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Field evaluation of a multi-point fibre optic sensor array for methane detection ("OMEGA")

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ABSTRACT

A multi-point fibre optic sensor array for methane detection ("OMEGA") has been developed and tested under semi-quantitative field conditions. The new system employed wavelength modulation spectroscopy using a DFB laser source scanned across the Q6 methane line at 1.665• m. A branched fibre network connected the single source to up to 64 sensor heads. Controlled releases of natural gas were provided for test purposes within an array of four optical sensors and four pellistor reference sensors. An automated system delivered standard gases to each sensor, to enable routine calibration checks to be carried out. Agreement between the conventional and optical systems was excellent in the range 0-100% LEL (lower explosion limit). The optical system offers a simple, intrinsically safe design with a low cost of ownership per sensor head.

Keywords: optical fibre sensor, methane, natural gas, DFB laser, field trial, gas leak

1. INTRODUCTION

For safety reasons, the gas industry has an interest in detecting accidental natural gas releases on exploration and production sites, using permanently installed sensors. Conventional pellistor sensors employ a catalyst bead on which, at high temperatures, flammable gases are oxidised. The resulting exothermic reaction raises the bead temperature still further and increases the bead's electrical resistance. These sensors thus provide a measure of gas concentration that is inherently related to the combustibility of the gas. Although pellistors are rugged and reliable, optical sensors could give an alternative solution with a lower cost of ownership. The requirements of intrinsic explosion safety for a detector containing a high temperature bead can add to its cost, while all-optical sensor heads offer a simpler intrinsically safe solution. Furthermore, pellistors can suffer from "fold-back" of the response at high concentrations when oxygen is displaced from the air, preventing combustion from occurring. This potential ambiguity in the gas concentration reading must be removed, usually by employing a second sensor element. Optical absorption spectroscopy would not suffer from this inherent problem.

The OMEGA system (Optical MEthane Gas Analyser) was the result of a DTI sponsored collaborative programme involving the University of Strathclyde, Optosci, GMI and BG Technology. The work was shortlisted for the IEE Measurement Prize in 1998. The prototype system used a DFB laser to detect the presence of methane via its infra-red absorption at 1.665 • m[1,2]. Up to 64 point sensors may be connected to a central source / detector unit using a branched

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fibre optic network. The instrument was designed to detect natural gas in air, in the range 0-50% of the lower explosion limit (LEL). The lower explosion limit of methane is taken to be 5%vol in air[3].

Field trials were carried out in order to test the ability of the system to detect controlled releases of natural gas, and to evaluate the system's long-term performance on a site exposed to a variety of weather conditions. Testing was carried out at BG Technology's Spadeadam test facility in Cumbria. Controlled releases of natural gas were provided within an experimental rig, on which four OMEGA point sensors were mounted. Each was paired with a conventional pellistor sensor provided by GMI, to give independent gas concentration measurements. Standard calibration gases could be delivered to the sensors automatically, using timed actuated valves, such that the behaviour of the system could be monitored over long periods and when the site was unmanned. The apparatus was exposed to a variety of weather conditions including snow, sleet, rain and even sunshine, over a 6-month period. Temperatures ranged between +15ºC and –4ºC.

2. OPTICAL SENSOR CONFIGURATION

The configuration of the optical fibre sensor has been previously reported in some detail[1,2]. The following represents a brief summary of the system, as installed in the field tests. The system uses wavelength modulation spectroscopy to give a first derivative spectrum of the Q6 methane line at 1.665• m. Because of the high spectral resolution employed, interference from other molecular species was not expected. The DFB laser source and detectors were located centrally, with sensor heads at a distance of up to tens of km away (in this case approximately 100m). Fibre splitters enabled up to 64 sensor heads to be addressed by one laser diode, enabling the high cost of this component to be spread over a number of measurement points. In the field test system, four sensor heads were implemented in a multiplexing scheme whose processing acted as though the full complement of 64 heads was present, enabling the worst-case response time and sensitivity to be evaluated. The system configuration is shown in Figure 1.

