FIBRE OPTIC LINEAR HEAT DETECTION APPLIED TO TUNNELS

Chris Conway – Sensa.

INTRODUCTION

This paper describes fiber optic linear heat detection technology and its advantages as an intelligent temperature profiling system for tunnels. Emphasis is placed on the ability of such systems to produce early and reliable alarm annunciations combined with maximum false alarm rejection. Reference is made to currently installed systems as well as fire test data, made available from full scale fire tests carried out in the Benelux tunnel, on behalf of the Dutch Ministry of Transport in Rotterdam (Nov 2001)\textsuperscript{i,ii}.

The DTS system is integrated into tunnel safety management systems and examples of current system design topologies are discussed. The temperature information is typically used to control the ventilation in the tunnel under normal operating conditions and also during emergency periods.

There is the basic assumption that that any automatic fire detection system should work to provide early and reliable detection of fires. The balance between early detection and maximum rejection of false alarms has most certainly been the focus for tunnel operators and equipment suppliers alike.

1. FIBRE OPTIC LINEAR HEAT DETECTION TECHNOLOGY

Generically this technology has been referred to as Fibre Optic Distributed Temperature Sensor Systems, or DTS Systems for short. It shall be referred to as such hereafter, within this paper. The DTS System comprises two main components:

1. The Sensor Control Unit
2. The Sensor Cable

Sensor Control Units

Optical fibre based distributed temperature sensing uses a combination of technologies which allows one to produce temperature profiles using a fibre optic cable as a temperature transducer. The optical fibre within the Sensor Cable is therefore analogous to a continuous “addressable” thermocouple up to several kilometres in length. The associated control equipment (Sensor Control Unit) can effectively quantify the temperature at any point along the path of the optical fibre. The Sensor Control Unit can determine temperature and distance data points along the length of the fibre.

The temperature information combined with position data enables the DTS System to produce a real time graph on a monitor, as shown in Figure 1. This profile is taken from a utility tunnel carrying high voltage power cables, with the x-axis is distance in meters, y-axis is temperature in centigrade.

![Figure 1 DTS Temperature Profile example](image-url)
DTS Systems are able to produce complete temperature profile measurements typically, approximately every 10 seconds. Each measurement may contain temperature data for every 1m of fibre optic cable. The maximum length of continuous fibre connected to a Sensor Control Unit, the measurement time, the spatial, positional and temperature resolution tend to vary between system manufacturers. The technology is therefore producing large quantities of data, which allow the control systems to make more effective asset monitoring and alarm decisions. The Sensor Control Unit is programmed with special fire detection algorithms so that the unit can make a verified alarm decision. In doing so, the DTS System can operate as a “stand alone” detector. The DTS Systems can also share the calculated temperature and distance data with other third party systems e.g. SCADA control systems. This data can then in turn be used to influence other decisions made by external systems.

![DTS system architecture](image)

**Figure 2 DTS system architecture**

A DTS System normally includes a number of different interface options as standard. Alarms decisions may be communicated to the main Fire Alarm Control Panel by monitored relay contacts. This low level interface often provides a very secure alarm communication path. Alternatively, the DTS System may communicate alarms and real time temperature and distance data via a secure Modbus communications path. Modbus is a well established industrial communications protocol and can offer interconnection over RS232 or TCP/IP. Fire Alarm Control Panels (and networks) often have a proprietary graphics command and control workstation which provides a single Graphical User Interface (GUI) to manage the entire fire detection system. There are a large number of accepted gateway solutions available to ensure effective data communication between DTS Systems and Fire Alarm Control Panels/Networks.

![DTS network system architecture](image)

**Figure 3 DTS network system architecture**
DTS Systems have TCP/IP connectivity and so it is possible to provide Ethernet based network solutions for larger system design requirements. A number of network topologies are available and for systems requiring the highest integrity, redundant topologies are available. A central workstation typically includes a “soft mimic” representing the entire system configuration. This type of package typically includes a programmable site graphic, alarm display and alarm management system. Internet connectivity is also used to provide remote monitoring at a clients site, or indeed to provide remote diagnostic and system maintenance checks from a remote location.

Sensor Cable Temperature Range
The temperature range of optical fibres is a function of the fibre coating and the outer jacket material. Standard acrylate coated fibres can operate between -40ºC to +90ºC continuously and up to +150º for short periods e.g. 48 hours. A wider temperature range can be achieved (-185ºC to +400ºC) using a polyimide coating but this is not considered necessary for normal Fire Detection applications.

