Conveyor fire detection & condition monitoring using fibre optic distributed temperature sensing (DTS)

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SUMMARY

Traditional fire detection on and around mine and process plant conveyors has been difficult to achieve using conventional point heat detectors and aspirating CO gas detectors. This is mainly due to the conveyors' long length and variable physical orientation (e.g. slopes, corners, enclosed or open structure), high speed of the belt dispersing any gases, harsh operating environment, and prohibitive costs for the supply, installation, and maintenance of effective conventional fire detection systems on this scale. The result has been inadequately performing conveyor fire detection systems, and in most cases no fire detection at all.

A fire detection system that can address these conveyor operating conditions would greatly increase fire safety for the protection of people, fixed assets, and minimise disruptions to plant production.

Distributed Temperature Sensing (DTS) technology using a resettable linear heat detector on a single fibre optic core has been successfully tested and deployed on underground and surface conveyor systems. This application of the DTS has been deployed in Europe in underground coal mines, and site trials have been conducted in Australia to prove the application of this technology.

The DTS system's capabilities have been proven to exceed conventional point or linear (copper wire based) heat detectors, or aspirating CO gas detectors. The ruggedized fibre optic based system has the capacity to detect fires quickly, and localise the source to within 0.5 metres. This precision is unaffected by wind and other environmental effects, because not only convective, but also conductive and radiant (infrared) heat is measured by the system.

In addition to its fire detection function, DTS has also been deployed on conveyors for temperature monitoring of idler and main drive bearings. This allows early detection and identification of overheating rollers, bearings, and issues with ancillary equipment. A significant advantage of collecting this temperature data is in predictive maintenance planning and the repair of main drive bearings and replacement of idlers.

Key words: Fire, temperature, DTS, fibre optic, condition monitoring.

INTRODUCTION

Fire risk control in both surface and underground mining is a key component of overall mine workplace risk management. The department of primary industry (DPI, NSW) clearly requires that fires are detected as early as possible (MDG1032, 2010) to remove people from harm. The same guideline goes on to emphasize the real-time detection of fires in areas such as single-entry development, belt conveyors and reclaim tunnels.

MDG1032 continues the theme of early detection of fires before they develop into a hazardous situation, by recommending condition monitoring systems be used, such as temperature monitoring on equipment bearings. In a mining environment, the relevant equipment bearings are mainly found on conveyor idlers, and drive pulleys. Other potential heat sources for early fire detection typically include the reclaim tunnel's coal valve area due to heat build-up on the coal stockpiles above the valves, and disused underground tunnels. It is recommended that these defective bearings be replaced before they constitute a fire hazard. In addition, any conveyor idler management system must identify defective idlers (AS/NZS 4024.3611, 2015), to minimize hazards.

Once the potential of a fire developing in and around conveyors is detected, then Australian standards (AS/NZS 4024.3611 p.13) recommends that the conveyor be stopped.

In addition, the equipment used for the detection of fires and heat sources in the mining environment must not be a source of ignition. Within the DTS system the energy source is the laser signal transmitted within the fibre. The laser energy level must be kept below the requirements of AS/NZS 60079.0 clause 6.6.2 (2012).

However, fire detection over long distances such as mine conveyors has traditionally been impractical due to the high costs and reliability issues associated with the high number of sensing devices required over long conveyor distances, being used in a dusty and damp (underground) coal mine environment.

The investigation process for the development of this paper has included review of the science of photonics used for DTS systems, equipment systems applications to meet the regulatory requirements for fire detection and condition monitoring, and DTS case studies relevant to the mining industry both overseas and in Australia.

The principal results of the investigation presented in this paper have shown that the DTS system has proven to be a robust, multi-functional, lower cost to install and maintain, alternative for the harsh mining environment, whilst meeting the requirements for equipment protection levels (EPL) for mines Mb to AS22901.1:2014 (High Degree of Protection) in explosive atmospheres.

The science of Photonics and DTS Technology

The origins of the use of photonics for measurement of physical variables dates to the 1970's. Chen (2012) describes how A.J.Rogers first used the theory of optical time domain reflectometry (OTDR) to calculate magnetic field, pressure, and temperature. However, it wasn't until 1983 that A.H. Hartog of the University of Southampton in the UK adopted the OTDR theory to practically provide a continuous profile of the temperature distribution along the fibre cable.

Raman Scattering Measurements

Distributed Temperature Sensing (DTS) measurement techniques are based on detecting the back-scattering of light using the Rayleigh, Raman, or Brillouin principles (Ukil et al, 2012).

