced in all engineered systems. In, for example, the electrical grid system, typically 5% of transmitted power is lost [2]. It is generally more difficult to precisely measure the losses of gaseous hydrocarbons. There have been attempts at doing this by field investigations in several gas transmitting systems to estimate the total gas releases, i.e., bottom-up estimates. With respect to state- and national-scale carbon dioxide (CO_2) and methane (CH_4) emissions from individual anthropogenic source sectors in the USA, the sector-specific CO_2 emissions are quite accurate. The CH_4 emission estimates are, however, according to Miller and Michalak [3], highly uncertain.

Mandal and Morshed [4] investigated the Titas Gas network of gas distribution in Bangladesh, for leak rates using soap screening and a Gasurveyor 500 series instrument. The most severe leaks were found for scrubber dump valves and pressure relief valves, with leak averages of 217 L/min and 438 L/min, respectively. Insulation points, tube fittings and connectors had average leak rates of 4.0, 8.0 and 1.6 L/min, respectively. Boothroyd et al. [5] investigated fugitive emissions from the UK high-pressure pipeline transport system, i.e., up to 85 barg pressure. Both soil and air emissions were detected, and they concluded that as much as 627 (241–1123 interquartile range) tonnes CH_4/km/yr was lost to the air. The loss to the soil was estimated to 62.6 kt/year. The total loss was approximately 2.9% of the annual CH_4 emissions in the UK. For one particular pipeline, the average distance between each leak was 9.32 m. Since the pipe sections were 10 m, this may indicate that they detected leaks from nearly all pipe welding joints.

Dyakowska and Pęgielska [6] arranged blind tests where operators compared two different quantification techniques for leak rates below 1.0 L/min, i.e., the EN 15446 and the Hi Flow sampler. In the EN 15446 method, the gas concentration is recorded in ppm, and correlation factors are used to estimate the leak rate. The Hi Flow sampling is organized, such that all the gas leak is collected, and air is supplied through a hose to uncontaminated air. The gas concentration is recorded at two different flow rates. Based on these recordings and the known total flow rate, the gas leak rate is calculated. Dyakowska and Pęgielska [6] concluded that the Hi Flow sampler gave them the best results. When following the procedures closely, the better of two operators recorded the blind test leak rates to within 3.5% of the real release rates.

Other methods are used to scan areas with significant releases by e.g., air planes, drones or a ground-based Differential Absorption Lidar (DIAL), i.e., top-down estimates. Large deviations have been recorded for top-down and bottom-up estimates from natural gas production regions. This may, however, be due to temporal variability, e.g., cold venting, flaring, etc. [7]. Comparing top-down and reported methane emission estimates for two regions in Alberta, Canada, Johnson et al. [8] found that the results deviated considerably. For a 50 km × 50 km measurement region close to Red Deer, with natural gas and light oil production, measured methane fluxes were 17 times larger than that derived from directly reported (bottom-up) data. The data was, however, consistent with their region-specific bottom-up inventory-based estimates. For a 60 km × 60 km measurement region near Lloydminster, characterized by significant cold heavy oil production, airborne-measured methane fluxes were five times larger than directly reported emissions from venting and flaring, and four times greater than their region-specific bottom-up inventory-based estimate [8].

These total leak rates cause concerns in national environmental protection agencies (EPAs). In several countries, e.g., the USA and Norway, the EPAs also want to quantify the leak rates as a basis for issuing environmental taxes. There are indications of methane leak rates being higher than the respective EPA's estimates [9,10]. Though EPAs may seem to be focused on total leak rates, the idea behind the tax system is indeed to reduce the leak rates. Methods that can be used close to the leak sources may better reveal where the leaks occur, and also that which leaks contribute most to the accumulated emissions. This paves the road for prioritizing the repair of the most severe leaks, i.e., the so-called super-emitters, which often represent the bulk part of accumulated emissions [11].

The leak rates and greenhouse gas (GHG) footprint of both the Norwegian LNG and pipeline gas imported to Europe have been found to be well below recently reported EU averages [12]. The estimated CH_4 emissions for the chains as a fraction of production were 0.01–0.04%. But there are leaks, and when enforcing the regular scanning of hydrocarbon process plants in Norway, the Norwegian Environmental Agency (NEA) requires DIAL recordings, which are frequently used to record methane emissions from e.g., landfills [13] and industry areas [14]. The DIAL technique can also be used to record leaks from single units, such as large process units and storage tanks. However, in order to search for leaks on a component level, close-up methods are required.

Test campaigns at Total's Lacq Platform in France have been performed using gas spectral imaging systems, i.e., mobile hyperspectral cameras in the Long-Wavelength InfraRed (LWIR) band (7.7–12 μm), multispectral LWIR camera with band (7–9 μm), and multigas LIDAR system. Five teams from the USA, Spain, Norway and France were also invited to assess the capacity of remote-sensing systems to quantify methane leaks [15]. These tests revealed that methane leaks ranging from 0.7 g/s to 140 g/s could be visualized and quantified in real time, using the mobile Telops Hyper-Cam, while also validating the performance of several remote sensing technologies. Open-path laser systems have also been used [16] to detect gas leaks at rates of about 1 L/min. Off-the-shelf, low-cost, metal oxide-based methane (CH_4) gas sensors have also been tested for methane monitoring and shown to give quite reliable data when properly corrected for the air temperature and relative humidity content in laboratory conditions [17], as well as in the field for ambient concentration recordings [18].