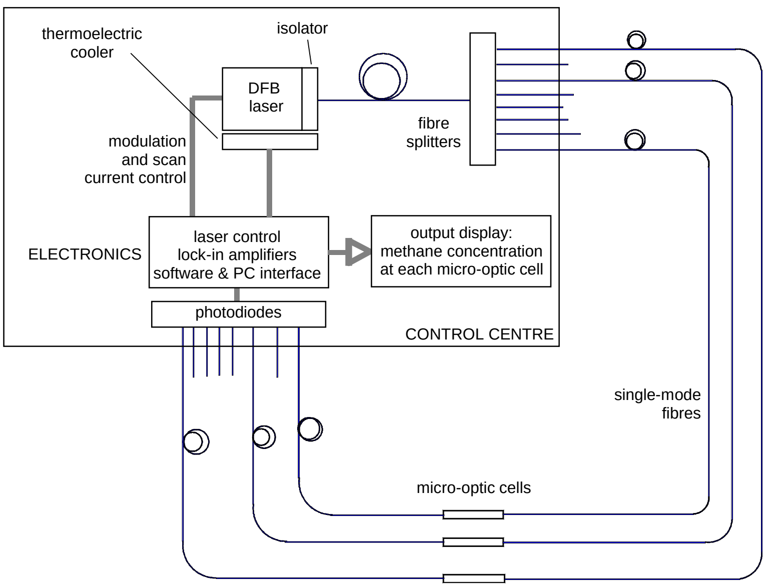


Figure 1. Configuration of the OMEGA system

Each optical sensor head consisted of a 5cm open absorption cavity into which the ambient air and gas could diffuse, as shown in Figure 2. Light from the laser diode entered via one fibre and left via a separate fibre. A GRIN lens was glued to the polished end of each fibre, designed such that a beam focus was formed midway along the absorption path. This design minimised the creation of interference fringes forming in the etalon created by the absorption cavity, since any reflections would be divergent.

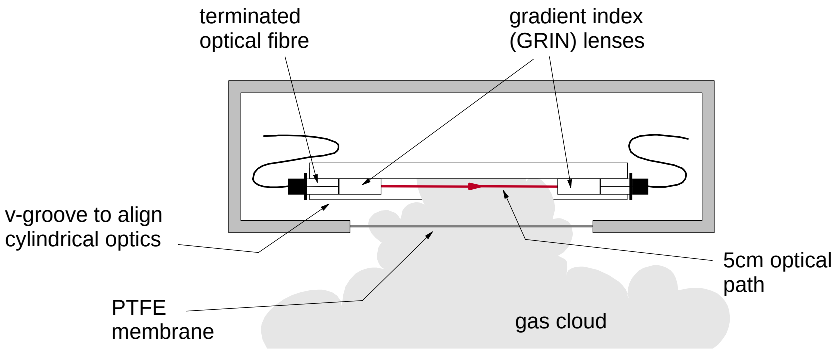


Figure 2. Cross-section through OMEGA detector heads

3. FIELD TEST INSTALLATION

Experiments to evaluate the OMEGA system were carried out at BG Technology's Spadeadam test site, located in the Pennines between Carlisle and Newcastle-upon-Tyne. Figure 3 shows a detailed plan of the eastern end of the site, including the position of the test rig. The Spadeadam site is normally used for large-scale explosion testing. However, its remote location and established safety procedures were also suited to tests that involved the controlled release of hazardous gases.

