Harpur Hill, Buxton
Derbyshire, SK17 9JN
T: +44 (0)1298 218000
F: +44 (0)1298 218590
W: www.hsl.gov.uk

HEALTH & SAFETY LABORATORY

Development of an advanced fire detector for underground coalmines - Final Report.

HSL/2005/39

Project Leader: **Peter Walsh**
Author(s): **Mike Hemingway & Peter Walsh**
Science Group: **Environmental Sciences**

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FOREWORD

This project was commissioned by HSE/HID and UK Coal. It was initiated by the Mine Fire Detection Working Group comprising: Mansel Williams (Chair, HID; replacing Gary Goodlad, retired), Peter Goodier, (HID), Neville Williams (Secretary, HID), Brian Parry (HID, retired), Stuart Jobling (UK Coal) and Stuart Hunneyball (TES Bretby). David Brenkley (Mines Rescue Service) was an invited guest.

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EXECUTIVE SUMMARY

In the UK, automatic fire detectors detect fewer underground fires than mine personnel, particularly during the early stages of smouldering and smoke emission. However, as collieries become more automated, there are fewer personnel to detect fires. Current fire detectors in use in UK coal mines, based on semiconductor sensors which detect gaseous products of combustion, are under-utilised. Moreover, they are not user-friendly, have performance limitations due to interferences, and are obsolete. A joint HSE/UK Coal research project was therefore instigated to develop an improved fire detector. This paper describes tests performed in an experimental mine roadway on various types of sensor. The sensors were exposed to smouldering conveyor belt, coal, wood, oil and grease, and diesel exhaust fume.

Objectives

1. To improve the techniques and technology for fire detection systems in mines and tunnels developed in earlier projects.

2. To evaluate a prototype, commercial-based (non-Intrinsically Safe) products of combustion (POC) monitoring system for potential use in underground mines based on a sensor array and pattern recognition system with the potential for improved performance over the current FIDESCO fire detection system used underground, with respect to cross-sensitivity to common interferents.

3. To recommend how the system may be further developed for actual use underground.

Main Findings

The following sensors were found to be unacceptable for use in an advanced underground fire detection system:

1. Products of combustion semiconductor sensors. The TGS 2106 proved to be the most sensitive semiconductor to all fire types but it was sensitive to water vapour and hydrogen. In addition, variations in its specification, as later models are brought out by the manufacturer, mitigate against using them as an integral component of a sensor array.
2. Ionisation smoke detector. This was sensitive to all fires and diesel exhaust but also to coal dust. Also, there is a general policy is to avoid the use of equipment containing an ionising source in underground mines.
3. Single wavelength optical smoke sensor. This was sensitive to most fires although not so sensitive to smouldering wood and grease. However, it was also sensitive to coal dust.
4. Thermal imaging camera. This could readily highlight heat produced from all fires. However, they do not work well in dusty environments, need line-of-sight to a fire and it would be very expensive to install and maintain the intrinsically safe versions required in coalmines.
5. Video Smoke Detection systems. This could readily detect smoke but it would be very expensive to install and maintain intrinsically safe versions required in coalmines.

The following sensors were found to be the most promising as part of an advanced mine fire detection system:

1. A high sensitivity (laser particle counter) optical smoke detector responded well to all fires and responded to smoke fumes up to a minute before they could be smelt. However, it could not distinguish smoke from coal dust and diesel fume.
2. A dual wavelength (blue/infrared) optical smoke detector was found to be sensitive to all fires and was able to distinguish smoke from coal dust. However, when the detector was tested against both smoke and coal dust together, the presence of coal dust was found to mask the response from smoke. The detector could not distinguish diesel fume from smoke and was found to be less sensitive than personnel smelling fumes.
3. The carbon monoxide, nitric oxide and nitrogen dioxide electrochemical sensors responded to diesel fume but not to the smouldering fires. This might prove useful in combination with optical smoke detectors that cannot distinguish smoke particles from diesel fume.

Recommendations

It is not recommended that POC semiconductor sensors, ionisation smoke detectors, single wavelength optical smoke sensors, thermal imaging camera systems and Video Smoke Detection systems should be used in an advanced fire detection system for coalmines.

It is recommended that an advanced mine fire detector system should be based on a combination of a high sensitivity optical smoke detector fitted with a cyclone to remove coal dust; and nitric oxide or nitrogen dioxide electrochemical sensors to distinguish smoke from diesel exhaust. If such a system proves to be too expensive then an alternative could be based upon a combination of blue/infrared optical smoke detector, which distinguish fires and diesel exhaust from coal dust, and a nitric oxide or nitrogen dioxide electrochemical sensor.

Further work is required underground to assess a high sensitivity optical smoke detector at typical coal dust levels in likely installation areas.

1 INTRODUCTION

Fires underground can be very serious both in terms of the risk to human life and the possible need to seal off sections of the mine with loss of production. The confined nature of mine workings means that evacuation and fire fighting are considerably more difficult than above ground. Hence, reliable and early detection of fires is essential. There are principally two types of real-time environmental monitor currently in use underground in the UK for detection of open fires and spontaneous combustion:

- general body carbon monoxide, CO, (based on an electrochemical sensor); and
- general body gaseous products of combustion (based on semiconductor and CO electrochemical sensors, termed the FIDESCO - Fire Detection Sensor & CO)

Fire detection technology tends not to be as effective as underground personnel for detecting fires, although the fraction of fires discovered by monitors has increased over the years. Moreover, personnel are mobile and can survey a larger area than fixed detectors, and possess a sensitive detector - the nose. However, as mines become more automated there are fewer personnel working underground than in previous years. This situation is perhaps illustrated by the failure of equipment to detect a significant conveyor event, which produced large amounts of fume, leading to a withdrawal of men from Kellingley Colliery, UK (Royals, 2001). The fire detectors at Kellingley were all based on carbon monoxide sensors; FIDESCO was not in use.

FIDESCO instruments currently suffer from the disadvantages of susceptibility to interferents, resulting in false alarms, and instrumental drift, which has restricted their use. A survey by UK Coal in 2002 (UK Coal, 2002) showed that from a sample of 14 collieries, 59% of FIDESCOs were fully utilised (92 out of 156) but the remainder were not in use. The highest percentage of FIDESCOs in use at a colliery was 80%. Industry guidance for underground environmental fire detection systems (eg RJB Mining UK, 1998) recommends that use of products of combustion (POC) instruments (ie FIDESCO) is limited to intake roadway installations where levels of contaminants are lower and less changeable than in return roadways. In addition, FIDESCO is now obsolete - only the sensors can be obtained as spare parts, and they too are about to be withdrawn.

POC sensors including FIDESCOs were shown to have the highest sensitivity for various types of smouldering fire including belt, coal, wood and oil compared to CO sensors and ionisation smoke detectors (Hambleton et al., 1997). Small, smouldering coal dust fires and conveyor belt heating are unlikely to be detected by CO sensors alone (Hambleton et al. 1997).

A review of early warning fire detection techniques for use in underground mines has recently been published by Walsh and Hunneyball (2002). This review outlined the types of sensor and tests which could be carried out in order to build on previous work carried out by HSL and work undertaken elsewhere on this topic, particularly that in the United States by NIOSH/PRL (Edwards et al, 2000; Edwards et al., 2002, Litton, 2002).

This joint project (partners: HSE/HSL, UK Coal and TES Bretby) was initiated to investigate the performance of proposed solutions to the sensor shortage and to explore the potential of an 'intelligent' monitoring system, i.e. an array of sensors. Such systems have been discussed by Walsh and Hunneyball (2002) for mining applications, and by Meacham (1994) and Liu and Kim (2003) for general applications. The system should have the sensitivity of existing FIDESCO but not be susceptible to typical interferents such as diesel exhaust, firedamp, coal dust, humidity, hydrogen.

The perceived benefits of investigating such a detection system are:

(1) Establishing for mines inspectors what can now be considered reasonably practicable for early smoke and fire detection in mines, taking account of technical progress, to assist them in regulatory decisions.

(2) Improved system for early detection of fire which reduces reliance on detection by personnel, as requested by the Deep Mines Coal Industry Advisory Committee.

(3) Improvement in fire detection over current technology used underground over the medium to long term period.

(4) Improving confidence of mining personnel in fire detectors.

(5) Improved ease of use of POC-based fire detection instrument.

This report details the work carried out under the joint project, draws conclusions and suggests recommendations for action.

2 SENSORS USED IN THE TESTS

2.1 INTRODUCTION

The review by Walsh & Hunneyball (2002) recommended a range of sensors to be considered in this project. This was then narrowed down to the following to be included in the tests as practicable potential mine fire sensors (as part of an array) and existing fire sensors to be used as benchmarks:

1. Semiconductor sensor: TGS 711 POC (as used in the FIDESCO instrument).
2. Potential alternative POC semiconductor sensors to TGS 711.
3. Ionisation smoke sensor: domestic, Trolex mine fire detector (obsolete).
4. Electrochemical carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2) sensors.
5. Optical smoke sensors: domestic, Blue/Infrared, HART, VESDA
6. Thermal imaging camera
7. Video Smoke Detection.

These sensors are described in more detail below. In addition the temperature of the fires were measured during the initial tests only with two thermocouples having a range 0-800 ºC (supplied by HSL Fire Safety Section); and percentage obscuration of the atmosphere at the detectors was also measured during initial tests with an in-house built obscuration meter, having 1 m separation (also supplied by Fire Safety Section).

2.2 TGS 711 POC SEMICONDUCTOR SENSOR

The TGS 711 sensing element (Figaro Engineering Inc., Japan. *www.figaro.com*) is used in current FIDESCO instruments. It has a sensitivity ratio of carbon monoxide/methane of approximately 40, which is considerably greater than those for other TGS sensors (Hoddy and Gibson, 1977; Watson and Yates, 1985).

Spare parts for the current FIDESCOs are now either becoming difficult or impossible to source (eg the TGS 711 POC sensor). A batch of sensors has recently been procured from a UK supplier by TES Bretby, which will provide cover for UK Coal in the short/medium term, assuming non-replaceable parts keep functioning. However, these sensors will become obsolete, as the manufacturer has stated that production will cease shortly.

This instrument was used as a benchmark in the field tests.

2.3 POTENTIAL ALTERNATIVE POC SENSORS TO TGS 711

The following POC sensors (Figaro Engineering Inc., Japan) were used in the tests:

- TGS 2106 – a sensor designed for diesel exhaust applications, particularly sensitive to nitrogen dioxide. Its predecessor, the TGS 2105, was used by NIOSH/PRL (Edwards et al., 2002).
- TGS 2442 – a CO sensor using a carbon filter to reduce cross-sensitivity to volatile organic compounds (VOCs). It was used by NIOSH/PRL in their experiments on mine fire detection (Edwards et al., 2002).
- TGS 2600 – a general purpose air quality sensor sensitive to VOCs, again used by NIOSH/PRL (Edwards et al., 2002).

Further details on the performance of these sensors can be found in the manufacturer's product data sheets (*www.figaro.com*).

2.4 IONISATION SMOKE SENSOR

An alarm based on ionisation detection was built for use underground (Trolex P3270). However, it was very old and is now not employed at all because of a lack of sensitivity. Nevertheless, ionisation smoke detectors are widespread in the domestic environment and perform satisfactorily. It was therefore decided to investigate the performance of a modern version of this type of sensor. Ionisation sensors were kindly loaned by Kidde plc. These sensors were not designed for use in mines, they are domestic sensors, and therefore their performance in these tests would not be indicative of that in their design environment.

The sensors were calibrated at Kidde by reference to a standard ionisation detector (MIC, output in pA) when challenged with smouldering cotton and flaming paraffin.

2.5 ELECTROCHEMICAL NITRIC OXIDE, NITROGEN DIOXIDE AND CARBON MONOXIDE SENSORS

An electrochemical carbon monoxide sensor as currently used in the FIDESCO instrument was used as a benchmark, along with a nitrogen dioxide sensor (Trolex TX3240 with 3NDHG Citicell sensor, range 0 - 20 ppm). A multigas detector (Rae Systems MultiRae Plus), fitted with electrochemical sensors, was also used to measure carbon monoxide, nitric oxide and nitrogen dioxide.