In recent years, hand held infrared (IR)-based optical gas imaging (OGI) cameras have been introduced for leak detection. There are several benefits when being able to walk into the field and visually see gas leaks. Ravikumar et al. [19] recently investigated whether or not the OGI technology could represent an effective method for methane leak detection. This was done based on the U.S. EPA-proposed regulations requiring the use of OGI-passive IR technologies in leak detection and repair (LDAR) programs. It was concluded that 80% of the emissions could be detected at 10 m distance. This study was followed up with a study where a commercially-available OGI FLIR-camera was used for blind tests at mockups resembling flange leaks [11]. The 50% detection likelihood was demonstrated to be about 20 g CH_4/h at 6 m imaging distances. The 90% detection likelihood limit was demonstrated to follow a power-law relationship with distance.

It is evident that the OGI technology may allow for valuable fugitive emission detection. There is, however, also another aspect to leaks, i.e., fire and explosion safety. The present study describes the results of the NEA leak detection campaign at a large scale LNG production plant. The interdisciplinary cooperation initiated by this campaign, and the process resulting from previously unknown leaks identified during the campaign, are also presented and discussed. The experience in the aftermath of the campaign and the benefits of introducing Ex proof (Sone 2) OGI cameras are outlined. The cooperation between specialists focusing on the environment, technical and operational issues is discussed, as well as the benefits of such cooperation with respect to environment, safety and production efficiency. Suggestions for training programs and further research are also presented.

2. Background for Leak Detection Campaign

2.1. Remote Sesing Method Required by the Norwegian Environmental Agency (NEA)

Prior to 2016, campaigns for detecting methane leaks at land-based hydrocarbon compression and processing facilities in Norway were mostly based on the DIAL technique, partly due to DIAL being considered as best available technology (BAT). Recording the methane emissions were mandatory, and enforced by the NEA due to the methane GHG potential. The leak rates detected by third-parties were used to issue taxes based on the recorded methane emissions.

The measurements were typically performed by a truck arriving on the site [13,14] and recording methane gas in the atmosphere upwind and downwind of the facility. Usually, the trucks had to be positioned within the "hot plant", i.e., where there should be no ignition sources. As a non-Ex safe unit, there was a need for work permits for this operation.

The truck was also only at site for 2–3 weeks, and the recordings were sometimes severely affected by surrounding nature, e.g., mire habitats releasing methane at various rates due to heating by sun radiation. Only in a few cases could the DIAL technique reveal which big unit was indeed leaking. Besides these issues, the DIAL technology is capable of getting a fair representation of the total fugitive emissions, however, generally without providing details about individual super emitters. An OGI technology inspection campaign was therefore suggested by the NEA. The campaign was also initiated in order to learn more about the potentials associated with OGI methods, and gain experience with these types of inspections. Non-Ex OGI cameras were already used at oil and gas platforms at the Norwegian continental shelf, where either company representatives or third-party consultants conducted the OGI scanning.

2.2. Optical Gas Imaging (OGI) Evaluation Program

In order to evaluate the OGI technology for land sites in Norway, the NEA engaged NEMS (previously, Add Novatech) for a study, where the purpose was to achieve a better overview of the direct emissions of methane and NMVOC (non-methane volatile organic compound) from land-based oil and gas plants. Since an LNG plant was up to DIAL scanning in the summer of 2016, and this LNG plant welcomed the third-party inspections, the NEA selected this plant for an OGI inspection campaign. The Norwegian Oil and Gas Association covered the third-party expenses related to the campaign, while the NEA covered expenses related to initiating the study. Since this plant is in an Arctic climate, the summer time was a good choice for the three-week campaign. Summer conditions would typically allow a trained inspector using an IR OGI camera to inspect approximately half the plant, on a detailed component level, within a three-week period. This was considered sufficient for evaluating the method.

Prior to the offer from the NEA, there had been some involvement from both technical safety and the environment disciplines for assessing leak rates after leaks had been detected. This was based both upon the environmental impact, as well as the safety issues related to possible leak ignition. The lower explosion limit (LEL) of methane in air is 5% by volume [20]. The prevailing method for estimating the safety risk associated with leaks was generally based on recording the leak by an aspiration gas meter, and relating the reading to e.g., <1% LEL, 1–20% LEL and >20% LEL. This practical approach made limited sense to technical safety and environmental specialists, typically educated at BSc, MSc or PhD levels, as the influence of wind or indoor air draft conditions, as well as density differences to the ambient air, would dominate the actual readings. Even though one would try to find the most pessimistic position to get a conservative reading, micro-local turbulence and the fact that the plume might go everywhere but to the aspiration gas detector, one would simply record very different values from one operator to the other, as well as from one day to the other.

A preliminary study had therefore been undertaken to use a spray (CRC leak finder) bubble test, or equivalent "soap bubble techniques", for quantifying leaks by blind test laboratory equipment set up at a land site production laboratory. These preliminary blind tests revealed that recording bubble dimension and time to make bubbles gave estimates well within 30% for leak rate estimates in the range 0.5 cm^3/s to 10 cm^3/s leaks. This would indeed be far better than a very "volatile" %LEL reading at 10 cm distance, which could never be transferred to a leak rate and an associated safety risk.