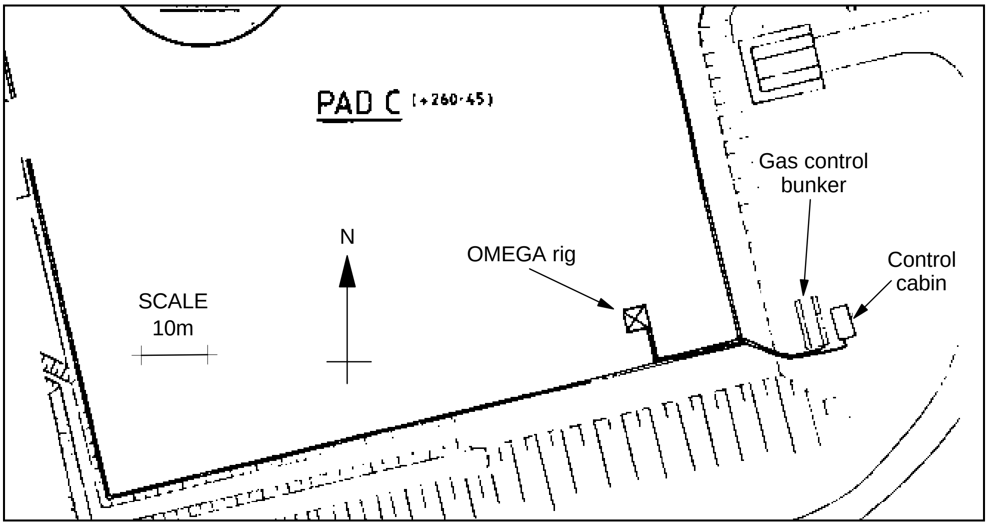
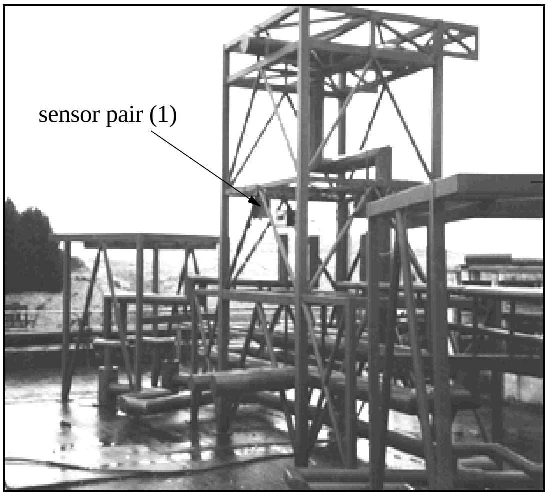


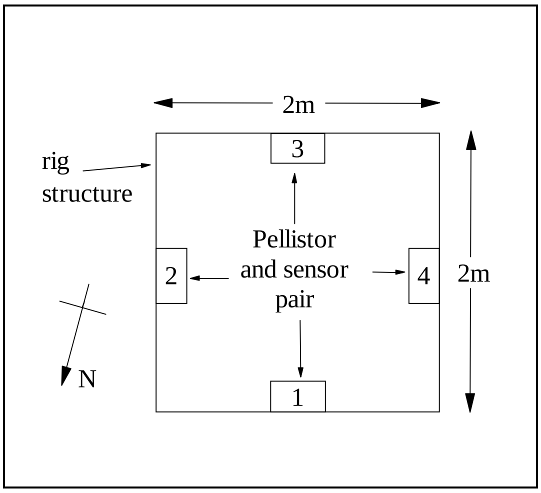
Figure 3. Spadeadam site plan: Test Pad C, showing OMEGA installation

The OMEGA point sensor units were attached to a test rig that was rigidly secured to the concrete surface of the test pad, as shown in Figure 4. The natural gas release point consisted of a pipe from a gas reservoir, manually controlled via a valve at a distance of approximately 50m from the rig. The release pipe could be clamped to various parts of the rig structure, pointing in different directions, as required.

Weather data was monitored and logged using a separate computer-based system (ELE International) and included the following parameters; wind direction and speed, temperature, relative humidity, rainfall, barometric pressure and solar radiation level. The weather station was located at a distance of approximately 400m from the test pad.



(a) Photograph of the test rig, from the test pad.