Outer Jacket Materials and Installation
The two jacket materials normally utilised are thermoplastic low smoke zero halogen and un-coated metal tubing (e.g. stainless steel 316) for harsh environment applications. In tunnels, the sensing cable will be subject to chemical attack and mechanical damage and therefore the un-coated stainless steel metal tubing is normally recommended. This produces a robust sensor with excellent thermal response characteristics and very long life.

2. MAJOR ADVANTAGES FOR TUNNEL DESIGNERS, OPERATORS AND RESCUE SERVICES

Immunity to EMI
The optical fibre uniquely acts as both sensing element and transmission medium and is immune to electro-magnetic interference. The quality of the measurement is therefore not affected by the application of the sensor cable close to high voltage power cables or leaky feeder cables. Using a Class 1 laser in the Sensor Control Unit, the system is also safe for use in occupied areas even if the sensor is broken. The sensor cable is also safe for use in hazardous areas.

Programmability
A DTS System is fully programmable. Physical fire zones can be programmed along the Sensor Cable and in each zone multiple fixed alarm thresholds may be specified according to design requirements. A combination of threshold temperature alarm and variable Rate of Rise alarm can be nominated for each fire zone and the number of iterative counts adjusted to increase or decrease system sensitivity. For each detection zone it is possible to configure pre-alarm levels to alert personnel to imminent alarm events. In practice, settings can be adjusted at site to correspond to prevailing conditions and recording tunnel temperatures during commissioning can be advantageous in determining appropriate thresholds.

Loop Design
The DTS System automatically detects and locates any break in the Sensor Cable. If the Sensor Cable is not connected to a Sensor Control unit at both ends, any severed section will not be addressable beyond the break. Designing the DTS System so that the Sensor Cable forms a continuous loop from and to a Sensor Control Unit produces a high integrity system, which is recognised by some authorities as essential. If “Double Ended Processing” is employed any break in the fibre will not affect the ability of a Sensor Control Unit to continue poling both end sections of the
Sensor Cable. Loop designs using Double Ended Processing therefore ensures that DTS Systems remain fully operational throughout the incident period and beyond, for end sections of fibre not destroyed by fire or explosion.

Assessment of Fire Development
The DTS System operates by analysing the back scattered light and therefore in a fire condition all unaffected fibre will continue to give temperature and positional information providing one end is connected to the Sensor Control Unit. As the fire develops and moves along the tunnel, more of the Sensor Cable will be affected and this real time information can be presented either as a temperature/distance trace or as a graphic mimic display. The location, affected area and direction of fire spread together with the prevailing temperature conditions elsewhere within the tunnel can therefore be viewed at a safe location on the appropriate user interface. Rescue services will find this level of information extremely valuable, particularly if combined with CCTV.

Dual Function Facilities
Another advantage of a DTS System is the ability to prescribe and identify either peak or average temperatures within a zone. Fire detection applications are normally based on identifying peak temperatures and therefore the average temperature function can be used for other applications such as general tunnel condition monitoring. This is particularly useful in underground rail networks, which use push/pull ventilation based on motion of a train. In times of congestion or power failure, tube trains can remain stationary in a tunnel for considerable periods. Heat given off from the train’s condensers can raise the stagnant air temperature above acceptable limits and require forced ventilation to be activated. However an increase in tunnel temperature may also be due to a fire condition and in these circumstances it would be dangerous to automatically switch on the ventilation fans. The DTS System can differentiate between the two conditions by setting up parallel zones to search for peak and average temperatures. The ventilation fans can be switched on and off between limits without concern that the temperature rise has been caused by a fire condition.

3. DESIGN STANDARDS AND SITE TRIAL DATA

Example Recommendation
It is currently widely accepted that linear heat detection technology has a significant role to play in the protection of tunnels. By way of example, RABT (Richtlinien Ausstattung und den Betrieb von Straßen Tunneln) provides a clear indication of the basic requirements of automatic fire detection systems within tunnels.

An English translation of the relevant section of the standard is given in the inset Table 1 below. The recommendation represents a not uncommon minimum expectation of automatic fire detection system performance. A fire of 5 MW approximates to a burning passenger car.
Table 1 RABT 2001, rev. 6, Section 2.5.3: Fire detection and alarm systems

<table>
<thead>
<tr>
<th>1. RABT 2001, REV. 6, SECTION 2.5.3: FIRE DETECTION AND FIRE ALARM SYSTEMS</th>
</tr>
</thead>
</table>

### 2.5.3 Fire Detection and Fire Alarm Systems

The fire detection and fire alarm system should be connected without using a main alarm routing equipment through the management system to the tunnel observation.

