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Fire hazards in tunnels and underground installations

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Abstract: Fire accidents in tunnels and underground installations have resulted in significant loss in terms of life and costs. Several large research projects are launched in Europe to find cost effective ways to upgrade and make such installation more robust against accidents from fires and explosions. For one single tunnel, severe fire accidents are rare and operators and users will have very limit experience, when they do occur. There is a trend to solve the problem with high tech instrumentation and monitoring techniques and to rely on the fire brigade to play a major role in the rescue operation. These precautionary measures are very difficult to validate for the severe fires. For protection against the most critical fires, the safety has to be considered in the design of the tunnel and the technical installation validated so that it operates as indented.

1. Introduction

For road traffic it is well known that human behaviour is the major cause for accidents. For instance speeding, driving under the influence of alcohol and not using a seat belt, cause tens of thousands deaths on the road every year in the European Union. The consequences of these accidents in tunnels are more or less given by technical layout and safety system to assist in secure evacuation. On the other hand, for metro systems, accidents are very rarely caused by the end-user. Quality of technical installation and human operation is far more important. However, safe rescue and evacuation are mainly driven by human behaviour both by users and operators. In case of a severe fire, the operators may have no experience of such an unlikely situation (probably once in their life experience) and will be faced with several difficulties.

Several major, high profile and costly tunnel fires have taken place in Europe in the past years. They have resulted in significant loss of life (about 500 persons) and damage to the structures. The Channel Tunnel, Mont-Blanc, Tauern, Kaprun and Gotthard are examples of tunnels where accidents occurred due to fire, thus clearly indicating the inadequacy of current design procedures. This is the main technical limitation of existing tunnels, from technological, methodological and from standards points of view. The costs incurred by the Channel Tunnel fire (in terms of repair costs and loss of business from lengthy closure of the tunnel) amounts to about 82 million Euros /European Commission 2003/

In Daegu Underground Metro South Korea, a vulnerable accident occurred where two 6-carriages trains were put on fire by act of terrorism causing 198 deaths. Even more severe was the fire in Baku Metro in Azerbaijan where the fire caused 289 deaths and 265 injured. The accident was caused by an electrical failure in one of the vehicles. Other severe disasters to remember are e.g. Kitzteinhorn (Kaprun, Austira) cable-rail (155 deaths), Gueizhou reil tunnel in China with over 80 people killed, King's Cross Station in London Metro (UK) where 31 were killed and about were 100 injured, Salang road tunnel in Afghanistan where military vehicles (petrol tankers) caught fire resulting in over 400 deaths /FIT 2003/. Additional to these accidents, there are a large number fires and explosions in mines which have caused a significant number of deaths, worldwide.

2. Research on tunnel fires in Europe

After a large number of tragic fires, several tunnel safety projects were launched:

- UPTUN; Ongoing project with the aim to develop innovative technologies to upgrade safety of exciting tunnels. Focus is on technologies in the areas of detection and monitoring, mitigating measures, influencing human response, and protection against structural damage.

- DARTS; The project started during year 2001. The aim is to develop a set of practical methods and operational tools for choosing the optimal tunnel type based on structural issues.
- The thematic network 'FIT – fire in tunnels', aims to establish and develop European networking and to optimise research efforts in the field of fire safety in tunnels. FIT seeks to improve synergy and to stimulate co-ordination between ongoing EC and nationally funded RTD projects in Europe.
- ADAC carried out investigations in 65 European road tunnels to classify the safety levels, which concluded that about 25 % of the tunnels under the review had severe lack of safety.
- PIARC/OECD: review of knowledge on fire and smoke control aspects in tunnels, indicating the need for more specific investigation into issues such as scenario development and suppression systems.