2.3. Benefits of Leak Rate Estimates

Other benefits of knowing leak rates are e.g., the possibility of estimating immediate safety risks related to potential ignition and any accumulated loss throughout a year. Knowing that an identified unit leaking e.g., 50 cm^3/s of methane, at a density of 0.656 kg/m^3, which amounts to 1034 kg/year, i.e., over 1 ton/year, makes it easier to get a focus on the environmental impacts, as well as the loss of a valuable product. Given an LEL of 36 g/m^3 [20], this 0.0328 g/s leak is capable of generating 1 m^3 explosive gas/air-mixture within 18 min. Given a heat of combustion of ΔH_c = 50 kJ/g [20], this leak would give a steady heat release rate of 1.6 kW, if ignited. Such quantifications made it easier to communicate the associated safety risk, e.g., explosion risk in an indoor volume of limited ventilation, fire exposure, etc.

Quantification also makes it possible to evaluate whether or not a leak of e.g., 5 cm^3/s or 50 cm^3/s should result in the shutdown of parts of the plant, depressurizing, flaring (always releasing some methane), repair and start-up, if the unit cannot be repaired during normal operation conditions. Quantification would give a better basis for deciding e.g., rather to wait for the next planned shutdown in order to repair the leaking component, since shut down and depressurization could also result in new leaks when starting up again after a repair. Quantification of the leak rate also provides information needed to monitor trends in leak rates, and possibly identify accelerated leak rates.

When the NEA initiated the study, and the Norwegian Oil and Gas Association offered to cover a third-party OGI survey, the LNG plant was very positive about becoming the test facility for simultaneous DIAL and OGI inspection campaigns. The environmental specialist became the contact person, while the technical safety specialists suggested where to implement the leak detection campaign, based on previous fire and explosion risk maps. They were also ready to evaluate leak rates and support decisions regarding an immediate repair or a delayed repair. The NEA campaign was seen as a possibility for improving risk assessments and risk understanding.

3. Third-Party Leak Detection Campaign Findings

3.1. Detected General Fugitive Emissions

Prior to the NEA-initiated OGI leak detection campaign, the LNG plant had a list of 10 leaks, i.e., fugitive emissions, which had been detected by aspiration gas meters in the areas and modules selected for the campaign. These were categorized according to the recorded %LEL at 10 cm distance, which then decided the follow-up actions, any immediate repairs, etc.

The NEA OGI leak detection campaign was performed using a non-third-party Ex (Sone 2) verified OGI camera (EyeCGas, Opgal Optronic Industries Ltd., Karmiel, Israel), and therefore required a work permit. The camera operator needed to carry a personal gas detector in order to get an alarm if any gas leak in the area should not immediately be detected by any fixed point or fixed line gas detectors (part of the plant's fire and gas safety system).

During the three week NEA campaign, 95 leaks were detected. The OGI camera operator detected all previous 10 leaks on the original fugitive emissions record, as well as 85 previously undetected leaks. Some of these detected leaks were quantified using leak finder spray by the local technical safety specialists, partly for educating the OGI camera operator, and for evaluating the leak rates the camera operator was able to detect in the outdoor plant environment. Since the operator was moving close to potential leak sources, leak rates down to, and even below, 1 cm^3/s was detected, i.e., confirmed by the bubble technique. Given a methane gas density of 0.656 kg/m^3, this corresponds to 2.4 g/h (21 kg/year). This is about an order of magnitude lower than reported by Ravikumar et al. [17]. The reason for the difference may be explained by the proximity to the leaks, which could be inspected much closer than at 6 m distance. There was, however, no information regarding how many leaks went undetected, and one can therefore not claim any 50% cut off detection limit.

The massive number of detected leaks, i.e., 95 versus the previously known 10 leaks, came as a surprise to plant managers and plant operators. This also resulted in some concern about safety when in the plant area. The environmental and technical safety specialists therefore started distributing some education material exemplifying the risk related to leaks of e.g., 1 cm^3/s and 10 cm^3/s. As examples, such leaks were presented by a rate in relation to e.g., a lighter for igniting cigarettes, to preventing the wording "hydrocarbon leak", which could make field operators anxious. The wording "fugitive emissions" (Norwegian: "*Diffuse utslipp*"), was better in describing most of the identified leaks. However, one leak rightfully attracted significant attention with respect to safety concerns from all involved parties.

3.2. A Detected Leak of Potential Severe Consequences

Only direct leaks from valves and equipment had previously been detected at the LNG plant. In the LNG plant there are, however, large modules of equipment and piping operating at cryogenic temperatures. After water, monoethylene glycol (MEG) and CO_2 removal, the well flow to the plant is separated into stabilized condensate (typically C5+), propane/butane and methane, while the CO_2 is reinjected in the subsea formations. The condensate is stored in an atmospheric tank at ambient temperature and pressure. The propane/butane is stored in a separate tank at atmospheric pressure and at −43 °C, i.e., as liquefied petroleum gas (LPG). The methane is compressed, cooled to liquefied natural gas (LNG), and stored within separate tanks at ambient pressure and at −163 °C. Significant areas of the plant are therefore operating at cryogenic temperatures, and are in need of thermal insulation. By surveying such thermally-insulated pipes, the OGI camera operator detected some leaks surfacing from joints or drain points in the stainless-steel cladding covering the thermal insulation. One of these leaks, on a 30 barg liquid propane system, was immediately recognized by the third-party OGI operator as a potential severe safety concern.