2.6 OPTICAL SMOKE SENSORS

Currently there are no smoke detectors used in UK coalmines based on the optical (photometric) principle. The technique detects smoke particles by light scattering. However, it was thought it would be informative to investigate the potential of this type of sensor for mine application. Photometric sensors were kindly loaned by Kidde plc. These sensors were not designed for use in mines therefore their performance in these tests would not be indicative of their performance in their design environment. Four types were used for the tests:

- Standard smoke alarm – a single wavelength infrared sensor as supplied for the domestic smoke alarm market.
- Blue/IR LED smoke detector – a dual wavelength prototype sensor for commercial applications with a sensitivity of $5\%.m^{-1}$ and supplied by Kidde. Smaller smoke particles produce a bigger response to the shorter wavelength of blue light, while larger general dust particles, such as coal dust, produce a bigger response to the longer wavelength of the infrared light. Therefore, the ratio of the response to blue light and infrared light should be large in the presence of smoke and small in the presence of coal dust. In this way the dual wavelength optical detector (or Blue/IR detector) can distinguish between smoke particles and coal dust in a coal mine.
- Blue/IR smoke detector (aviation) – a more rugged version of the blue/IR smoke detector designed for use in the aviation market, supplied by Kidde, and used in latter tests at Welbeck.
- Hart XL – a single wavelength infrared high sensitive smoke detector as supplied for the commercial smoke alarm market by Kidde. It is an aspirated, laser based smoke particle counter with a sensitivity range of $0.005\%.m^{-1}$ to $1\%.m^{-1}$ obscuration. It is designed to respond to particles within the range 0.001μm to 10μm and so may not have a significant response to coal dust. Air is drawn through a network of pipes with a number of sample orifices (for details see www.kfp.co.uk/HartXLHSSD.shtml)
- Vesda – another single wavelength infrared high sensitive smoke detector similar to the Hart XL but it uses filters to remove larger dust particles allowing only smoke fume through to the

sensing zone (www.vesda.com). The Vesda was not tested during this study but it was observed in use in a safe document storage area in Winsford salt mine.

The standard smoke alarms and the two types of Blue/IR smoke detectors were calibrated at Kidde by reference to visible obscuration ($\%.m^{-1}$) when challenged with smouldering cotton and flaming paraffin. The Hart XL was calibrated during manufacture to an equivalent white smoke sensitivity

2.7 THERMAL IMAGING CAMERA

A FLIR SC 2000 thermal imaging camera (supplied by HSL Explosion Control Section) was used to measure temperature. The camera uses a military specification un-cooled matrix micro-bolometer detector that measures infrared radiation over the wavelength range 7.5 -13 µm and has a built in atmospheric filter with cut-on at 7.5 µm. The measured radiation is converted into a black body temperature by a calibration function stored in the electronics of the camera based on the Stefan-Boltzmann law.

The system was set to download images to a personal computer for analysis. Each image consists of 76,800 pixels (320 x 240). The temperature range covered by the imager is -40 to 1500°C, which is divided into three ranges (low, -40 to 120°C, medium, 0 to 500°C, and high, 350 to 1500°C). According to the manufacturer, ignoring emissivity effects, the accuracy was ±2% of the absolute temperature, e.g. ± 11°C at 300°C.

The maximum frame rate of this instrument is 50 frames per second.

2.8 VIDEO SMOKE DETECTION

Video Smoke Detection (VSD) was performed by computer image-analysis of video images of the fires at Welbeck training galley by Intelligent Security Ltd (ISL, www.intelsec.com). A standard CCTV camera was used to obtain video footage that was then kindly processed by ISL after the tests were completed; although the VSD system can work in real-time. The system detects smoke by processing only the areas in a video image that are changing against a library of known smoke signatures. Alarm conditions, such as amount of smoke and duration, can be altered to match the local ambient conditions and camera field of view.

3 LABORATORY TESTS

3.1 POC SEMICONDUCTOR SENSORS

To determine the most sensitive POC semiconductor sensor with the least cross-sensitivity, brief laboratory tests were carried out on their response to a mixture of hydrocarbon gases, carbon monoxide, methane and nitrogen dioxide in the presence and absence of water vapour. The sensors' response times were not measured accurately but were generally of the order of 2-3 min. The complete results can be found using the index in Appendix 6.1, details of the hydrocarbon test mixture are given in Appendix 6.2. and example results are shown in Appendix 6.3. These should be viewed as an indication of the sensors' amplitude of response only.

The TGS 2442 was only sensitive to carbon monoxide to which the TGS 2106 and the TGS 2600 were not as sensitive. The TGS 2600 and the TGS 2106 were both sensitive to water vapour and to methane. The TGS 2106 and 2600 were both sensitive to nitric oxide and nitrogen dioxide.

3.2 SMOKE DETECTORS

The smoke detectors from Kidde were only subjected to brief checks on their response to smoke aerosol. These sensors had already been calibrated by Kidde. However, further tests were carried out by Kidde on the Blue/IR optical smoke detector to show it could distinguish between smoke particles and coal dust with reference to visible obscuration. Smouldering cotton was generated from cotton wick, the oil mist was marine lubrication oil heated on hot plate, the smouldering paper was filter paper on hot plate as BS EN54 calibration (BSI, 1996), the flaming polystyrene was a small piece of polystyrene cup flaming and the coal dust was ground domestic solid fuel sieved to less than 53 µm. Figure 1 shows the results summary and the location of the complete results are given in Appendix 6.1.

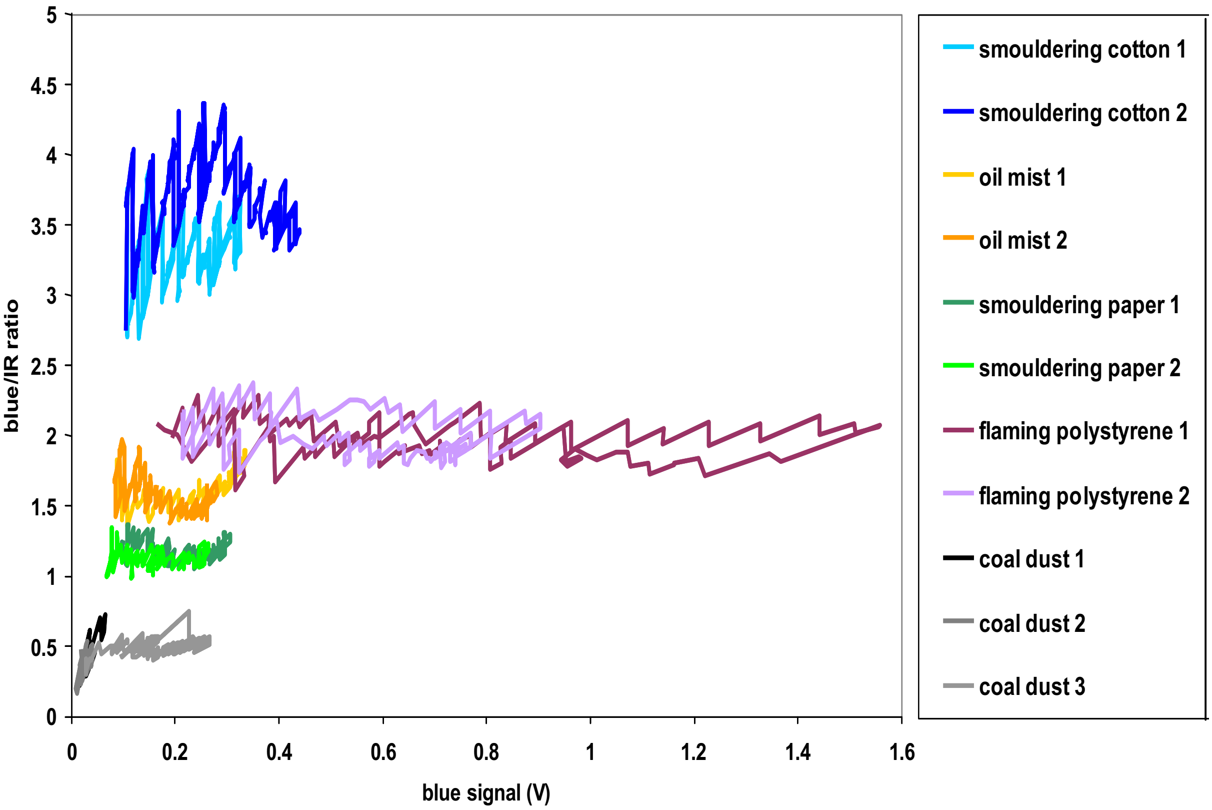

Figure 1. Response of the Kidde Blue/IR detector as a function of the blue sensor signal.

The Blue/IR sensor characterises airborne dusts by the ratio of their response to blue and IR light. Smouldering cotton, flaming polystyrene and oil mist have ratios of the blue to IR signals significantly above 1. Smouldering paper has a ratio just above 1 and coal dust has a ratio of about 0.5. This suggests that the Blue/IR detector can distinguish smoke particles from coal dust.

4 FIELD TESTS

4.1 INTRODUCTION

Field tests were performed in the surface training gallery at UK Coal's Welbeck Colliery. The gallery is equivalent to a standard UK coalmine gallery with the exception that equipment used in it need not be intrinsically safe. The sensors were connected to two dataloggers (Trolex PSC) except for the MultiRae and Hart XL, which had internal datalogging, and the Blue/IR sensors, which were connected to laptop computers.

Fire detectors were exposed to a series of test fires and diesel exhaust fumes initiated in the training gallery in a ventilated air stream moving at approximately 1.5 $m.s^{-1}$ provided by an auxiliary fan. The test fires were:

- Smouldering conveyor belt.
- Smouldering grease and oil.
- Smouldering coal fire simulating spontaneous combustion.
- Smouldering wood.
- Rapidly evolving diesel pool fire.

The test fires were relatively small scale. The conveyor belt test fires comprised of 0.45 m square sample of belt clamped to a 6 mm steel plate, which was heated on the non-belt side using electrical strip heaters. The power supply to the heaters was slowly increased to a maximum of 3.3 kW. The coal test fires comprised approximately 14 kg of coal sized up to 60 mm placed in a 0.6 m square and 0.1 m deep container and having the electrical strip heaters embedded in the coal. The power supply to the heaters was slowly increased to a maximum of 2.4 kW. Wood test fires comprised a crib made from roof support timber cut into 0.3 m strips. The crib was then placed onto the same hot plate used in the conveyor belt experiments. Grease and oil fires comprised of a patch of oil about 0.3 m in diameter surrounded by a grease dam and heated on the hot plate. The diesel pool fires comprised a shallow pool of diesel held in the same container that was used for the coal fires. This was ignited, allowed to burn for approximately 3 min and then extinguished.

The detectors were also exposed to diesel exhaust gases provided by a Free Steered Vehicle (FSV). Tests were carried out with the diesel engine running at idle and on-load, close to (2 m) and far away (30 m) from the detectors. In some cases the exhaust was directed straight at the sensors using a 0.5 m diameter flexible duct and in one case the the FSV was run while approximately 100 m away from the sensors.

After each fire or exhaust exposure, the tunnel was purged with clean air to reduce the sensor responses near to their zero level. Repeats of fires and diesel exhaust experiments were carried out.

The gas monitoring instruments were placed as close as possible to each other in an array across the centre of the gallery at just below roof height at a distance of 20 m from the fire site (see Figures 2 and 3).

Some of the sensors were also exposed to coal dust that was collected from a Welbeck coalmine gallery. The dust dispersal system comprised of a feed hopper, turntable, and aspiration system. Coal dust falling from the hopper is spread evenly across the turntable by a knife-edge and passes beneath a collection nozzle. The dust is entrained into airflow and directed out of the exit nozzle towards the sensors. The dispersal system produced an inconsistent airborne dust plume with peak concentrations of between 40 $mg.m^3$ to 60 $mg.m^3$.