Furthermore, significant results are achieved from research project and incidents in the past, like:

- SAFESTAR; addressing road safety in general, including effects of tunnel lay-out and design on driving behaviour and comfort
- FIRESTARR; addressing the fire spread (reaction to fire) in rolling stock.
- FIRETUN, project carried out under the EUREKA programme; aiming to improve the protection of people and infrastructures against fires in underground transport facilities by carrying out large-scale experiments, mainly addressing small and medium-scale fires to define fire growth.
- MEMORIAL TUNNEL; addressing issues as longitudinal and transverse ventilation in road tunnels, covering pool fires in the range of 5-100MW
- OSIS; mainly addressing venting conditions within underground metro and railway tunnels. The project aims to develop numerical simulation tools, based on experimental studies using hot smoke generators (0.5-1.0MW).
- The conclusion from severe tunnel fires in Storebælt, Channel Tunnel, Mont-Blanc, Tauern, Kaprun and Gotthard.

The focus of these has been on life safety issues, emphasising the conditions developing in a tunnel under fire and by ventilation control. Limited work is available on design scenarios for fire, mitigation measures or human response factors. Major knowledge gaps exist in evaluating these matters, how to implement them and how to upgrade the safety of existing tunnels. Fire safety tools in general are developed for buildings and industrial plants, which are not always cost efficient when applied in tunnels. Upgrading of tunnel safety may need expensive installation or even construction work, therefore it is necessary to develop cost effective innovative means for existing tunnels, as the aim of the UPTUN project /UPTUN 2003/

3. Safety measures in tunnels

Higher safety can either be achieved by reducing the probability for accidents and/or reducing the consequences. The probability can be made less by simple and robust user-friendly technology and by improving human skills. A reduction of the consequences (potential hazard) can be achieved by either reducing the flammability of vehicles and goods and/or by mitigating the consequences when a fire does occur.

Ventilation systems are the most used mitigation measures in tunnels. It has a good track record in controlling small fires, but for larger fires, they have for various reasons been less successful /Duffé 1999/. They may even make large fires more severe and have small mitigating effects on explosion /Ingason 1999/ and /EUREKA 1995/. The use of active suppression systems raises several questions and the main concern is the break up of stratified smoke layers. Also more cost efficient solutions are required compared to traditional suppression systems – suppression system interacting with the ventilation system.

Mathematical models play a key role in several countries. When relying correlations on mostly laboratory-scale testing of existing or innovative solutions, models have to extrapolate the measured performance into real scale performance. Current models lack key features needed to fulfil the above roles, specifically when attempting to describe complex interactions such as smoke flow and sprinkler action. Simple but reliable consequence models are needed in any risk analysis model to assess the hazard of a particular branch of the decision tree /PIARC 1999/ and /Arvidson 1999/. Even advanced CFD codes may lack possibilities to achieve realistic results when complex fire issues in tunnels are simulated.

Recent developments in dynamic compartmentation (air or water screens, sometimes combined with flexible screens) have yet to be verified in a rigorous way. In order to achieve innovative solutions, they have to be engineered and verified in full-scale tests. The efficiency of mitigation systems is depending on scale and scenario, which means that several tests should be conducted to reflect possible fire scenarios.

4. Heat exposure, fire scenario

Currently, fire scenarios or design fires vary from about 5MW, 20MW or even up to 100MW. These are mainly based on experimental work done within the EUREKA fire tests. The main conclusions are that the maximum temperatures in these experiments reached between about 800 °C and 1000 °C. The rail cars showed maximum energy release rates between about 15 MW and 35 MW and the heavy good vehicle (HGV) was measured to more than 100 MW. The subway and road car fires used 10 to 15 minutes to develop /EUREKA 1995/.

Designed fires at more than 100 MW are rarely seen. Even, when theoretically fires may become much more sever. If the amount of air passing the fire scene is considered, depending on the tunnel cross-section and the ventilation rate, the theoretical heat release rate is shown in Figure 1. Normal air contains 21% oxygen and with 100% consumption of this air, it is represented by curve labelled "Max", see Figure 1. The amount of oxygen consumed is depending on the temperature at the fire scene. If the average temperature in the cross section is above 600-800°C, all oxygen can be consumed.

