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GUIDELINES FOR STRUCTURAL FIRE RESISTANCE FOR ROAD TUNNELS

DIRECTIVES POUR LA RESISTANCE AU FEU DES STRUCTURES DE TUNNELS ROUTIERS

BY

Working Group No.6 Maintenance and Repair

Groupe de Travail N° 6 Entretien et Repaire

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GUIDELINES FOR STRUCTURAL FIRE RESISTANC FOR ROAD TUNNELS

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1. Introduction

1.0 General

Fire resistance of tunnel structures is an important issue. If it is not properly addressed, fire in a tunnel can result in loss of life to both tunnel users and the fire and rescue services. The resulting economic losses for both the tunnel owner/operator and to the local economy and environment can be catastrophic.

This document is the result of a co-operative effort between the World Road Association (PIARC) Technical Committee on Road tunnel Operation (C 3.3) and its Working Group 6 *Fire and Smoke Control*, and the International Tunnelling Association (ITA) Working Group 6 *Repair and Maintenance of Underground Structures*. The purpose of this co-operative effort is to develop guidelines for resistance to fire for road tunnel structures. However, many of the issues addressed in these guidelines are relevant to rail tunnels and these will be referenced as part of this document at a later date. (Part B).

An agreement for a co-operative effort has been established between both parties to develop a common approach to fire resistance for structures. PIARC and ITA deem that such a guideline is necessary for the protection of the public. In this co-operation, the role of PIARC has been to define the objectives of resistance to fire of road tunnel structures, i.e. to develop appropriate design fires (mainly as time - temperature curves) and specify the required resistance times. Recent developments emerging from full scale fire tests carried out as part of the EC Funded Research Project “UPTUN” have shown that fires in tunnels can be much more severe than previously assumed (even with non-hazardous goods). For this reason, this document makes reference to the time - temperature curves developed in these tests. It also references the relative heat release curves (RHR) developed from these full-scale fire tests as separate graphs. The role of ITA is to develop guidelines for techniques and materials to answer these structural requirements and make tunnels and their ancillary structures more resistant to fire damage.

1.1 Scope

The scope of this document is to provide recommendations for the design of underground structures which function as tunnels and ancillary structures for the safe operation of road tunnels. These guidelines take into consideration the time - temperature curves as recommended by PIARC and develop suitable means and methods for the protection of the structures from collapse both during the fire event and during rescue operations. These guidelines also reference the actual time - temperature and Heat Release Rate curves generated from the full-scale fire tests carried out in the Runehamar tunnel in Norway in September 2003.

This document is intended to be a guideline and is to be used for road tunnels only and not for rail, mass transit, or pedestrian tunnels. However the basic principles for the protection of tunnels and underground structures may be applied to other types of structures; in such cases special consideration must be given to the particular application and its own unique operational and other site-specific elements.

This guideline is for informational purposes only and applicable codes, standards and local regulations must be consulted for compliance to specific structural and life safety requirements of the locale in which the structure is located.

1.2 Reason for Developing Guidelines

Over the last 10 years there have been a number of serious underground fires in road tunnels. These fires have caused extensive loss of life and severe collateral loss to the infrastructure. Aside from the tragic loss of life, the long-term financial effects to the local infrastructure, the loss of public confidence in the safe use of tunnels have necessitated the development of these guidelines. This guideline is document is intended for use to identify the categorisation of road tunnels and propose methods for the protection of the structural elements to allow users to safely evacuate, to allow rescue personnel to enter the scene and effectively perform their required duties and to limit damage to the tunnel. Improved specifications for tunnel fire resistance are required in order to mitigate the consequences of a serious fire, which could result in structural failure or complete collapse.

Assessment methods are constantly being developed to demonstrate the ability of materials and insulation coatings to prevent concrete spalling and steel and metal elements from heating and melting due to rapid heating under fire exposure conditions and to mitigate both structural and economic consequences of fire.

1.3 Document Authors

This document has been developed by the members of ITA working Group 6 with the assistance of individuals from PIARC Technical Committee on Road Tunnel Operation (C 3.3) and its Working Group 6, in particular Mr. Arthur Bendelious (Animateur 1999 – Present) of the USA, and Mr. Didier LaCroix (Animateur 1991 – 1999) of France. Prof. Alfred Haack of Germany has been the liaison between PIARC and this Working Group.

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The primary contributors wish to express their appreciation to the many members of the Working Group, who have provided stimulating debate and comments on this document.

2. Design Criteria for Fire Resistance

2.0 Introduction

The design of tunnels to be resistant to damage as a result of vehicle fire is a topic that has become an important design parameter for the construction of new tunnels and the rehabilitation of existing underground facilities. The objectives of tunnel structural fire resistance are to allow for users to evacuate safely in the event of a tunnel fire, rescue operations to be performed under safe conditions, and tunnel to suffer minimal loss of property.

The primary focus of this document is to provide for the safety of the public and rescue personnel in the event of a fire within the tunnel system. For these purposes, the tunnel system must be protected from collapse during a specified time period. The potential for collapse is particularly important for submerged tunnels (Immersed Tube Tunnels), and tunnels in urban environment that are located under other buildings or structures. The second focus of this document is to ensure appropriate protection of property, which also involves indirect costs associated with the disruption to business, the local economy and the restoration of the facility to normal operation.

The World Road Association, (PIARC) has issued two reports related to tunnel fires. Both were prepared by PIARC Working Group 6 *Fire and Smoke Control* and edited by the PIARC *Technical Committee on Road Tunnels* (now *Technical Committee on Road Tunnel Operation – C3.3*):

– The report *Fire and Smoke Control in Road Tunnels* [2.1] was published in 1999. This document is the results of the review of numerous fire scenarios and actual case histories. The report has identified typical scenarios for heat generation caused by a fire event.

– The new report *Systems and Equipment for Fire and Smoke Control in Road Tunnels* [2.3] was published in 2004. It includes a final recommendation on the question of design criteria for resistance to fire for road tunnel structures.

2.1 Data on Tunnel Fires from the PIARC Report of 1999

In Section II.4.1 of the PIARC report of 1999 [2.1] indicates the heat release from vehicle fires is dependent on many variable factors such as:

– Number of vehicles involved
– Type of vehicles (passenger cars, coaches, heavy goods vehicles, petrol tankers)
– Cross section of the tunnel
– The type and quantity of flammable material available
– Rate and method of extinguishing the fire

The temperature is highest on exposed surfaces and particularly at the higher elevations of the tunnel structure. This is illustrated in Figure 2.1

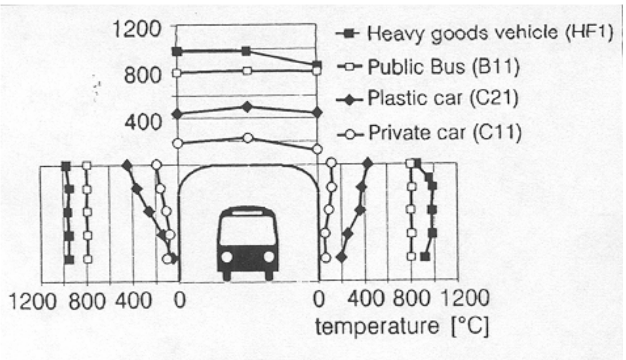


Figure 2.1 PIARC Maximum Temperatures within Tunnel Cross Section [2.1]

PIARC has also established from tests the limits of the areas affected by a typical tunnel fire. These limits were based on a single fire event occurring in a tunnel. This information is useful structurally in the determination of areas to be inspected for damage. However, since the location of a fire within a tunnel is random and may occur at any location, the entire tunnel must be designed to resist fire. Figure 2.4 documents the maximum ceiling temperature in relation to the fire location for various scenarios as found in the Eureka tests.

Figure 2.1 indicates the temperature distribution within the test tunnel. There seems to be little difference between the temperature distributions at the ceiling and near the road surface, when the cause of the fire is Heavy Goods Vehicles (HGV) and public buses. In the cases of plastic cars and private cars, the temperature is relatively low at the road surface when compared with that at the ceiling.

The reason for this is that HGV and buses have a relatively large cross-sectional area, or in other words the ratio between projected area of the vehicle and tunnel cross-section (blockage ratio), which is relatively high. The blockage ratios between vehicle and cross sectional area of actual road tunnels are relatively lower than those for the fire tests. This means that the measured values in Figure 2.1 include some allowance of safety for the correspondence to tunnel safety planning. Even if the conditions pertaining to fire source in the tunnel are similar, temperature distribution is influenced by the tunnel configuration.

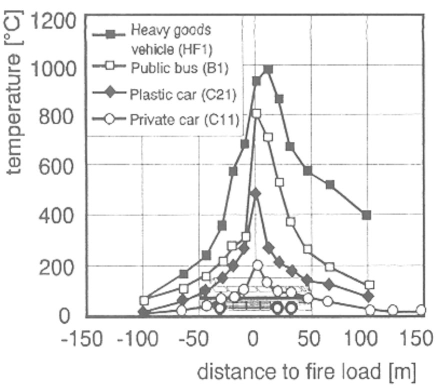


Figure 2.2 PIARC Maximum temperatures in the ceiling area of the tunnel [2.1]

In addition to the maximum temperature and limits of various fire scenarios, the report also present temperature vs. time duration plots for the various types of fires encountered in the Eureka Tests as shown in Figure 2.3 and the full scale fire tests carried out in the Runehamar Tunnel in Norway in September 2003 in figure 2.4.

Temperatures recorded in actual tunnel fires such as the Channel Tunnel, Mont Blanc and St. Gotthard should also be considered.

Taking all current test data into account, this document considers

On the whole, the 1999 PIARC report considered that the following maximum temperatures at the tunnel wall or ceiling could be developed [2.1] for the following vehicles types:

• Passenger car	400° C*
• Bus/small lorry	700° C*
• Heavy Lorry (HGV) with combustible goods (not petrol or specially flammable materials)	1,350ºC
• Petrol Tanker (general case)	1,350ºC
• Petrol Tanker (extreme case) (for instance to avoid flooding of an immersed tunnel with bad drainage)	1,400° C

** Higher if flames touch the wall*

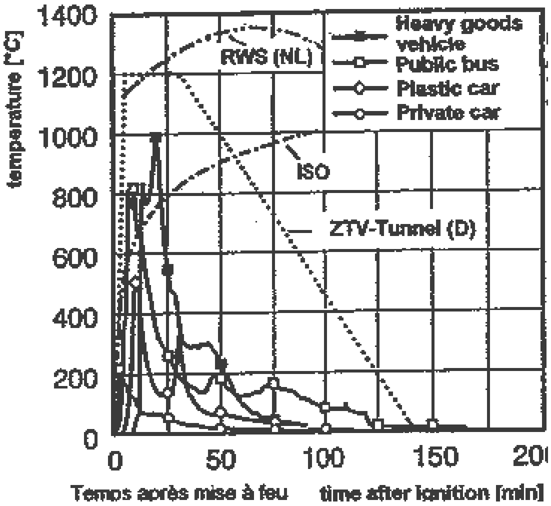


Figure 2.3 Time Dependence Temperature Data from Eureka Test Program [2.1]

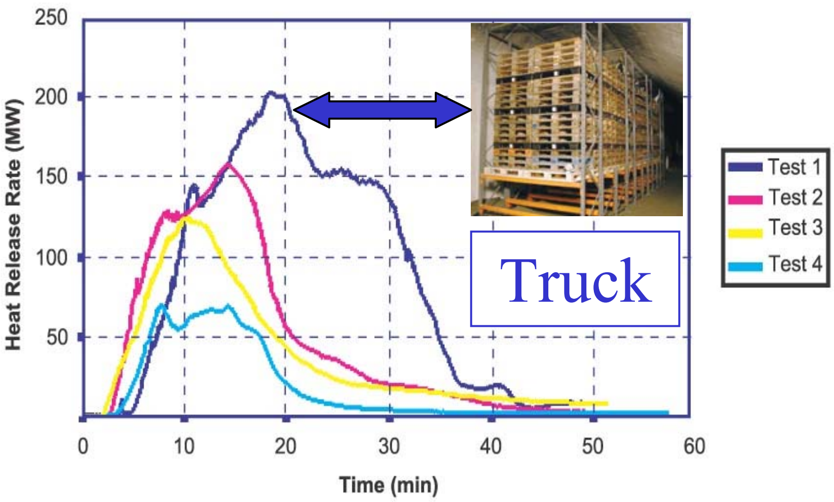


Figure 2.4 Heat Release Rate Curves from the Runehamartunnel Tests

2.2 Design Criteria Established by PIARC

After the publication of its 19999 report, the PIARC *Working Group 6 Fire and Smoke Control* continued its work on resistance to fire of road tunnel structures. This paragraph presents its final recommendation on the question of design criteria for resistance to fire for road tunnel structures, which has been included in the 2004 PIARC report *System and Equipment for Fire and Smoke Control in Road Tunnels* [2.3]

Although fire safety engineering is more and more used in other fields as a performance-based approach to fire resistance, it had been agreed between PIARC and ITA that such an approach was currently not mature enough with regard to tunnels. Consequently the joint PIARC-ITA effort has aimed at a deterministic temperature-time curve design (more classical, prescriptive approach), at least as a first step.