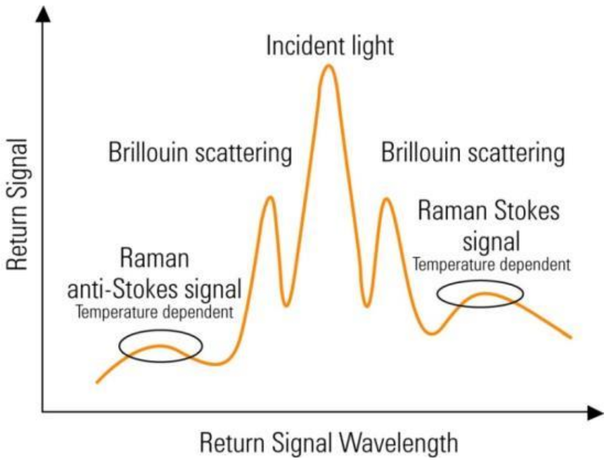


Figure 1 Optical fibre dispersion spectrum

This diagram describes the three types of back-scattering that occurs when an incident laser light is transmitted down the fibre optic cable. The frequency range is typically in 100's of MHz.

Typically, the Brillouin and Rayleigh detection principles provide the highest resolution of temperature measurement down to 15 cm. However, this is accompanied by more expensive costs for equipment, making the Raman scattering principle more affordable. It is the predominant method used in temperature sensing equipment, and recent developments in Raman scattering using Total Variation deconvolution as achieved by Bazzo et al (2015), have also achieved accurate temperature measurement resolution down to 15 cm.

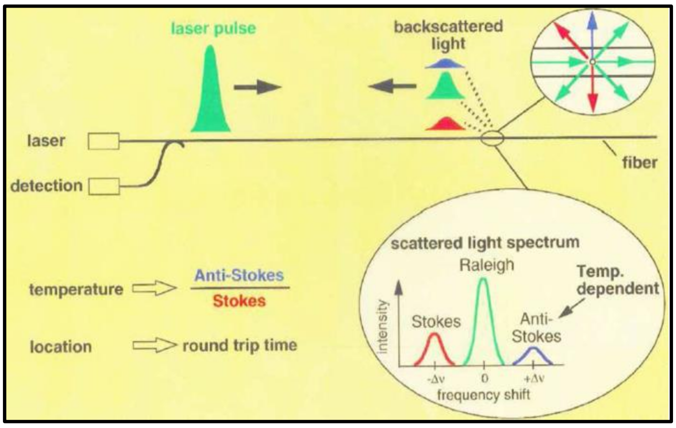


Figure 2 DTS using Raman scattering

The Raman scattering effect has both a Stokes and anti-Stokes component, which are temperature dependent.

Figure 2 displays the Raman scattering effect which is used for temperature measurement in current DTS systems. The ratio of the anti-Stokes and Stokes light intensities provides the local temperature measurement (Ukil et al, 2012).

The distance location of each temperature reading is defined as the round-trip time from the laser pulse transmitted to the back-scattered light receival.

Leitao et al (2012) provide the formula to represent the distance along the fibre cable for each of the temperature measurements as follows:

$$L = (c*t)/(2*n)$$

L : distance between the scattering point and the injection point (DTS unit) of the fibre,

t : time at which it returns to the injection point

c : is the speed of light

n : is the refractive index of the optical fibre (typically doped quartz glass, a form of silicon dioxide SiO_2)

Spatial Resolution

Spatial resolution is one of the main parameters of a DTS system. Chen et al (2012) defines it as the smallest section of the fibre cable length that can be used to measure temperature accurately. The smaller the spatial resolution the more accurate the DTS system.

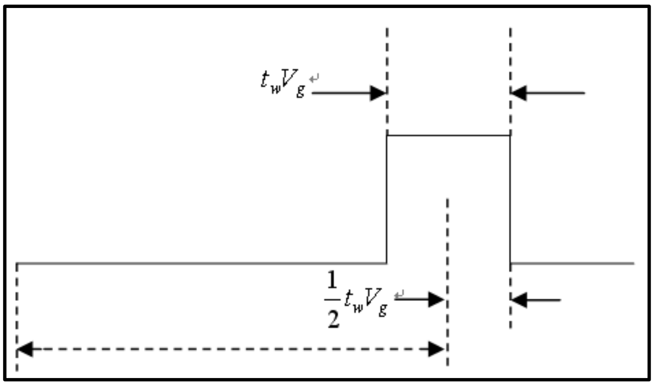


Figure 3 Relationship between pulse width and spatial resolution

Leitao et al (2012) provide a definition of spatial resolution of the incident light being transmitted as follows, with the key parameters shown in Figure 3;

$$R_{pulse} = (t_w * V_g)/2$$

R_{pulse} : Spatial resolution,
t_w: optical pulse width,
V_g : is the speed of light in optical fibre

Chen et al (2012) conducted experiments with varying lengths of DTS fibre cable with a DTS unit with a fixed spatial resolution of 4m. The lengths were inserted in a water bath and the temperature set at 50ºC (actual reading 50.14ºC using a thermocouple).