(b) Plan view of the numbered sensor positions

Figure 4. OMEGA test rig, mounted on the edge of the test pad.

Each OMEGA sensor was mounted next to a standard production pellistor sensor supplied by GMI. A typical sensor pair is shown in Figure 5. In order to calibrate the instruments in situ, and to check the calibration settings automatically, supplies of standard gases were introduced to the sensors from cylinders stored in the gas bunker shown on the site plan in Figure 3. Two cylinders were used, containing hydrocarbon free air (for the calibration zero point) and 2.5% methane in air (50% LEL). The calibration gas lines can be seen in Figure 5 as black pipes entering both the front of the optical head, and the rear of the protruding pellistor sensor. The cable entering the optical head at the bottom contained the two optical fibres connecting the source and receiver with the sensing optical path. Released gas entered the optical head through the white slot in the front face, which was protected from the elements by a "Gore-tex" PTFE membrane, held in place by a grey retaining clip. In the case of the pellistor, released gas entered through the bottom of the protruding steel cylinder, diffusing through two stainless steel sintered filters before entering the pellistor cavity.

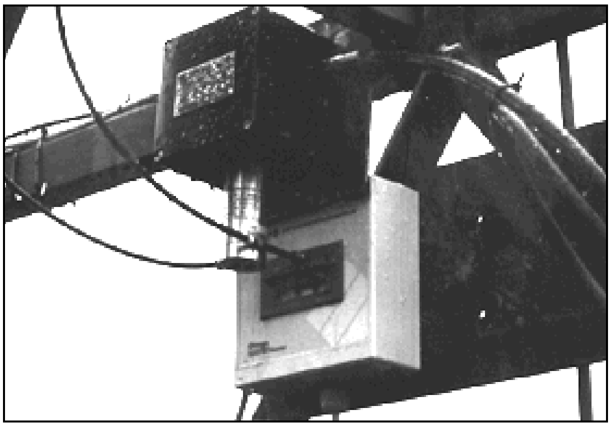


Figure 5. OMEGA sensor (lower white box) next to a GMI pellistor (upper black box), both mounted with their gas inlet as close as possible, to give accurate comparisons of the gas concentration.

The central OMEGA unit, provided by Optosci, is shown in Figure 6. It contained the single DFB laser source, individual detectors for each point sensor, fibre optic splitters and signal processing hardware. The outputs from the Optosci system were integrated into a standard GMI pellistor controller and alarm management system (also shown in Figure 6), from which all data were logged on a PC, using GMI software. Heating was provided in the control cabin, because very low temperatures might have caused problems with the equipment.

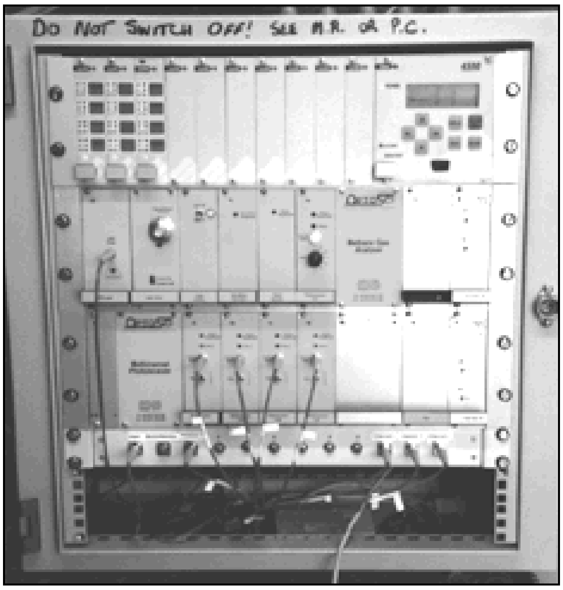


Figure 6. Central OMEGA control and measurement panel, incorporating the single DFB laser source, detectors, signal processing, alarm management and data output.