A first draft proposal was put forward to ITA in February 2001 as an initial definition of the resistance objectives. The revised recommendation below takes into account the comments and contributions to the discussion from ITA.

The first draft proposal of February 2001 was also presented to the International Standardisation Organisation (ISO) and the European Committee for Standardisation (CEN). Their comments have been taken into account in this revised recommendation, especially as regards to future steps. Comments from the members of the PIARC Technical Committee on Road Tunnel Operation were also integrated.

2.2.1 PIARC Recommendation

A preliminary and basic criterion to be met by any tunnel structure is that there should not be any risk of progressive collapse: the local failure of any element should not lead to an increased load on other parts of the structure which may cause their failure.

- **Terms of Reference for the Time-Temperature Curves**

There are several time-temperature curves proposed to the date. Figure 2.4 sketches the ISO 834, RWS, RABT (former ZTV) and a modified Hydrocarbon (HC) curve, HC_{inc}, in which the temperature are multiplied by a factor of 1300/1100 from the basic HC curve of Eurocode 1 Part 2-2.

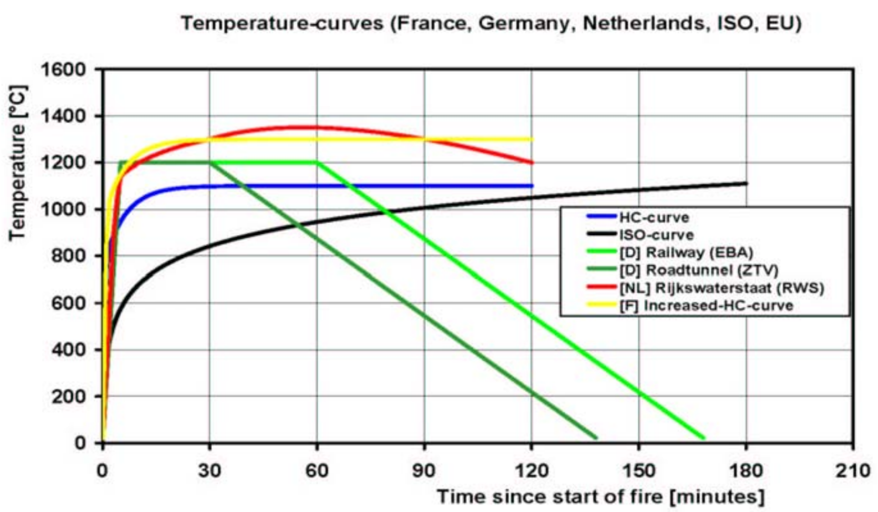


Figure 2.4 PIARC Recommended Temperature versus Time Curves for ZTV, RWS, HC_{inc}, and ISO Standards[2.2]

Recommendations for design of the structure should consider the time-temperature curve with regard to the possible events within the tunnel. Hence the early stages of the fire development, following the first part of the curve, will require a consideration of escape and the time conceived for evacuation. There should be no collapse during this period that can affect the zones where there may be users or rescuers.

Spalling of the structure can occur in the early stages of a fire but no incidents have been reported where it has had major consequences for firemen, although it may indicate a rapid deterioration of the structure. The main concern at the time of fire service intervention would be the collapse of items, such as jet fans, signs or lights from the tunnel ceiling or walls. This question of fire resistance has been addressed in the PIARC 19999 report [2.1], which states:

"In all cases, the minimum requirement is that heavy equipment should not fall down when evacuating users or rescue personnel are in the tunnel. This means no heavy item must fall under exposure to temperatures of 400-450°C during the time necessary to fight fire (in a tunnel, such temperatures can produce a radiation level of about 5 kW/m^2, which is the maximum tolerable value for firemen)."

Shelters should only be provided in a tunnel if there is an escape way for rescuers to reach the users waiting in the shelter and assist them to the outside. If such shelters are available, then a resistance of about two hours would be needed for protection prior to rescue.

The overall duration defined by the curve will need to be considered. For instance, in France current thinking is 2 hours for the fire brigade intervention; after 2 hours it would be considered to be unsafe. If the tunnel is under a building and in other cases where protection of property is an important issue, then a longer time may be considered.

– **Proposed Guidelines**

The proposed guidelines for design criteria are presented in Table 2.1. This table makes a distinction according to the type of traffic (consequently the possible fire load) and the consequences of a structural failure due to a fire (when the consequences are unacceptable, a protection against a very severe fire is required – e.g. submerged tunnel or in unstable ground; when the consequences are limited, no protection is needed – e.g. tunnel in stable ground.

Traffic Type	Main Structure				Secondary Structures[4]			
	Immersed or under/inside superstructure	Tunnel in unstable ground	Tunnel in stable ground	Cut & Cover	Air Ducts[5]	Emergency exits to open air	Emergency exits to other tube	Shelters[6]
Cars/ Vans	ISO 60 min	ISO 60 min	[2]	[2]	ISO 60 min	ISO 30 min	ISO 60 min	ISO 60 min
Trucks/ Tankers	RWS/ HC_{inc} 120 min[1]	RWS/ HC_{inc} 120 min[1]	[3]	[3]	ISO 120 min	ISO 30 min	RWS/ HC_{inc} 120 min	RWS/ HC_{inc} 120 min[7]

Table 2.1: Recommendations of PIARC

[1] 180 min maybe required for very heavy traffic of trucks carrying combustible goods

[2] Safety is not a criteria and does not require any fire resistance (other than avoiding progressive collapse). Taking into account other objectives may lead to the following requirements:

- ISO 60 min in most cases
- No protection at all if structural protection would be too expensive compared to cost and

inconvenience of repair works after a fire (e.g. light cover for noise protection)

[3] Safety is not a criteria and does not require any fire resistance (other than avoiding progressive collapse). Taking into account other objectives may lead to the following requirements:

- RWS/HC_{inc} 120 min if strong protection is required because of property (e.g. tunnel under a building) or large influence on road network
- ISO 120 min in most cases, when this provides a reasonably cheap protection to limit damage to property
- No protection at all if structural protection would be too expensive compared to cost and inconvenience of repair works after a fire (e.g. light cover for noise protection)

[4] Other secondary structures should be defined on a project basis

[5] In case of transverse ventilation

[6] Shelters should be connected to the open air

[7] A longer time may be used if there is a very heavy traffic of trucks carrying combustible goods and the evacuation from the shelters is not possible within 120 min

Table 2.1 uses the ISO curve and either the RWS or the HC_{inc} curve to define design criteria for different circumstances. PIARC believes that the RWS and HC_{inc} curves correspond to very similar levels of fire resistance, and only one of the two should be used. ISO TC92/SC2 also believes that which one you use has no impact, but considers that the HC_{inc} curve is a more natural, better choice, should one only be kept. Currently PIARC proposes that any of these curves can be used, with very similar results.

2.2.2 Future Steps

- **Introduction of Tunnel Fire Curves into European and International Standards**

PIARC has contacted the European Committee for Standardisation (CEN/TC250 *"Structural Eurocodes"*) and proposed that a temperature-time curve representative of very severe tunnel fires (either RWS or HC_{inc}) be introduced into the relevant European standard. CEN/TC250 answered in March 2001 that there was no fundamental objection to the inclusion of such a new curve. However, the Eurocode dealing with "Actions in case of fire" was in the process of being converted from a pre-standard into a full standard, and it was too late to include any new material. This should be considered at the first revision of the Eurocode. At the same time, the introduction of the supporting calculation rules should be considered for inclusion in the "material" dependent Eurocodes. In the meanwhile, they suggested that PIARC ask CEN/TC127, in charge of fire test methods, if it would be possible to define a tunnel fire curve for fire resistance tests. This could give a more official status to tests carried out using this curve.

PIARC similarly proposed ISO/TC92/SC4 "Fire Safety Engineering" to include the same temperature-time curve representative of very severe tunnel fires into the relevant international standard. In March 2001, ISO/TC92/SC4 answered that they were hesitant to recommend only one temperature-time curve as being representative of fires that could develop in all tunnels. Indeed their mandate was to recommend how design fire scenarios and design fires should be tailored for a fire safety engineering assessment of a specific facility. A similar answer was received in August 2001 from their colleagues of ISO/TC92/SC2 "Fire Containment". This issue is dealt with in the following paragraph.

- **Fire Safety Engineering**

Both ISO/TC92/SC2 and SC4, as well as several members of PIARC Technical Committee on Road Tunnel Operation and ITA WG6, mentioned that every tunnel is unique as concerns the development of a fire scenario and numerous parameters are of importance:

- The type and density of traffic, and consequently the fire load and its distribution (area), as well as the possible fire spread

- The cross-section configuration, the length and inclination of the tunnel
- The ventilation design and ventilation capacity of the tunnel
- The possible use of active measures such as sprinklers or water mist
- The roughness of the tunnel surface and changes in cross-section
- The thermal inertia of the tunnel boundaries, etc.

Due to the very high temperatures, there might be a risk for an over design of tunnels when applying the RWS or HC_{inc} curves independent of the real situation of the tunnel. New safety engineering principles should be explored and developed to establish more appropriate design fires for tunnels in the future. ISO/TC92/SC4 has proposed PIARC to establish a formal liaison to further explore this approach. PIARC is currently considering how to proceed with this proposal.

In addition to all of the above, the EU Funded Research Project “UPTUN” (“cost effective, sustainable and innovative Upgrading methods for fire safety in existing Tunnels”), will continue to provide valuable data and information on full scale fires through its fire test programme (such as the Runehamar tests) and these will be incorporated in future.

UPTUN is a four-year research and development project, which will be completed by 2006. It will pay a pivotal role in linking up with various national and international projects such as FIT, DARTS and SafeT as well as with tunnel associations such as the International Tunnelling Association (ITA), the World Roads Association (PIARC) and the United Nations Economic Commission for Europe.

The Runehamar Large Scale Fire test Report is included in Appendix A. for reference.

2.3 ITA Classification

Based on the information shown here and provided by the PIARC Committee it has been determined that the temperature vs. time curves should be modified to reflect the typical use of road tunnels and a more general classification of tunnel fires. Consideration was given to the types of tunnel structure, cross section, materials and experience of tunnel operators and designers. The modified ITA time/temperature plot also classifies the fires based upon the use and does not consider the fire suppression system or methodology. For ease in design, road tunnel categories are presented in the following Table 2.2:

Classification	Type of Vehicle
Category 1	Cars only (no HGV).
Category 2	Heavy Lorries (HGV)
Category 3	Petrol Tankers
Category 4	Special Cases (ITT)

Table 2.2 — Road Tunnel Categories

Notes:
- Category 1: Passenger vehicles, light vans, and pickups.
- Category 2: Heavy goods vehicles (HGV), including straight and trailer trucks, petrol tankers and other flammable hazardous materials.
- HGV Heavy goods vehicle

The general classification of tunnels as determined by fire heat release and fire time duration is further expanded by the tunnel type and potential risk of collapse.