By notifying plant operators, who informed the shift leader, it was promptly decided to shut down and depressurize the involved unit for inspection. To the surprise of the operators, it turned out that a $\frac{3}{4}$" drain plug in a 12" valve at the propane line operating at 30 barg pressure, was the leak source. It had become loose during operation, and was releasing liquid propane. The evaporating propane at −43 °C had been freezing out humidity from the ambient air. The ice temporarily locked the plug, preventing it from loosening more. However, at each plant shutdown, or local maintenance shutdown, during the warm season the ice would melt, and the plug would likely loosen even more. This could possibly happen quickly as a result of the vibrations caused by the gas release itself. If undetected, the drain plug could eventually completely give way.

A release of liquid propane at 30 barg from a $\frac{3}{4}$" hole would lead to an initial leak rate on the order of 10 kg/s. This would result in a very serious safety incident. A significant ignitable heavy vapor cloud would manage to build up in the congested process module before the activation of the Emergency Shut Down (ESD) system and depressurization by the blow down system could have limited the leak rate. An early ignition of such a release would, given a 46 kJ/g heat of combustion for propane [20], give a heat release rate of 460 MJ, i.e., potentially a very severe fire. In a dense process module with many obstructions, a delayed ignition could have led to a considerable gas cloud buildup, high explosion-initiated turbulence levels and potentially significant explosion pressures. It was therefore very important that this leak was detected before a possible development towards any of these potentially severe scenarios.

The leak from the drain plug had previously not been detected using gas meters close to the valve. The leaking propane gas had been traveling several meters within the insulation, along the pipe, before being released to the ambient air trough openings in the protective stainless-steel cladding.

3.3. The Organizational Reaction at the Plant

The experience of an undetected potentially severe leak condition in the plant, which was previously considered safe, came as a shock to the whole organization. After depressurizing the involved system and repairing the leak, and getting the module up and running, it was decided to order an OGI survey by a third-party for investigating the remaining parts of the LNG plant.

It was also realized that the critical propane leak could in principle have been found by the established aspiration gas detector leak detection program. This would, however, involve checking all insulated piping and equipment. Such an inspection program would require a significant number of man-hours as well as lifts or scaffolding to be set up. This would be very costly and labor-intensive, and involve unnecessary exposure of personnel in the "hot plant".

The fact that this propane leak was detected revealed that the OGI technology was a tool, not only for identifying fugitive emissions, but also for detecting safety-related leaks with a potential for very severe outcomes. Fully recognizing this was a game-changer when it came to the OGI technology.

Though these cameras are quite expensive, the scanning of the plant for safety-related leaks could be done much faster, compared to using aspiration gas meters. It was therefore decided to order an IR-based OGI camera. At that moment, OGI cameras were, however, not third-party verified Sone 2 Ex-proof. An Ex safe OGI camera would be much more flexible in use, i.e., not requiring a work permit, etc. The psychological aspects involved when bringing a non-Ex safe OGI camera in the field, when looking for gas leaks, was also a concern. Based on advice from operations, technical safety and environmental specialists, it was therefore decided to wait a few months until a third-party verified that Sone 2 Ex cameras were available for purchase.

3.4. The Company Response

At, for example, a large gas process plant or a refinery, shutdown of one process train, including the loss of a few hours of production, is very costly. There had been a preparatory initiative at two of the other company land sites regarding getting OGI cameras in the future. Sound argumentation based on previous leak incidents was used to argue that an OGI camera could have given information that would have prevented production losses in previous leak incidents. Such incidents had indeed led to losses of an order of magnitude higher than the cost of an OGI camera, including a complete test campaign. Therefore, there was also a commercial driver for getting this new technology into the plants.

Since it was possible to get a better price when purchasing more than one camera, two OGI Ex-cameras were ordered (FLIR GFx320, FLIR, Wilsonville, OR, USA), to be delivered when available, one for the LNG plant, and one for an oil refinery. At the oil refinery, the use would be for general assessments of the fugitive emissions, and as a support to proactively detect possible safety-related leaks. For the LNG plant, a plant maintenance shutdown was approaching, and it was decided to use the camera prior to, during, and after, the shutdown, for checking all units after the modules had been pressurized. Additionally, within both places, the OGI cameras would be used as a tool for identifying fugitive emissions, and proactively identifying leaks which had possible safety concerns.

4. Experiences with an in-House OGI Camera

4.1. Experiences with an OGI Camera at the LNG Plant

Personnel with a general safety background and personnel with general knowledge of common IR cameras were selected for a 1-h train yourself web-based program supplied by the camera producer. Two of these were in the local technical safety group. Unless none of the trained persons were available, the camera was generally not handed out to untrained personnel. A few cases of field experiences will be presented. These cases are quite representative for the experiences with the new OGI camera technology.

4.2. Used by an Untrained Operator

In one case, a leak was detected through its odor by personnel in one of the densely built production modules. The leak was not sufficiently large enough to activate fixed point or line gas detectors, with respectively 10% LEL and 1 LELm alarm limits, and not found while searching with an aspiration gas detector or by personal gas detectors. The operators were also, quite understandably, considerate regarding approaching the leak. The maintenance work to be started in the area was therefore paused. At the administration building, an operator was given a brief introduction to the OGI camera while the camera was cooling down a few minutes to be ready for use. When in the field, he used less than 30 s to identify the leak, i.e., which component was leaking, and exactly from where it was leaking. The leak was quickly repaired, and the maintenance work could be resumed.