4. RESPONSE TO THE CALIBRATION CHECKING SYSTEM

The purpose of the calibration gas supply was to enable sensor calibration to be carried out in situ and to allow the calibration settings to be easily checked thereafter. The system was programmed to perform routine calibration checks every 24 hours at 12.00 midday, with a further option to perform hourly checks. These calibration checks did not involve making any changes to the calibration settings, merely supplying two standard gases (hydrocarbon free air and 2.5% methane in air) so that the sensor responses could be checked and logged. The design of the calibration gas supply is shown in Figure 7. Flow rates of approximately 1 litre min^{-1} through the optical heads and 2.5 litre min^{-1} through the pellistors were controlled using a flow restrictor on each gas line.

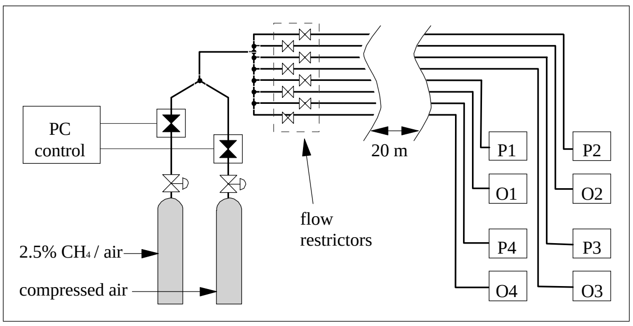


Figure 7. Calibration gas supply, using a flow restrictor in the gas line to each sensor giving a high degree of flow regulation.

4.1 Results of calibration checks

The result of a typical calibration check for one pellistor / optical sensor pair is shown in Figure 8.

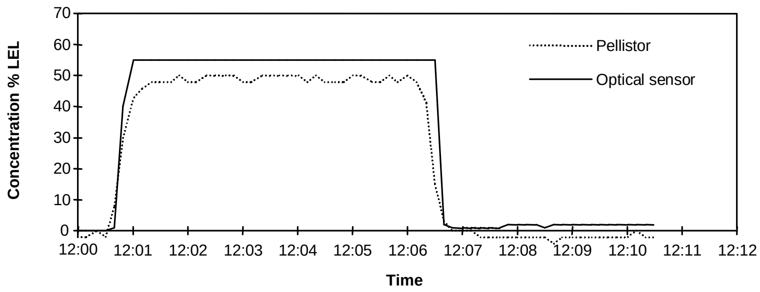


Figure 8. Response of optical and pellistor head in position 4 to calibration gases: 50% LEL methane followed by air.

The optical sensors appeared, in general, to have a slightly faster response than the pellistors, with t_{90} less than 10 seconds, which was the time taken for the system processor to take 64 absorption readings and deliver the concentration measurements. The noise level of the optical system also appeared consistently lower than that of the pellistor sensors. However, the calibration span and zero were observed to drift somewhat throughout the program, and were periodically readjusted. Although initially stable, by the end of the test programme the zero response was found to drift significantly over short time periods, the worst example being a drift from zero to +14% LEL over only 30 minutes. Any drift in the response to 50% LEL methane was low in comparison. The zero drift can be explained by higher than expected levels of optical interference in each OMEGA fibre loop. Interference fringes in the spectral scan were interpreted as positive or negative methane peaks, depending on their position, which might vary with the temperature of the interference cavity. Laboratory experiments conducted by GMI confirmed this possibility, showing zero shifts as rapid as the 30-minute change observed in the field.

5. RESPONSE TO CONTROLLED GAS RELEASES

OMEGA was tested with controlled releases of 100% natural gas from the Spadeadam reservoir. The release point consisted of a short metal pipe connected to a length of hose, the gas flow controlled via a valve at some distance. The release point was generally positioned approximately 1m underneath the sensors, pointing upwards. The concentration of gas registered by each sensor pair depended strongly on the speed and direction of the wind. By the time the released gas reached the sensors, it was usually sufficiently diluted by the surrounding air that the concentration was in the required 0-100%lel range.