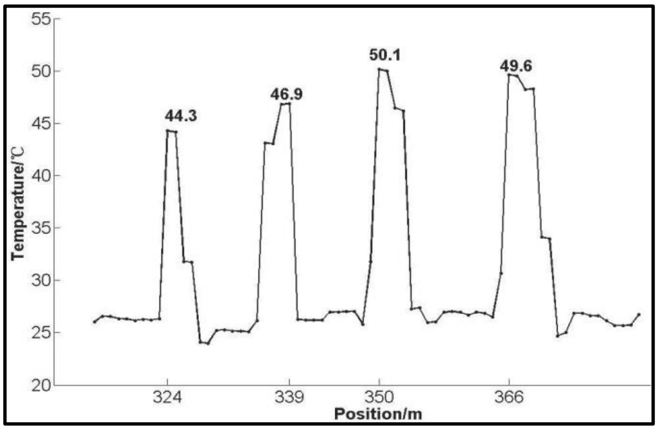


Figure 4 Temperature results for varying cable lengths, with spatial resolution of 4m

Figure 4 displays the temperature readings of the various lengths of cable going left to right of 2m, 3m, 4m, and 5m. The best DTS accuracy was measured with cable lengths of 4m and 5m. In other words, the accuracy of the DTS unit improves if the section of cable being measured is equal to or greater than the spatial resolution.

OTDR vs OFDR

When applying a DTS system for temperature measurement it is important to understand the underlying technologies used; namely OTDR (Optical Time Domain Reflectometry) or OFDR (Optical Frequency Domain Reflectometry). Table 1 provides a brief comparison of these two technologies.

Description	OTDR	OFDR
Discontinuities along the fibre optic cable	More robust to cable physical anomalies, only impacted by discontinuities as pulses are exactly correlated to the position of the anomaly and can be corrected during the sensor calibration. Used extensively in the telecommunications industry.	More sensitive to fibre cable discontinuities, distortions, cable stress and bends, due to the extensive signal processing plus conversion from frequency to time domain using fast Fourier analysis (FFT). May result in measurement errors.
Semiconductor Laser life span	Code Correlated OTDR (CCOTDR AP Sensing patented), allows a dramatically reduced peak power while keeping high laser performance. CCOTDR semiconductor laser is pulsed which gives a low unction temperature and long laser lifetime.	The life time of a semiconductor laser is dominantly dependent on the junction temperature, which is related to the average power in the active area. OFDR uses continuous wave operation (100 % on), systems are specified at 110 mW average and 200 mW maximum power. In summary OFDR semiconductor lasers are always on leading to high junction temperatures and reduced laser lifetime.
Laser Power Levels	CCOTDR on the other hand uses low power laser maximum 17mW, which are well below IEC60079.0 power levels for hazardous areas, such as coal mines, zone 0 (gas), and zone 20 (dust) areas.	Some OFDR based DTS systems recommend that the measurement should be automatically stopped in case of a fibre break, which is due to the high-power laser used. Which in turn could be a source of explosion ignition in hazardous areas.
Technology Development	Pulsed OTDR is used extensively in telecommunication and data transmission industries, instead of OFDR, which results in increased research and development due to the size of the industry. The resulting OTDR technology transfer allows the DTS systems to evolve and improve at a faster pace.	OFDR systems were mainly developed in the 1990's due to limiting patent issues with OTDR. OTDR patents are now public domain.
Water Peaks Contamination	CCOTDR systems that operate at 1064 nm, are unaffected by water peak effects.	Water peaks are caused by contamination from hydroxyl ions (OH), that come from the manufacturing process. After several years, the fibre can get "blind" at certain wavelengths, and not measure accurately or at all A laser wavelength of 1550 nm used in some OFDR is affected by this.
Laser Safety	Class 1M laser (eye safety), however still warning not to look into the open end of the fibre optic.	Early OFDR systems were laser class 3B (980nm wavelength, 100 to 200mW, but are now mainly Class 1M (only due to the 1550nm wavelength), there is still a warning to not look into open end of the fibre optic.

Table 1 OTDR vs OFDR Comparison

Therefore, based on the criteria above, the focus of this paper will be the system design and application of the DTS using OTDR technology with Raman Stokes scattering.

DTS Equipment System

Figure 5 provides a simplified block diagram (Leitao et al, 2012) of a DTS system.

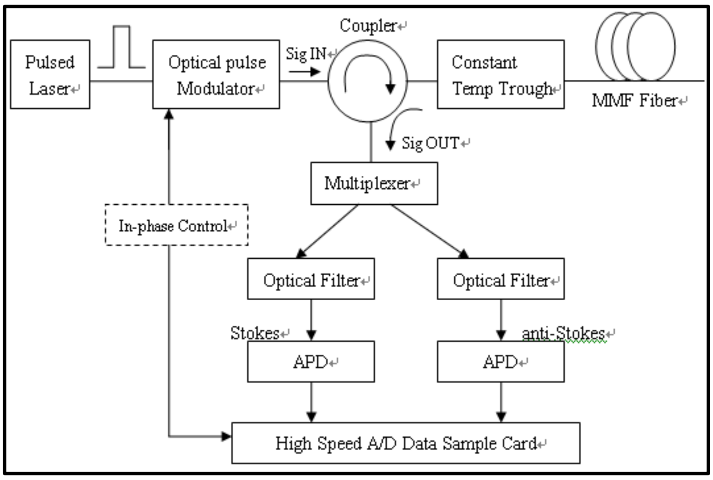


Figure 5 DTS Light transmission & receival components

The key internal components of a DTS unit are the:

- laser generating the pulse,
- coupler directing the signal out (incident light) to the fibre,
- coupler directing the signal in (back scattered light) received from the fibre cable,
- Optical filters with amplifiers,
- A/D (analogue to digital) converter for interfacing the temperature measurement and location to PLCs, DCS, SCADA, and fire alarm panels.