Figure 2. Sensors used in the field tests. Ionisation smoke detector (1), domestic optical smoke sensor (2), blue/IR optical smoke detector (3), Fidesco POC: TGS 711 and CO electrochemical sensor (4), Trolex ionisation smoke detector (5), TGS 2106, 2442 and 2600 POC semiconductor sensors (6), NO_2 electrochemical (7).

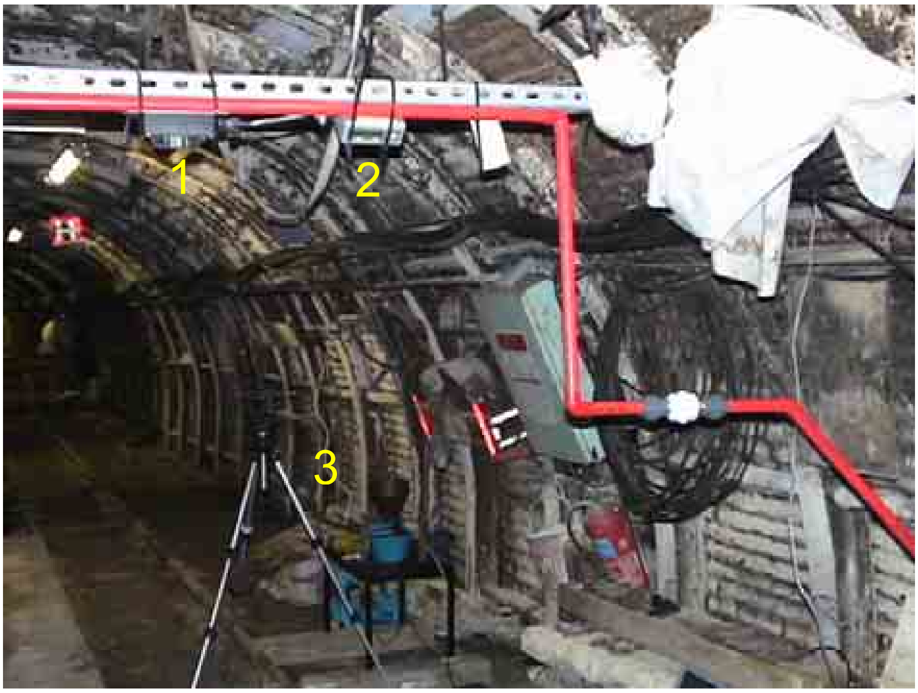

Figure 3. Sensors used in the field tests. The Hart XL is connected to the red aspiration tube. Beneath the tube is an aviation Blue/IR sensor (1) and a MultiRae (2). In the background is the coal dust dispersion apparatus (3).

4.2 RESULTS

All the fires produced visible smoke at the sensors that could easily be smelt except for the oil and grease fires. Table 1 shows the temperature and atmospheric obscuration during the tests. The diesel pool fire rapidly produced large quantities of smoke that were easily detected by all of the sensors (see Table 1). The remaining fires tended to produce many small puffs of smoke that caused large variations in the visible quantities of smoke at the detectors. This resulted in noisy signals from all of the sensors except for the semiconductors, which had a slow response time.

Table 1: Temperature and obscuration during tests.

Fire	Maximum temperature (°C)	Obscuration (%.m^{-1})	
		Background	During fire
Smouldering conveyor belt.	405	0.025	0.051 - 0.065
Smouldering grease and oil.	230	0.065	0.065 – 0.080
Smouldering coal fire simulating spontaneous combustion.	415	0.025	0.038 – 0.065
Smouldering wood.	225	0.051	0.065
Rapidly evolving diesel pool fire	695	0.065	0.638
FSV diesel exhaust	-	0.012	0.025

4.2.1 TGS 711 POC semiconductor sensor

Example results for the TGS 711 as used in FIDESCO are shown in Figures 4 and 5. Further results can be found from Appendix 6.1. Figures 4 and 5 show that the TGS 711 had a large response to smouldering coal, belt and grease fires and to diesel fume. Results, not shown here, show that the TGS 711 had a similar response to smouldering wood and diesel pool fires.

4.2.2 TGS 2106, 2442 and 2600 POC sensors

Example results for the TGS 2106, 2442 and 2600 POC semiconductor sensor are shown in Figures 4 and 5 and further results can be found from Appendix 6.1.

The TGS 2106 sensor had a significant response to all the fires and a very low response to diesel fume from the FSV. The TGS 2442 was not sensitive to either smoke or diesel fume and the TGS 2600 sensors had much lower responses than the TGS 711 or TGS 2106 sensors.

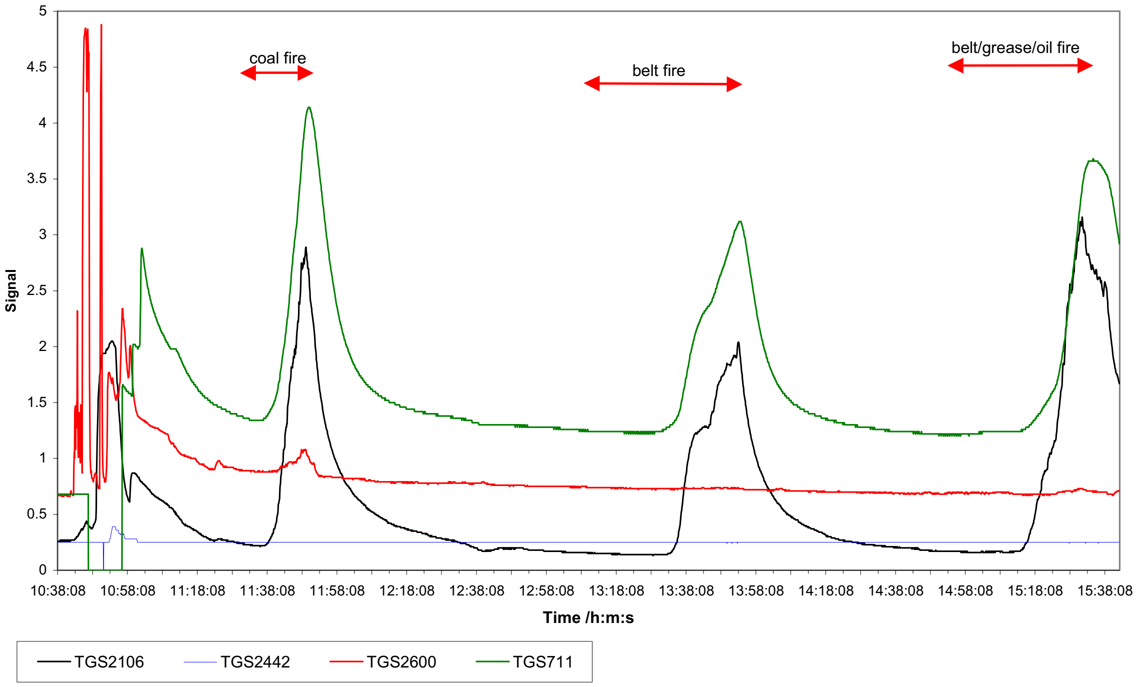

Figure 4. POC semiconductor sensor response to smouldering coal, belt and grease fires.

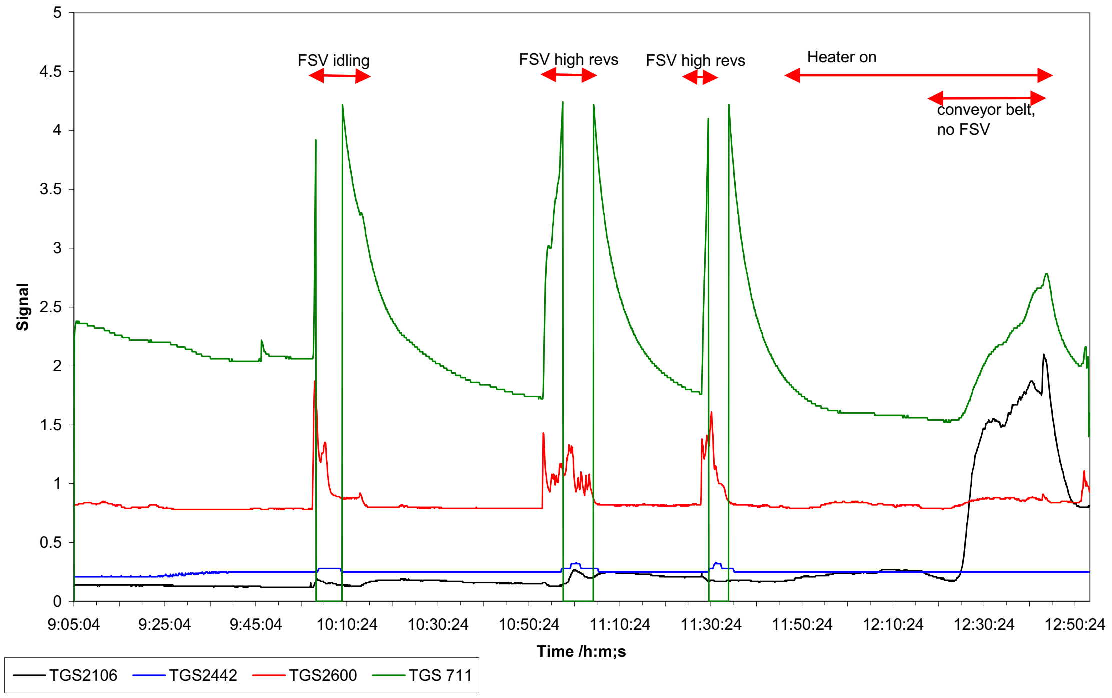

Figure 5. POC semiconductor sensor response to diesel fume from a Free Standing Vehicle (FSV), light fume (heater on) and smouldering conveyor belt fire.

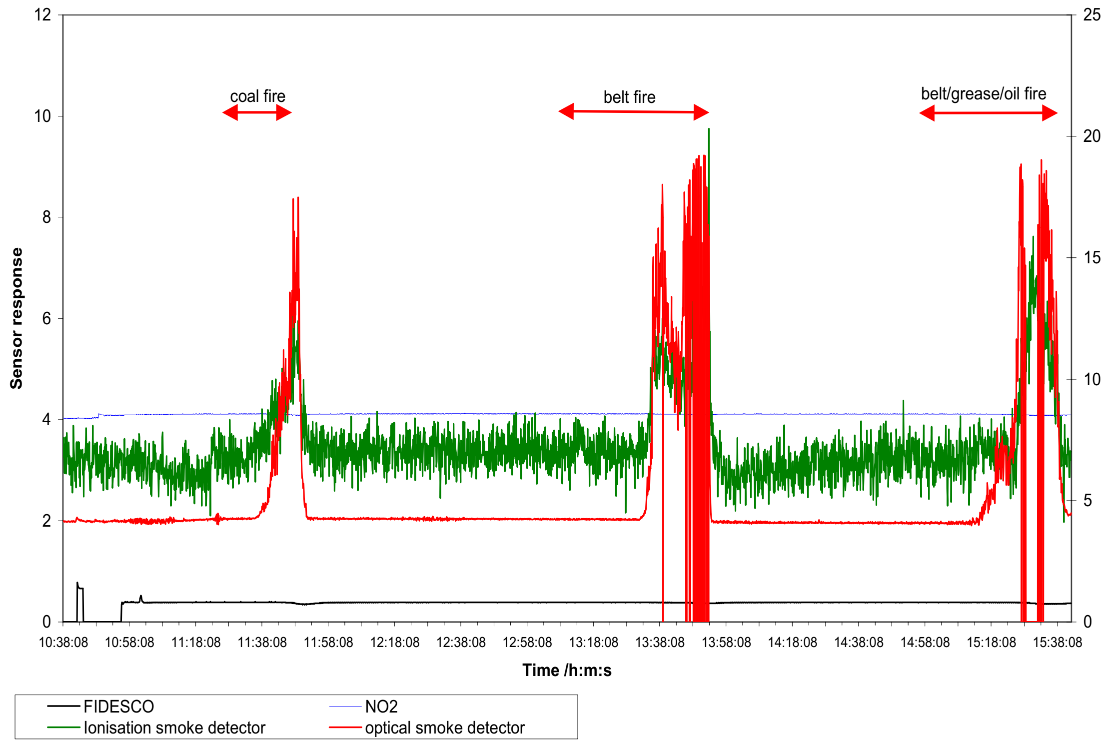

Figure 6. Electrochemical CO (FIDESCO) and NO_2 sensor and ionisation and optical smoke detector response to smouldering coal, belt and grease fires.