Cate-gory	**Number Vehicles Involved**	**Immersed Tunnel**	**Tunnel in Unstable Ground**	**Tunnel in Stable Ground**	**Cut & Cover**	**Air Ducts**	**Exit to Open**	**Exit to Other Tube**	**Shelter**
1	1-2	ISO 60 min.	ISO 60 min.	[2]	[2]	ISO 60 min.	ISO 30 min.	ISO 60 min.	ISO 60 min.
1	> 3	ISO 60 min.	ISO 60 min.	[2]	[2]	ISO 60 min.	ISO 30 min.	ISO 60 min.	ISO 60 min.
2	1 -2	RWS/ HC_{inc} 2 hrs.	RWS/ HC_{inc} 2 hrs.	[3]	[3]	ISO 2 hrs.	ISO 30 min.	RWS/ HC_{inc} 2 hrs.	RWS/ HC_{inc} 2 hrs.
2	>3	RWS/ HC_{inc} 3 hrs.	RWS/ HC_{inc} 3 hrs.	[3]	[3]	ISO 2 hrs.	ISO 30 min.	RWS/ HC_{inc} 2 hrs.	RWS/ HC_{inc} 2 hrs.

Table 2.3 Guidelines for Design Criteria for Fire Resistance of Road Tunnel Structures (Modified from Reference 2.2)

[2] Safety is not a criteria and does not require any fire resistance (other than avoiding progressive collapse). Taking into account other objectives may lead to the following requirements:

- ISO 60 min in most cases
- No protection at all if structural protection would be too expensive compared to cost and inconvenience of repair (e.g. light cover for noise protection)

[3] Safety is not a criteria and does not require any fire resistance (other than avoiding progressive collapse). Taking into account other objectives may lead to the following requirements:

- RWS//HC_{inc} 120 min if strong protection is required because of property (e.g. tunnel under a building) or large influence on road network
- ISO 120 min in most cases, when this provides a reasonably cheap protection to limit damage to property
- No protection at all if structural protection would be too expensive compared to cost

and inconvenience of repair works after a fire (e.g. light cover for noise protection)

Table 2.3 uses the ISO and RWS/HC_{inc} curve and either the RWS or the HC_{inc} curve to define design criteria for different circumstances. PIARC and ITA believe that the RWS/HC_{inc} curves correspond to very similar levels of fire resistance, and only one of the two should be used.

2.4 References

[2.1] World Road Association (PIARC), *Fire and Smoke control in Road Tunnels*, Paris, 1999.

[2.2] World Road Association (PIARC), *PIARC Proposal on the Design Criteria for Resistance to Fire for Road Tunnel Structures*, Paris, Revision 1 – February 2002

[2.3] World Road Association (PIARC), *Systems and Equipment for Fire and Smoke Control in Road Tunnels*, Paris 2004

3. Lining Material Behaviour

3.0 Concrete

In the following is briefly described the behaviour of the lining material during heating from a fire. The behaviour associated with the heating itself and the associated loss of strength and stiffness is discussed separately. The context of the structural behaviour is dealt with in section 5.
In the normal load cases the thermal properties of concrete are of limited importance to the design. However in case of a fire the thermal properties are important for the transfer of heat into the structures, the increase in temperature, which subsequently influences the mechanical properties and the load-bearing capacity.

Heating

The heat inside the tunnel will be transferred to the lining with a rate depending on the tunnel material. This process which is in general well described involves heat transfer in terms of convection as well as emission.
The transmission coefficient of the emission (radiation) is described by an equation as indicated below. The transmission coefficient determined can be added to the coefficient concerning convection. The radiation heat transfer is dependent on the surface of the segments and e.g. the smoke conditions in the tunnel.

$$\alpha_r \cdot (T_g - T_w) = \varepsilon_w \cdot \varepsilon_g \cdot C_s \cdot (T_g^4 - T_w^4),$$

where
ε_w is the emission factor for wall
ε_g is the emission factor for gas
C_s is an emission constant
T_g is the gas temperature (K)
T_w is the wall temperature (K)

For the determination of the heating due to emission the shadow effect is relevant. A view factor is introduced depending on the location of the heated object relative to the direction of the radiation. If objects shadow for the radiation the heating will be reduced. For a smooth concrete lining the influence is limited but for evaluation of the heating of gaskets placed deep in a gap between the segments the view factor may influence the temperature.

The heat flow through the outer surface, q_w, serves as boundary condition for the determination of the temperatures in the structure.

$$q_w = (\alpha_r + \alpha_c) \cdot (T_g - T_w),$$

where α_c is the heat transmission coefficient for convection.

Convection describes the heat transport in gases. The coefficient of heat transfer is described by a formula depending on the air flow [54, Mandry]. A range of observed values is reported. However, the determination of temperature is not very sensitive to the coefficient.

The convection coefficient for the fire exposed surface of the concrete is normally taken as 50 W/mK.

The conductivity is classically described by the differential equation. In this case the situation is not stationary and a transient model will have to be used. Also various numerical methods can be used.

$$c \cdot \rho \cdot \partial T/\partial t = \lambda \cdot (\partial^2 T/\partial x + \partial^2 T/\partial y),$$

where,

c is the specific heat capacity (J/kgK)
ρ is the density (kg/m²)
λ is the conductivity (W/kgK)

The above "constants" may be dependent on both location and temperature.

Conventional programmes available on the market can determine the heating by transmission and radiation. It is possible to establish models of the structure and the surroundings in FEM (Finite Element Models). The models can be established a 1 dimensional strings, two-dimensional areas and 3 dimensional models. For a uniform (concrete) lining a one-dimensional model may for most purposes be sufficient. For temperatures at the joints and other details on a concrete segment and for the more complex geometry of a SGI lining a 2 dimensional model may be required. 3D models are only required for very complex details. For heavily reinforced items it may be necessary to model the influence of the reinforcement on the conduction of heat. This may require a 3D model.

The models normally require some few characteristics, i.e. material constants or temperature dependent functions (see below). It must be considered that decomposing reactions may take place during the heating. The heat consuming so-called decomposing reactions in concrete can be observed at the entire range of temperatures. An example is the evaporation of water at about 100°C. Whereas the most thermal characteristics in most cases can be taken from handbooks or codes, the decomposing reactions depend highly on the specific concrete mix its water content etc. The reactions can be modelled in different way either by establishing the respective formulas for the heat equilibrium or as an approximation to modify the material characteristics.

If decomposing reactions are not taken into account the estimated temperature will be an upper value.

The information required for the determination of heating of the lining is a.o:

- Thermal conductivity (depending on aggregates, temperature and humidity)
- Specific heat /heat capacity (depending on aggregates and temperature)
- Density (depending on concrete mix)
- Convection coefficient (depending on temperature and boundary conditions)
- Emissivity coefficient (depending on surface and shape)
- Thermal properties for surrounding ground and other thermal boundaries.
- Decomposing reactions (dependent on material mix and water content)

The properties will depend on the type of concrete, light-weight concrete and gas concrete will have extreme low conductivity, but these types are of little use to normal tunnel construction. Also the cement aggregate ratio and the aggregate material (granite, limestone, quartz) as well as the moisture content may influence the conductivity. In addition the conductivity is decreasing with the temperature. In normal cases the conductivity is simplified by a double linear curve with values between 1.5 and 0.5 W/mK.

The specific heat capacity for the dry concrete will be in the magnitude of 0.5 to 1.5 kJ/kgK increasing with temperature and depending on the aggregates. Concrete with limestone aggregates tends to have higher capacity than concrete with siliceous aggregates. Taking into account also the moisture content the specific heat capacity is in the magnitude of 0.8 - 1.2 kJ/kgK, with a peak at about 100°C dependent on the moisture content. For a water-content of 3% the peak value is in the magnitude of 2 kJ/kgK. Alternatively a coefficient indicating the capacity multiplied with the density can be indicated. The coefficient is for siliceous concrete in the magnitude 2.3 MJ/m^{3}K, (EC value). The 100°C peak is in the magnitude of 4.5 MJ/m^{3}K for a water-content of 3%.

For calculations of the temperatures in a tunnel it will often be necessary to model also the thermal properties of the surrounding ground, in which case the thermal properties of the ground will have to be modelled.
In principle it may be possible by use of CFD to determine the temperature in the tunnel and in the lining at the same time. This will ensure the modelling of the interaction between the lining and the gas temperature. However, it makes the CFD model even more complex and makes an extreme detailing necessary. So in most cases it is practical to separate the two calculations.
Due to the migration of the heat front through the segment, the maximum average temperature of the segment may be reached at a point of time after the fire.
By means of fire protection the heating can be reduced. The types of fire protections vary from organic to inorganic materials, sprayed-on material and boards. Fire isolating paint also exists but is not normal to use in tunnels. The common products are:

- Fiber / cement
- Vermiculite /cement
- Mineral wool slabs
- Ceramics
- Calcium Silicate Aluminate boards
- Composite panels

Reference is made to special studies and product information in section 5.[Glarum, Barry]. Fire protection materials are discussed in section 5.14.9.

Mechanical properties

Concrete

The different parts of the lining will at the same point of time experience temperatures, which can range from room temperature up to more than 1000°C. Particularly for a tunnel lining which will be heated from one side the temperature and the constitution of the concrete on the inside will be very different from the conditions at the outside. The mechanical properties of each part of the section will be affected according to the depth and the heating of this particular point. The loading of the individual points of the section is dependent on the reduction of the stiffness. Overall the boundary conditions of strain compatibility and static equilibrium will govern.

Expansion

As all other materials concrete will expand when heated. In the most simplified form the expansion is described by a coefficient giving a linear relationship between the increase in temperature and the expansion. However, for the calculations of concrete structures subjected to fire it is relevant to define the expansion by curves giving the relationship between the strain and the temperature. This curve will depend on the type of aggregate the aggregate cement ratio and the water cement ratio. For siliceous concrete the thermal elongation will be about 0.5 % at 400°C and 1.4% over 700°C. Simplified linear or double linear relationships can be found from codes or handbooks.

In addition to the thermal expansion also transient strain, creep strain and strain from external

forces contribute to the deformation of the concrete. The creep will be dependent on the aggregates, the temperature and the load level. The strain from external forces depends on the reduced stiffness and the strain compatibility.
The deformation of the cross sections, the segments and the tunnel structure in general shall be investigated in order to find the degree of confinement. Often the deformations are able to redistribute the loads and relieve confinement stresses.
When the thermal expansion is confined it will produce a mechanical stress. The stress is determined by multiplication of the confined expansion with the stiffness at the particular point. It should be noted that the stiffness will be significantly reduced at the points of the highest increase of temperature. The thermal strain is an expansion of the concrete, however, the total deformation may in some cases be a compression.

Reduction of strength and stiffness

The concrete is weakened in compressive strength and in stiffness due to the heating, i.e. thermal decohesion and thermal damage of the concrete. The reduction of strength and stiffness is normally expressed in curves indicating f_c respectively E relative to the value at 20°C for temperatures up to 800°C - 1000°C. Values can be found in handbooks or codes, e.g. Eurocodes, national codes and e.g. CEB. The curves found in codes are in many cases a reasonably good estimate for the remaining strength and stiffness. It should be noted however, that the curves depend on the concrete mix: in Eurocode curves are indicated for siliceous aggregates respectively calcareous aggregates. In the work of Prof. Glerum, a number of curves for different aggregates are indicated [52, Glerum]. Furthermore test results reveal a variation of strength reductions, ref. [41, Phan].

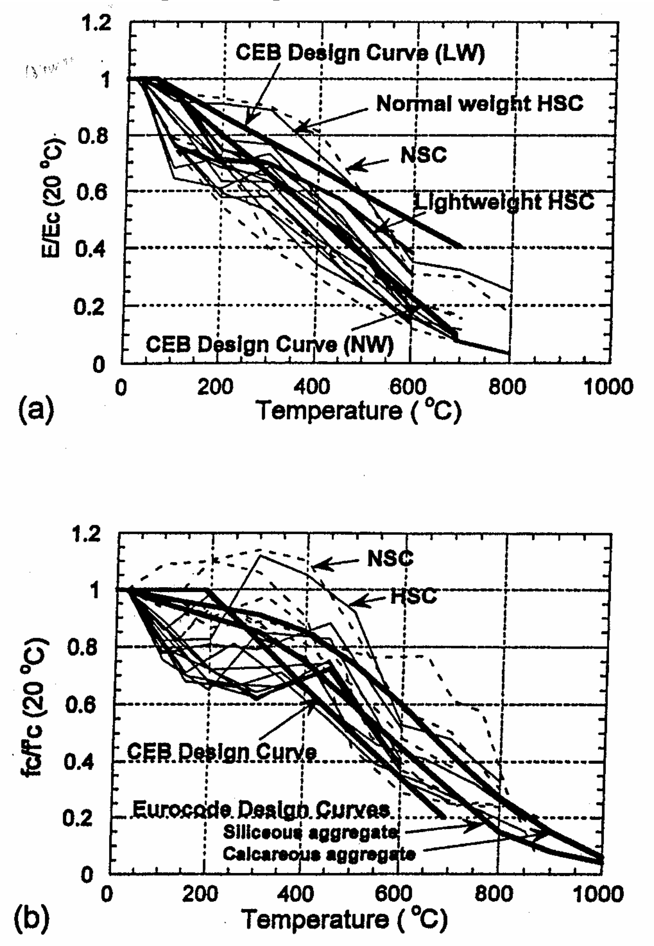


Figure 3.1 Reduction of strength and stiffness of concrete Example from [41, Phan]

Generally in structural design, permissible stress in structural members is assumed to be within the range of 30% - 50% of the compressive strength of concrete by the suitable scale of fire with comprehensive risk assessment.