DTS Integrated System

A full system diagram of a modern DTS system integrated into a fire alarm system, and equipment temperature monitoring is provided in Figure 6.

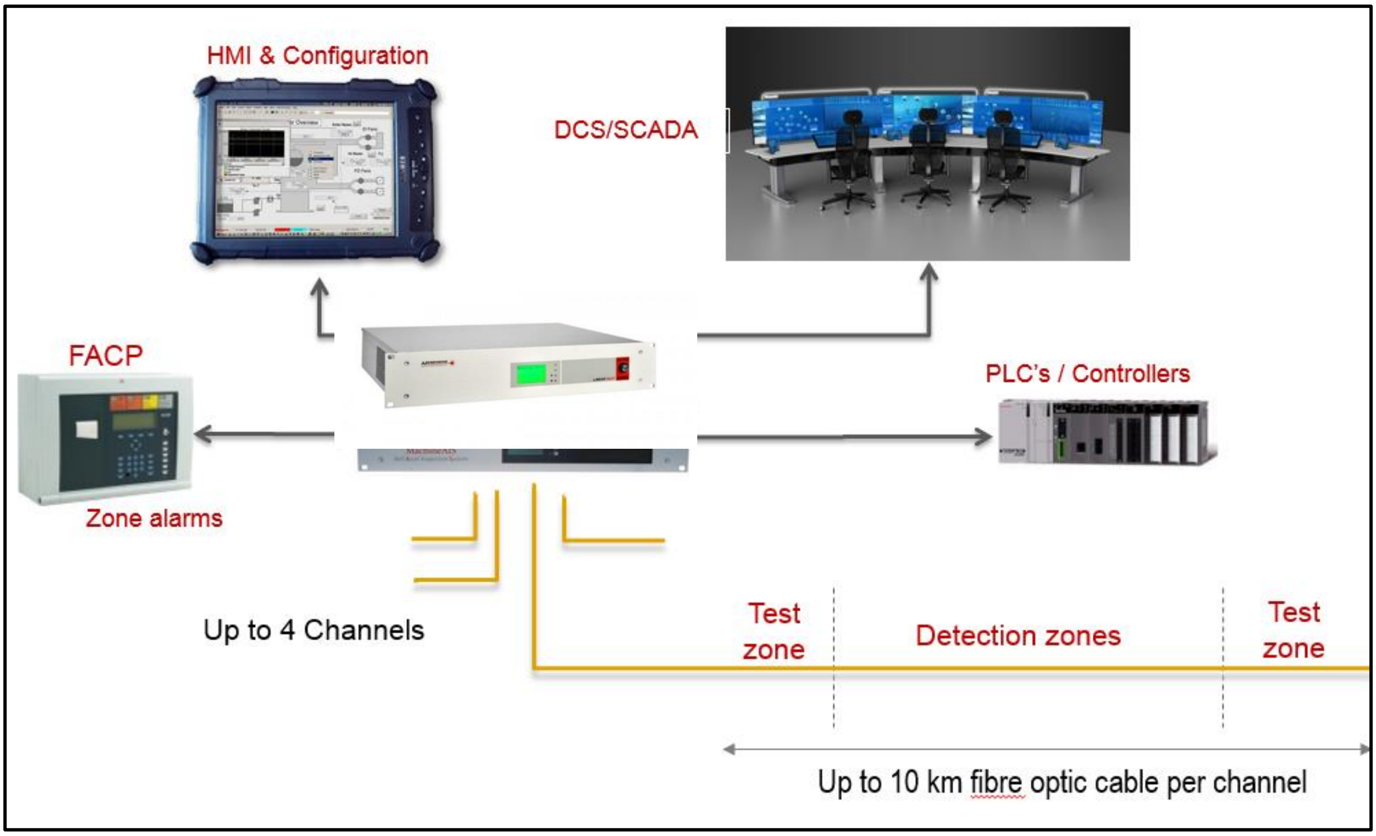


Figure 6 DTS system diagram

DTS Test Performance Results

Fire Detection – Coal Mine

Coal mining conveyor belt systems are the most frequent contributor to the development of a fire (Großwig et al, 2008). The sources of heat ignition of fires in coal mining include idler and pulley bearings, conveyor belt electrostatic charge, and spontaneous combustion due to build-up of coal dust in and around the conveyor. It is therefore important to detect and alarm smouldering coal before it sparks into a fire.

Großwig et al (2008) focused on the properties of a high-risk smouldering coal fire, which was defined as a CO gas emission of 10 l/min (1000cm^3/min or 10ppm theoretical CO concentration) for a 0.25 m^2 area of smouldering coal.

However, with an air flow rate of 5000cm^3/min (approx. 0.83m/s), this dilutes the CO gas to 2ppm which cannot be accurately detected by conventional CO detectors. This condition is made even more difficult to measure using a fixed stationary CO gas detector, as the smouldering coal gas plume would move quickly down the underground coal mine tunnel, or disperse rapidly for a surface coal mine environment.