4.2.3 Ionisation smoke detector

Example results for the ionisation smoke detector are shown in Figures 6 to 8 and further results can be found using Appendix 6.1. The detector had a reasonable response to all fires, diesel fume and coal dust.

4.2.4 Electrochemical nitric oxide, nitrogen dioxide and carbon monoxide sensors

Example results for the FIDESCO carbon monoxide and nitrogen dioxide electrochemical sensors are shown in Figures 6 to 8 and further results can be found from Appendix 6.1.

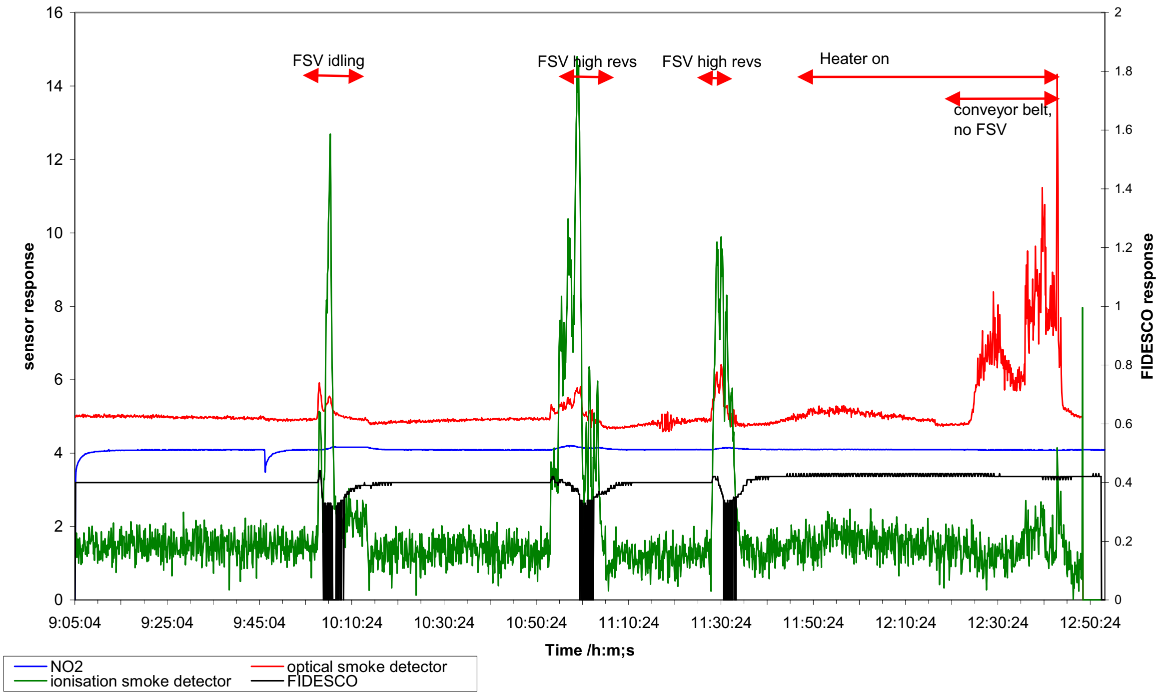

Figure 7. Electrochemical CO (FIDESCO) and NO_2 sensor and ionisation and optical smoke detector response to diesel fume from a Free Standing Vehicle, light fume (heater on) and smouldering conveyor belt fire.

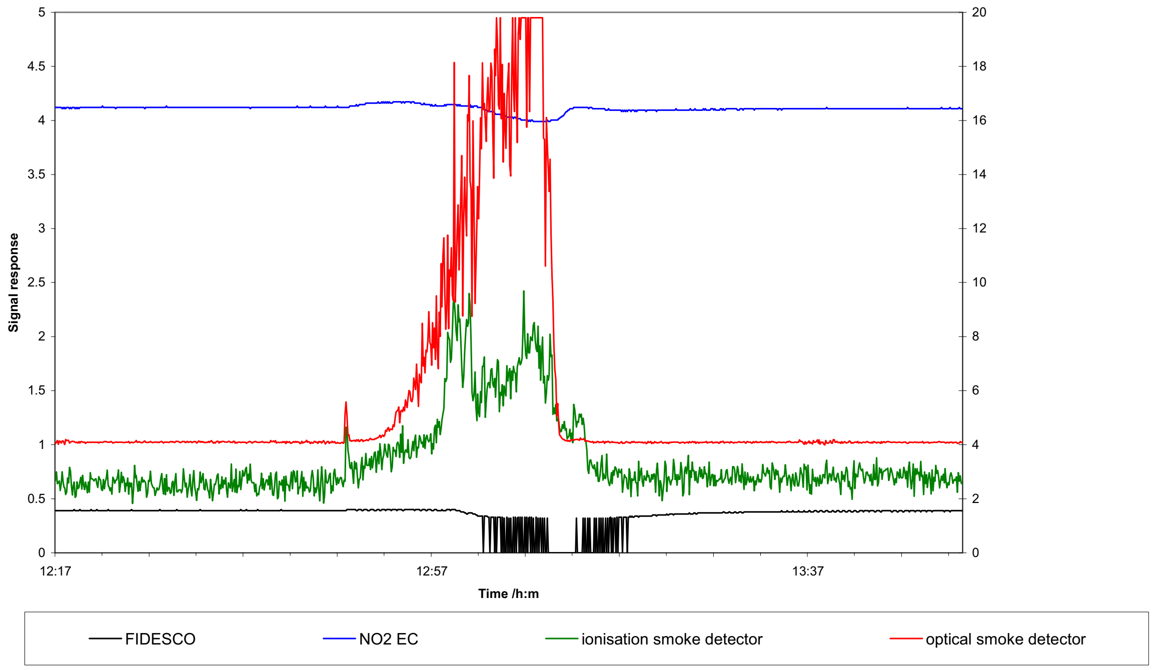

Figure 8. Electrochemical CO (FIDESCO) and NO_2 sensor and ionisation and optical smoke detector response to generated coal dust.

Example results for the nitric oxide and nitrogen dioxide electrochemical sensors as used in the MultiRae Plus, are shown in Figure 9 and further results can be found from Appendix 6.1.

None of the electrochemical sensors responded to any of the smouldering fires. The FIDESCO did, however, show signal deterioration on exposure to coal dust. The nitric oxide, nitrogen dioxide and carbon monoxide sensors responded to diesel pool fire and diesel fume.

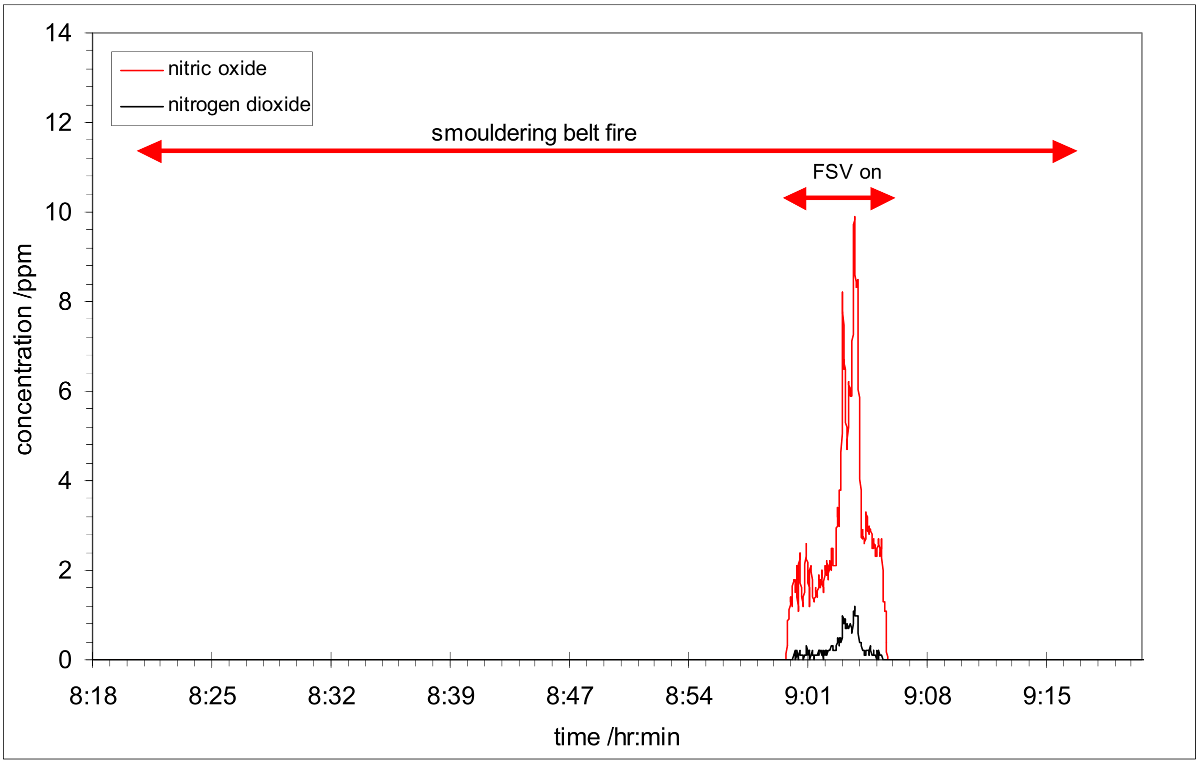

Figure 9. MultiRae Plus electrochemical NO and NO_2 sensor response to diesel fume from a Free Standing Vehicle (FSV) and smouldering conveyor belt fire.

4.2.5 Single wavelength optical smoke detector

Example results for the single wavelength optical smoke detector are shown in Figures 6 to 8 and further results can be found from Appendix 6.1. The detector had a large response to all fires and coal dust and a much smaller response to diesel fume.

4.2.6 Blue/IR optical smoke detector (domestic and aviation versions)

Example results for the aviation version of the Blue/IR optical smoke detector are shown in Figures 10 to 13 and further results can be found from Appendix 6.1. The domestic version responded in a similar manner. The detector was sensitive to all fires, diesel fume and coal dust.

The Blue/IR optical smoke detector distinguishes between smoke and coal dust using the ratio of blue signal to IR signal. A ratio greater than one indicates smoke or fume, and less than one indicates dust. Figure 10 shows that the blue and IR responses are very noisy so the ratio of the signals has been smoothed with a 60 s moving average. It does show that the ratio remains above one, indicating that the detector can distinguish smoke from coal dust. However, although the ratio remains above one, the blue signal did not rise significantly above the background level until some 8 min after the subjective test of being able to smell smoke at the sensors. The IR signal took even longer. Similar results were also obtained for smoke from wood, diesel pool, and grease and oil fires.

