Safety in Mines Research Advisory Committee

Final Report

(Revised)

Remote flammable gas detection/measuring device

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Executive summary

This research report presents the results of an evaluation of the existing open path remote flammable gas detection/monitoring technology and provides recommendations on possible limited implementation of this technology and future development for improving safety in South African mines.

Open path remote gas sensing instruments have undergone rapid development over the last 25 years. In essence, the theory involves an infrared beam of a specific wavelength travelling through the atmosphere and being attenuated by the gas of interest. This technology originated on the battlefield where the detection and early warning of the release of poisonous gases was essential. This was followed by application for gas level monitoring of chemical plants and early warning in the event of gas release or the gas concentration in the air exceeding a preset level. A range of commercial equipment is available for military and industrial use.

No portable commercial equipment suitable for underground application has been identified. Some R&D aimed at the development of an open path remote flammable gas measuring device has been carried out in the USA but due to various technical drawbacks, the device never reached the stage of a commercial prototype.

Moreover, an evaluation of the effectiveness of these devices and the method itself demonstrated that the method of open path, remote flammable gas measurement, in its existing form does not comply with the current safety regulations and hence should not be used for routine underground flammable gas monitoring. The main problem of the method used lies in the fact that it provides an integrated measurement of gas concentration along the path, or, in other words, a percentage of gas concentration per metre. It is impossible to identify an area with a dangerous level of flammable gas using this method.

This therefore is an example of how a technology developed for another application area must be adopted before it can be used for improving mine safety.

The measurement of flammable gas concentration in a sealed area seems to be the only possible application of existing open path remote methane detectors. The reason for this is that there is no significant air movement in sealed areas and the methane and air mixture remains relatively homogeneous. Therefore, an integrated measurement of methane concentration per metre will directly correspond to the actual point concentration of the gas.

The South African coal mining industry requires flammable gas monitoring of a dangerous zone from a safe position. Therefore, it is proposed that the *time sampling or ranging open path remote sensing* methodology be developed for underground application. This is a more sophisticated technology enabling the distribution of flammable gas concentration along the open path to be determined, thus ensuring that the safety regulation requirements for routine methane monitoring and early warning are met.

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Table of contents

List of Figures

Definitions and abbreviations

IR - infrared (spectrum, radiation, source, detector, filter etc.)

OPRES - open path remote sensing (method, technology, instrumentation etc)

1 Introduction

Flammable gas is an ever-present hazard in underground coal mines and monitoring its level is an important safety aspect. The term Aflammable gas@ has no legal definition in South African regulations. For practical purposes, flammable gas refers to a methane/air mixture *Gardiner (1989)*, and, therefore, methane is used throughout the report; however, all findings can be equally applied to other flammable gases belonging to the hydro-carbon group, for example, butane.

When ventilation is not sufficient, methane, having a specific gravity of 0,55, accumulates towards the roof. This makes measuring methane difficult in conditions of thick strata and an unsupported roof. A telescopic extension and a pump to convey a sample to a handheld methanometer are used for such measurement, but it is difficult to provide the telescopic extension for more than 4,5 m.

In order to reduce, or even eliminate, this time consuming and somewhat dangerous measuring operation and extend the range of measurement up to 20 m without entering the dangerous zone, another class of methanometer should be developed or adopted.

It is impossible to achieve the required output using Aconventional@ type sensors and they are therefore not discussed in the report. These sensors require direct thermal, chemical or other physical interaction with the gas/air mixture.

2 Methods of flammable gas detection/ measurement

It is important to note that there are two methods of methane concentration measurement that can be identified:

- *point measurement* of the methane level just around the sensor at any given moment which is provided by conventional types of methanometers. This method gives no information on methane level in any other areas.

- *open path remote sensing (OPRES),* which provides an integrated measurement of the gas level along the optical path between a measuring device and an area of interest. This gives no information on the location of the highest methane concentration areas.

3 Optical flammable gas sensors

Infrared (IR) gas analysers have been used for many years as laboratory tools but only in the last 20-30 years have found the application in industry. The optical method of gas concentration measuring is based on the gas molecule absorption of IR radiation.

3.1 Infrared spectrum and gas absorption lines

The portion of the electromagnetic spectrum between 0,75 ìm and 1,0 mm, or between visible light on the one hand and microwave on the other, is called the infrared (IR) band. IR radiation is responsible for heat transfer or thermal radiation.