Though it is not generally recommended that untrained personnel operate an OGI camera, this clearly shows that a plant operator with no previous OGI experience, given less than 10 min instruction, was able to use the camera for quick identification of one concrete gas leak. This reduced the waiting time for the maintenance workers to a minimum.

4.3. Flare Line Leak Scenario

During the start-up of a process module, a dripping leak of LNG from a flare header was discovered by an operator. The leak, estimated to 0.2 L/s, originated from the lower part of a flange in a 32″ flare header. The startup was aborted, the hot plant evacuated, and the process module was put into a safe state. Scaffolding was built, and then at ambient temperature, the flange was dye tested and X-rayed for potential damage. It should be noted that the flare header was rated to operate at −196 °C (liquid N_2), and should in principle not get any damage when exposed to LNG. Even in an N_2-atmosphere purge, i.e., low partial pressure of CH_4, the temperature had likely been closer to −163 °C than to −196 °C.

In flaring scenarios, any entrained droplets of LNG being transported through the flare header will evaporate and cool it in an even manner. It was, however, evident that in the leak incident, an overfilling of LNG had happened during the startup. This resulted in LNG entering the flare header and draining, as it should, towards the flare drum, while cooling only the lower part of the flare header. In a 32″ flare header this results in uneven thermal shrinkage, which forced the flange slightly open in the lower part, letting LNG sip out. The X-raying and dye testing for crack identification revealed no concerns. However, it could very well be that after being exposed to uneven tension, the flare header could be leaking when pressurized again. The question then was, how could it be verified that the flare header flange was not leaking after this incidence, when pressurized?

It was not considered safe to pressurize the flare header and to send personnel up to check its containment function by e.g., bubble tests or the like. However, by flaring from a high-pressure source of methane gas to pressurize the flare header, the OGI camera came in handy as the previously leaking flange could initially be inspected remotely. By carefully conferring with the OGI camera operator, the flare header pressure could gradually be increased while the camera operator gradually approached the flare header, confirming that the flare header flange was not leaking. If the OGI camera had not been available, it would have taken a much longer time, and exposed personnel to a potential damaged flare system flange, to confirm that the flare header was indeed not leaking. This clearly shows the potential for less down time after leak incidences when the containment function in the field can be assessed by using an OGI camera. The concept of starting to inspect remotely, for later on to approach the object close up, is a valuable and unique characteristic of the OGI camera technology.

4.4. General Experiences with OGI Camera Inspections at the LNG Plant

To have an OGI camera at the plant adds significant flexibility when it comes to detecting leaks, evaluating severity, risk management and supply decision support in leak incidents, e.g., whether repair work could be commenced based on a small leak gas plume behavior (light buoyant gas). There is a drawback related to the time it takes to cool down the FLIR GFx320 camera prior to inspections. On the other hand, since such a camera, with an internal cold reference, has a far better resolution than cameras without this feature, the sensitive camera is very versatile. It thereby allows for detecting smaller fugitive emissions or, if there is a safety incident, to start analyzing a leak scenario remotely, i.e., from a safe distance.

It was experienced that personnel watching available videos, without the proper theoretical background, got anxious and uncertain about their own safety, especially when seeing high sensitivity (HS) mode OGI videos. One should therefore be aware of the sometimes overwhelming impressions which quite marginal leaks may give when recorded at HS mode, especially when gas temperature, wind conditions, gas type and background conditions favor a strong gas IR signal.

Some other experiences are related to understanding the limitations of the %LEL at 10 cm distance aspiration gas detector method for estimating leak risk. This has improved the motivation for learning more about leak rates and risk implications at the LNG plant, as well as motivated a search for better quantification methods. The focus of the present campaign was, however, not to quantify the leaks, but rather leak detection and repair (LDAR).

To be able to identify leaking pipes and equipment, and see exactly where the leak originates, is a highly valuable quality of the OGI cameras for LDAR campaigns. The Ex safe version also reduces the risk when operating the camera.

5. Suggestions for the Future

Being able to see gas leaks raises some concerns among plant operators. It is not easy to explain that what seems overwhelming may best be described as fugitive emissions. Venting e.g., gas already inerted by nitrogen gas (N_2), to well below the explosion limits, could look like a very large and dangerous ignitable gas cloud. It was not intuitive to untrained camera operators that such a gas cloud was not necessarily as hazardous as it seemed to be when filmed in the OGI camera IR mode, and especially in the high sensitivity (HS) mode. It is therefore recommended that such issues are explained by the personnel with detailed knowledge about e.g., vent release compositions.

The plant operators are used to calibrating gas detectors by injecting e.g., a 50% LEL hydrocarbon in air calibration gas to the gas detectors, i.e., a standard calibration procedure. Since they already understand that this 50% LEL calibration gas is safe, it is suggested that each plant make a small mockup where the operators can practice with controlled releases of different types of calibration gases to get familiar with seeing conspicuous gas clouds that are still safe, even at the release point, i.e., even before being further diluted. By varying parameters such as air speed (wind) by a fan, gas temperature, camera distance and camera mode, the operators would better learn what they can see and cannot see in which mode. By comparing what they see in the OGI camera with aspiration detectors in 10 cm distance and bubble tests, the operators can learn what they can measure with each technique. Such simple training sessions would probably reduce unnecessary anxiety as well as turning the camera sensitivity to an acknowledgment of the technology rather than anxiety. A one-day training session is recommended before a plant operator earns certification to take the OGI camera out in a plant.