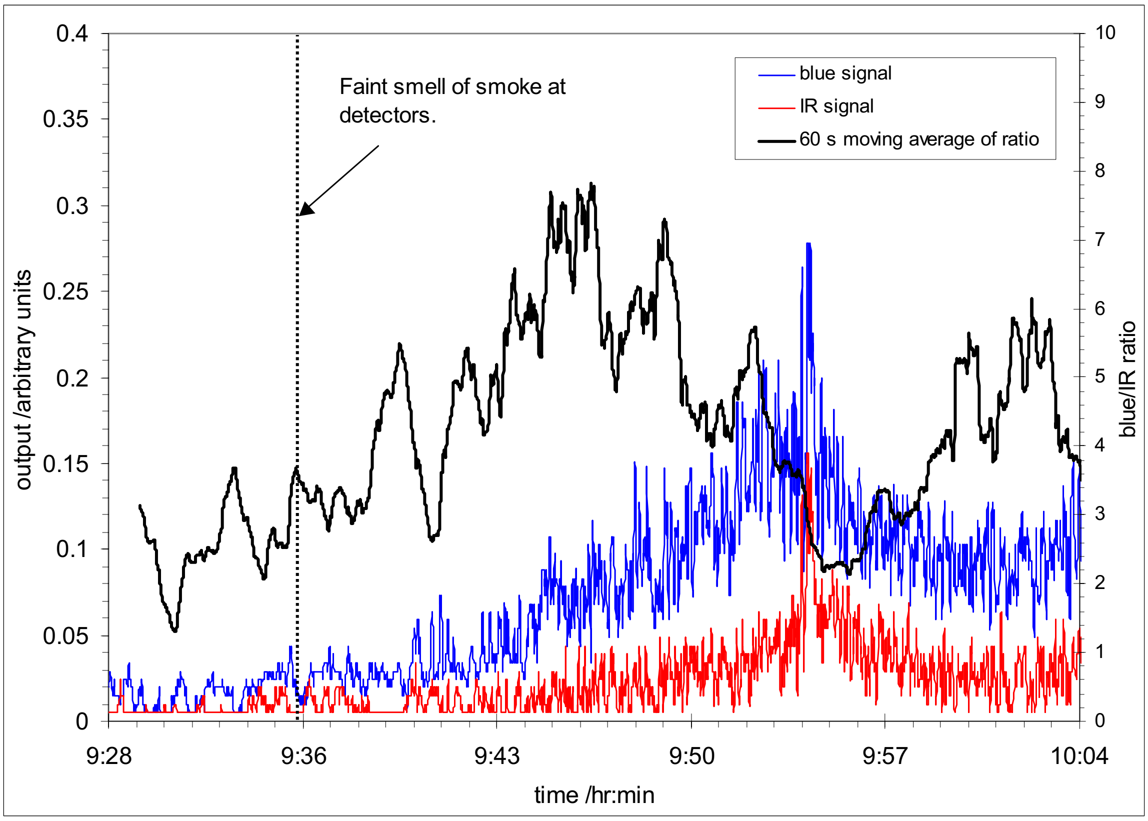

Figure 10. Blue/IR optical smoke detector response to smouldering coal fire.

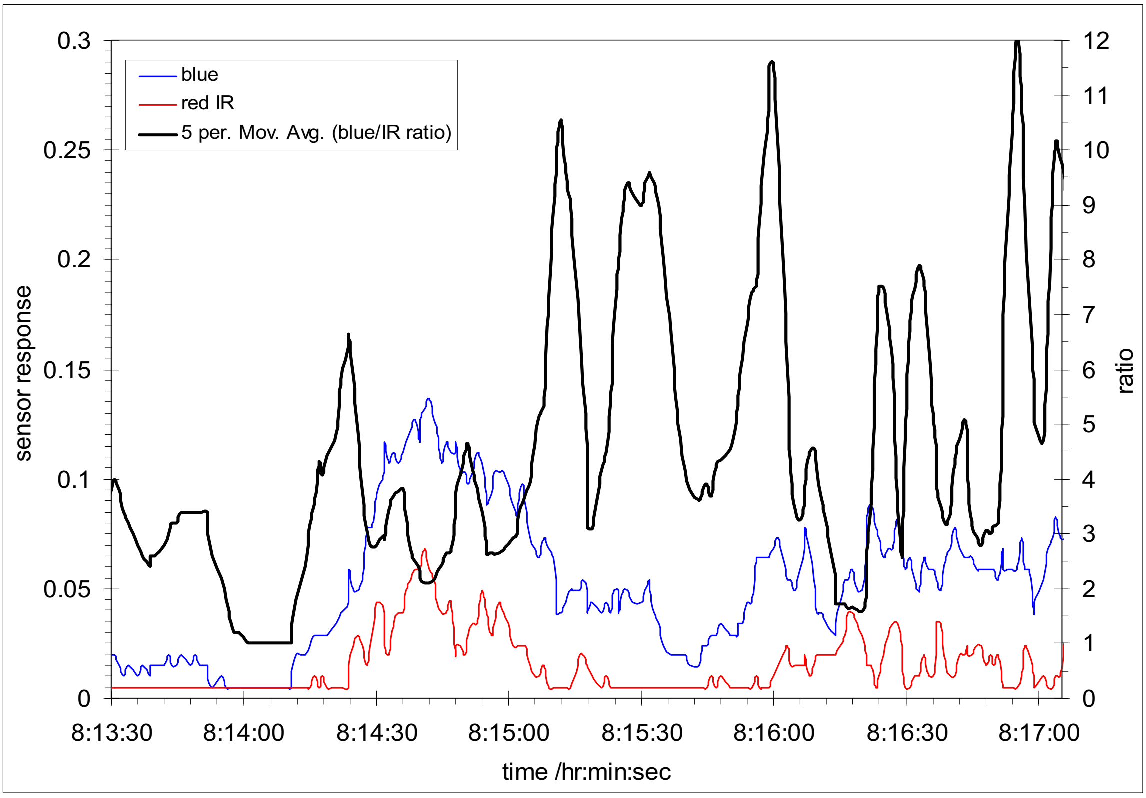

Figure 11. Blue/IR optical smoke detector response to FSV diesel fume.

Figure 11 shows that the blue/IR ratio remains above one in the presence of diesel fume.

Figure 12 shows the blue/IR optical smoke detector's response, initially to smouldering wood smoke and then combined with generated coal dust. In the presence of only wood smoke, the ratio remains above one indicating smoke. The coal dust plume was very intermittent producing a noisy signal response that is difficult to interpret. However, it can be seen that when coal dust does impinge upon the detector, the IR signal peaks above 0.2 and the ratio tends to fall to about one. This suggests that coal dust may mask the presence of smoke from the blue/IR optical smoke detector.

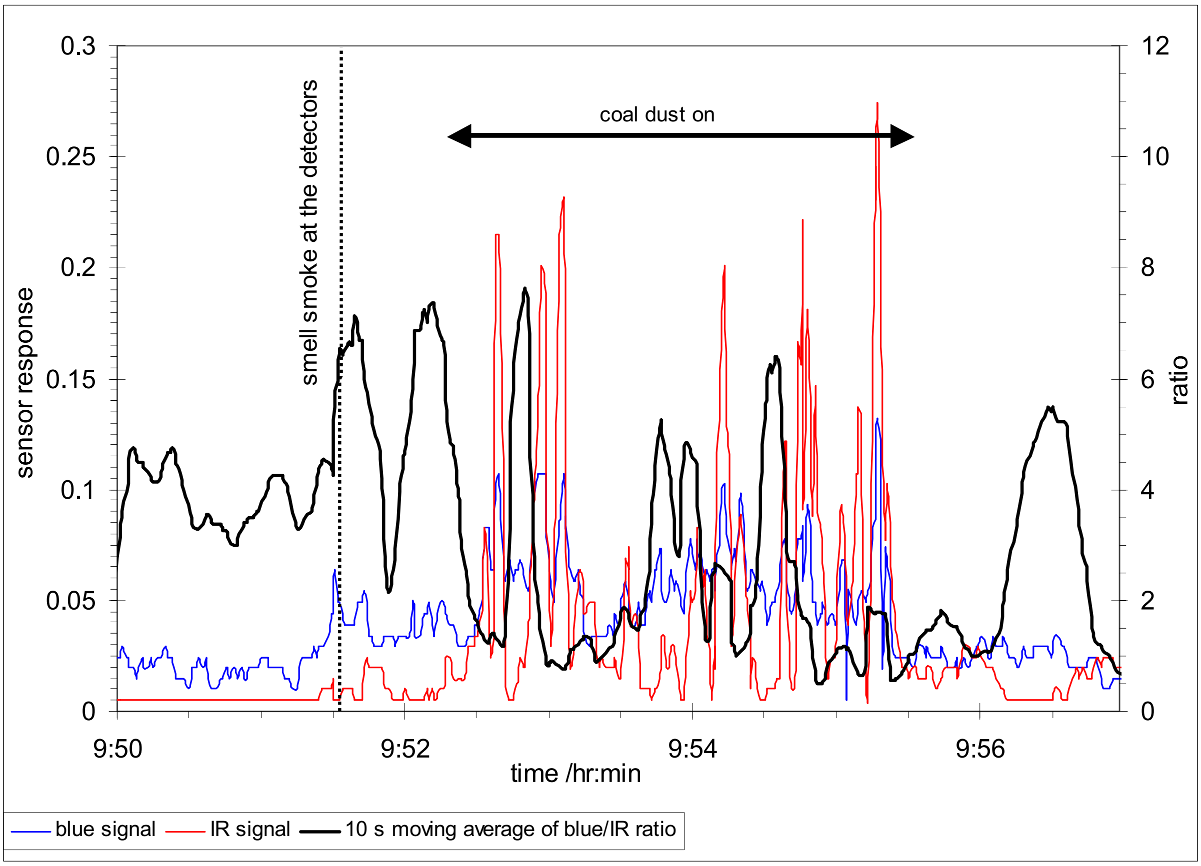

Figure 12. Blue/IR optical smoke detector response to smouldering wood smoke and generated coal dust.

Figure 13 shows the blue/IR optical smoke detector's response to a smouldering used conveyor belt fire, and shows that initially the blue/IR ratio peaks significantly above one as is expected for smoke. However, the ratio quickly falls below one as the smouldering belt fire progresses. In the latter stages of the fire, relatively large particles are generated that produce a large IR response, causing the ratio to fall to a value indicating dust particles rather than smoke fume. This type of response only occurred if the cleanest face of the belt was face up when heated. The wear on the belts appeared to indicate that one face remained in contact with the rollers and the opposite face was more damaged and dirty from contact with coal. If the dirtiest face was face up then a more standard signal profile similar to Figure 10 resulted.

Friction testing of belt samples was carried out at Fenners Dunlop (Hull), the belt manufacturer's test laboratory, to observe if a similar response to that above occurred. Most belt fires are caused by the edge of a conveyor belt rubbing against machinery (jammed rollers), therefore friction testing a belt sample is more realistic test. Testing was carried out on a drum friction testing apparatus according to BS 3289 (BSI, 1990). A sample of belt was held under tension and turned through 180^{o} around a metal drum that rotates at high speed (see Figure 14). Samples of used PVC belt were taken from Welbeck and tested along with clean samples of PVC and nitrile coated belts supplied by Fenners Dunlop.

Although the smouldering fires progressed much more swiftly than those observed at Welbeck, results were always similar to those shown in Figure 13. Further results can be found from Appendix 6.1

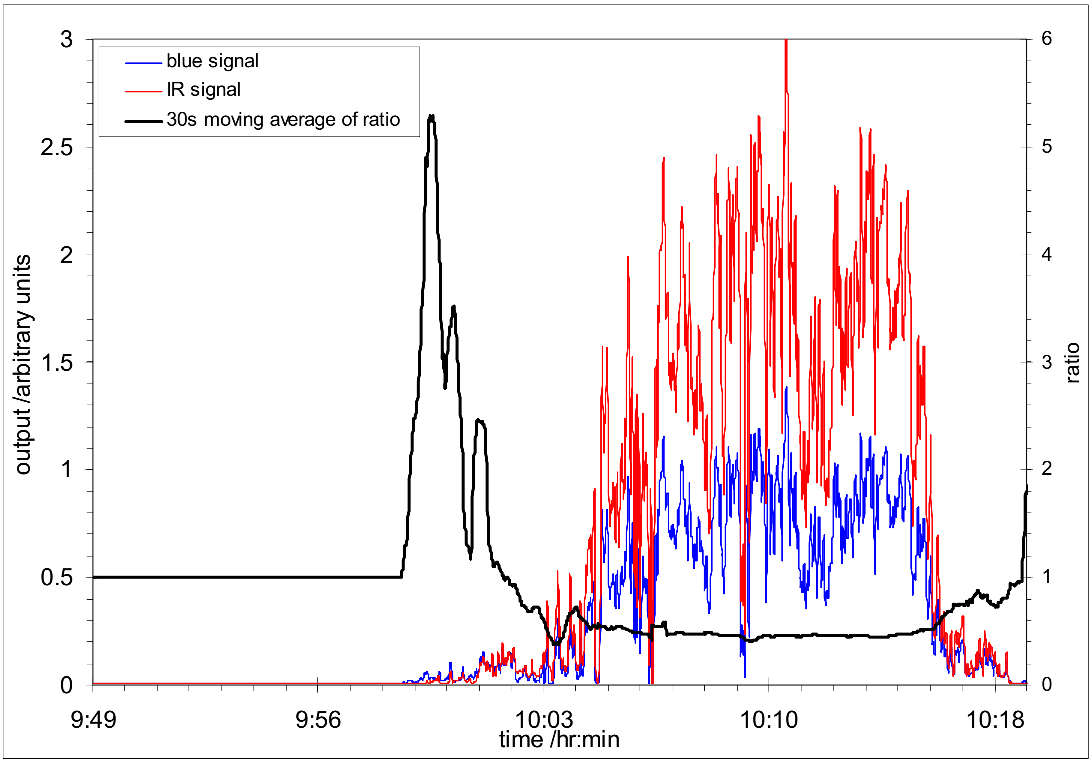

Figure 13: Blue/IR optical smoke detector response to smouldering used conveyor belt with its clean face up.