According to Figure 3.2, if the initial strength is maintained at the level of 100%, temperature of concrete is set to be in order of 350°C as the limit. This way of thinking agrees with RWS and the research findings of TNO.

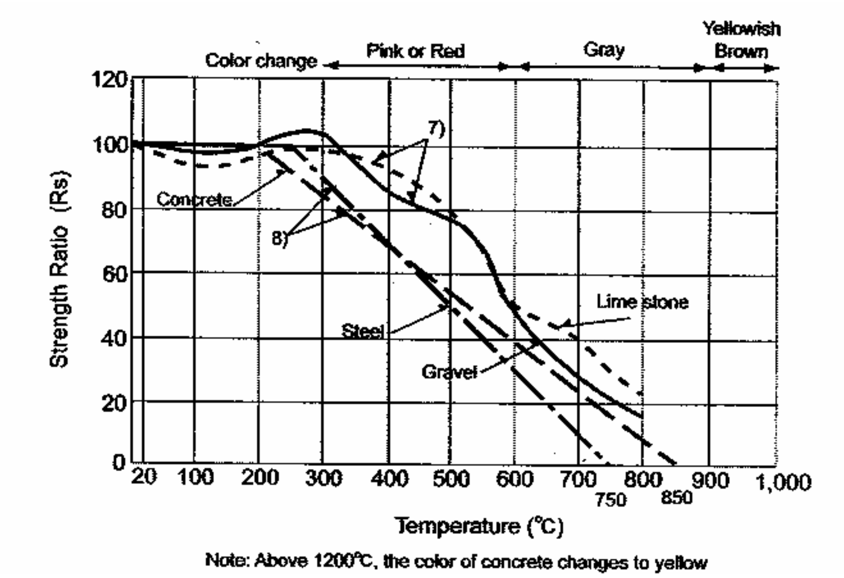


Figure 3.2 Compressive strength of concrete after temperature increase

The temperature at which concrete spalling may occur will vary between the condition of the temperature which entire concrete structure receives, the concrete strength, cement water ratio and the quality of aggregate. The relationship between temperature and strength, showed in Figure 3.2, would not have any strength reduction up to 200°C.

Figure 3.2 shows the effect of temperature on the strength of concrete and steel. The strength of concrete is still 100 % at a temperature of approximate 200°C and ends at 750°C. The effect of temperature on high tensile steel is worse than on reinforced steel. Before 1992 we only had one safety coefficient to calculate the safety of concrete structures built in the Netherlands, and this was 1.7. This means that if the strength of the concrete is reduced to 100% / 1.7 or 59%, the safety of a structure is 1.0, in the other words it is no longer a safe structure (very simplified). The graph shows that the temperature of concrete and steel can rise to approximately 450°C before a structure fails.

However, based on experience, the accepted maximum temperature of 380°C is applied to concrete and 250°C to steel for the following reasons:

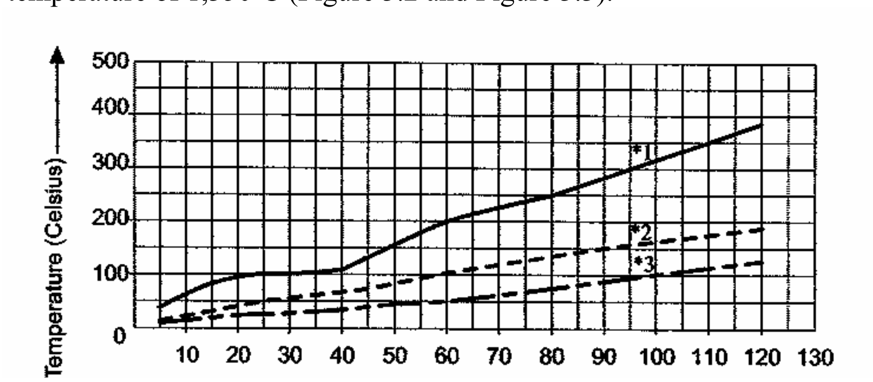
Concrete:

- Both concrete and lining have a high thermal capacity. They hold the heat and even after the fire has been extinguished, the temperature within the concrete continues to rise;
- To minimise concrete damage to limit concrete replacement after the fire;
- Large shear forces are concentrated near the supports (walls), at places where there is no shear reinforcement, which occurs especially in the older tunnels;
- Still to have a certain safety, as 450°C is a very simplified temperature limit.

Steel:

- It is true that the strength of steel is not reduced at 250°C, but deflections occur. Due to the permanent load on the roof of the tunnel, the chance is high that the deflections will be permanent.

According to Figure 3.2, it can be thought that hair crack or spalling already exists over the concrete surface, which has already been affected by high temperature, in the area of temperature where initial strength gets lower (decreases). Therefore, it is necessary to limit the temperature that the concrete is subjected to a range within 350°C - 400°C. In any of these cases, if the temperature concrete is subjected to in a fire is between 1,000ºC and 1,350ºC (RWS standards), set at planning or design stages, it is required to provide materials that shield an approximate maximum temperature of 1,350ºC (Figure 3.2 and Figure 3.3).



Time (minutes)

Figure 3.3 Time/Temperature curve of concrete with fire protection material

Note: Figure 3.3 illustrates a concrete tunnel liner with 25 mm of fire protection material on exposed surface, curve 1 is concrete surface, curve 2 is temperature at reinforcing steel (25mm) and curve 3 is temperature at a depth of 150mm.

Spalling

Whereas the reduction of strength and stiffness is relatively well described, the spalling is an area for which the mechanisms are still discussed. A practical engineering model for determining the risk of spalling and the possible thickness of spalling does not exist yet.
On the other hand the topic of spalling is important to take into account. There is not much point in discussing the reduction of the strength and stiffness if it is not known whether 50, 100 or 150 mm may spall during the fire.
In the Appendix is enclosed a discussion of some topics concerned with spalling. It has been prepared originally for planning of experimental determination of spalling for a particular project.
Some of key observations concerning spalling are listed below:

- The mechanisms are disputed: The pressure clog consideration or the thermal dilatation are two possible explanations
- Dense, impermeable concrete is more susceptible than low quality concrete
- Hence, the concrete mix and production conditions are important parameters
- Spalling can occur both for high strength concrete and classical concrete.
- The diffusion of water and the water content are important
- A lower limit of water content exist below which spalling does not occur
- It is disputed how to determine the water content
- The aggregates influences the spalling (calcareous aggregates are reported to give more spalling than siliceous aggregates)

- The arrangement of reinforcement influences the spalling but it does not prevent the spalling (contrary to indication in some codes).
- Spalling of unprotected concrete commences within minutes
- Fires with rapid increase of temperature are worse than fires with gradual increase of temperature
- Mechanical pressure on the structure is reported to influence the spalling.
- The geometrical shape of the element influences the spalling pattern.
- The occurrence and course of the spalling is a random process
- Self Compacting Concrete is reported to suffer from more spalling compared to regular concrete.

A realistic practical engineering estimation of the spalling is not common practice and may not be possible with analytical tools. The question is then what can be done to take into account the extent of spalling in the estimation of fire resistance: Some ideas are given:

1. The spalling characteristics can be determined experimentally. This estimation has the disadvantage that it is performed in a relatively advanced stage of the construction. Due to the size effect, and the production conditions, a full size sample should be taken from the production and the sample should have a reasonable age, as the spalling is dependent on the water content.
2. The spalling can be assumed. It has earlier been indicated in codes etc. that spalling could (in case it is taken into account) be assumed to be limited to the cover, i.e. 30 - 50 mm. This has in case of especially the Channel Tunnel shown to be too little. However, in place of other design basis one can assume a certain spalling e.g. 50, 100 or 150 mm and test the structure towards this spalling damage. The spalling can in turn be confirmed or updated by experimental testing.
3. It can be aimed to prevent or limit the spalling. A classical idea is fire protection, in form of boards or sprayed-on material. Especially pre-mounted material has disadvantages in connection with segmental lining, as it may be damaged during erection or will hinder the erection rate. In any case also fire protected concrete may under circumstances spall, so the fire protection must have a suitable thickness (see [40, Both]). Other fire protection measures like admixture of polypropylene and steel fibres are not discussed in this document. Reference is made to relevant research [48,Steinert].
4. Methods to reduce the fire risk i.e. by reducing the frequency or extent of the fire are part of the risk analysis and not only a measure to reduce the spalling. The introduction of fire suppression systems e.g. sprinklers is a disputed measure.

3.1 Reinforcement

Thermal

The thermal behaviour of the reinforcement can be described by the conductivity, the heat capacity, etc. similar to the parameters indicated for the concrete.
The detailed description of the heating and heat flow in the reinforcement can be important for the analysis of details around the reinforcement or for heavily reinforced parts of the tunnel.
For less reinforced parts of the tunnel the calculation of the heating of the reinforced concrete may often be simplified as a homogeneous material.

Mechanical

Similar to the concrete the strength and stiffness of the reinforcement is reduced due to the heating. For many types of structures the load bearing capacity during a fire is directly dependent on the moment capacity and thereby on the remaining capacity of the reinforcement. For tunnels the capacity id often determined by a combination of bending and normal force, (see section 5.2).

The reduction of the strength and stiffness is dependent on the type of reinforcement: cold deformed reinforcement will loose more strength at high temperatures than hot rolled reinforcement.

Examples of the yield strength reduction are indicated in figure 3.4 and 3.5. The yield strength is defined as the 0.2 % strain limit. The stiffness and the stress-strain relationship of the reinforcement in general will be affected by the heating; hence, if other strain limits are defined or if the ultimate strength of the reinforcement is the relevant parameter, the strength reduction curves will have a different shape. Illustration is given in Figure 3.4 by the comparison between the 0.2% and the 2% proof strain.

The stiffness of the reinforcement is similarly to the stiffness of the concrete reduced at a higher rate as illustrated in figure 3.6.

Simplifications of the strength reduction curves are indicated in different handbooks and codes (the curves of figures 3.4 – 3.5 are taken from Eurocode 2 Part 1-2). These indications will in most cases be sufficient; if more information is necessary the producer of the reinforcement may have test results. Otherwise particular tests will have to be made.

The reinforcement will to some extend regain its strength after cooling. The hot rolled reinforcement will regain most of its yield strength and ultimate strength. The cold deformed reinforcement will regain most of its strength up to a heating of 300°C, for heating up to 600°C about 60% of the yield strength and ultimate strength will be remaining.