When IR radiation propagates through an atmosphere, which contains different gases, it could be identified that radiation of some specific wavelengths are missing or attenuated. In order to understand why this happens it would be useful to refer to the Bohr model. Hydrogen with its single electron is the simplest atom available for atomic spectrum explanation. The electron of the hydrogen atom can remain indefinitely in certain orbits without radiating energy. These orbits are those in which the angular momentum of the electron is an integral multiple n of the quantity *h/2ð* where h is Planck=s constant. The value of the angular momentum for an orbit determines its energy level.

The electron can jump only between these specific orbits and the energy difference will be gained or lost by the absorption or emission of a photon. The energy of the emitted photon is the difference between two energy levels and equal to Ä$E=hv$, where v is the frequency. In its normal state, $n=1$, the hydrogen atom has its lowest energy, as the only electron is in the orbit close to the nucleus.

If the atom acquires energy through collision with other atoms in an electrical discharge, the electron will jump to an outer orbit or be raised to an exited state. This state is an unstable one and the electron falls back to his stable lower energy level, emitting a photon in the process. This Bohr explanation for hydrogen works perfectly but requires some probability distribution for other atoms= orbits.

Coming back to the process which occurs when IR radiation passes through a gas, at some specific absorption wavelength the atom absorbs incident radiation in the form of a photon having the energy required to rise it to an excited state. Then the atom shortly returns into a stable condition with emission of a photon. As this photon could be emitted in any direction of a sphere *4ð* differently from the incident radiation, this particularly wavelength will be attenuated.

In the IR spectra, absorption occurs mostly due to transitions between the energy levels of molecules rather than atoms. The energy of a molecule is of four types: electronic, translational, rotational and vibrational. Considerable energy is required to produce transitions between the electronic states in a molecule. The resulting absorption lines can be found in the ultraviolet, visible and near IR spectra. Changes in translational energies have a negligible effect on the molecular energy level. The rotational spectrum of a molecule results from changes in its rotational energy. As the energies of the various rotational states are relatively small, the frequencies are low and such absorption lines occur in the extreme IR.

The vibration spectrum results from changes in the vibrational energy of a molecule. The energy differences between vibrational states are many times greater than those between rotational states which correspond to higher frequency. Absorption lines could be observed in the IR spectrum from 2,0 ìm to 30 ìm.

For the production of absorption spectra, an interaction between the incident IR radiation and the molecular system must occur. This is only possible in an IR spectrum when the resulting vibration/rotation of the molecule produces a change in its electrical dipole moment. This is why there are no absorption spectra (lines) for the symmetric vibration of the molecules of nitrogen, oxygen, argon and hydrogen.

Without entering into much detail, it should be noted that water vapour and carbon dioxide are mostly responsible for the absorption of IR radiation in the atmosphere. In Figure 3.1.1 a standard average, low resolution transmittance curve of the atmosphere at sea level is given. Some Awindows of IR transparency@ exist, for example in rages of 0,4-1,3 ìm, 1,5-1,8 ìm, 1,9-2,8 ìm and so on *(Hudson 1969:115).* Methane is present in a very low concentration in the surface atmosphere and its absorption line is not presented.