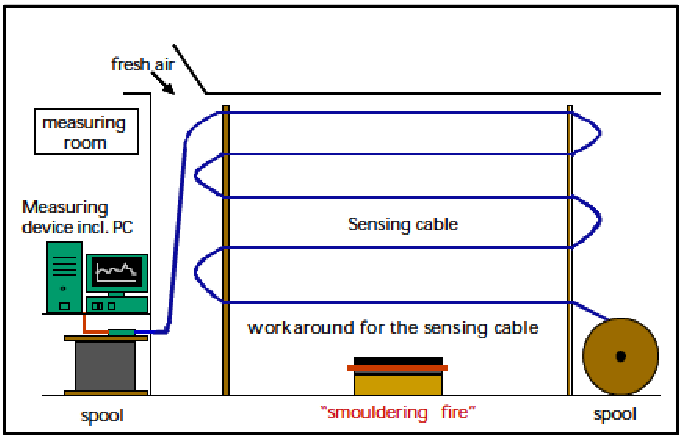


Figure 7 Smouldering Fire Test Setup

Tests were conducted by Großwig et al (2008) to determine if, and under what conditions a DTS fibre optic based system would detect the beginnings of smouldering coal fire. Figure 7 and Figure 8 provide the layout of equipment for this test.

A 0.25m^2 area on the floor was used as the smouldering coal source using an electric heating element and layers of dry coal dust.

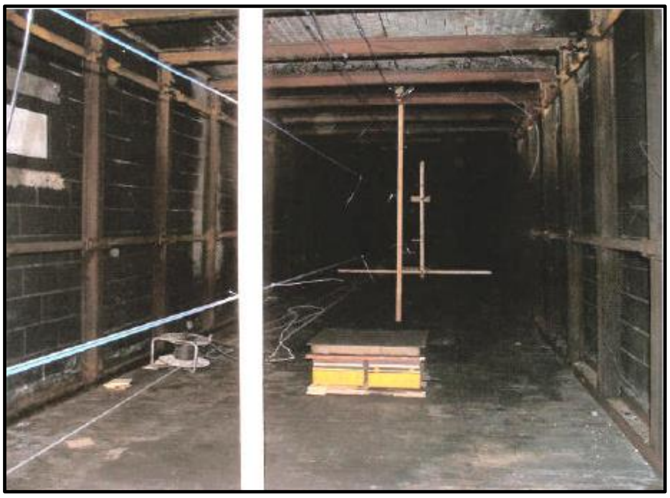
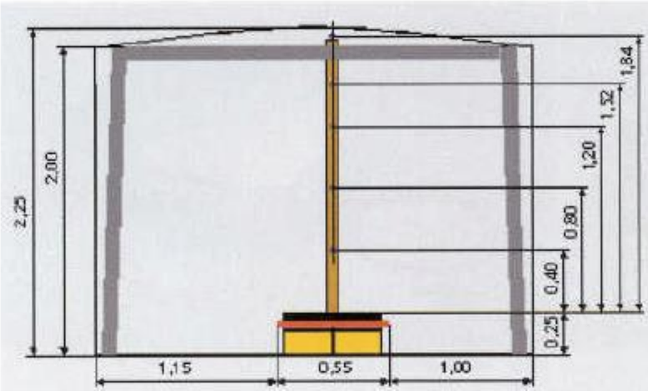


Figure 8 Smouldering Fire Field Arrangement



The DTS fibre optic detection cable were run across the smouldering coal fire box at various heights from 0.4m to 1.84m above the box, as shown.

Figure 9 Fibre Cable installed above smouldering fire

The smouldering fire was then started by the heating element in the fire box with various wind speeds blowing across the tunnel to simulate the conditions in a typical coal mine.

The results showed that the DTS fibre optic cable successfully detected the coal dust smouldering fire at all levels with increasing tunnel wind speeds of up to 4.5m/s.

Temperature Monitoring – Conveyor Pulley Bearings

The fibre optic based DTS system has also been tested by Dobinson and Torre (2015), for the purposes of temperature monitoring of conveyor drive pulley bearings. Figure 10 describes the heat detection principles used for bearing surface temperature measurement.