Figure 14. Conveyer belt drum friction apparatus.

4.2.7 Hart XL high sensitivity optical smoke detector

Example results for the single wavelength high sensitivity optical smoke detector are shown in Figures 15 and 16 and further results can be found from Appendix 6.1.

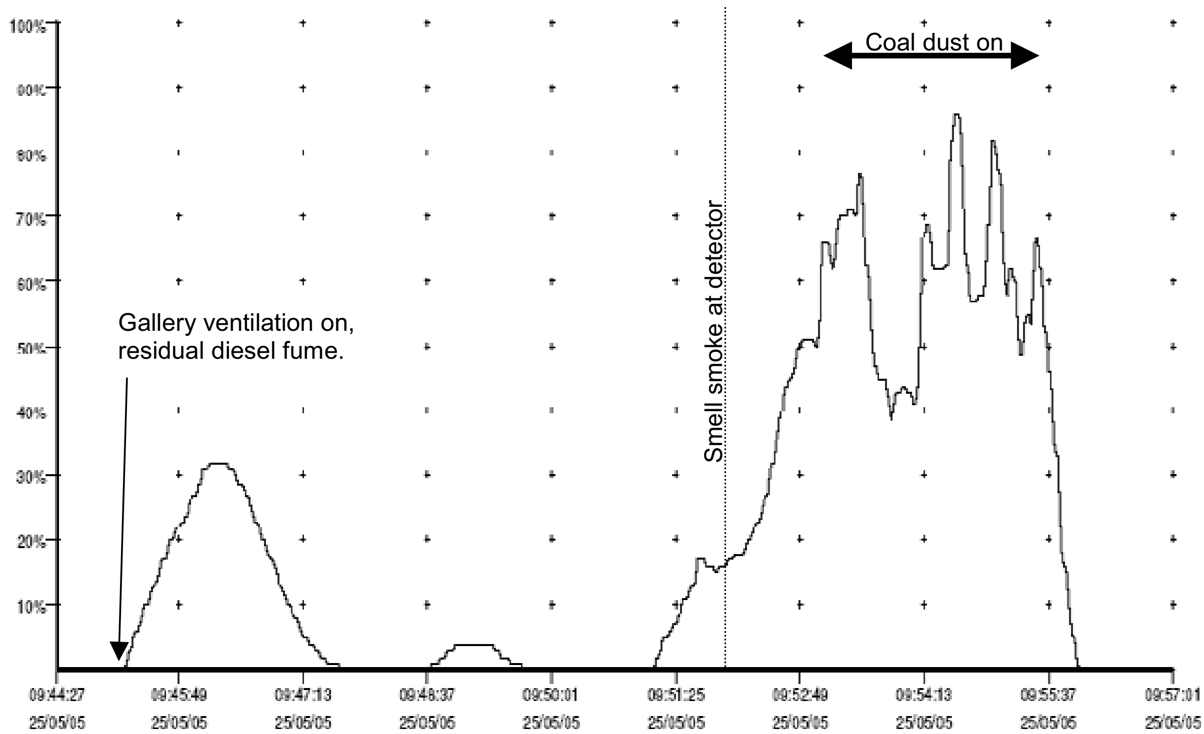

Figure 15. High sensitivity optical smoke detector response to smouldering wood fire, FSV diesel fume and generated coal dust.

The detector responded to smouldering wood fires, smouldering coal fires, diesel fume and generated coal dust. Figure 15 shows that the detector responded to smouldering wood fire about a minute before the fumes could be smelt. The intermittent coal dust plume produced a noisy response after approximately 09:52:49. The response to coal dust can be seen more clearly in Figure 16.

The Hart XL is designed to ignore particles larger then 10μm but the level of response to coal dust indicated in Figure 16 suggests that a significant proportion of the coal dust is smaller than this. To confirm this a sample of Welbeck coal dust was passed through a 30μm sieve and then sized using an API Aerodynamic Particle Sizer. The particle size distribution (see Figure 17) had 90% of the particles smaller than 10μm.

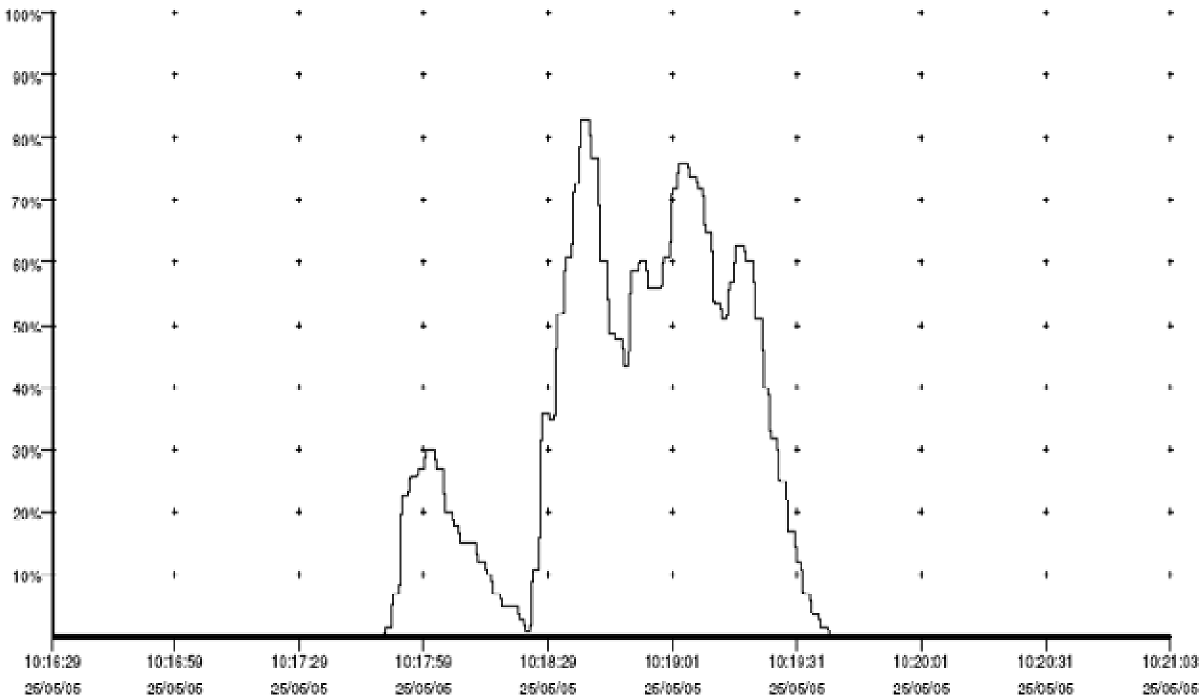

Figure 16. High sensitivity optical smoke detector response to generated coal dust.

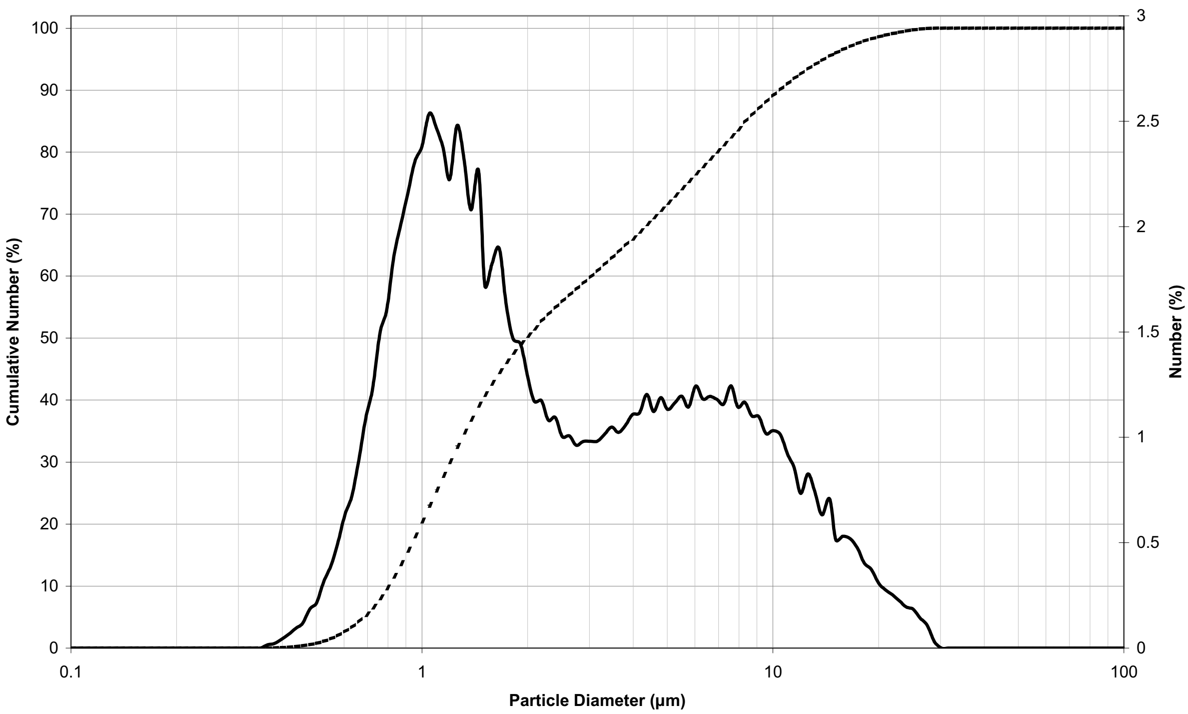

Figure 17. Particle size distribution of Welbeck coal dust.

4.2.8 Thermal imaging camera

The thermal imaging camera could detect both smouldering fires and well-established fires (see Figure 18) but it could not detect any change in the temperature of the atmosphere of the training gallery.

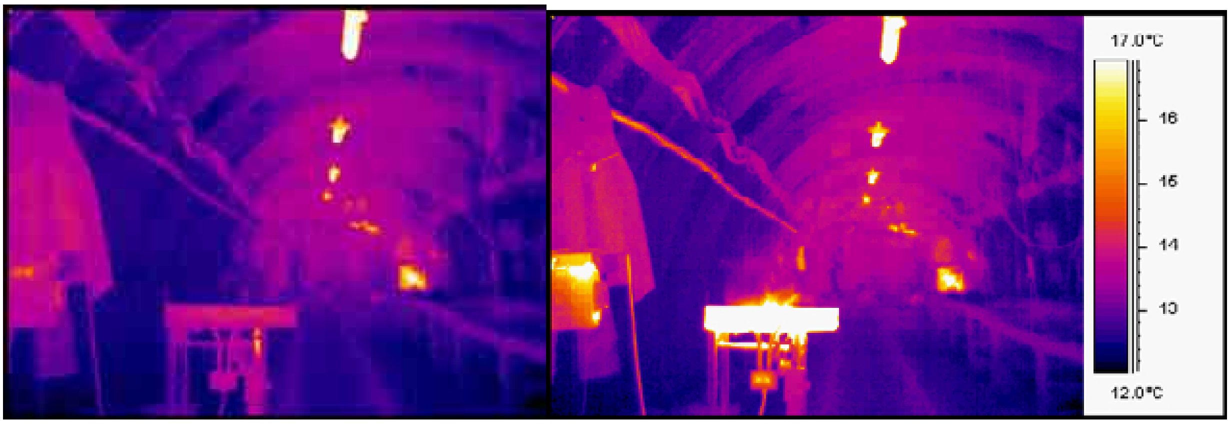

Figure 18. Thermal image of a smouldering coal fire before heat is applied (left) and once it is well established (right).