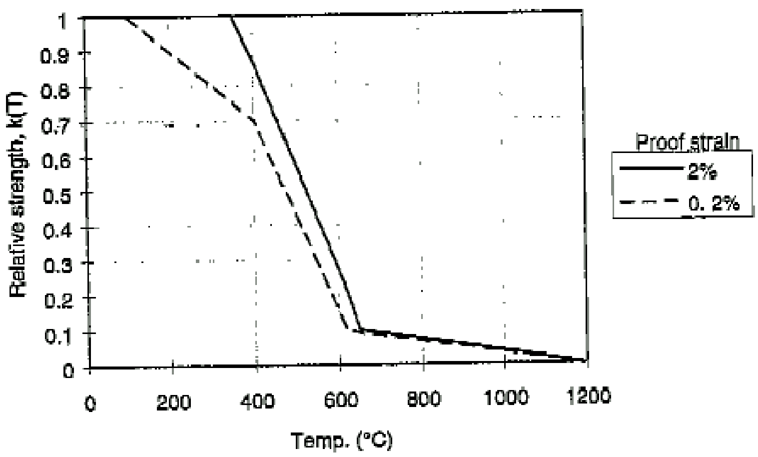


Figure 3.4 Relative strength of ordinary reinforcement steels as function of temperature (EC-2, Part 1-2 (1995)

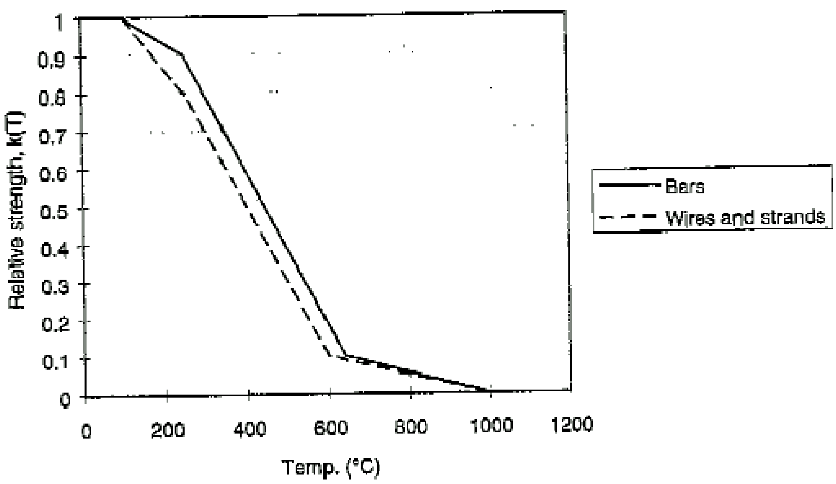


Figure 3.5 Relative strength of prestressing steels as function of temperature (EC-2, Part

1-2 (1995))

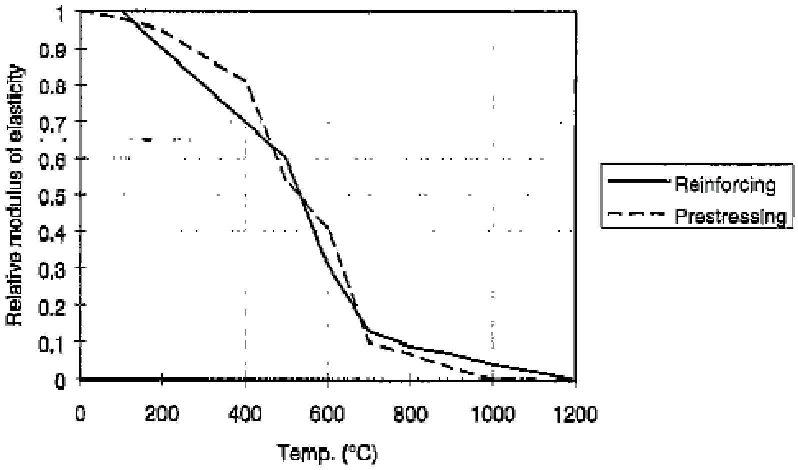


Figure 3.6 Relative modulus of elasticity of cold worked steels as function of temperature (EC-2, Part 1-2 (1995))

When subjected to very high temperatures the steel may melt or decompose.

Details should be particularly observed: welds will also loose strength and corrosion protection by paint or similar may influence the behaviour of the structure during the fire.

Thermal expansion

The thermal expansion of the reinforcement is in most cases modelled by a linear or double linear temperature- strain relationship. The expansion coefficients are moderately influenced by the type of reinforcement. The coefficient is higher for prestressing cables than for reinforcement bars. The coefficient for reinforcement is in the same magnitude as the initial thermal expansion coefficient for the concrete.

Bond of reinforcement

Due to the heating, the reinforcement will gradually loose its bond. The reason is mainly cracking in the concrete and the reduction of the strength of the surrounding concrete. Curves indicating the relationship between the bond and the temperature are given in the literature, but the exact models are still disputed. It has been observed that ribbed steel remains more of its bond up to temperatures of 400°C - 500°C compared to smooth steel. At temperatures over 600°C, no or very little bond will be left.

If possible structures should be designed so that the reinforcement is bonded at the side of the structure that is less subjected to fire.

For the design and analyses of details such as joints and fixations a closer study of the bond of the reinforcement might be relevant. For larger structural elements it may not be necessary to study the bond in detail.

4. Tunnel Classification

4.0 General

Tunnels are classified in regard to the original design the type of construction and the physical properties of the tunnel in regard to the method of ventilation, egress and potential for collapse as a result of a fire event. Tunnels are generally classified as follows:

- External configuration (circular, box section, arch)
- Structural lining type
- Method of construction
- Type of environment for tunnel construction (stable, unstable ground)
- Ventilation configuration
- Location (under/near other structures, in water course)
- Types of emergency access (rescue tunnels, cross passages, emergency shafts)

External configuration of tunnels is divided up into the following subsets:

- Circular
- Box (Square or rectangle)
- Arch
- Twin Tube (Immersed Tube Tunnel,} {ITT}

The structural lining type is divided up into the following subsets:

- Cast-in-place concrete
- Shotcrete
- Precast concrete segmental
- Precast concrete
- Exposed cast iron/ steel segmental
- Concrete covered cast iron/steel segmental
- Dimension Stone (Asher stone)
- Masonry (brick)

The Medium or environment that the tunnel is constructed is divided up as follows:

- Stable ground
- Unstable ground
- Bedrock

The type of ventilation means of egress and proximity to other structures is a variable for each type of tunnel. These variables have been classified to illustrate each type of ventilation configuration and are best illustrated in the attached figures. The use of external rescue tunnels, emergency access shafts and cross passages and proximity to other structures are modifiers to each general type of tunnel illustrated.

4.1 Tunnel Classification Description

The tunnel description is intended to simply classify tunnels into numerous classifications that will allow the tunnel type to be placed in a database for rapid retrieval and to standardise the description of tunnels. The most common types of tunnels are as follows:

Type 1	Circular; Exhaust above; supply air below roadway
Type 1A	Circular; Supply & exhaust below the roadway
Type 1B	Circular; Supply over the roadway, no exhaust
Type 1C	Circular; Exhaust over the roadway, no supply
Type 1D	Circular; Jet fans over roadway, no separate supply or exhaust
Type 1E	Circular; Supply and exhaust over the roadway
Type 2	Arch; Exhaust over the roadway
Type 2A	Arch; Supply air over the roadway
Type 2B	Arch; Jet fans in arch, no separate supply or exhaust
Type 2C	Arch; Supply air below the roadway
Type 2D	Arch; Jet fans in arch, supply air below the roadway
Type 2E	Arch; Supply and exhaust below the roadway
Type 2F	Arch; Supply and exhaust above the roadway
Type 3	Box; Exhaust above the roadway, supply air under
Type 3A	Box; Exhaust over the roadway, no separate supply air
Type 3B	Box; Supply air over the roadway, no separate exhaust
Type 3C	Box; Supply air below the roadway, no separate exhaust
Type 3D	Box; Jet Fans in roof, no separate supply or exhaust
Type 3E	Box; Supply and exhaust below the roadway
Type 3F	Box; Supply and Exhaust above the roadway
Type 4	Immersed Tube; Exhaust above the roadway, supply air under
Type 4A	Immersed Tube; Exhaust above the roadway, no separate supply air
Type 4B	Immersed Tube; Supply air above the roadway, no separate exhaust
Type 4C	Immersed Tube; Supply air below the roadway, no separate exhaust
Type 4D	Immersed Tube; Jet fans above the roadway, no separate exhaust or supply
Type 4E	Immersed Tube; Immersed tube tunnel with cross passages
Type 5	Tunnel with external egress tunnels (any type of construction)
Type 6	Urban tunnel with structure above tunnel (any type of construction)

4.2 Tunnel Classification Modifiers

Tunnels can be rated or classified in regard to other modifies that are influential in the potential hazard /or benefit to the structure. They are:

Hazard /Benefit component coding

Type of Component	Symbol	Description
Stable Ground	SG	Ground that will not collapse in the event of fire
Unstable Ground	UG	Ground that will collapse if unsupported
Emergency Egress	EE	External rescue tunnels, emergency shafts
Cross Passages	CP	Cross passages to other tunnel

Safety Chambers	SC	Safety chambers with self contained air supply

Each tunnel is to be classified in regard to the general classifications illustrated here with a sub-script for the inclusion of emergency rescue tunnels, cross passages and other unique characteristics to the tunnel. For example; a Type 1E tunnel (circular section, Exhaust and supply air above the tunnel) with an emergency access tunnel would be described as follows 1E (rt) or Type 1 E tunnel with emergency access tunnel. The same tunnel with a structure above it would be described as type 1E(rt, os) or Type 1 E tunnel with a rescue tunnel and structure over it.

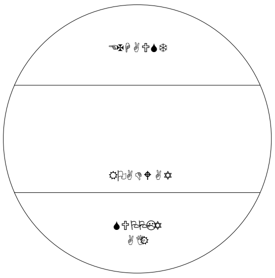
4.3 Tunnel Classification for Risk Analysis

The classification of tunnels as shown here are intended to allow the owner/operator to easily evaluate the risk associated with a fire in the type of tunnel structure that one is evaluating. The key elements for protection are those that are to be protected form collapse or are necessary for the safe evacuation of the public and for protection of fire-fighters. Tunnels that are located in urban environments and/or are in soft unstable ground have the greatest potential for risk associated with collapse or the potential to effect other nearby structures, (Types 4,5,6) therefore more attention must be made to the protection of the structural elements from fire.

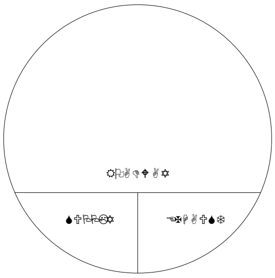
The information as to classification of tunnels is for informational purposes only and each tunnel type must be classified according to local codes and ordinances. The intent of this classification system is to standardise classifications to allow local codes and ordinance to adequately evaluate the potential risk and thereby develop appropriate guidelines for protection of the structural elements as described in Sections 5 and 6 of this document.

4.4 Tunnel Classification Sketches

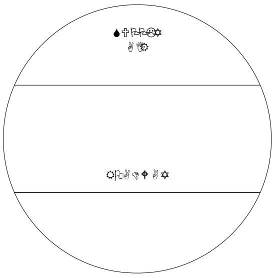
The following sketches are for informational purposes only and are representative of the classifications illustrated here. Variations in these configurations are common and is to be documented as discussed in Section 4.2



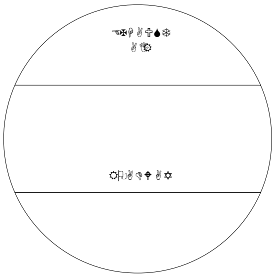
TYPE 1



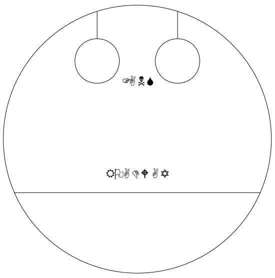
TYPE 1A



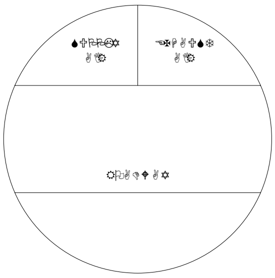
TYPE 1B



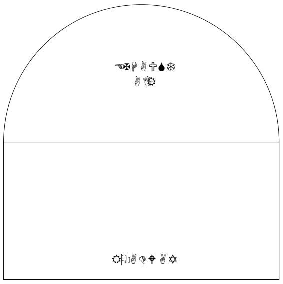
TYPE 1C



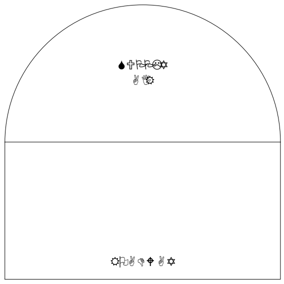
TYPE 1D



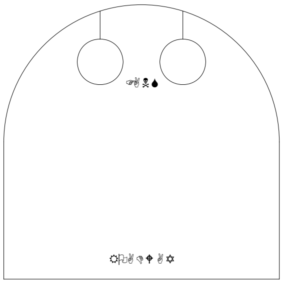
TYPE 1E



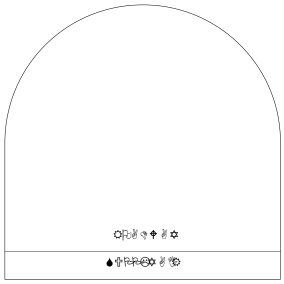
TYPE 2



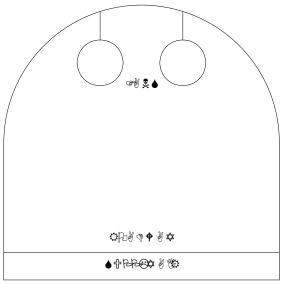
TYPE 2A



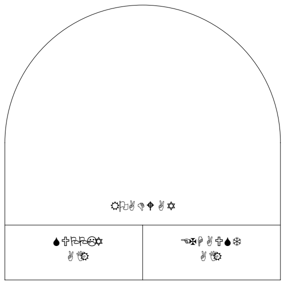
TYPE 2B



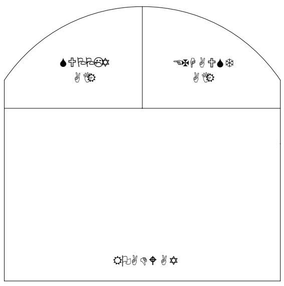
TYPE 2C



TYPE 2D



TYPE 2E



TYPE 2F

The following table is provided to illustrate typical elements of a tunnel to be protected from rapid heat rise that would cause collapse or an unsafe condition in the tunnel the protection should be based on the criteria provided in Sections 5 and 6 of this document and after consultation with local Authorities an applicable codes.