#### 2.5.3.1 Manual Fire Detection Equipment

Manual fire detection equipment in tunnels with a length of ≥ 400 m should be a manual call point according to DIN 5411 and placed at each emergency call station.

#### 2.5.3.2 Automatic Fire Detection Equipment

In tunnels with a length of ≥ 400 m and in tunnels with a mechanical ventilation system automatic fire detection equipment should be used.

Automatic fire detectors in tunnels should be able to detect a fire with a fire load of 5 MW (that means a 20 litre gasoline fire on a 4 m² surface) and longitudinal air speeds with up to 6 m/s within one minute after fire ignition and provide a localisation within 50 m.

There should be installed line type heat detectors, which respond on a rate of rise of temperature as well as on a fixed temperature. The sensor has to be fixed on the tunnel-ceiling above the clear space. Line type heat sensors should be subdivided into several sections. If one section is damaged, all other sections must stay in operation.

Opacity meters may be used for fire detection (pre alarm). (Distances see Section 2.3.6)

The use of temperature cameras or suitable video devices instead of fire detectors can be permitted, if the same requirements are fulfilled. Such systems should be equipped with an image detection, which allows a judgement of the situation (digital video analysis).

Automatic fire alarm systems should also be installed in operating rooms with equipment worth to be protected, e.g. electrical devices.

At the entrance of the premises or at other suitable places (e.g. portal) fire detection panels should be installed in order to display

---

Some may argue that the automatic fire detection systems should be able to detect such an incident at a relatively earlier stage. It is also worth noting above that other incident detection systems, e.g. opacity meters and CCTV systems, can be used to assist in producing early “pre-alarm” warnings to imminent alarm incidents. DTS Systems can provide the flexibility, quality of measurement and reliability that enables early incident detection.

**Example Product Standard**

Reliability can be defined not only in terms of system availability but also by the number of false alarms produced by the system. British Standards definition for false alarms\(^\text{v}\) as applied to fire systems indicates that a false alarm is a fire signal resulting from a cause(s) other than fire.

A false alarm event is further categorised into one of four classes:

1. Unwanted alarms from a fire-like phenomenon or environmental influence, accidental damage, inappropriate human action.
2. Equipment false alarms: the alarm is raised by a fault in the system.
3. Malicious false alarms;
4. False alarms with good intent

As part of the design process for any fire system, the system designer must design out the possibility of false alarms, especially with regard to classes 1 and 2, as far as reasonably possible. Classes 3 and 4 are often out the system designer’s control.

Likewise, insurers, tunnel operators, owners and the authorities normally require some third party verification of the manufacturers’ stated level of functionality and reliability of
proposed equipment. This is achieved to a large extent by the test and certification schemes adopted throughout Europe and the rest of the world. This practice has proved successful over the last number of decades and has prompted the further development of new standards and refinement of established standards. The approval from the third party provides assurance that product and services conform to a known and “accepted” standard.

Many of the product standards for fire detection devices can trace a history back through the decades. The current European product standard for fire detection devices is the CEN standard BS EN54:2001. EN54 part 5 is the product standard for point heat detectors and can trace its origins back to BS3116-1:1970. The purpose of minimum response times

Referring to Annex C of EN54 part 5 one can see that the lower limit of response time is an established parameter and is included to “minimise the incidence of false alarms due to changes in air temperature which occur under non-fire conditions”.

Table 2 Response time limits for Class A1 heat detectors

<table>
<thead>
<tr>
<th>4. EN54 PART 5</th>
<th>5. CLAUSE 5.4 AND 5.1.5</th>
<th>Response Time Lower limit of response time (mins:secs)</th>
<th>Time Upper limit of response time (mins:secs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROR 1°C/min</td>
<td></td>
<td>29:00</td>
<td>40:20</td>
</tr>
<tr>
<td>ROR 3°C/min</td>
<td></td>
<td>7:13</td>
<td>13:40</td>
</tr>
<tr>
<td>ROR 5°C/min</td>
<td></td>
<td>4:09</td>
<td>8:20</td>
</tr>
<tr>
<td>ROR 10°C/min</td>
<td></td>
<td>1:00</td>
<td>4:20</td>
</tr>
<tr>
<td>ROR 20°C/min</td>
<td></td>
<td>0:30</td>
<td>2:20</td>
</tr>
<tr>
<td>ROR 30°C/min</td>
<td></td>
<td>0:20</td>
<td>1:40</td>
</tr>
</tbody>
</table>

The above standard also considers detector behaviour when the ambient temperature is a low as 5°C. Devices compliant with this clause 6.2, and the other relevant parts of the standard are defined as class A1R devices. There are DTS systems available that are approved by LPCB as Class A1R detectors.