4.2.9 Video Smoke Detection (VSD)

The VSD system detects smoke by real-time image analysis of the areas in a video image that are changing against a library of known smoke signatures. Areas of video footage in which smoke is detected are highlighted with a red box and an alarm is triggered. The system could identify smoke using video footage of smouldering coal, wood and oil and grease fires (see Figure 19). Typically VSD identification time was about the same as that of a viewer concentrating on the image.

Figure 19: VSD smoke identification of a smouldering coal fire before the fire starts (left) and once smoke has began to be generated. Red squares indicate the detection of smoke.

5 CONCLUSIONS AND RECOMMENDATIONS

The TGS 711 (as used in FIDESCO) was sensitive to all fires except oil and grease, and was very sensitive to diesel exhaust. Of the alternative POC semiconductor sensors used in the trials, the TGS 2106 proved to be the most sensitive semiconductor to all fires. However, results from laboratory tests, indicate that these sensors are sensitive to methane, water vapour and hydrogen. In addition, the TGS 2106 sensor specification has changed compared to earlier work by NIOSH/PRL (Edwards et al., 2002) who used its predecessor - the TGS 2105. Therefore, variations in specification over time mitigate against using it as an integral component of a sensor array. For these reasons it is recommended that current semiconductor sensors should not be used as part of an underground fire detector system.

The ionisation smoke detector was sensitive to all fires and diesel exhaust but also to coal dust. Its potential when used with an optical light scattering sensor for discrimination of fires in the presence of diesel exhaust and coal dust has been discussed (Litton, 2002). However, because of ionising radiation regulations, the use of equipment containing an ionising source would cause complications in underground mines; the general policy is to avoid their use. For this reason it is recommended that ionisation smoke detectors should not be used as part of an underground fire detector system.

The carbon monoxide, nitric oxide and nitrogen dioxide electrochemical sensors responded to diesel fume but not to the smouldering fires. This might prove useful in combination with optical smoke detectors that cannot distinguish smoke particles from diesel fume. The presence of smoke particles combined with a response from a nitric oxide or nitrogen dioxide sensor would indicate the presence of diesel fume and not a smouldering fire.

The single wavelength optical smoke sensor was sensitive to most fires although not so sensitive to smouldering wood and grease. It was not sensitive to diesel exhaust. It is sensitive to coal dust and may even have a baseline shift after exposure to coal dust. However, it must be noted that the design was not intended for use in coalmines. For these reasons it is recommended that simple, single wavelength optical smoke sensors should not be used as part of an underground fire detector system.

The dual wavelength Blue/IR optical smoke detector was sensitive to all fires and the ratio of blue to IR response was always above one and frequently above five for all these fires except for belt fires. Laboratory tests showed a ratio of about 0.5 when exposed to coal dust, which indicates these sensors should be able to distinguish smoke from coal dust. This was confirmed by tests in Welbeck on coal dust on its own. However, when the detector was tested against both smoke and coal dust together, the presence of coal dust was found to mask the response from smoke fume by reducing the blue/IR ratio below that expected for smoke. The coal dust generated at Welbeck was probably not a good representation of the concentrations and variability of airborne coal dust found underground so the extent of this lack of discrimination is not known. Further work is required in an underground coal mine to assess the levels and variability of airborne coal dust where the detectors would be positioned.

The Blue/IR optical smoke detector initially responded to belt fires with a blue/IR ratio above one but this quickly fell below one. This response occurred for all belt samples except for dirty, used belts that had their dirtier face up. This behaviour is not yet understood but it should not prevent the detectors from alarming in the presence of smouldering belt fires because the peak in the ratio is of sufficient duration to trigger an alarm.

The Blue/IR optical smoke detector also responded to diesel fume and could not distinguish it from smoke. However, diesel fume could be distinguished from smoke by combining results from a nitric oxide or nitrogen dioxide electrochemical sensor.

A further limitation of the Blue/IR sensors is that they have a sensitivity of only 5%.m^{-1} obscuration; at this level a person could see and smell a fire in advance of the detector (see Figure 10). Ideally, these sensors would need to be made more sensitive. However, as collieries have become more automated and there are fewer personnel to detect fires, this level of sensitivity may still be acceptable. For these reasons it is recommended that Blue/IR smoke detectors could be used as part of an underground fire detector system but more sensitive systems that are more able to discriminate coal dust from smoke should be considered first.

The HART XL high sensitive optical smoke detector responded well to all fires but also to diesel fume. The detectors use laser light sources and so are much more sensitive than the standard optical smoke detectors. As a result, the detector responded to smoke fumes up to a minute before they could be smelt. The Blue/IR usually responded one to three minutes after smoke fumes could be smelt and sometimes much longer.

However, the Hart XL could not distinguish coal dust from smoke fume. Again, the extent of the lack of discrimination would depend upon the concentrations and variability of airborne coal dust in mines where the detectors would be positioned. If the coal dust concentration remained low or constant then the Hart XL would be sensitive enough to detect small concentrations of smoke above the background level. Further work is required underground to assess this.

If the dust levels are high or variable then a particle trap, such as a cyclone designed to remove particles larger than about 0.5µm, should remove coal dust before it reached the detector. The cyclone should also require minimum maintenance by not allowing larger particles to block the system. As the Hart XL is an aspirated system, a cyclone should be easy to attach. Indeed, the Vesda smoke aspirating system, a smoke detector similar to the Hart XL, uses a dual filter system to remover the larger dust particles. This is known to work well in many industrial situations including safe document storage areas in Winsford Salt Mine. However, these situations are far less dusty than coalmines and it would be expected that the discrimination filters would need replacing much more frequently in coalmines. A visit to Winsford Salt Mine suggests that these filters could need changing every 2 to 4 months and the system cleaned every 3 to 9 days in typical underground coalmine conditions.

Both the Hart XL and Vesda systems are about 15 times more expensive than the other types of sensor discussed here and could have significantly higher maintenance costs, especially for the Vesda system. However, their high sensitivity could mean that many fewer units would be needed to protect a mine, which may reduce costs to a more acceptable level. A better understanding of underground ventilation networks, coal dust levels and likely areas that a fire could start is required, along with further measurements underground. Despite these limitations, it is recommended that an advanced mine fire detector system should be based upon a high sensitive optical smoke detector such as the Hart XL.

The thermal imaging camera could readily highlight heat produced from smouldering and well-established fires but it could not detect any change in the atmosphere of the training gallery. This means the thermal camera requires direct line-of-site to a fire to be able to detect it. Also, they do not work well in dusty environments and it would be very expensive to install and maintain the intrinsically safe versions required in coalmines. Similarly, Video Smoke Detection systems would also be very expensive to install (eg requirement for intrinsically safe cameras) and maintain.

Although none of the sensors tested here have proved to be totally acceptable, the most promising for a potential advanced mine fire detector system is based on a combination of a high sensitive optical smoke detector based on laser particle counting (such as the Hart XL) fitted with a cyclone to remove coal dust; and nitric oxide or nitrogen dioxide electrochemical sensors to distinguish smoke from diesel exhaust. If such a system proves to be too expensive then an alternative could be based upon a combination of Blue/IR optical smoke detector, which distinguish fires and diesel exhaust from coal dust, and the nitric oxide or nitrogen dioxide electrochemical sensor. The latter system maybe more preferable if airborne coal dust concentrations are low and remain constant in the areas the detectors would be positioned.

6 APPENDICES

6.1 LOCATIONS OF COMPLETE SETS OF RESULTS

Table 2. Locations of data files

Results	Section	Files	Location
Laboratory results			
POC semiconductor sensors	3.1	All files in directories	\Gas sensors 2004
			\labtests
Kidde smoke detectors	3.2	All ".xls" calibration files and "coal dust ratio.ppt"	\Kidde_data
Field results			
POC semiconductor sensors	4.2.1 and 4.2.2	"keysensors.xls"	\Welbeck2003
Ionisation smoke detector	4.2.3		
FIDESCO electrochemical NO, NO_2 and CO sensors	4.2.4		
MultiRae electrochemical NO and NO_2 sensors	4.2.4	"welbeck1.dat", "welbeck-day2-CO.dat", "welbeck-day2-NO.dat" and "welbeck-day2-K4.xls"	\Welbeck 23-08-04 and \Welbeck 27-08-04
Optical smoke detector	4.2.5	"keysensors.xls"	\Welbeck2003
Blue/IR optical smoke detector	4.2.6	"Welbeck-day1.K1.xls", "Welbeck-day1-K4.xls"	\Welbeck 23-08-04
		"Welbeck-day2.K4.xls"	\Welbeck 27-08-04
		"Welbeck-day3.K1.xls", "Welbeck-day3-K4.xls"	\Welbeck 1-10-04
		"Welbeck-day4-K1.xls"	\Welbeck 25-05-05
		"Fenners-K1.xls" and "Fenners-K4.xls"	\Fenners 25-11-04
High sensitive optical smoke detector	4.2.7	All ".smk" files and "HART results summary.doc"	\Welbeck 25-05-05
Thermal imaging camera	4.2.8	All files in directory	\Thermal imaging
Video Smoke Detection	4.2.9	VHS video tape	Section archive

All directories are sub-directories of ":H\WORK\HSE\REACTIVE\SUPPORT\S2003135 Mine fire detection".

6.2 DETAILS OF LABORATORY TESTS ON POC SEMICONDUCTOR SENSORS

Table 3. Hydrocarbon mixture used for the laboratory tests on the POC semiconductor sensors.

Hydrocarbon	Concentration /ppm	Hydrocarbon	Concentration /ppm
Methane	102	n-Pentane	56
Ethane	102	n-Hexane	48
n-Butane	96	n-Heptane	54
Ethylene	101	Octane	55
Propane	100	Nitrogen	balance

6.3 EXAMPLE RESULTS OF LABORATORY TESTS ON POC SEMICONDUCTOR SENSORS.

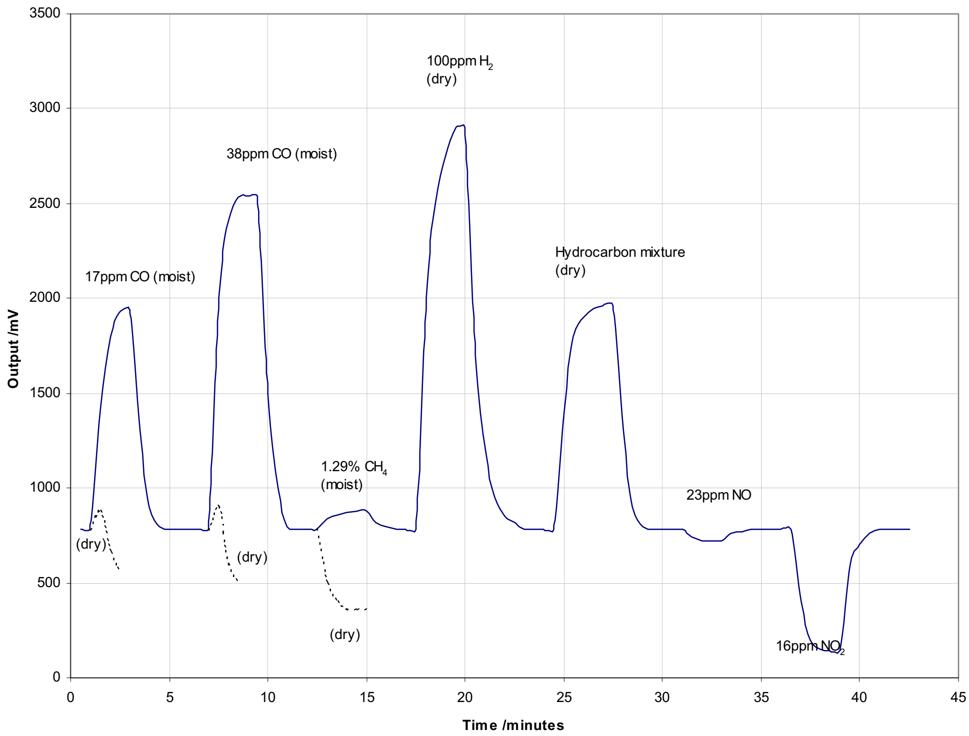

Figure 20. TGS 711 POC semiconductor sensor response to carbon monoxide, methane, hydrogen, hydrocarbon mixture, nitric oxide and nitrogen dioxide.