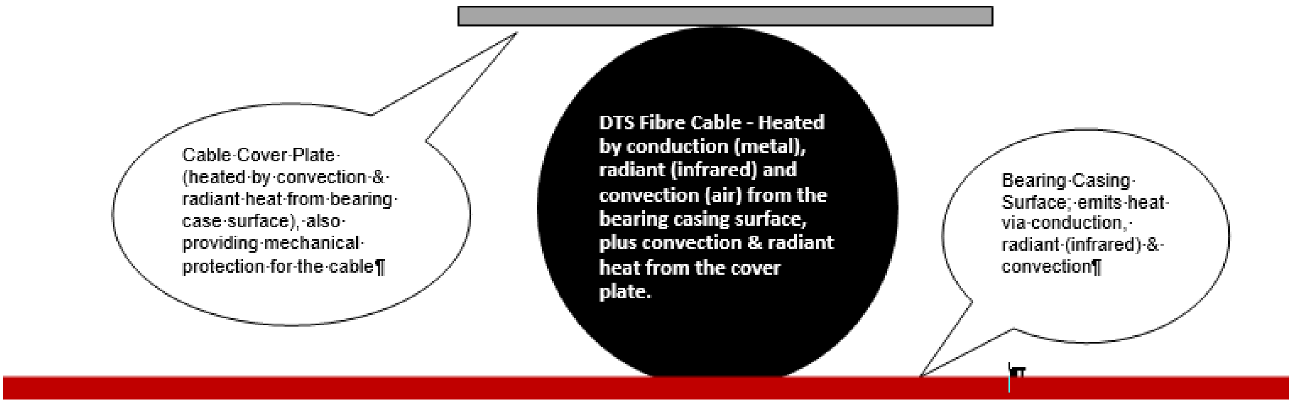


Figure 10 DTS Fibre Cable Heat Detection Principle

The fibre optic cable was looped across the top of the bearing housing surface and covered by a stainless-steel plate as shown in Figure 11, for both cable protection and maximising the contact surface between the fibre cable and the bearing.

With the conveyor running for several hours with an ambient temperature of 21.6 ºC, the DTS system measured a temperature on the surface of 34.8ºC, compared with a manual reading using an infrared probe of 35ºC.

Figure 11 Conveyor2106 Drive-Side Bearing with Fibre Cable

DTS Application Case Studies

One of the major applications of DTS systems is for fire detection in road tunnels, where it is widely deployed.

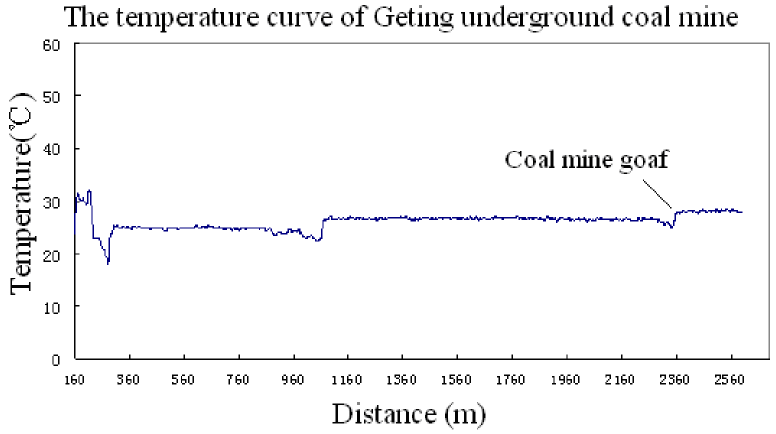
For industrial applications, DTS technology has been used for (Ukil et al, 2012):

- Power Cables (both using embedded fibre in HV cable) or within the same cable tray
- Transformer Winding Monitoring (Embedded fibre in the transformer winding)
- Switchgear Monitoring (inside HV switchboards)
- Rotating Machinery Monitoring (Embedded fibre in the motor stator winding)
- Pipework Monitoring (Gas, Oil, LNG, ammonia) for leakage and security
- Tanks and Vessels
- Boiler Furnaces

Some brief examples are presented here related to mining.

Fire detection – Coal Mine Goaf

Letaio et al (2012) describe the application of a DTS system in China's coal industry for fire detection. In particular, the Getting and Dongtan underground coal mine goaf areas are monitored as they are considered a probable source of spontaneous combustion. Simplicity of installation, strength of the fibre optic cable, reliable heat detection, and lower total cost of ownership over long distances were seen as the main benefits for the application. Figure 12 displays the typical results of the DTS temperature monitoring.



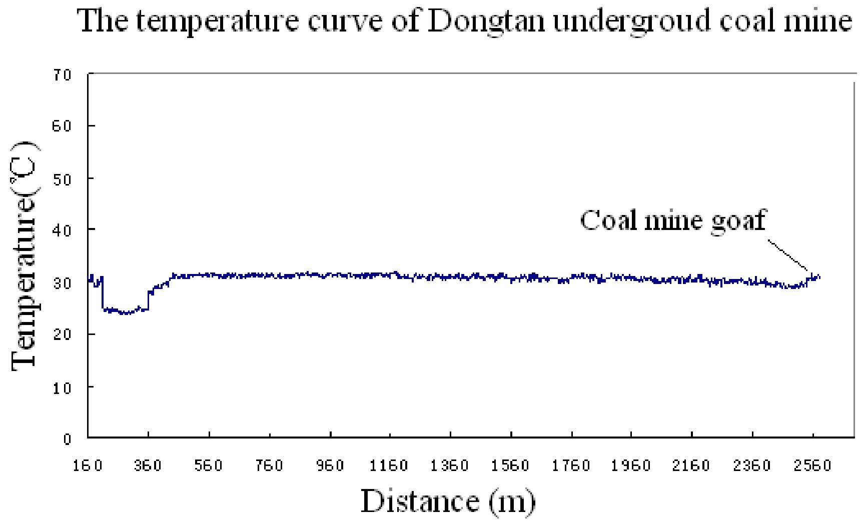


Figure 12 Geting & Dongtan Coal Mine Temperatures

Fire Detection – Coal Conveyor

Figure 13 is an example of using a DTS system for fire detection in and around a coal conveyor. It has one sensor cable going out along one side of the conveyor and returning along the other side. This provides full fire detection coverage around the conveyor structure area.