Tunnel Type	**Liner UG**	**Liner SG**[1]	**Ceiling**	**Roadway Slab**	**Duct Walls**	**Cross Passages**[2]	**Fan Anchorages**	**Ceiling supports**
1	X		X	X		X		X
1A	X			X	X	X		
1B	X		X			X		X
1C	X		X			X		X
1D	X					X		
1E	X		X		X	X	X	X
2	X		X			X		X
2A	X					X	X	
2B	X					X	X	
2C	X			X		X		
2D	X			X		X	X	
2E	X			X	X	X		
2F	X		X		X	X		X
3	X		X	X		X		X
3A	X		X			X		X
3B	X		X			X		X
3C	X			X		X		
3D	X					X	X	
3E	X			X	X	X		X
3F	X		X		X	X		
4	X		X	X		X		X
4A	X		X			X		X
4B	X		X			X		X
4C	X			X		X		
4D	X					X	X	
4E	X					X		
5[3]	X		X	X	X	X	X	X
6[4]	X		X		X	X		X

Notes: 1. SG = Stable Ground and is assumed to be constructed in stable rock
2. Cross Passages used only for twin tunnel construction
3.Interior protection dependent on ventilation system refer to Type 3
4., Interior protection dependent on type of ventilation refer to Type 1

Table4.1 Typical levels of protection based on tunnel type

5. Structural Elements

5.0 General

The following discussion is focused on the types of linings used for road tunnels and may be applicable to other types of tunnels and underground structures. This discussion is in general and is an attempt to illustrate the various behaviour of lining subjected to intense heat from a single fire event.

5.1 Structural Elements

Construction materials used for main and secondary structures must be non-combustible or very little combustible (Euroclass A1 or Euroclass A2, s1, d0) from the point of view of reaction to fire. Lightweight roof structures may have less severe fire reaction requirements (i.e. Euroclass C) since the loss of these does not represent any risk to safety provided that fire propagation risks are limited.

All materials used for internal linings must be non-combustible or very little combustible (Euroclass A1 or Euroclass A2, s1, d0) when located at the crown of the tunnel. Little combustible materials (Euroclass A2 or B) may be permitted for the linings of the walls provided they do not promote fire propagation

This section specifies the minimum level of fire resistance of materials to ensure the safety of persons, including the emergency and rescue services engaged in their work. The tunnel owner may specify higher levels of resistance in order to provide improved fire resistance for the tunnel and limit both the extent and cost of repairs and closure period following a fire.

Time/Temperature curves are to be used as appropriate justification of the fire resistance of structures and certain items of equipment.

Fires in which the temperature rise is relatively slow, but which may have long durations are characterised by the standard ‘cellulosic’ Time/Temperature curve as defined in ISO 834.

Fires involving heavy goods vehicles may have a much faster temperature rise, particularly if they involve highly combustible materials (even if they are not classed as hazardous for the purposes of transport).

Such fires are characterised by modified hydrocarbon time/temperature curves such as the Rijkswaterstaat (RWS) and Hydrocarbon Increased (HC_{inc}) curves described in 2.2.1, which reach 1200°C within 10 minutes and may reach 1300°C or 1,350º shortly afterwards.

Materials used to provide structural fire protection in buildings may not be suitable for use in tunnels because they may fail (by either melting, burning or disintegrating) at temperatures above 1,200ºC.

5.2 Objectives and Fire Resistance Levels

Fire resistance required for structures and equipment is designed to provide the following main objectives:

- Protection of users inside the tunnel for the time taken for them to reach the exit.
- Maintain a safe environment for the emergency and rescue services.

- Maintain electricity supply and communications on either side of the fire.
- Prevention of flooding by surrounding ground water into the tunnel or catastrophic collapse of the structure.
- Protection of structures or buildings, which are in close proximity to the tunnel.

5.3 Fire Resistance Levels

In order to meet these objectives without unnecessary additional costs, the following four levels of fire resistance from the French Inter-ministry circular 2000-63 may be considered:

Level NO

No risk of progressive collapse in the event of a local failure. The loss of one element should not result in a transfer of load, which is likely to cause other parts of the structure to fail.

Level N1

This level corresponds to the majority of fires excluding the most violent ones. It should be used for structures which are important for emergency action to take place.

In tunnels where all types of vehicles are allowed, level N1 corresponds to resistance to the ISO curve during 2 hours.

Level N2

This level corresponds to high intensity fires, with a very quick development. It should be required for structures which must resist the most violent fires during the period required to allow evacuation and action by the emergency services.

In tunnels where all types of vehicles are allowed, level N2 corresponds to resistance to the HC_{inc} curve during 2 hours.

Level N3

This level corresponds to the most onerous fire exposure conditions and applies to structures, which must resist the most violent fire throughout the prescribed exposure period.

In tunnels where all types of vehicles are allowed, level N3 corresponds to resistance to both the ISO curve during 4 hours and the HC_{inc} curve during 2 hours.

Tunnels Reserved for Passenger Cars

Where only passenger cars and vans are allowed, with average fire loads of 7MW each, levels N1, N2 and N3 are identical and correspond to resistance to the ISO curve during 1 hour.

5.4 Evidence of Fire Resistance

The level of fire resistance of structures and equipment must be proven by testing, reference to previous testing, by calculation or by a combination of all three of the above.

Calculation may not be used in isolation where curves more severe than the ISO curve are used, (RWS or HC_{inc} for instance) and also where the ISO curve is used for a high-strength concrete.

- Concrete slabs used for the application of fire protection materials, for fire testing purposes, shall have dimensions of at least 1400x1400 mm and a nominal thickness of 150 mm. The exposed surface will be approximately 1200x1200 mm.
- The fire protection material must be fixed to the concrete slab using the same fixation material (anchors, wire mesh, etc) as will be used during the actual installation in the tunnel.
- In the case of board protection, minimum one joint in between two panels must be created, in view to judge if any thermal leaks will occur in the case of a real fire in the tunnel.
- In case of spray materials, the number of applications (amount of layers) must be registered when preparing the test specimen. This amount of layers must be respected while applying the spray material in a real tunnel.
- Temperature recordings by thermocouples shall be done:
  - At the interface in between the concrete and the fire protection material
  - At the bottom of the reinforcement
  - On the non-exposed face of the concrete slab

5.5 Minimum Requirements for Main Structures

The main structure of the tunnel must satisfy Level NO when local failure alongside the source of the fire will have no harmful consequences for the safety of users or cause structural failure. In other circumstances, a higher level of fire resistance must be provided.

Level N1

This level applies to structures supporting a roadway or an area, which is accessible to the public above it.

It also applies when stability of the structure is necessary in order to maintain the structural stability of an adjacent tube when there is direct communication or escape to the outside of the tunnel

This level shall also apply if local structural failure is likely to cut a ventilation duct which is important to allow action by the emergency services.

Level N2

This level applies when the structure is required to maintain the stability of another tube or separation from it when there is no direct communication with the exterior.

This level shall also apply if local structural failure is likely to cut a ventilation duct which would compromise safe shelters and their access-ways to the exterior.

Level N3

This level applies to immersed tube tunnels or tunnels located below the water table which are at risk of flooding in the event of local structural collapse. This also applies if local failure of the structure is likely to result in catastrophic collapse, damage at the surface or likely to affect the stability of an adjacent structure.

5.6 Lining, Material Types and Fire Behaviour

The following types of concrete lining can be considered:

- Horseshoe Tunnels
  - Cast in-situ concrete lining
- Circular Tunnels:
  - Cast in-situ concrete lining
  - Segmental lining with gaskets and packers.
- Box/rectangular Tunnels
  - Cut and cover tunnels
  - Immersed tunnels including joints

Concerning damage to the Lining of a circular (and horseshoe) tunnel, the load is mainly transmitted as compression in the hoop direction. The parameters affecting the remaining strength of the tunnel are

- amount of segment remaining after spalling
- temperatures reached during the fire and consequential concrete strength loss
- tunnel deformations and tunnel - ground interaction
- possibility of rehydration of cement
- position of damage within the ring relative to possible disturbed ground outside the lining
- squatting of the ring

For a rectangular tunnel, where the load is transmitted mainly by bending, the parameters affecting the strength of the tunnel are:

- the possibility of spalling revealing the reinforcement
- the temperature reached in the reinforcement during the fire (with or without spalling)
- the amount of concrete remaining to transmit normal force
- temperatures reached during the fire and consequential loss of strength and stiffness.
- ability to redistribute the load after damage to part of the tunnel (creation of hinges)
- possibility of rehydration of cement

5.6.1 Loads

In order to discuss the behaviour of the fire damaged structural element it is necessary to deal with the loads on the structure. On a tunnel the main loads are normally water load and ground load. For a discussion of fire resistance also the thermally induced load must be taken into account.
It shall be noticed that the definition of fire resistance is duration (time) of a specified fire, which results in a reduction of the strength of the structure to a level corresponding to the magnitude of the load at a specific point of time. The fire will influence the load due to the thermal expansion and the load may influence the spalling and thereby the remaining strength.

Water and Ground Load

The water and ground loads are generally regarded as unaffected by the fire. However, for very long duration fires the ground may be heated so much that the load is affected (for bored tunnels). Strong heating may also influence the water pressure. For most fires and especially for thick concrete lining the heating at the outside of the tunnel (extrados) will be marginal.
Water and ground load can be taken from design assumptions, from geometrical information or from measurements. The load will vary along the alignment. As the design of the segments will be uniform or stepwise uniform the fire resistance will depend on the location in the tunnel.
Water- and ground load will result in normal force and moment in the lining. For circular and horseshoe shapes tunnels it is aimed that the load is transmitted as normal force as far as possible. For rectangular tunnels the moment action will be more pronounced.

Thermal Load

A thermal load derives from the restricted expansion of the material due to the heating. See also section 3.1.
Distinction must be made between 1. Internal stresses, which may be contributing to the explanations of reduction of strength and in some theories to the spalling and 2. The external overall loads on the segment, which are added to the water and ground load.
In addition to the deformation from thermal expansion also transient deformation, creep and deformation due to loading and loading history should be taken into account.
It is particular important to take into account the reduced stiffness of the concrete. At the position where the temperature is highest the stiffness is reduced most. Therefore the thermally induced load may have its largest contribution from the middle range temperature increases.
The stresses from thermal expansion come only from restrained expansion; the elastic, plastic and stiff body deformations tend to relieve the thermal loads on the structure. Particularly segmental lining has the ability to deform. Interaction with the stiffness of the ground is particularly important for segmental lining in relatively soft ground. The weakened stiffness of the ring will transfer more load to the ground and deformations will be allowed to relieve the thermal stresses.
Also here it is worth to notice the boundary condition of strain compatibility.
In the concrete cross section the areas with the highest stiffness will attract the loads, which is fortunate, as the strength is also available here.