Since super-emitters may dominate the accumulated plant methane emissions [11], analyzing the benefit of more frequent and less detailed campaigns, i.e., less labor-intensive and less costly campaigns, may be beneficial. Frequent search for super-emitters may also reveal leaks that bring safety concerns, thus also improving the plant safety levels. Focusing on super-emitters may therefore be a valuable approach for future emission LDAR programs.

In a recent study, Metallinou [21] has revealed that there are many myths regarding the behavior of LNG release gas clouds. Using an OGI camera in LNG spill training sessions, where the participants can see where the gas plume moves, may strengthen the learning in such courses. This may also be valuable when teaching the public about the dangers of other hazardous fuels, such as bioethanol, i.e., a fuel that has resulted in severe burn incidents in the home environment [22].

6. Analysis and Discussion

This case started with the NEA wanting to initiate an OGI inspection campaign and seeking a host plant for this campaign. Though generally using DIAL as the solution to emission estimates for taxation purposes, the NEA was interested in having new technologies for leak identifications tested together with a DIAL campaign. This could result in new knowledge to the NEA, as well as to a pilot plant. The Norwegian Oil and Gas Association offering a three week OGI campaign to the plant, free of charge, was very welcomed by the company environmental and technical safety specialists. They were very keen on hosting the campaign, which was therefore also supported by the plant management. This clearly shows that governmental authorities and national associations may help accelerate development by offering services that are making way for new technologies.

Organizations processing huge quantities of highly flammable products under pressure are at risk of major accidents. As with other organizations in high risk fields, e.g., nuclear power plants and air transport operations, the organizations avoiding accidents in the long term show some characteristic features. Weick and Sutcliffe [23] call these companies high-reliability organizations (HRO).

HROs demonstrate five interrelated organizational mindfulness behaviors at multiple organizational levels. These include: (a) Preoccupation with failure, (b) reluctance to simplify, (c) sensitivity to operations, (d) commitment to resilience, and (e) deference to expertise. When the LNG plant accepted to host the NEA initiated three weeks OGI leak detection campaign, it was likely that leaks and weak signals of possible challenges could be discovered. Allowing for, and wanting, studies such as an OGI inspection campaign is in line with several of the HRO mindfulness characteristics. Letting third-party personnel into the plant to search for leaks with new technology opens for better risk management and cooperation [24,25].

There are always some additional work and manpower requirements when allowing new third-party companies access to a plant processing hazardous products, such as the need for local safety courses, guidance when in the process areas, etc. This could be recognized as a loss for a process plant. This was, however, never addressed as an issue when the NEA suggested an OGI inspection campaign. Preoccupation with failure, reluctance to simplify, sensitivity to operations and deference to expertise was evident when the environmental specialists and the technical safety specialists approached the management who welcomed the third-party OGI inspection campaign. When the potentially severe gas leak was discovered, the prompt actions to depressurize, check and repair this leak may be an indication of commitment to resilience. During the three weeks campaign also four other leaks needed increased attention with respect to the safety risk involved, though not as promptly as the potentially severe propane leak. The decision to get an OGI camera at the plant may be taken as a sign of the management's future sensitivity for operations. This decision was very much appreciated by the environment and safety specialists.

The prior concern with risk assessment based on aspiration gas detectors held at 10 cm distance from possible leaking objects was recognized as an important motivation for the recommendation from these specialists. An OGI campaign could be the start of a journey towards an improved approach to leak detection campaigns. In the future it could possibly make way for quantification of leak rates in cm^3/s, g/h, etc. Being able to see whether the leaking gas had the plume shape of e.g., a jet or a very diffuse release, could also immediately give valuable information about a leak without further in-depth analysis.

These factors represented common interests for the field of environmental protection, technical safety and operations. Joining forces interdisciplinary meant that these groups could support each other in their respective professional networks. One of the benefits of such support was the concept of presenting e.g., a 10 cm^3/s fugitive methane emissions of low fire and explosion risk as a yearly loss of 200 kg of methane product. Usually, loss aversion results in negligence to safety [24]. However, when presenting leaks as a direct monetary loss, the loss aversion can be turned around to be a motivation for environmental protection and improved safety. The discovery of 95 leaks in the OGI campaign therefore brought the yearly accumulated losses to the table. And, compared to the DIAL technology, the OGI campaigns revealed exactly which components were leaking. This made it easier to prioritize repairing the largest and easily-corrected leaks, i.e., harvesting the "low-hanging fruits" and super-emitters. The NEA OGI-initiated inspection campaign thereby resulted in an improved LDAR program at the plant.

When the potentially severe propane leak was detected, the organization responded quickly with full trust in the third-party OGI camera operator. This is quite indicative for sensitivity to operations, commitment to resilience and deference to expertise, i.e., three of the HRO characteristics. Module shut down was administered by the shift, in line with the principles of leadership redundancy [26].