One end of each of the two fibre cores of the cable is connected to the DTS, and the other ends are terminated with an 8º connector signalling the end of the cable run to the DTS.

The DTS unit is installed outside the hazardous area, with only the fibre optic cable inside the hazardous zone.

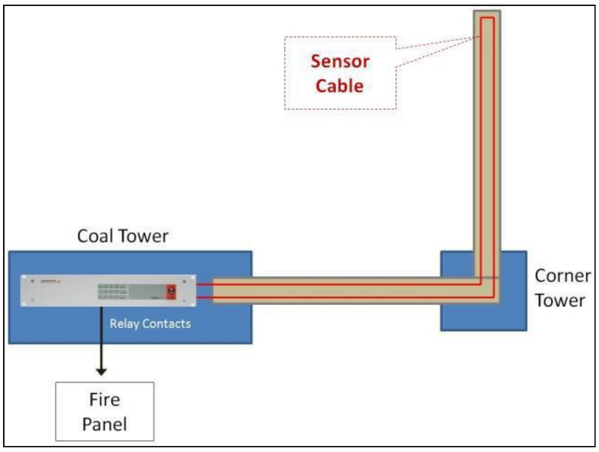


Figure 13 Coking Plant Fire Detection - Germany

Fire Detection – Coal Bunker

In November 2007, an incident at the coal bunker in Puerto Coruna in Spain caused a fire within the bunker (27m high, 105m diameter). The facility is adjacent to the city as shown in Figure 14. It was determined that the fire was caused by insufficient ventilation, high pressure in the bunker, and friction which lead to spontaneous combustion within the coal stockpile. The installed infrared cameras and gas detectors were not able to detect the smouldering fire early enough to stop the fire taking hold.

Subsequently, a DTS system fibre optic cable was installed along the inside of the bunker in a ring layout. The fibre was run at heights of 0.6m, 1.6m, and 2.5m above the floor level of the bunker. The fibre cable was mechanically protected by inserting it in a slot within the bunker wall. This was proven as the most effective method of monitoring heat build-up and smouldering coal within the body of the coal stockpile.

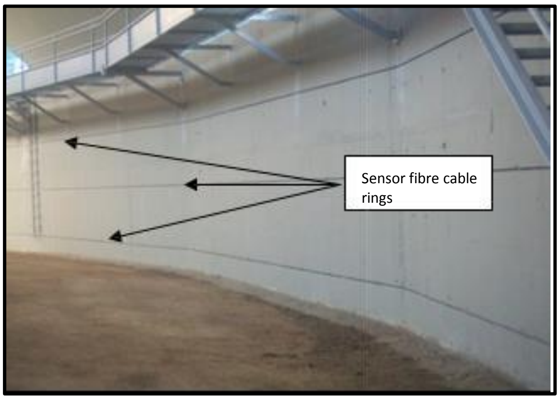


Figure 14 La Medusa Coal Storage Facility with DTS – Spain

Equipment Condition Monitoring – Motor Bearings

The application of DTS to monitor motor bearing temperature allows us to infer by using soft sensing modelling techniques, the temperature of other components connected to the bearing being monitored.

Maru and Zotos (1989) performed various testing on 2 and 4 pole motors to measure the temperature of not only the bearing outer hub, but also the bearing outer race, fan-end bearings, and the motor windings. A machine's bearing temperature is the second most important parameter in deciding the bearing and lubrication life, with the first major factor being contamination (Maru and Zotos, 1989).

Table 2 data provides a comparison of the relative temperature throughout the motor, with Figure 15 providing the temperature rise curve between the motor's bearing and winding.

TEMPERATURE (°C) READINGS (THERMOCOUPLE)—50 HP. 460 V, THREE-PHASE, 60 HZ, 1800 R/MIN

Percent Load	Ambient	Winding	Winding	Winding	Winding	FE	Drive-End Bearing Outer Race	Drive-End Bearing Hub	Fan-End Bearing Outer Race	Frame
0	26	38	38	36	36	38	41	42	31	32
50	26	51	52	49	49	51	49	50	36	40
75	27	68	69	67	66	68	57	58	44	50
100	27	97	99	96	93	97	75	75	56	66
125	27	154	160	153	148	152	113	113	73	95