Moment Action

Ideally bored tunnels are subjected to hoop load, i.e. a unidirectional load (the term axial load is used even though a ring is not an axis). But due to limited (small) overburden, variation in ground stiffness, cross passage joints etc. the segments are subjected to a certain moment. These moments are generally not a problem for the relatively thick segments. However, during the fire the cross section is decreased, the strength in the remaining cross section is decreased and the moment capacity is therefore decreased. More important, due to the spalling and the heating at the intrados, the line (curve) of action of the hoop force moves towards the extrados. The contact point between the segments is at the centre line. This means that the segment is subjected to an increased moment.

In turn the moment will cause a deformation of the segment (in interaction with the stiffness of the ground) and the contact point will move slightly towards the extrados, but this results only in a slight reduction of the moment.

For Bored tunnels ground-structure interaction may to some degree relieve some of the loads occurring during a fire. For immersed tunnels the tunnel-ground interaction is normally in terms of the (hydrostatic) ground load and the foundation. Cut and cover tunnels may have similarities with bored tunnels or immersed tunnels depending on their shape.

For rectangular tunnels the moment action is more pronounced, depending on the load and the geometry of the tunnel. The load on immersed tunnels will in most cases be dominated by a hydrostatic water pressure, which will tend to give compression in walls, roof and bottom and negative moments in the corners of the rectangle and positive moment at mid-span of walls, roof and bottom.

With respect to fire the critical point is often the centre span of the roof, as it often will have a positive moment activating the inside reinforcement in tension and at the same time this point of the tunnel is subjected to the maximum heating of the fire.

The fire will heat up the concrete and reinforcement and the moment capacity will gradually decrease as the strength and stiffness of the inside reinforcement is lost.

In case of spalling the reinforcement may be directly exposed to the fire and the moment capacity is immediately lost. As the spalling may take place within the first minutes of the fire, this type of structure is vulnerable towards fire damage.

Even though the moment capacity at mid -span is reduced to nearly nothing, it may not lead to total collapse of the tunnel. The mid span may be regarded as hinge and the loads may be carried by increased negative moment at the corners.

For immersed tunnels further development of the damage will result in flooding. For cut and cover tunnels the consequences will depend on the use of the surface over the tunnel.
Narrow tunnels e.g. single track railway tunnels may have the ability to carry the load after damage at mid-span, whereas wide tunnels e.g. road tunnels may be too wide to carry the redistributed load.

In practice it is common to fire protect the roof and the upper part of the walls for immersed tunnels by fire isolation material. The fire protection prevents both unacceptable heating of the reinforcement and also spalling.

Immersed tunnels can in some cased be prestressed by cables in the axis direction. Damage of these cables can also result in lost functionality of the tunnel.

5.6.2 Segmental capacity

Normal Force

In the ideal situation the load on a bored tunnel segment is a perfect hoop load, and the product of the area and the factored strength determines the capacity of the segment. In case of a fire damaged cross section the spalled area is of course disregarded and the heated areas contribute with their remaining strength as far as the strain compatibility allows it. The capacity towards normal force can be expressed in terms of MN or in a normative value, which is 100% at the start of the fire.
A curve describing the development of the remaining strength during and after the fire can be established. The curve will have a steep decrease at the time of spalling, a more gradual decrease during the remaining heating and the decrease is expected to continue some time after the fire has ceased.

Normal Force + Moment

Due to the moment action mentioned in the section concerning the load, the capacity will be further reduced. The well-established calculation of concrete or steel for combinations of normal force and steel can be used. The calculation is due to the heating complicated by the fact that the segment does not have the same properties all over the cross section. The capacity can be expressed as the maximum uniformly distributed load or simply by a relative figure, which is 100% at the start of the fire.
The curve describing the development in reduction of capacity will be more pronounced than the one only taking normal force into consideration.

Biaxial or triaxial loading condition

For the design of tunnel lining it will in most cases be sufficient to consider a uniaxial loading. For circular tunnels the main load will be in the hoop direction and for rectangular tunnels the

main load is normal force perpendicular to the tunnel axis and moment around the axis. The normal forces in the tunnel axis direction comes from forces built in during construction and prestressing.
The capacity of a bi-axially loaded concrete will be higher than a uniaxially loaded structure, so the consideration of uniaxial conditions will be on the safe side.
For consideration of details the biaxial and even the triaxial conditions might to worth to take into account. An example is the joints of the segmental lining.

Shear and splitting

At the joints the segments have shear and splitting forces. The segment is normally reinforced in this area for these forces.
The calculation of the shear and splitting is following the same principles as design of cold joints. However, with the reduced strength of the concrete and reinforcement this detail comes out as a critical point in the calculations.
Some complications occur in the calculation of a shear failure line through strongly varying strengths and stiffness and from the fact that the shear/splitting reinforcement is heated so much at the intrados side that the bond is doubtful.
The capacity of the joint observed in real fires benefit from the fact that the spalling tend to be substantially less (or not occurring at all) near the joints.
The curve indicating the capacity of the joint can be indicated for points of time during and after the fire as the normal force + moment.

5.6.3 Capacity of elements in bending

For elements mainly in bending towards the fire exposed side the capacity is determined by the remaining capacity of the reinforcement. The heating of the reinforcement is calculated and based on the remaining strength and stiffness of the reinforcement the moment capacity of the element can be determined.
In case of spalling the reinforcement may be exposed to the fire temperature and loose its strength immediately.
For elements in bending away from the fire exposed side the reinforcement will normally by heated only marginally. The moment capacity can often be calculated by as an equivalent cross-section, where the concrete reduced to less than e.g. 60% of its original strength is disregarded.
For elements subjected to combined bending and normal force reference is made to the comments above concerning capacity of segments.

5.6.4 Fire Resistance

When the relative curves indicating the capacities of the segment in terms of normal force, moment, splitting and shear are not intersected by the load curve in the same units then the fire resistance has not been reached. A parametric extension of the fire duration until the curves intersect can be made. The duration of the fire, which results in intersection, represents the fire resistance.
It should be noticed that the structure in some cases may have redundancies which can ensure fire resistance even after failure of a single element. For rectangular tunnels reference is made to the description above.
In must be noticed, that a number of the parameters used in the calculation of the fire resistance have large uncertainties. It is advisable to evaluate the importance of the uncertainties.
The evaluation of uncertainties can be done in dedicated software, where the uncertain values are modelled as stochastic variables. This can be done with a full representation of the uncertain values as stochastic variables or as a more simple sensitivity analysis, in which the uncertain values can be varied between e.g. +/-1 or two standard deviations or similar.
The result of the fire resistance estimation shall be given with the information of these evalua-

tions.
Safety considerations, i.e. partial coefficients and similar, will strongly influence the fire resistance. The best estimate on the fire resistance will be found by calculation with factors equal to 1 and with central estimates of the material characteristics. A best estimate can make sense in connection with risk analyses. However, for evaluation of structural behaviour and structural safety characteristic values and factors according to the respective codes may be required. In the latter cases the estimated time to failure will be a lower fractile. It shall be taken into account in estimation of characteristic values (and safety) which part of the information has been found by testing - and the uncertainties associated to the tests.

5.7 Linings

5.7.1 Concrete Linings

Concrete linings generally fall into two categories, cast concrete and pre-cast high strength concrete segments or beams. Each type will behave differently under fire exposure conditions.

Cast concrete used for cut and cover or immersed tube tunnels use ‘normal’ strength concrete (30Mpa - 40Mpa). This type of concrete will begin to lose its strength when its temperature exceeds 380°C. Spalling will also occur under most fire exposure conditions in tunnels.

In addition, the temperature of the steel reinforcement within the concrete (particularly the soffit) will begin to lose its strength when its temperature exceeds 250°C.

In order to prevent concrete spalling and collapse of tunnel soffits, measures should be taken to prevent rapid rise of the structure or lining by the application of an insulating coating (passive fire protective coating).

This coating may be either a proprietary spray applied material or a rigid or flexible board system fixed to the tunnel lining.

The insulating coating must be capable of limiting the temperature of both the concrete and the steel reinforcement below their critical temperatures under the relevant fire exposure conditions (Cellulosic or elevated hydrocarbon, depending on the tunnel classification).

In immersed tube tunnels, consideration must also be given to the critical temperature of both immersion and segment joints in order to maintain the structural stability of the tunnel under the relevant fire exposure conditions.

Bored tunnels are usually lined with high strength pre-cast concrete segments (55 - 90Mpa), which under fire exposure conditions, will begin to spall at lower temperatures than cast concrete. It is therefore necessary to prevent this type of concrete from exceeding temperatures of 180°C to 220°C after 120 minutes of fire exposure under the relevant conditions in order to preserve the full lining thickness for the duration of the fire. However, during a fire test these temperatures are not the criteria to judge if the system failed or not. The real criterion for high strength concrete is “no spalling”.

In general, the temperature of the reinforcement within pre-cast concrete segments can be ignored since it provides no structural function once the tunnel ring has been completed and the lining is in compression.

Pre-cast concrete roof beams may be treated in the same way as pre-cast segments.

Polypropylene fibre reinforced concrete is commonly used in tunnel construction. Under fire exposure conditions, the fibres melt to form 'channels' within the concrete matrix relieving the thermal stresses and allowing steam generated by the heat to escape, reducing the extend of spalling.

After fire exposure, reinforced concrete must be repaired in order to reinstate the structural integrity of the lining. Prevention of damage can be achieved by the installation of an insulating coating.

5.7.2 Steel Linings

Steel linings will begin to lose their structural strength when its temperature exceeds 500°C - 550°C. It is therefore necessary to limit the critical temperature of steel linings below this temperature under the relevant fire exposure conditions by the use of an insulating coating or lining in the same way as for concrete linings. A safe temperature for steel linings is <300°C.

If the lining is constructed using segments, consideration must be given to the critical temperature of the tunnel joints and seals in order to maintain the structural integrity of the tunnel under the relevant fire exposure conditions.

5.7.3 Cast Iron Linings

Cast iron linings may be treated in the same way as steel linings with respect to their critical temperature.

In 'wet' cast iron lined tunnels, consideration must be given to the tunnel seals which may have a lower critical temperature that the lining. (for example, lead seals will begin to melt at approximately 300°C).

5.7.4 Masonry Linings

Masonry linings are generally considered to be fire resistant. However, under the most onerous fire exposure conditions, consideration may be given to the use of an insulating coating to prevent extensive damage or collapse.

Where masonry linings are used on walls separating two adjacent tubes where the adjacent tube is used as a means of escape, the use of an insulating coating may also be considered.

5.7.5 Gaskets

The water tightness of segmental lining is generally ensured by use of gaskets. In most cases the gaskets are placed near the extrados, but in some cases a supplementing gasket has been placed also at the intrados. The gaskets have no load bearing effect but a failure of the gaskets will lead to more or less water inflow and subsequent repair. It will not be possible to replace the gaskets, so the water tightness will have to be established by other means. It should be discussed how much the tunnel should leak before it is regarded as failed.
It is beyond the scope of this note to describe the possible types of gaskets, but in many cases the gaskets are made from a rubber compound.
The heating of the gasket depend both on the location and adjacent materials. In case of a steel or cast iron segment the gaskets will be heated more than in a concrete segment. The calculation of the heating of the gaskets can be made together with the determination of temperatures in the segment (in this case in minimum a 2D model).
It may be relevant to ask the producer of the gaskets for specific material information. The following may serve as a guideline for the characteristics of the gaskets subjected to fire:

- For even long duration exposure to about 150°C the appearance of the rubber does not alter, the elasticity is decreased, but in many cases it may serve its purpose also after the fire. This depends of course on the margin of water pressure for which the gasket was designed. Deformations during the fire may in theory influence the long term sealing characteristics.
- For long term exposure to 250°C the rubber becomes brittle and looses all elasticity. As it is probably subjected to high mechanical pressures from the segments during the fire, the gasket will most likely have lost its sealing properties after the fire. A replacement with another sealing medium will be necessary.

Heat ageing and chemical attack may be a problem for the areas exposed. However, only a very small area will be exposed and hence the problem small.

The fire resistance of the gaskets is dependent on the protection. If the gaskets are exposed directly to flames they will be destroyed by fire.