Only two drawbacks were discovered with the OGI camera (FLIR GFx320) used at the LNG plant. The first was related to the 6–7 min cool-down time. When the technical safety staff specialists should use the camera, they switched it on to initiate the cool-down while changing into the required protective working clothes, safety boots, hard hat, gloves and safety glasses. Since this takes some minutes, the camera was always ready for use when entering the plant processing areas.

When field operators would come to collect the OGI camera, which was always kept close to the administration building central control room (CCR), personnel in the CCR could be radioed to switch the camera on and initiate the cool-down process. Thus, no time was actually lost when the field operator arrived back in the field, i.e., with the camera ready for use. When planning for the needed cooling time, this associated drawback was generally compensated for, and thereby eliminated as a concern.

The second drawback, i.e., personnel getting anxious when viewing gas releases by the camera or viewing videos afterwards, is to a large extent related to the high OGI camera sensitivity, i.e., a camera quality. The challenge related to minor leaks in some conditions being overwhelming can be solved by proper training sessions and demonstrations. It is therefore recommended that plants investing in this technology rather quickly arrange simple test rigs for e.g., 50% LEL calibration gas release studies. A one-day theory and practical training session before using the camera in the plant may give plant operators a good introduction to the OGI camera technology.

In line with the test field study presented by Ravikumar et al. [19], the present study concludes that the OGI technology is sufficiently advanced for field use, both with respect to searching for fugitive emissions, and for safety-related leaks. One may argue that there could be situations where an OGI camera could not detect e.g., a methane leak when the gas temperature and the background temperature match exactly. However, given the Joule Thompson effect when pressurized gas is released, it is quite unlikely that the gas would end up exactly at the temperature of the background objects. The 10 previously detected leaks, all unknown to the third-party OGI camera operator, were detected during the EPA leak detection campaign. Indeed, 85 previously undetected leaks were also discovered, including five that had to be repaired, one of which could have resulted in a severe leak incident if it had remained undetected. This implies that the OGI camera, when used properly in the field, is a very good tool for leak detection. The authors therefore recommend OGI campaigns, and as well, recommend cameras in-place at larger facilities. A camera at hand can significantly reduce down-time after leak incidents and thereby represent an economic driver for the technology.

It is apparent that the cooperation between the environmental specialists and the technical safety specialists was trigged by a new tool, i.e., an OGI camera. The NEA leak detection campaign initiative at the LNG plant turned out to give much more than just a comparison of DIAL and OGI technologies. This may thus represent a learning point for others. Letting in external experts, who operate under confidentiality, may give unforeseen environmental and safety-related benefits.

7. Conclusions

An OGI test campaign initiated by the NEA, and a field study funded by the Norwegian Oil and Gas Association, was shown to stimulate cross-disciplinary cooperation at an LNG plant for better control of fugitive hydrocarbon emissions and potentially hazardous leaks. A surprising and potentially severe leak detected in the campaign triggered the introduction of in-house OGI cameras at plants and refineries, and an increased inter-disciplinary cooperation between specialists in the environment, technical safety and operations. The general experience is that a third-party Sone 2 Ex safe OGI camera represents a very valuable tool for detecting, and thereby possibly limiting, fugitive emissions. It also turns out to be a valuable tool for fire and explosion safety management, and was shown to reduce downtime after a leak incident. Based on the LNG plant experiences, it is recommended that specialists in the environment, technical safety, operations and teaching fields cooperate regarding the introduction and use of OGI cameras. A simple mockup for safe calibration gas mixture releases for teaching purposes, and a one-day course for the plant operators regarding the OGI technology, is highly recommended.