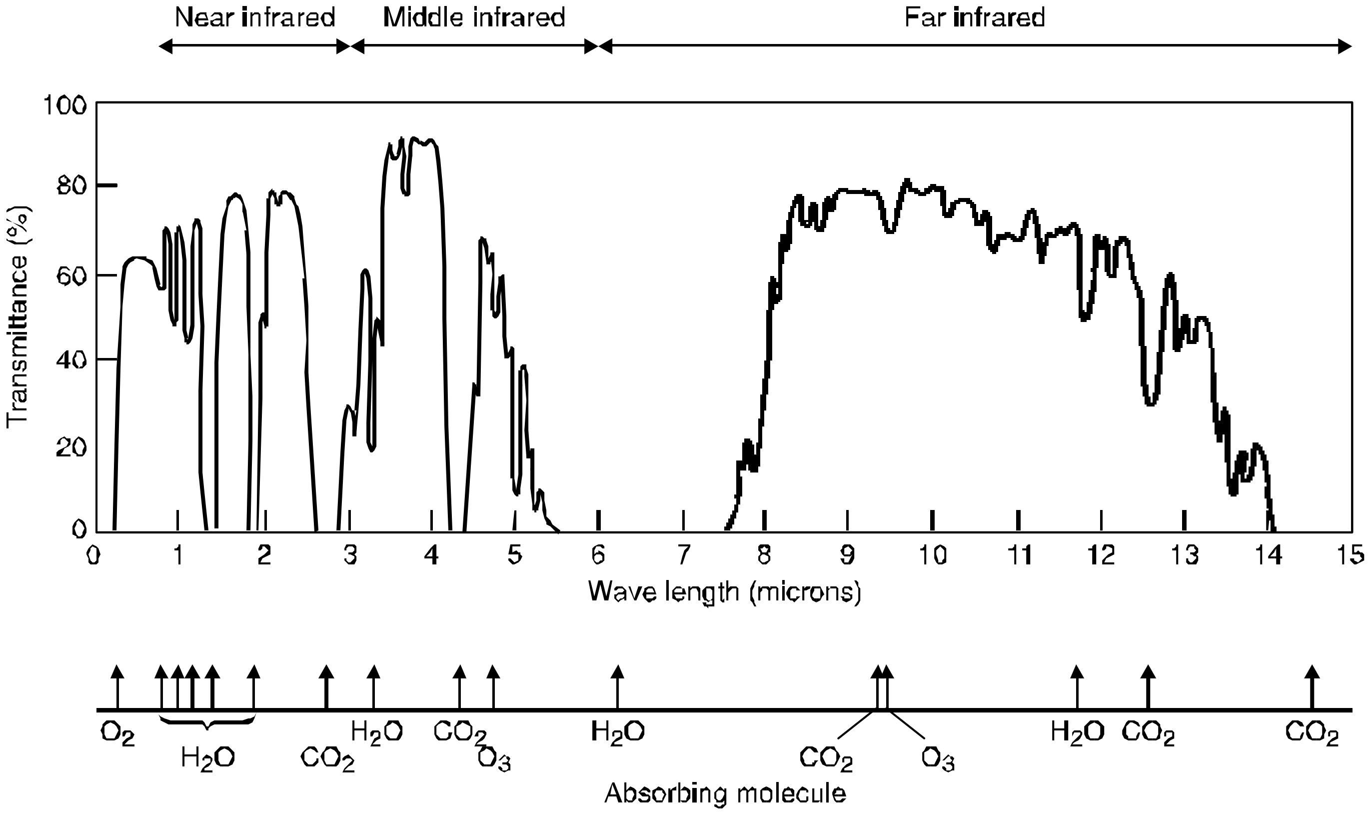

Figure 3.1.1. Transmittance of the atmosphere (after Hudson)

Methane has seven absorption lines at 1,33; 1,665; 3,31; 3,39;3,85 and 7,66 μm. There are also about 115 absorption lines between 7,21 and 8,29 μm *(Smith 1957:447)*. The absorption at 1,665 μm has greater spectral width and is often used for measurement, particularly in a system which uses fibre-optic lines due to their limitations at longer wavelengths. The 3.31 μm principal absorption line provides highest attenuation of the signal and is also used for measuring attenuation of radiation by methane.

The last absorption line is not practical to use as it lies on the edge of the transparency window and optical parts for this band are not cheap. In Figure 3.1.2 one of the areas of the IR spectrum with methane absorption lines is presented as an example.

When IR radiation of a specific wave length (3,31 μm) propagates along a path *L* in an atmosphere which contains no methane, the received energy or signal level is I_0. The presence of methane attenuates this radiation and the received signal *I* will be lower. The level of attenuation is proportional to the number of methane molecules along the path, or to the *integral methane concentration*.

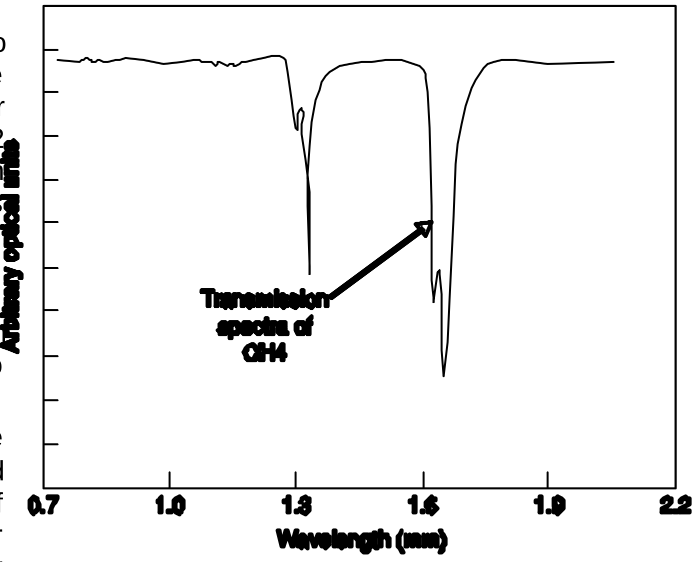

Figure 3.1.2. Methane absorption line

Therefore, the integral methane concentration along the path is inversely proportional to:

$$\frac{I}{I_0} = e^{-a_m L} \tag{3.1.1}$$

where: ám - methane absorption coefficient under the given temperature and atmospheric pressure, 1/m.

3.2 Sources of infrared radiation

Strictly speaking any physical body radiates some amount of IR radiation according to its surface, temperature and emissivity. An efficient IR source should be used in order to provide portable operation along a 20 m path.

A tungsten-halogen lamp with a quartz envelope is a sufficient source of IR radiation for the selected wavelength which radiates about 70 % of power in the IR spectrum up to 4,0 ìm, beyond which their glass envelopes are not transparent. The gas in the lamp and glass are responsible for the other 20 % of power loss. This also demonstrates that tungsten lamps are an inefficient source of visible light as only 10 % of the input power is converted into the visible spectrum.

Lasers provide a coherent, very pure spectral and extremely high density level of radiance in the portion of the spectrum extending from UV to microwave. They provide very short light impulses.

IR light emitting diodes (LED=s) are a very compact and fairly efficient (4-8 %) source of IR radiation. They provide very short light impulses.

A natural source of IR radiation such as sun or the atmosphere itself could be used for measuring in so called Apassive@ remote gas sensing, (*Bezuidenhout 1999).*

3.3 Spectral resolution

It is obvious that the better spectral resolution provided by a measuring system, the better the system accuracy that can be achieved. Two solutions can be applied.

- Narrow spectrum at 1,665 or 3,31 ìm radiation source, such as a laser or IR LED;
- Broad spectrum IR radiator (tungsten halogen lamp) and very narrow, such as interference bandpass filter on the receiving side.

It should be noted that the use of a simple bandpass filter is required for the first option in order to reduce photoreceiver noise due to the possible ambient illumination.

3.4 Point measurement

There are many different IR methane sensors available for point measurement in mines; such as those manufactured by Astra Resources Instruments, Simrad, Sieger and, the latest, MSA, Dräger and EEV.

They generally employ the same principle of IR attenuation by methane absorption with a length of optical measuring path of only between 5 to 50 mm. Such a sensor is positioned in a casing with an optical path to be opened to the air/methane mixture flow.

The Model 3600 IR gas monitor by MSA uses a somewhat different principle of IR photo-acoustic absorption. The sample gas enters the monitor and the IR radiation excites the gas molecules. This excitation causes pressure or sound waves to be generated. The amplitude of the sound waves is proportional to the concentration of methane. A very small and sensitive microphone detects the sound and converts it into an electrical signal. After amplification and filtration, this signal is used for the readout.

As the point measuring method and sensors are not within the scope of this project, their detail design will not be discussed.

3.5 Open path remote sensing

The OPRES instruments have undergone rapid development over the last 25 years. In such an instrument, an IR beam of a specific wavelength travels up to 10 km, being attenuated at an absorption line of the gas of interest.

This technology originated from systems for the detection and early warning of the release poisonous gases on a battlefield. The next application was for average gas level monitoring over or within chemical plants and early warning in the event of gas release or gas exceeding some level. There is an important difference between the above applications and the use of such technology for methane monitoring in underground mines, that will be discussed further in Chapter 5.

When an IR beam propagates in underground mines, the mining atmosphere and environment will affect propagation conditions and, therefore, these effects should be analysed.

3.5.1 Compensation of environmental impact on measurement

It should be borne in mind that IR beam attenuation by an absorption line depends on the gas pressure and temperature. Simplistically, the output of a detector can be considered in terms of the well known equation (*Markley1989:229)*:

$$PV = nRT \tag{3.5.1}$$

where P - atmospheric pressure;
V - gas volume;
n - number of molecules;
R - Boltzmann gas constant and
T - temperature.