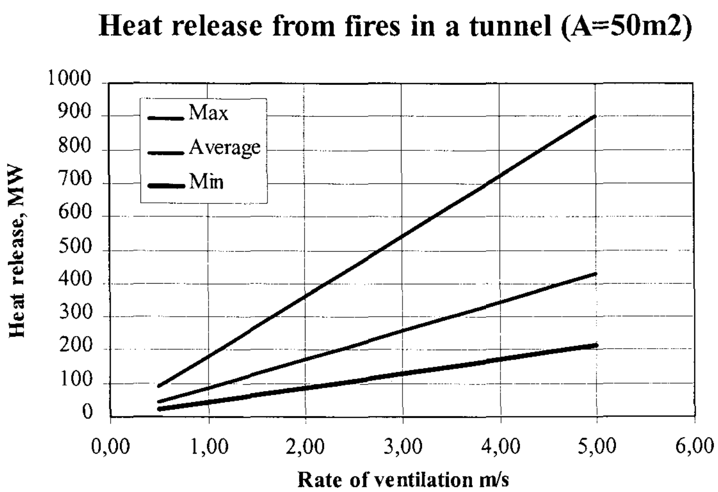

Figure 1. Theoretical possible heat release in tunnels, based on oxygen consumption. "Max" represents all oxygen consumed, "Average" represents 50% and "Min" represents only 25% of available oxygen consumed (5.25% volume concentration of oxygen consumed).

Figure 2, shows a photo of a 200MW experimental tunnel fire, where a mixture of wood and plastic pallets is burned. Total amount is about 9000kg, with a ratio of 5 times as many wood pallets than plastic pallets are used. The results gave an oxygen concentration of about 7% at high temperatures. This means that even the 200MW fire in this test is fuel controlled. It is the amount of fuel available to burn at the same time, which predicts the heat release rate. Whit more fuel (e.g. flame spread to other vehicles) this fire could have been 300MW based on a ventilation rate of approximately 2m/s. A release of significant amount of fuel, either as an accident or by action of terror, may lead to significantly more sever fire than seen or reported today.

A 200MW fire gives severe conditions in the tunnel and temperatures may rise above 1300°C. Tests show that the RWS–curve (RWS, "RijksWaterStaat", is a Directorate-General of the Dutch Ministry of Transport, Public Works and Water management) is relevant to be used for protection of tunnel lining, see Figure 3.

For severe fires, where the average cross section temperature increases form about 20°C to more than 900°C, the fire creates a thermal expansion of the air by a factor of 4. Such expansion creates a pressure, which has to be realised by pushing air from the fire scene, in both directions. Such expansion was observed in the Runehamar tests, creating a pulsating fire, partly pushing exhaust gases upstream against the inlet ventilation. How this will act with longer tunnels and fire scene at various locations in the tunnel is not yet shown, but it is a phenomenon to be studied in the future /Runehamar 2003/.

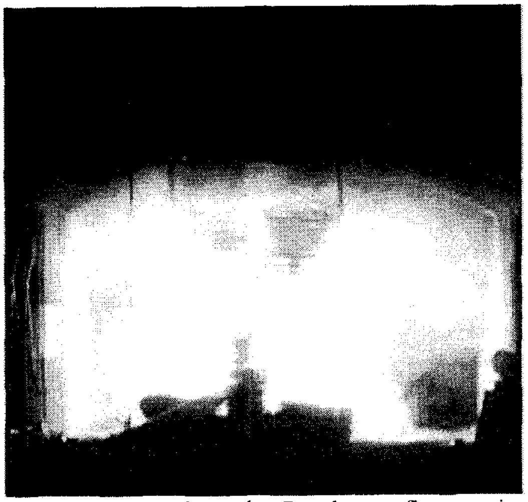

Figure 2. Photo from the Runehamar fire test in Norway in 2003. A 200MW fire is released in a 1.6km long tunnel /Runehamar 2003/.