Example Site Trial Data

During fire tests in the Benelux Tunnel in Rotterdam (Nov 2001), a number of full scale tests were completed with linear fire detection systems. One of the fire detection systems was a DTS System. The fire size, the place of the fire according to the position of the detectors and the longitudinal ventilation speed were varied. The aim of the tests was to determine the time between ignition of the fire and fire detection and to determine the location of the fire accurately.

![Figure 4 Position of the detection cable and fire location in the test tunnel](image-url)
The tests began with an initial false alarm test where the control systems to be tested had to differentiate between a 0.5m² pool fire and a 1.1m² pool fire by producing no alarm and producing an alarm condition respectively. Regardless of the detection algorithm employed, one would expect the false alarm criteria of test OC & OD to influence the desired results (*) of the following set of tests, from OE to 4.

A complete set of data from the tests was stored so that the data could be used for retrospective tests. The measurement time for the DTS System under test produced a new tunnel profile every 7.5 seconds, with temperature values plotted for every 1 metre of sensing cable on the circuit. One of the tests carried out, was to replay the logged test data using an algorithm, primarily focusing on the response time requirements of EN54 part 5, but specially adapted for tunnels. The results of such a test are indicated in Table 1 column (**).

<table>
<thead>
<tr>
<th>Test</th>
<th>Fire Size</th>
<th>Position</th>
<th>Wind</th>
<th>Purpose(*)</th>
<th>Tunnel/EN54-5 Algorithm(**)</th>
<th>Location of fire alarm from fire source</th>
</tr>
</thead>
<tbody>
<tr>
<td>OC</td>
<td>6L pool</td>
<td>Pos.1</td>
<td>0 m/s</td>
<td>False Alarm Test</td>
<td>Not relevant, alarm in 24 s</td>
<td>0.5 m</td>
</tr>
<tr>
<td>OD</td>
<td>6L pool</td>
<td>Pos.2</td>
<td>0 m/s</td>
<td>False Alarm Test</td>
<td>Not relevant, alarm in 24 s</td>
<td>0.5 m</td>
</tr>
<tr>
<td>OE</td>
<td>12L pool</td>
<td>Pos.1</td>
<td>0 m/s</td>
<td>Alarm Required</td>
<td>Alarm in 22 s</td>
<td>0.5 m</td>
</tr>
<tr>
<td>OF</td>
<td>12L pool</td>
<td>Pos.1</td>
<td>3 m/s</td>
<td>Alarm Required</td>
<td>Alarm in 59 s</td>
<td>2 m</td>
</tr>
<tr>
<td>OG</td>
<td>12L pool</td>
<td>Pos.1</td>
<td>5 m/s</td>
<td>Alarm Required</td>
<td>Pre-Alarm in 60 s</td>
<td>6 m</td>
</tr>
<tr>
<td>OH</td>
<td>12L pool</td>
<td>Pos.3</td>
<td>3 m/s</td>
<td>Alarm Required</td>
<td>Alarm in 66 s</td>
<td>4 m</td>
</tr>
<tr>
<td>OI</td>
<td>12L pool</td>
<td>Pos.1</td>
<td>0 m/s</td>
<td>Alarm Required</td>
<td>Alarm in 23 s</td>
<td>0.5 m</td>
</tr>
<tr>
<td>OJ</td>
<td>Truck Exhaust</td>
<td>Pos.1</td>
<td>0 m/s</td>
<td>False Alarm Test</td>
<td>No alarms</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>4MW pool</td>
<td>Pos.1</td>
<td>0 m/s</td>
<td>Alarm Required</td>
<td>Alarm in 22 s</td>
<td>0.5 m</td>
</tr>
<tr>
<td>4</td>
<td>15 MW pool</td>
<td>Pos.1</td>
<td>2 m/s</td>
<td>Alarm Required</td>
<td>Alarm in 20 s</td>
<td>0.5 m</td>
</tr>
</tbody>
</table>