The IR sensor is in fact a Amolecule counter@ in a media where V and R are constant. Thus,

$$n \propto \frac{P}{T} \tag{3.5.2}$$

which makes the sensor output inherently dependent on pressure and temperature. An 8 ^{0}C change in ambient temperature, for example, will lead to the output drifting by three percent of methane. By using on board pressure and temperature sensors, both dependents could be compensated for *(Markley 1989:229)*.

While propagating through coal/rock dust, water and oil mist, IR radiation is attenuated not only by the absorption lines of methane, but radiation is also scattered off and absorbed by dust particles and molecules which additionally attenuate the signal. There are some means of preventing deterioration of accuracy by environmental factors as follows:

Dual wavelength
A general approach in many measuring instruments is to have a reference channel to compensate for drifts and other disturbance. In the case of IR methanometer, the second, reference wavelength should be selected as close as possible to 3,31 μm. The reference wavelength must be free from any absorption line. Providing a reference wavelength as close as possible to the measuring wavelength enables the same scattering and reflection conditions of dust and mist particles for both the measuring and reference channels.

When IR beams propagate, both channels experience the same attenuation due to the environmental conditions, but the measuring channel is additionally attenuated by methane. Both wavelengths could be received simultaneously by two photoreceivers, or one photoreceiver could be used and exposed to each channel in turn. The differential signal between both channels is proportional to the number of methane molecules along the beam path or to the integrated methane concentration. This method is used for both, point and OPRES detectors.

The problem of hydrocarbon film contamination of instrumentation transmission or receiving windows is difficult to resolve as only the measuring channel is affected.

Single wavelength and a reference sample.
Using this method, the receiver alternatively sees the atmosphere sample and a zero reference with the same source and light path (*Markley 1989:229)*. This method is mostly used for point measuring detectors.

Another interesting solution for compensation of the environmental influence is given by *Franks (1997)*. This method of compensation will be fully described in Chapter 4.2 where the most advanced OPRES methanometer is discussed.

3.5.2 Single path technology

Such devices employ an IR radiator and a photoreceiver positioned at the path end. Such an arrangement is not suitable for the required application as it can only be used for fixed installations, where gas concentration monitoring along a permanent path is implemented.

3.5.3 Dual path technology

In order to provide measurement of methane in inaccessible areas, a dual path technology should be used. Such instruments have an IR radiator and a photoreceiver positioned in the area from which measurement is to be taken. Usually both of them are enclosed in the same enclosure.
The IR beam propagates along the path and is reflected back by any surface at the other end of the path. The surface could be coal or the rock face, machinery or a specially installed reflector.

Such an approach provides measurement of an integrated methane concentration along the 10 -15 m optical path without entering the measuring zone.

4. Evaluation of the open path remote flammable gas detection/measuring technology

Developments for both areas of application in surface and underground conditions are discussed.

4.1 Available technology

Two of the early 1970's examples of this commercial technology are a LIDAR instrument and G.P.Elliots AEagle@ system. Both of them used laser sources and detected either reflected or backscattering radiation from the beam. Such instruments are able to detect very low gas concentrations but are bulky and cost hundreds of thousands of dollars.

Latest developments include the Swedish AOPSIS@, USA AWright and Wright@ and UK manufactured ASieger Searchline@ instruments.

The AWright and Wright@ was developed from an R&D project at Exxon Research and Engineering Company and consisted of two flameproof housings having weights of around 17 kg each. The British ASeiger Searchline@ originated from a laboratory prototype constructed by Shell Thornton Research in UK.

In all these devices the IR beam is either monitored by a separate detector on the other end of the path or reflected back by a multi-corner cube reflector. They use sources of IR radiation ranging from 1,5 W for short paths to 60 W for a 200 m path.

There is no commercially available portable OPRES flammable gas detector designed for underground applications.

4.2 Developments for underground application

Among the R&D projects that have been carried out over the past 10-15 years, two developments should be evaluated as they provide acceptable performance.

The U.S.Bureau of Mines, together with Westinghouse Electric Corp., undertook research to develop an IR OPRES methanometer *(Litton 1987)*. As the result of these efforts, a laboratory prototype of a portable IR open path methanometer capable of measuring the average methane concentration along 12 m path was produced. A dual-path dual-wavelength method was used, and original design was modified to improve overall performance.

An 18 W tungsten-halogen lamp with a quartz envelope was used as a light source in the original design. A modified version used a 50 W bulb that placed the design beyond the intrinsically safe level. A two-stage thermoelectrically cooled lead selenite photoreceiver was used. The device operated from 12 V rechargeable battery. The methanometer had overall dimensions of 160x160x200 mm.