It is well known that visibility is the first critical parameter for human safety in case of fires. Even for a single car burning in a tunnel, the visibility my by reduced down to critical level for evacuation even though the toxicity is minor /Opstad 1997/. For large severe fires with heat release rate more than 100MW, it will provide very toxic conditions upstream and probably no smoke stratification. For the fire in the Runehamar test, there are only a few minutes available for escape in the downstream direction.

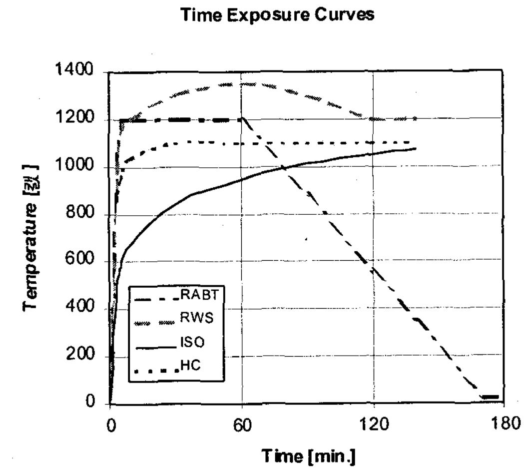

Figure 3. Some Time temperature curves used for evaluation of fire resistance. The RABT curve (developed in Germany), RWS curve, (Dutch Ministry of Transport), ISO curve (International organization for standardization) and HC curve (Hydrocarbon-Fires) developed by SINTEF.

5. Structures can be improved

Structural fire protections are for some tunnels important due to risk of structural collapse. In terms of heat exposure, the RWS-curve from the Netherlands gives heat exposure at the highest level ever measured in tunnels and it covers the exposure seen in the Runehamar tests.

One of the main structural problems in tunnels exposed to fire is the serious damage caused by explosive spalling of the concrete (e.g. Channel Tunnel, Great Belt Tunnel, Mont Blanc Tunnel). While recent developments have made progress in this area, the subject is not fully understood and solutions not optimised. However, resent research has shown that small amount of synthetic fibres added to the concrete may give significant improvement /Both 1999/ and /Both 2001/. The recipe for Polypropylene Fibres (PP-fibres) is available on the marked and the solution is well proven. Tests recently conducted by Rail Link Engineering came to the following conclusion; "The addition of polypropylene fibres gave the most significant indication of improved fire resistance throughout the test program, with particularly monofilament fibre mixes showing no indication of spalling." http://www.adfil.co.uk/cemtech.htm.

6. Mitigation and suppression

For tunnels, fire ventilation is the main mitigation measure to either extract the exhaust fire gases or to dilute and direct the smoke by longitudinal ventilation. Ventilation reduces stratification of the smoke layer. For transverse ventilation, the capacity has a limited extraction capably, normally designed for fires in the range of 20 to 100MW.

If a fire exceeds the design criteria, the tunnel will be filled with smoke and creates significant problem for users. Well knowing that such limits exits, it is still common to rely on the fire- and emergency services to bring those fires under control. Work that has been carried out as part of the National Board of Civil Defence, Rescue and Fire Services' 'Rescue Work in Tunnel Fires' project has shown that the rescue services must be well prepared. It has also shown that the rescue services alone cannot play a decisive active role in the evacuation of passengers from a fire in a rail tunnel /Ingason et.al. 2001/ and /Berqvist 1999/. For the Runehamar test, the fire service has to be operative at the fire scene within the first 5 minutes after ignition. Which could only be possible if they were waiting outside the tunnel, ready to go in and interfere with the flames.

Currently, probably the only way to control the most severe fire early enough to secure safe evacuation is by means of active fire suppression systems. Most active fire suppression systems on the marked to day are developed for other purposes than tunnels, which means they may not be as efficient as needed. Sprinkler for dwellings are designed to moisten the fuel surface, which may be difficult for fires in enclosed vehicles. Other type of suppression systems as water mist, having great success in the maritime sector (www.iwma.de) is not yet ready for tunnels. Tunnels are well-ventilated compartments where it is difficult to inert the air, which is the main principle of operation of water mist systems. Cost efficient suppression systems for tunnels are still under development and new products are expected in the near future (www.uptun.net).