A subtle problem emerged during gas release tests. Although responding well to calibration checks (when methane was introduced to the sensor heads along narrow gas lines), the optical sensor system showed a very poor response to real natural gas leaks. This is illustrated in Figure 9, in which a natural gas release was followed immediately by a calibration check.

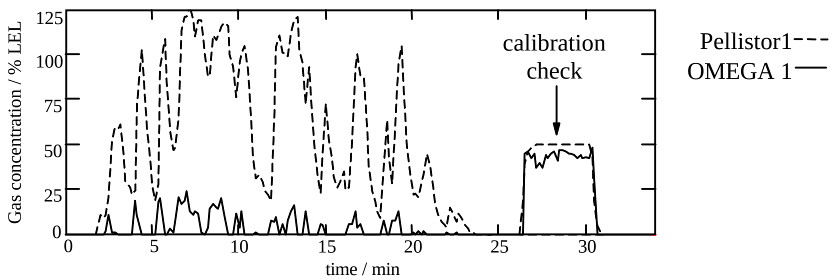


Figure 9. Optical sensor 1 showed a poor response to this open natural gas release, despite good performance in a subsequent calibration check.

A number of possible sources of this effect were ruled out experimentally before a likely cause could be postulated, as follows. It was noted that the condition of the optical system had deteriorated throughout the test programme, with greater optical losses than at installation and larger interference fringes. Both these effects are consistent with debonding of the adhesive joint between the GRIN lenses and the optical fibres at either end of the sensor cell. The effect could have caused the zero drift referred to in section 4.1, but would be insufficient in itself to account for the lack of performance during gas releases. The interference fringes can be seen superimposed on the three scanned optical spectra in Figure 10. During calibration tests, they were observed to shift across the scan by almost two full fringes, possibly because of the tiny temperature difference between the air from the cylinders and the ambient air.

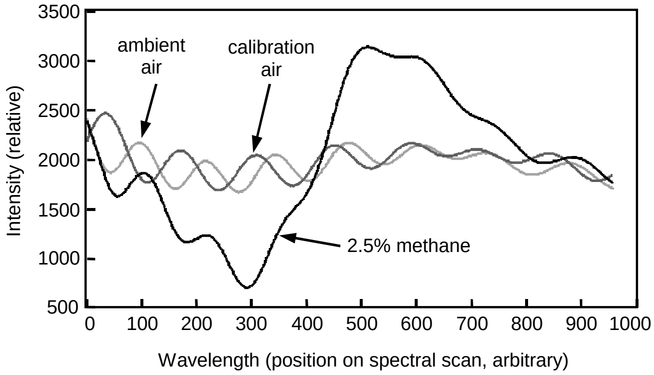


Figure 10. Spectral scans taken directly from optical channel 1 under different conditions. Interference fringes can be seen across all three scans, and the large differential absorption signal, due to a methane line, is clearly superimposed for the 2.5% methane trace.

As well as the calibration test observed in Figure 10, a spectral scan was also directly viewed during a natural gas release, confirming that a methane absorption line was observed to rise and fall with the pellistor-measured gas concentration. However, at low methane concentrations, this absorption signal was not properly detected.

The system made use of the DC offset in the photodiode signal, as follows. The DC reference was obtained from the temperature dependence of the photodiodes and used to compensate for temperature drift of the laser diode. Since the wavelength emitted by the DFB laser was temperature dependent, it was necessary to use temperature compensation in order to identify the region of the spectral scan in which the methane line was expected. Increased optical losses, caused by debonding of the adhesive in the optical system, produced an error in the DC reference and caused the software to look for the methane line at the wrong wavelength. The level of absorption at that wavelength was much lower and could be easily dominated by the interference fringes observed in Figure 10. Because those interference fringes could change wavelength after the slightest temperature change, the zero level could shift significantly during calibration with the cylinder gases. It was therefore not possible to correct for the problem during calibration with 50% LEL methane. This explains why the system could apparently be successfully calibrated with methane, but could not respond to natural gas leaks.