Laboratory testing of the device indicated satisfactory operation, however, there is no available information on the underground application of the device.

Apparently, one of the latest and most advanced development sponsored by NIOSH *(Franks 1997)* is a further improvement of the U.S.Bureau of Mines a Afirst generation@ methanometer *(Franks 1986)*. It was recognized that the first generation instrument responded inadequately to methane in controlled experiments. Based on these results, a second generation of open path gas sensing instrument was developed by Westinghouse which incorporated two major changes: the use of a single IR detector instead of two, and the replacement of the two bandpass filters with a single bandpass filter and two gas correlation cells. It is claimed that correlation cells provided a more accurate determination of the light attenuation by methane absorption along the optical path between the detector and the reflective coal surface. The instrument is placed into flameproof enclosure, which has dimensions of 180 mm by 430 mm by 540 mm and weighs less than 17 kg. Some explanation of the employed gas correlation technique is required. The intensity of an IR beam which travels along a path and is reflected back to the detector is measured twice. The first time it is measured after the beam passes through a cell with a reference sample of the gas of interest (methane) at a specific concentration of usually 100 per cent. The second time is after the beam passes through a cell with an inert gas sample. Both transparent cells must have the same design.

The IR beam passing through the cell with the reference methane sample experiences a high level of attenuation due to the methane purity. This attenuation is much greater than signal attenuation along the open path by a low methane concentration. Therefore, when methane is present in the open path, the second measurement made via the cell with an inert gas sample will be reduced more significantly. The presence of dust and moisture vapour will affect equally both measures, leaving the ratio between them dependent only on methane concentration. The calculation of the ratio between two measures will again be inversely proportional to the integrated methane concentration along the measuring path.

The device was tested in a calibration tunnel and several factors which affected the device accuracy, such as inability to maintain adequate detector cooling, dependence upon distance from the device to reflective surface, and others have been identified. It was planned to develop an improved version of the device. No further information on the development has been found.

In the process of evaluation of this development, it was noted that the calibration tunnel diameter of 0,4 m used by R.Franks was too small to obtain reliable information. The IR beam radiated from the device had a divergence of less than 0,5 m per 10,67 m of path length. This means that in the tunnel of 0,4 m diameter the amount of IR radiation incident on the tunnels= walls was about 2 % at 1 m path and about 40 % at 11,6 m. IR radiation scattered on the walls along the path and reflected back to the receiver was a main source of the device error. It is suggested that use of a test tunnel of at least 2-3 m in diameter could provide much better testing results.

The latest information obtained on the OPRES system development is dated back to 1997. At present, all further such systems development in U.S.A. has been terminated *(Van Zyl 1999)*, due to lack of funds.

5 Open path remote flammable gas sensing and regulation requirements

5.1 Technology use for routine gas monitoring

Throughout the report the OPRES measuring methodology has been emphasised and should be stressed again:

> *The OPRES provides the only true integrated (averaged) concentration of methane per metre along the path. It does not detect areas where a dangerous level of methane is built-up. The longer the path the more uncertain (from the point of safety) the results.*

From a safety point of view and in terms of the current regulation requirements, such a measurement is pointless and could compromise the miners safety.

As an example, an integrated methane concentration of 1,0 per cent per metre has been measured at a distance of 12 m from the coal face. This is still a permissible level. In reality, the point concentration of methane at the face could be much higher, for example, 5,0 per cent or even more. There is no way that the point methane concentration measurement which is required by regulations could be achieved by using the OPRES technology.

5.2 Proposed technology application

Methane monitoring in a sealed area is usually problematic due to the lack of oxygen, high level of methane concentration and presence of sulphur compounds. This is where IR technology is able to provide reliable and long life operation. The Model 3600 IR detector by MSA is designed for such a purpose.

Use of the OPRES could provide an even better solution to the problem. Measuring methane concentration in a sealed area appears to be the only possible effective use of the open path remote methane detection. This is because there is no significant air movement in the sealed areas and thus exists a relatively homogeneous and stable methane and air mixture behind the seals. Therefore, integrated measurement of the methane concentration per metre will correspond to the point concentration measurement.

In order to implement the method, a transparent window should be provided in a seal. To measure the methane level in a sealed area only requires sending the IR beam through the window and taking a reading. The method offers also an important research possibility. Having more than one window spatially spread in a vertical plane, will make it possible to monitor the methane concentration vertical distribution in a sealed area.