7. Summary and Conclusions

Tunnel construction activities are accelerating worldwide. Tunnelling can be said to be a major challenge of the future transport systems. Increase of traffic and the trend for longer tunnels consequently result in higher risks. Safety, and in particular safety in case of fires in tunnels, has received tremendous attention. However, we still see a lack of fundamental understanding on how fire behaves and develops in an underground construction. There is a trend to solve the problem with high tech instrumentation and monitoring techniques. If those systems are not carefully designed and integrated to provide clear and easy to understand information for operators, they may well confuse under a critical accident. Normally careful training can avoid such situation. Large critical fires occurs rarely and it may not be possible to sufficiently challenge the technical installation in advance and be prepared on how it response to the fire. If a severe fire occurs in a tunnel, it will probably be the first time experience for the operator and for the technical installation. Currently, it will be very uncertain how this will work after several years in service. Therefore safety installations in tunnels and underground installations should be simple and robust and well proven before they are installed.

Accident management is very important and it has to be learned prior to an emergency operation. Training on accident management is frequently carried out by rescue services, based on well-known accidental scenarios. Many countries practise such training for tunnel fire as well, but I am afraid that most of those are on small none critical fires.

Severe tunnel fires are rare, and it is therefore very important that we collect experience worldwide when recommendations on design fires for tunnels, regulations, guidelines, code of practices and safety requirements are given. Too many still trust the fire brigade to play a major role in the rescue operation. The help from the fire services is important, but designer should be aware of their capabilities in case of a tunnel fire. For the most critical fires, the safety has to be considered in the design of the tunnel and the technical installation validated so that it operates as indented.

References

Arvidson 1999 — Arvidson, M., Fixed Fire Suppression System Concepts for Highway Tunnels, Tunnel Fires and Escape from Tunnels, International Conference 5-7 May 1999, Lyon, France, pp. 129-136

Bergqvist 2001 — Bergqvist, A., et.al., Räddningsinsatser vid tunnelbränder, FoU Report P21-391/01 - The Swedish Fire and Rescue Agency

Both 2001 — Both, C. "Tunnel Fire Safety", Edinborough, Interflam 2001

Both 1999 — Both, C. et al, "Fibrous concrete, safe and cost-effective tunnels", Brisk Rotterdam 1999

Duffé 1999 — Duffé, P., and Marec, M., Report on the Technical Enquiry into the Fire on 24 March 1999 in the Mont Blanc Tunnel, 30 June 1999

EUREKA 1995 — Proceedings of the international conference Fire Protection in Traffic Tunnels, Dresdnen, Germany 1995

European Commission 2003: http://europa.eu.int/comm/transport/road/roadsafety/index_en.htm

FIT 2003 — http://www.etnfit.net/

Ingason 2001 — Ingason, H., et.al., Planning for manual fire fighting and rescue tunnels, Proceedings 4th International conference on Safety in Road and Rail tunnels, Madrid 2-6 April 2001, p. 595-604

Ingason 1999 — Ingason, H., An Overview of vehicle fires in Tunnels, Int. Conf. on Tunnel Fires and Escape from Tunnels, Madrid, 2001 pp.425-434.

Opstad 1997 — Opstad, K., Fire Emergency Ventilation Capacity for Road Tunnels with Considerable Slope. 9th International Symposium on Aerodynamics and Ventilation of Vehicle Tunnels, Italy 1997.

PIARC 1999 — Fire and Smoke control in road tunnels, PIARC report 05.05.B, 1999

Runehamar 2003 — Presented on WEB sites, nbl.sintef.no (http://nbl.sintef.no/news/tunnelbrann_en.htm), www.sp.se and www.tno.nl. The results from Runehamar tests to be presented at International Symposium on Catastrophic Tunnel Fires (CTF), Borås, Sweeden 20-21 November 2003

UPTUN 2003 — http://www.uptun.net