Once the DC offset level was correctly adjusted and the system recalibrated, OMEGA performed well and consistently in natural gas release tests, despite the persistently high magnitude of the interference fringes. Figure 11 shows such a release, in which the optical response appeared to be slightly faster than the pellistor response, as expected. The optical response was also slightly lower on average compared to the pellistor response. We would expect OMEGA to give slightly lower readings for natural gas and the pellistor to give slightly higher readings, if calibrated using methane alone.

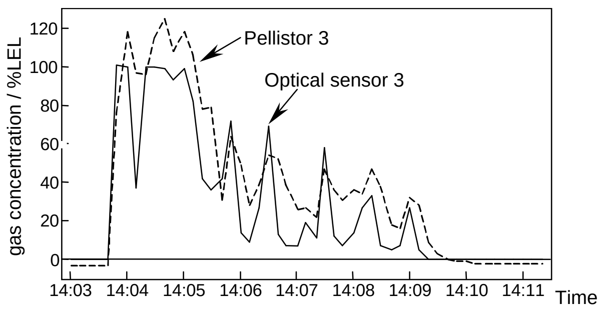


Figure 11. Natural gas release test, showing good agreement between the OMEGA response and pellistor readings following readjustment of the DC offset levels. Note that the optical system responded more quickly than the pellistor.

A further issue was noted during the field trials, for both the optical sensors and conventional pellistors. Gas releases of 100% natural gas were used, with a release rate that, although not measured, was considerable (large enough to be audible from a distance of 100m). Despite the high release rate and close proximity of the four sensors to the release point, it was clear that (a) the gas was considerably diluted by the time it reached the sensors, and (b) at any one time, only one of the sensor pairs would respond to the leak, if any. This work thus highlights the difficulty of detecting gas leaks with arrays of point sensors on an exposed site. A low limit of detection and careful location of arrays of point sensors are therefore of great importance.

6. DISCUSSION AND CONCLUSIONS

OMEGA has been comprehensively tested in the field, at BG Technology's Spadeadam site in Cumbria, with good agreement observed between the OMEGA response and readings from traditional pellistor sensors. OMEGA had a slightly faster response in testing, with an update period limited by the signal processor to 10 seconds. Performance during natural gas releases was good, with excellent agreement with the pellistor references in the range 1% to 100% LEL. Calibration checks established that the optical system had a slightly faster response time than the pellistor detectors.

A subtle problem emerged during testing, which caused OMEGA to register lower readings than expected during releases. The cause of this problem was identified as optical interference fringes resulting from gradual delamination of adhesive joints in the optical path, within the sensor heads. Optosci and Strathclyde University have since made a number of changes to the system design, in order to eliminate these problems. Without a rigorous approach to release testing, the difference in magnitude between the pellistor and OMEGA responses might not have been apparent, and this problem may not have been identified. Good quality field trials are therefore essential if new instruments are to be developed rapidly and used with confidence.

OMEGA has the potential to offer the following key advantages over other gas leak detection systems;

- low maintenance requirements,
- low levels of interference from gases other than methane,
- fast response times
- intrinsic safety.

Using a branched fibre optic network would reduce the cost of ownership of each sensor head for a number of reasons:

(i) The cost of the DFB laser and detector unit could be shared over up to 64 sensors.
(ii) Having no electrical connectors, the sensor heads had a simple, intrinsically safe design.
(iii) Maintenance would be simplified by locating sophisticated equipment (emitter, detector, fibre couplers and switches) at a central point.
(iv) Using low loss fibre enables the system to monitor over a very wide area (kilometres).

The controlled gas leaks generated in field tests proved difficult to detect, with both conventional pellistor detectors and with the OMEGA system. This confirms that careful location of point sensors is needed in order to provide comprehensive coverage of complex plant.

ACKNOWLEDGEMENTS

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