The most significant factor in achieving the response times indicated in Table 3 is the setting of the rate-of-rise function in the detection algorithm. Predominantly, the alarms are achieved using a rate-of-rise function, rather than temperatures reaching a fixed (maximum temperature) predetermined value. In order to determine alarms in a rapid manner it is imperative that the rate-of-rise function is able to make relatively rapid measurements and so determine the effective temperature gradient experienced at the ceiling, or wherever the sensor cable is located. The nature of the DTS System is such that the sensing cable is a continuous sensor and therefore has complete profile for the tunnel for every meter of sensing cable. The detailed temperature and position data generated by the DTS System permits earlier and more reliable alarm decisions. The air velocity in the tunnel, the tunnel dimensions, location of the fire source as well as the detection cable within the tunnel can also have a significant effect on the length of time it takes for a system to produce an alarm.

Table 3 Overview of conducted tests

International Conference „Tunnel Safety and Ventilation“ 2004, Graz
Discussion

The reasons for selecting the three examples above are such that each example illustrates a separate point view regarding fire risk and acceptable automatic detection methods to help minimise that risk. The concept of false alarm rejection is inherent to the automatic fire detection products as they are applied to the risk area. So, not only is there the possibility of false alarm from the equipment itself, there is also the possibility of false alarm from the external environment e.g. the tunnel in which it is applied. EN54 part 5 not only defines acceptable response times for heat detectors (for buildings), but it is also the purpose of the standard to help identify and quantify a device’s susceptibility to false alarms. For devices that rely heavily upon software algorithms for generating alarms, a detectors compatibility with EN54 part 2 (Control and Indicating Equipment) may also be appropriate when reviewing a device’s software integrity. EN54 is a fire products standard, which has been defined for fire products as they are used in buildings. Although the standard does not specifically currently address some of the issues raised by application of detection products in the tunnel environment, the standard currently serves as an effective benchmark for detection systems. As an example one could reason that a detector which meets the requirements of an A1R detector, could meet with the recommendation indicated in the RABT document. At this time, a CEN working group, is developing a new standard for linear heat detectors – EN54 Part 22. This standard plans to develop new test criteria to establish effective benchmark tests for application of line type heat detectors in a tunnels environment, as well as for the current buildings environment.

6. CASE STUDY – BRITOMART QUEEN STREET STATION, AUCKLAND NEW ZEALAND

Britomart’s underground railway station has three platforms and five rail lines, which can currently handle up to 40 trains and as many as 17,000 passengers an hour. The station was designed with the future very much mind as there is capacity to extend beyond that.

A DTS System is installed throughout the platform areas and within the tunnel section approaching the station. The DTS System is primarily concerned with the identification of major train fires. A secondary function of the DTS System is to provide the SCADA system with temperature and position data, to provide effective ventilation control during normal system operation. The fibre optic sensor cables are run in the ceiling space above the tracks in both the station box and tunnel areas and provide digital feedback of temperature in each of 32 zones of the platforms and tunnel.

Zone temperatures are monitored by the DTS System on a continuous basis. If the temperature in any of the 32 zones rises above pre-determined levels, the Fire Control Panel will initiate deployment of foam in the corresponding zone(s). The system is also programmed to provide staged alarms (pre-alarm and alarm levels) so that early warning of an impending event can be altered. The actual operating alarm and pre-alarm temperatures were adjusted following initial trials. When the building and tunnel were originally designed an estimate was made of the ambient temperatures within these areas. The predicted ambient temperatures and profiles within the area fluctuated depending upon whether electric or diesel rolling stock were present. Seasonal temperature changes also effected ambient temperatures within the area. The operator wanted the flexibility offered by the DTS System to adjust the alarm levels after the sensor cable was installed and after the trains were running.
Please refer to Figure 5. The primary alarm path is achieved through a monitored relay interface to the main fire alarm control panel. A more sophisticated level of data is concurrently available from the Modbus port and this data is gather by the tunnel SCADA system and integrated into the main Safety Management System.

By using an additional RS232 communications port from the Sensor control Unit, dedicated PC is also used to display a mimic of the site and may include access to view temperature traces and other important system diagnostic and facilitate remote maintenance.

All three forms of output can operate concurrently, which results in a flexible system design.