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References

1. Brandt, A.R.; Heath, G.A.; Cooley, D. Methane Leaks from Natural Gas Systems Follow Extreme Distributions. *Environ. Sci. Technol.* **2016**, *50*, 12512–12520. [CrossRef]
2. IEA. Energy Efficiency Indicators: Fundamentals on Statistics. 2014. Available online: https://www.iea.org/statistics/ (accessed on 22 January 2019).
3. Miller, S.M.; Michalak, A.M. Constraining sector-specific CO_2 and CH_4 emissions in the US. *Atmos. Chem. Phys.* **2017**, *17*, 3963–3985. [CrossRef]
4. Mandal, P.C.; Morshed, S.M. Localization of fugitive methane emission from natural gas distribution network of Titas Gas. *Polish J. Chem. Technol.* **2017**, *19*, 127–131. [CrossRef]
5. Boothroyd, I.M.; Almond, S.; Worrall, F.; Davies, R.-K.; Davies, R.J. Assessing fugitive emissions of CH4 from high-pressure gas pipelines in the UK. *Sci. Total Environ.* **2018**, *631–632*, 1638–1648. [CrossRef]
6. Dyakowska, E.; Pęgielska, M. Comparison of the accuracy of two methods of methane fugitive emissions measurements—One according to EN 15446 standard and the other using the Hi Flow Sampler device—GERG (The European Gas Research Group) project results. *Nafta-Gaz* **2016**, *72*, 660–665. [CrossRef]
7. Vaughn, T.L.; Bell, C.S.; Pickering, C.K.; Schwietzke, S.; Heath, G.A.; Pétron, G.; Zimmerle, D.J.; Schnell, R.C.; Nummedal, D. Temporal variability largely explains top-down/bottom-up difference in methane emission estimates from a natural gas production region. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 11712–11717. [CrossRef]
8. Johnson, M.R.; Tyner, D.R.; Conley, S.; Schwietzke, S.; Zavala-Araiza, D. Comparisons of Airborne Measurements and Inventory Estimates of Methane Emissions in the Alberta Upstream Oil and Gas Sector. *Environ. Sci. Technol.* **2017**, *51*, 13008–13017. [CrossRef]
9. Brandt, A.R.; Heath, G.A.; Kort, E.A.; O'Sullivan, F.; Petron, G.; Jordaan, S.M.; Tans, P.; Wilcox, J.; Gopstein, A.M.; Arent, D.; et al. Methane Leaks from North American Natural Gas Systems. *Science* **2014**, *343*, 733–735. [CrossRef]
10. Harriss, R.; Alvarez, R.A.; Lyon, D.; Zavala-Araiza, D.; Nelson, D.; Hamburg, S.P. Using Multi-Scale Measurements to Improve Methane Emission Estimates from Oil and Gas Operations in the Barnett Shale Region, Texas. *Environ. Sci. Technol.* **2015**, *49*, 7524–7526. [CrossRef]
11. Ravikumar, A.P.; Wang, J.; McGuire, M.; Bell, C.S.; Zimmerle, D.; Brandt, A.R. "Good versus Good Enough?" Empirical Tests of Methane Leak Detection Sensitivity of a Commercial Infrared Camera. *Environ. Sci. Technol.* **2018**, *52*, 2368–2374. [CrossRef]
12. Borda, E.S.; Korre, A.; Nie, Z.; Durucan, S. Comparative assessment of life cycle GHG emissions from European natural gas supply chains. In Proceedings of the 14th International Conference on Greenhouse Gas Control Technologies, GHGT-14, Melbourne, Australia, 21–25 October 2018.
13. Innocenti, F.; Robinson, R.; Gardiner, T.; Finlayson, A.; Connor, A. Differential Absorption Lidar (DIAL) Measurements of Landfill Methane Emissions. *Remote Sens.* **2017**, *9*, 953. [CrossRef]
14. Robinson, R.; Gardiner, T.; Innocenti, F.; Woods, P.; Coleman, M. Infrared differential absorption Lidar (DIAL) measurements of hydrocarbon emissions. *J. Environ. Monit.* **2011**, *13*, 2213–2220. [CrossRef]

15. Watremez, X.; Marblé, A.; Baron, T.; Marcarian, X.; Dubucq, D.; Donnat, L.; Cazes, L.; Foucher, P.Y.; Danno, R.; Elie, D.; et al. Remote Sensing Technologies for Detecting, Visualizing and Quantifying Gas Leaks. In Proceedings of the Society of Petroleum Engineers, SPE International Conference and Exhibition on Health, Safety, Security, Environment, and Social Responsibility, Abu Dhabi, UAE, 16–18 April 2018. [CrossRef]
16. Gibson, G.; van Well, B.; Hodgkinson, J.; Pride, R.; Strzoda, R.; Murray, S.; Bishton, S.; Padgett, M. Imaging of methane gas using a scanning, open-path laser system. *New J. Phys.* **2006**, *8*, 26. [CrossRef]
17. Van den Bossche, M.; Rose, N.T.; De Wekker, S.F.J. Potential of a low-cost gas sensor for atmospheric methane monitoring. *Sens. Actuators B Phys.* **2017**, *238*, 501–509. [CrossRef]
18. Eugster, W.; Kling, G.W. Performance of a low-cost methane sensor for ambient concentration measurements in preliminary studies. *Atmos. Meas. Tech.* **2012**, *5*, 1925–1934. [CrossRef]
19. Ravikumar, A.P.; Wang, J.; Brandt, A.R. Are Optical Gas Imaging Technologies Effective For Methane Leak Detection? *Environ. Sci. Technol.* **2017**, *51*, 718–724. [CrossRef]
20. Drysdale, D. *An Introduction to Fire Dynamics*, 2nd ed.; John Wiley: New York, NY, USA, 1999; 476p, ISBN 0-471-97291-6.
21. Metallinou, M.M. Liquefied Natural Gas as a New Hazard; Learning Processes in Norwegian Fire Brigades. *Safety* **2019**, *5*, 11. [CrossRef]
22. Log, T.; Moi, A.L. Ethanol and Methanol Burn Risks in the Home Environment. *Int. J. Environ. Res. Public Health* **2018**, *15*, 2379. [CrossRef]
23. Weick, K.E.; Sutcliffe, K.M. *Managing the Unexpected: Sustained Performance in a Complex World*, 3rd ed.; John Wiley & Sons: Hoboken, NJ, USA, 2015; ISBN 978-1-118-86245-2.
24. Murata, A.; Nakamura, T.; Karwowski, W. Influence of Cognitive Biases in Distorting Decision Making and Leading to Critical Unfavorable Incidents. *Safety* **2015**, *1*, 44–58. [CrossRef]
25. Bateson, M.; Nettle, D.; Roberts, G. Cues of being watched enhance cooperation in a real-world setting. *Biol. Lett.* **2006**, *2*, 412–414. [CrossRef]
26. Johannessen, I.A.; McArthur, P.W.; Jonassen, J.R. Informal leadership redundancy: Balancing structure and flexibility in subsea operations. *Scand. J. Manag.* **2015**, *31*, 409–423. [CrossRef]