Table 2 Temperature readings motor components

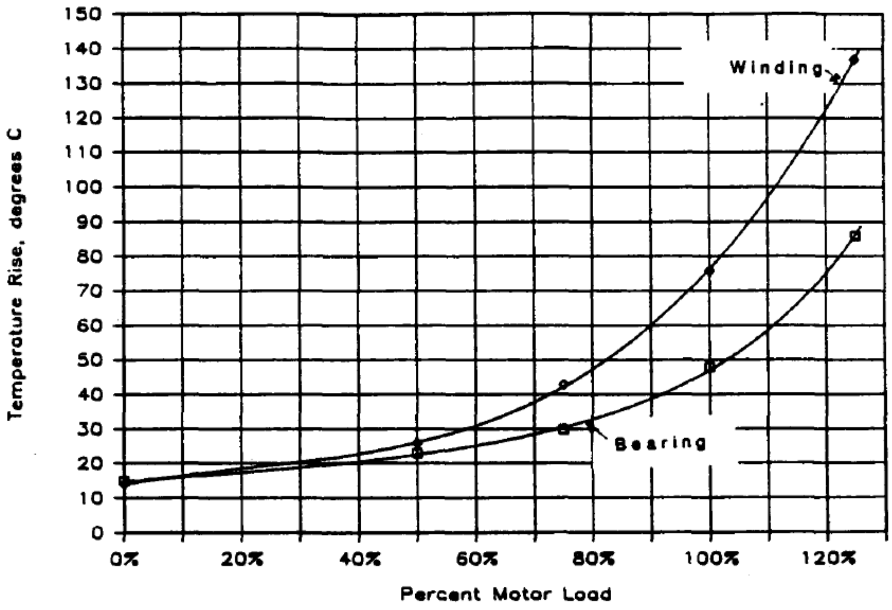


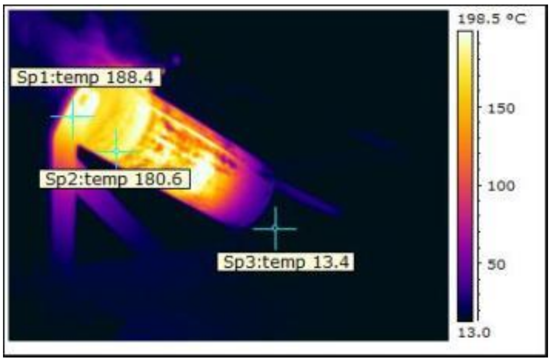
Figure 15 Temperature rise versus motor load

Therefore, by using the DTS to measure the bearing outer hub we can therefore infer through soft sensing modelling techniques the temperatures of various parts of the motor, or drive gearbox system, without the need to install costly thermocouple type sensors throughout the machine and wiring to a central monitoring system.

Equipment Condition Monitoring – Conveyor Idler Bearings

Conveyor Idler bearing failure (or failing) causes the idler bearing to heat up. A thermographic image of an overheated bearing is shown in Figure 16, showing not only the bearing but most of the idler body overheating.

Traditional fire sprinkler systems using glass bulbs installed well above the conveyor itself have fixed settings around 70ºC, but will usually not be able to detect these overheated idlers.



This overheated bearing has reached over 180ºC, which is well above typical coal combustion temperatures of 140ºC.

These overheated bearings can damage the conveyor belt via gouging, and become a fire ignition hazard.

Figure 16 Overheated idler bearing image

The DTS system fibre is used to detect the overheated idler bearing mainly through heat conduction from the idler bearing to the metal suspension elements to the conveyor frame. The DTS sensor cable is installed adjacent to the idler and is fixed to the conveyor frame, as shown in Figure 17. Heat from the frame is detected by the fibre cable, and the exact idler location and temperature is relayed back to the main DTS unit, for either setting off a fire alarm and/or an alarm on the site PLC/SCADA/DCS system.

The fibre cable requires no maintenance, self-diagnoses any fibre breaks with their location, and immediate alarming. It also meets the standards requirements for underground coal mines explosive environments, due to the use of very low power laser, and is immune to electro-magnetic interference.

This has proven to be a reliable cost-effective method of temperature monitoring conveyor idler bearings, at the Polaniec power plant underground coal mine in Poland, and has been "operating flawlessly since 2011" (Krol, 2016).

Figure 17 Polaniec Coal Mine Carry and Return Idler Temperature Monitoring Fibre Installation

CONCLUSIONS

The photonics based temperature measurement uses various principles of detection such as Raman-Stokes, Brillouin, or Rayleigh back-scattering of light. Each of these principles have been applied to the DTS technology currently used in a variety of industrial applications.

The DTS using Raman-Stokes scattering has been reviewed in this paper and shown to be the most used in current DTS systems today. This is due to it achieving a balance between DTS equipment complexity, overall cost, and accuracy compared to the other principles.

DTS test results have shown how effective the DTS system can be in the early detection of heat build-up even across large areas with high wind speeds. This is important for fire detection in mining operations, particularly for conveyors where both these environmental conditions exist.

In addition, this report has shown another major benefit of the DTS technology in the area of equipment condition monitoring. The integration of the DTS system as part of a plant predictive maintenance approach, greatly enhances its value beyond fire detection alone.

The DTS technology has evolved over the past 30 years from theoretical photonics research, to its being deployed as a reliable, safe, and practical way of temperature measurement. Future developments in the areas of laser signal processing and analysis, will further improve the accuracy of both the temperature and location measurement.

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