6 Application of light detection and ranging for open path remote flammable gas sensing

As the current OPRES technology is not able to satisfy mine safety needs, the concept of *time sampling or ranging open path remote sensing* is proposed for further research. This concept involves a more sophisticated technology enabling the point distribution of the methane concentration along a required path to be measured.

The main idea of the concept is based on an active optical range measurement. Active ranging can be accomplished by the use of pulsed IR radiation in a manner analogous to the pulsed radar system *(Stuart 1993:192).*

The ranging system can obtain a high level of distance resolution which is better than the shorter time interval that can be measured by electronic techniques. In order to provide 1 m resolution along the path, the duration of a sampling IR impulse must not be longer than 6 nsec. The radiation of such an optical impulse of 3,31 ìm is one of the development problems.

Another problem lies in obtaining the reflective signals. In the current OPRES systems, any available surface such as the coal face, rock, machinery or angle cube reflector could be used to reflect the signal back. Taking into account that some level of coal/rock dust, water and oil vapours are constantly present in the underground atmosphere, it is assumed that some portion of the light impulse will be scattered on dust particles and molecules along the path and thus be registered. In the proposed ranging system, the operational distance fully depends on the IR light scattering ability of the underground atmosphere.

7 Conclusion

1. The open path remote gas sensing technology was originated for military use and from the early 1970's was accepted for atmosphere monitoring of chemical plants, etc. Devices are bulky and expensive.

2. Some development has been done in using the technology in underground conditions but these devices have never reached the level of a commercial prototype.

3. The open path remote gas sensor provides the only true integrated (averaged) concentration of methane

per metre along a path. It does not detect areas where a dangerous level of methane has built-up. From the point of view of safety and the current regulation requirements, such a measurement in its existing form is inadequate for underground mine safety and could even be dangerous.

4. Measuring methane concentration in a sealed area seems to be the only possible application of the current open path remote methane detectors. The reason for this is that there is no significant air movement in sealed areas and the methane and air mixture is relatively homogeneous. Therefore, integrated measurement of methane concentration per metre will directly correspond to the point concentration measurement.

5. In order to use open path remote flammable gas sensing, it is proposed that the *time sampling or ranging open path remote sensing* methodology be developed. The operational distance of the proposed detection device depends on the conditions of underground atmosphere as the device will use light scattering off dust particles and vapour molecules.
   It is assumed that this more sophisticated technology will enable the point distribution of methane concentration along an open path to be obtained. This in turn will allow the regulation requirements for routine methane monitoring and early warning to be met.

8 Recommendations

1. Open path remote methane sensing could be used for methane concentration monitoring in a sealed area.

2. The method in its existing form can not be recommended for routine underground use.

3. Further research is required to develop the time sampling or ranging open path remote sensing to the level suitable for underground application.

References

Bezuidenhout, D.F., 1999. Personal communication, CSIR: Defencetek, May.

Franks, R.A., Opferman, J.J., Freiel, G. and Edwards, J.C., 1997. A Second-Generation Remote Optical Methanometer. *Report on Investigations 9640.* US Department of Health and Human Services, Pittsburgh, PA, May. 9p.

Franks,R.A., Sapko, M.J., Denes, L.J. and Ryan, F.M. 1986. Optical Remote Methanometer. *Proceedings of the Eighth WVU Mining Electrotechnology Conference.* Morgantown, WV: West Virginia University, p.114-118.

Gardiner, L.R. 1989. Methanomentry in mining - a South African case study. *Journal of the Mine Ventilation Society of South Africa, 6:102-108.*

Hudson, R.D., 1969. Infrared System Engineering. New York/London/Sydney/Toronto: John Wiley & Sons, 642 p.

Litton, C.D., Denes,L.J., 1987. Optical Remote Methanometer. *Proceedings of the 22-nd International Conference of Safety in Mines Research Institutes*. Beijing, p.643-651.

Markley, J.I., 1989. Infra-red Gas Detection Comes of Age. ISA Calgary 89 Symposium, p.227-239.

Smith, R.A., Jones, F.E. and Chasmar, R.P. 1957. The Detection and Measurement of Infra-red Radiation. *Clarendon Press,* Oxford, 458 p.

Stuart, A.D., 1993. Some applications of infrared optical sensing. *Sensors and Actuators,* Vol: B11, p.185-193.

Van Zyl, K., 1999. Personal communication, CSIR: Miningtek, July.