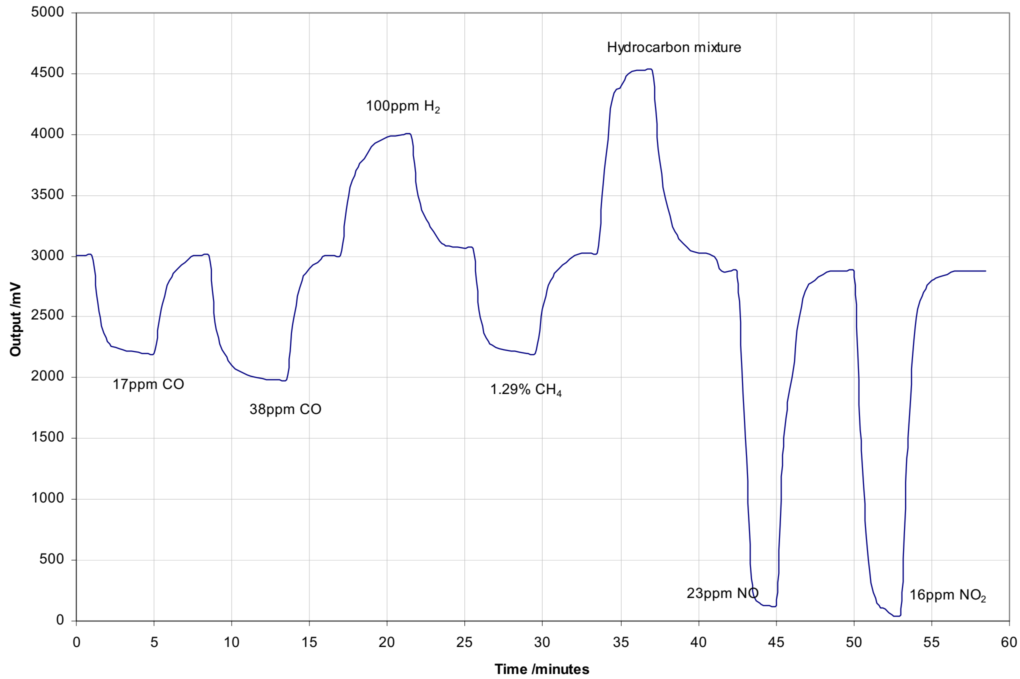

Figure 21. TGS 2106 POC semiconductor sensor response to carbon monoxide, methane, hydrogen, hydrocarbon mixture, nitric oxide and nitrogen dioxide.

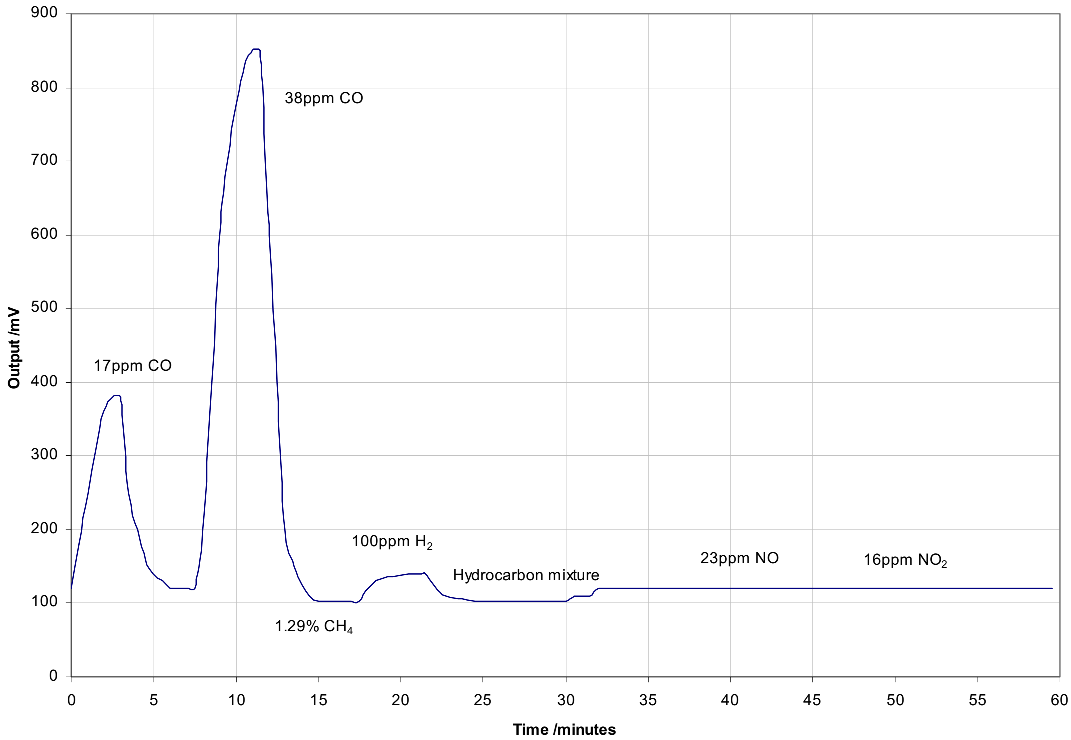

Figure 22. TGS 2442 POC semiconductor sensor response to carbon monoxide, methane, hydrogen, hydrocarbon mixture, nitric oxide and nitrogen dioxide.

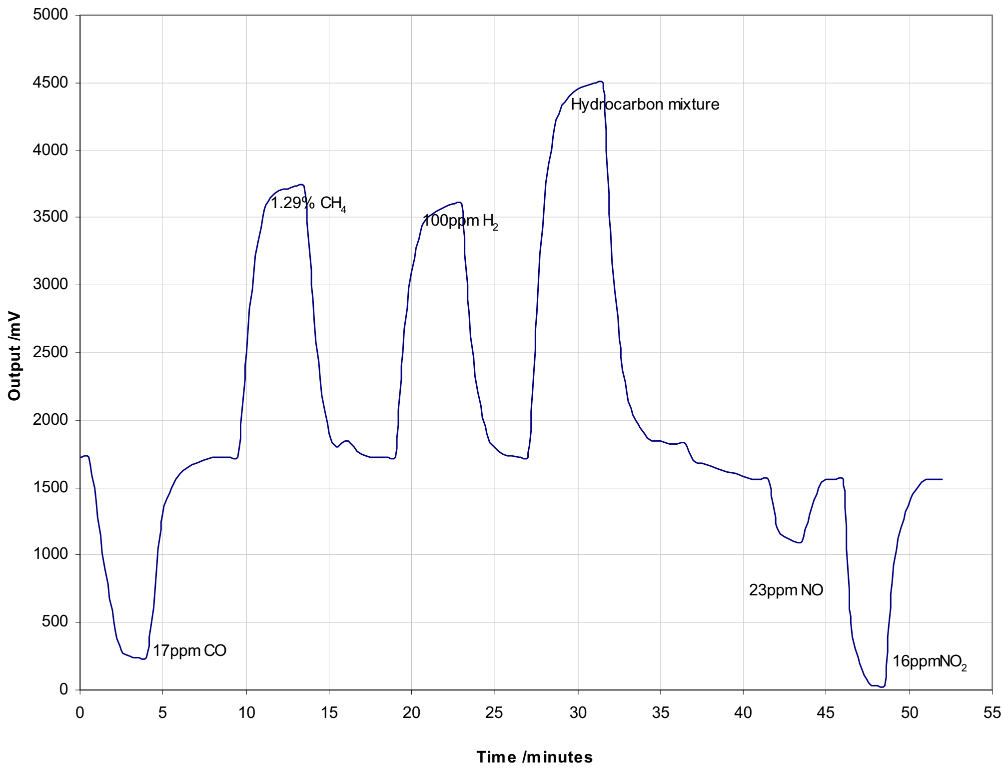

Figure 23.TGS 2442 POC semiconductor sensor response to carbon monoxide, methane, hydrogen, hydrocarbon mixture, nitric oxide and nitrogen dioxide.

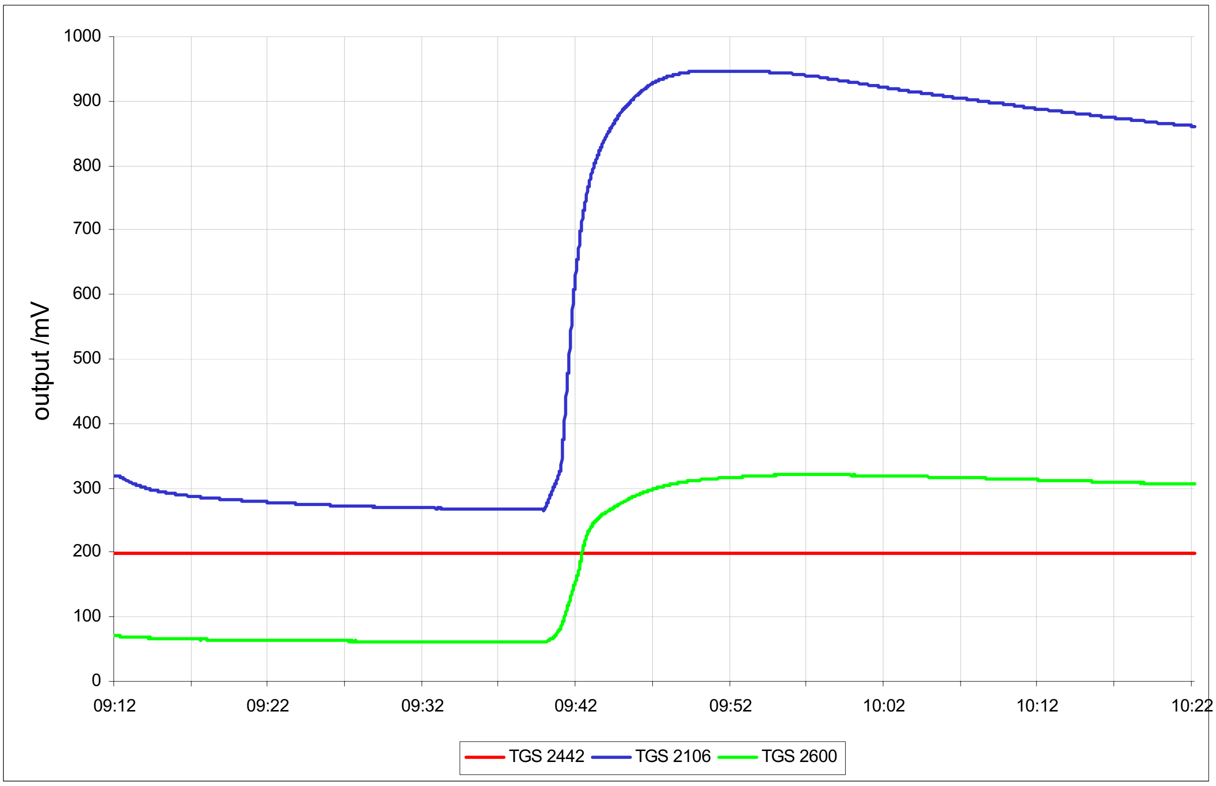

Figure 24. TGS 2106, 2442 and 2600 POC semiconductor sensor response to clean humid air.

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