One of the main the responsibilities of the SCADA System is control of the implementation and coordination of the station Emergency Response Scenarios. The system components which may be called to respond in the implementation of an Emergency Scenario are as follows:

- Ventilation Systems
- Escalators
- Passenger Information Displays
- Evacuation Announcements
- Fire Systems

Figure 5  Britomart Fire System Block Diagram
The Foam Deployment System is designed to work in coordination with the DTS System. The Foam Deployment System is comprised of 32 Foam Deluge Valves installed over the 32 zones of the DTS and water / foam concentrate system to supply low level foam discharge nozzles at a pressure level to ensure adequate aeration of the foam concentrate / water mix.

Manual activation of Foam Deluge Zones is provided via the SCADA Emergency Touch Screen and via each SCADA Workstation given appropriate User Access rights. The Foam deluge system incorporates a standard 60 second delay, in order to protect against false alarms and also to ensure that the operator has time to acknowledge the alarm event. Alarm verification is achieved by automatically switching to CCTV and viewing the corresponding zone.

The SCADA system is interfaced to the DTS System by a dedicated Modbus communications link. This communications link provides the SCADA system with analog temperature feedback for each of the 32 zones in the platform and tunnel areas.

The SCADA system has a dedicated DTS and Foam Control Screen to display the current temperature in each of the zones and foam deluge system status. This screen presents temperature feedback in a numeric format, but also show a colour representation of the temperature (eg gradation from yellow (cool) to red (hot)). This provides the operator with some visual feedback as to the temperature map for the DTS monitored areas.

**Figure 6  Emergency Response Scenario SCADA Screen**

Foam Deployment System

The Foam Deployment System is designed to work in coordination with the DTS System. The Foam Deployment System is comprised of 32 Foam Deluge Valves installed over the 32 zones of the DTS and water / foam concentrate system to supply low level foam discharge nozzles at a pressure level to ensure adequate aeration of the foam concentrate / water mix.

Manual activation of Foam Deluge Zones is provided via the SCADA Emergency Touch Screen and via each SCADA Workstation given appropriate User Access rights. The Foam deluge system incorporates a standard 60 second delay, in order to protect against false alarms and also to ensure that the operator has time to acknowledge the alarm event. Alarm verification is achieved by automatically switching to CCTV and viewing the corresponding zone.

The SCADA system is interfaced to the DTS System by a dedicated Modbus communications link. This communications link provides the SCADA system with analog temperature feedback for each of the 32 zones in the platform and tunnel areas.

The SCADA system has a dedicated DTS and Foam Control Screen to display the current temperature in each of the zones and foam deluge system status. This screen presents temperature feedback in a numeric format, but also show a colour representation of the temperature (eg gradation from yellow (cool) to red (hot)). This provides the operator with some visual feedback as to the temperature map for the DTS monitored areas.
7. CONCLUSIONS

DTS System solutions are developing further in terms of measurement capability and detection algorithms employed. System architectures are also more flexible than before, with respect to the integrity of the sensor cable connection and well as the networking options available.

DTS Systems are LPCB approved as class A1R heat detection devices in accordance with EN54 parts 2 and part 5.

There are many standards in existence which provide guidance on how automatic fire detection systems should behave with respect to alarm response times and also with respect to false alarms. These standards continue to be referred to within fire system design, in buildings and in tunnels. There are relatively few standards available which are particularly well suited to the special hazard environment of tunnels. Steps are currently being taken to address this particular application area.

DTS systems are proven to be reliable components in fire detection systems. They offer critical time, temperature and position data to facilitate more effective alarm decisions. DTS Systems are implemented in an ever increasing range of Special Hazard applications.

References:

i Report fire tests Project ‘Safety Proef’, Steunpunt Tunnelveiligheid, Bouwdienst Rijkswaterstaat The Netherlands, August 2002

ii Tests on Fire Detection Systems and Sprinkler in a Tunnel, Ir. J.W. Huijben, Bouwdienst Rijkswaterstaat Centre for Tunnelsafety

iii “Optical Fibre Intelligent Linear Heat Detection for Road and Rail Tunnels”, Roger Hampson ITC2001 Proceedings, Madrid

iv BS 5839 Part 1:2002 Code of Practice for installation of fire Detection Systems in Buildings, British Standards Institute, UK

v ‘European Standards and Certification Procedure’, AUBE 2001, 12th Conference on Automatic Fire Detection, March 25-28th NIST, Gaithersburg, Maryland USA

Acknowledgements:

VdS Schadenverhütung GmbH, Cologne, Germany, Contact - Martin Hessels (for information regarding Table 1

Downer RML, Australia Head Office, Level 7, Compaq House, 76 Berry Street, Sydney NSW 2060 Australia, Contact Rod Harle (for information regarding the Britomart Case Study).