5.7.6 Packers

Packers between the segment rings have the purpose of distributing the load during erection of the segments. The packers are often made of bituminous material or of wood, and hence combustible.

- The bituminous packers may melt and the melted material burn. It is considered that this is a minor problem as the packers will melt relatively slowly and the combusted material will be small compared to the fire load in general. On the other hand the heating, softening and melting of the packers will to some degree relief the stresses originating from the thermal expansion in the longitudinal direction.
- Plywood packers will hardly burn due to the limited surface; the relieving effect from heat of the plywood packers will be small.

5.7.7 Immersed tunnel Joints

For immersed tunnels it is particularly important that joints are well designed and that they are water tight under all load conditions. With respect to fire the joints are normally placed at a position where they are protected against the heat. Otherwise they will have to be protected by fire protection material.

The joint normally has a component of a butyl rubber or similar, in form of e.g. an omega or gina joint. This material cannot withstand fire or heat, as mentioned in the section on gaskets above.

For cut and cover tunnels the joints are often a less critical part of the structure. For joints with rubber components the same comments as above apply. For concrete-concrete or concrete-steel-concrete construction joints, the fire resistance will not be critical.

5.8 Suspended Ceilings

5.8.1 Concrete ceilings

Loading on concrete suspended ceilings is normally limited to the dead load of the ceiling and pressure from the ventilation system.

False ceilings and walls separating ventilation ducts from a tunnel should have a minimum fire resistance (NO) where loss or collapse will have no harmful consequences for the public or emergency and rescue services.

In other circumstances, where continuity of the suspended ceiling is essential, such as escape routes, higher levels of fire resistance may be required.

Consideration should be given to the interfaces between the suspended ceiling/walls and the tunnel lining. If structural integrity is required in order to maintain the stability of the tunnel and allow safe escape, an insulating coating should be used.

In voids above suspended ceilings or walls which are used as a means of escape, consideration should be given to providing means of limiting the temperature within the voids to below 60ºC for the duration of the fire.

5.8.2 Steel Ceilings

Where used, steel suspended ceilings may be treated in the same way as concrete ceilings, particularly where the void is used as a means of escape.

Since the suspended ceiling is unlikely to be fully loaded, a higher critical temperature than that of the lining may be considered.

Suspended ceilings constructed of cast iron or masonry (if used) should meet the same requirements as those for concrete and steel.

5.9 Supported Floors and Decks

Supported floors and decks will have a high live load due to traffic movement.

Structural integrity of the floor or deck must be maintained where the void below is used for escape. It is also important that the stability is maintained in order to allow the rescue and emergency services to perform their function.

Propagation of fire underneath the supported floor or deck must be prevented (particularly with the flow of burning hydrocarbon spills such as petrol).

If there is another level of traffic below the supported floor deck, consideration should be given to maintaining the stability of the deck under fire exposure conditions by the installation of an insulating coating.

5.10 Suspended Ceilings-Fire Behaviour, Concrete and Reinforcement

The load of the suspended ceilings is normally limited to the dead load and the pressure from the ventilation air.
It should be noted that the suspended ceiling shall form the ducts for the ventilation, which is particular important in case of fire. In some cases failure of the ceiling can be accepted just over the fire, but it has to be carefully investigated.
Reduction of strength in case of fire similar to the mechanisms mentioned for the lining. The structural particularities of the ceiling are:
The structural interface at the tunnel wall supports/ bearings or cast-in reinforcement bars.

The supports are sensitive to shear failure, movements resulting in loss of supports, and spalling / disintegration of the concrete.
The suspended ceilings will to some extend (if it remains in place during the fire) protect the main structure from being subjected to the fire. However, the ventilation ducts might be used for extraction of the hot gasses, in that case the main structure will be heated by the gas in the duct.
It is discussed whether a fire protection of a tunnel with suspended ceiling should be on the lower side of the ceiling or on the main structure.

5.11 Supported Floor/Deck - Fire Behaviour, Concrete and Reinforcement

The supported floors have a high live load from the traffic. The floor has normally one or two intermediate supports and will span between the supports and the tunnel wall. In connection with a fire it is of high importance that the rescue forces can use the road (deck) when they enter the tunnel. The degree of damage of the floor may also be one of the determining factors for the decision of resuming the traffic after a closure of the tunnel due to fire.
Normally the structural parts of the floor will be subjected to less heating and less damage than the ceiling and the lining, due to:

1. the movement of hot air toward the ceiling and the feeding of the fire with fresh cooler air along the floor,
2. the pavement of the floor.

Reduction of strength in the case of fire similar to the mechanisms mentioned for the lining.

The consequences for the floor are:

The floor will be subjected to high point loads, giving rise to high shear forces.

5.12 Anchorages, Fire Behaviour, Concrete and Reinforcement

Internally in lining and other main structures, bond necessary to obtain shear and bending capacity. Similar for Secondary structural elements like suspended ceilings, finally anchorage is necessary for fixation of equipment like jet fans etc. inside the tunnel.
The installation of fire protection materials should be done with anchors having the following properties:

- The diameter should be limited to maximum M6, in order to reduce the heat sink effect through the steel anchor into the concrete. It is reported that thicker anchors can create a local spalling effect of the concrete. This local effect is only temporary because the spalling will spread all over the surface once a small part of the concrete is directly exposed to fire.
- The use of stainless steel anchors is recommended. Types that can be used are A4, 316, 1.4401 and 1.4571. In some countries even higher requirements are applied.
- If necessary a washer must be used to avoid a pull through effect when the system is exposed to dynamic loads
- The anchors should be suitable for use in the tension zone of concrete (cracked concrete)
- The anchors should be suitable for use under dynamic loads

Cast-in items

Cast-in item shall be considered due to failure of their own function: (anchorages for installations for jet fans for example, may fail and the fans will drop). Furthermore the influence on the segments shall be considered. The thermal expansion etc. of the cast in item can be compared with the concrete, in order to consider damage to the structure from heating of the cast in item. The cast in item can function as a path for the heat into the concrete (for large items only).

On the other hand box-outs hollow parts and smaller voids can function as drains for the migrating water and may reduce the spalling in this area.

5.13 Concrete Spalling

When subjected to intense fire, concrete will spall. This was demonstrated in connection with the fire, which occurred in the Dania tunnel fire in June 1994, and the Channel Tunnel fire on 18 November 1996 and the Mont Blanc and St. Gotthard tunnel fires, as well as at a number of other occasions since the start of the century.

The objective of the present review of mechanisms of concrete spalling has originally been to obtain the knowledge necessary for performing a proper design of fire testing experiments suitable for investigation of the rate of progress of concrete spalling. Furthermore, and equally important, is to obtain the knowledge necessary for proper interpretation of test results.

The review has been performed by conducting both a literature survey and discussions with experts in the field of concrete spalling. The persons and literature consulted are indicated in the list of references of this note.

5.14 Mitigation Technology for Tunnel Structures

5.14.1 Bored Tunnel (Horse Shoe Tunnel)

In-situ concrete lining and sprayed concrete lining; it is verified thorough experimentation on actual tunnels that horseshoe tunnels are generally not prone to severe damages in fires, water flood and structure collapse. These cases are: EUREKA - Repaaford Tunnel (Norway), Memorial Tunnel (USA), Nihonzaka Tunnel (Japan), Mont Blanc Tunnel (France - Italy), Tauern Tunnel (Austria).

5.14.2 Circular Bored Tunnel (Shield Tunnel)

In shield tunnels, there are high dense concrete with high strength segment for main structure which will be spalling down by high temperature in short time, in case of fires and also may deemed to be difficult to repair them after failure. Therefore it is necessary to discuss on installation of fire resistance materials in them.

Especially as far as the fire resistance policies in shield road tunnels, the above two methods are considered typical. Segment ring in shield tunnels theoretically employ pressure and additionally, in case of concrete segments, they are of high density and high strength that when subjected to direct fires, this will result in spalling damages at a severe degree. In the case of shield tunnels, the damages on segment rings are strong enough to affect the entire tunnel.

Figures 5.1 shows the Trans-Tokyo Bay Expressway Tunnel in Japan (TTB) standard cross-section and Figure 5.2 shows the same of Elbe Tunnel of Germany, respectively. On the one hand, the 4th Tunnel has an outer diameter of 13.75m, and an inner diameter of 12.35m (segment thickness of 70cm).

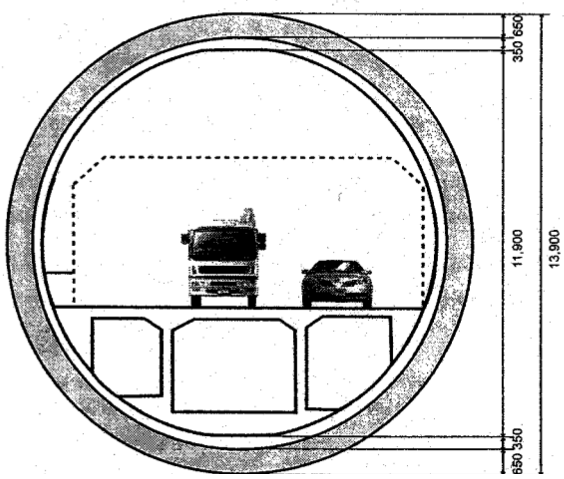


Figure 5.1 Standard TTB Cross-Section[61, Kumagaigumi, Hazama]

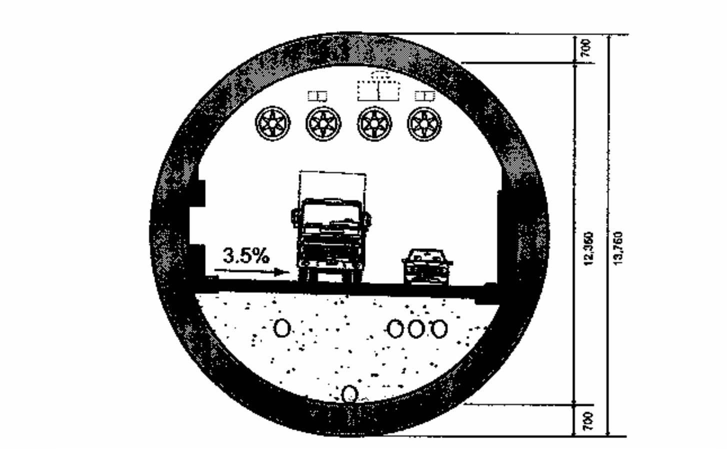


Figure 5.2 Standard Cross-section of No.4 Elbe Tunnel[62, Bundesrepublik Deutschland]

When to compare the main characteristics of these two tunnels:

- In TTB tunnel, there is a secondary lining of 35cm thickness. Therefore, the effective inner diameter of the tunnel has become smaller than that of No. 4 Elbe Tunnel.
- On the other hand, in No.4 Elbe tunnel, without using a secondary lining, it is planned to install fire resistant material, and therefore, the effective space above the carriageway is larger than that of TTI3 Tunnel.

Both these tunnels are underwater tunnels, that it is necessary to consider the buoyancy of the tunnel bodies. In TTB Tunnel, this secondary lining plays the role of counter weight suppressing buoyancy, in addition to the protective effect it provides on the segment itself. Therefore, it has become possible to use the passage below the carriageway as escape route and an access path in emergencies.

On the other hand, it is necessary to adopt anti-buoyancy policies using passage below the carriageway as a counter weight. As described in the above two categories of examples, there exist two approaches for shield type road tunnels with large cross-sections.

5.14.3 Immersed Tunnel

Both concrete elements (RC, PC), and steel elements are normally placed on the bottom of undersea with high pressure, stress and strain. These may be deemed to be severe damaged if these concrete elements are prone high temperatures due to fire. So many immersed tunnels in Europe are installed board and spray type of fire protection materials.

5.14.4 Tunnels of Rectangular Cross-sections with Open-Cut and Cover Method

Since high stress and strain force to each members are similar to those of submerged tunnels, damage to them in the event of fire is believed the same. Therefore, methodology for fire resistance material is similar as in submerged tunnels, however, there are several advantages in case of thickness setting of elements (structural margin), and repairs etc. than the submerged tunnels.

5.14.5 Mitigation measures for protection of reinforcement and concrete and steel in general

Concrete and steel performance variation due to temperature rise

Generally in structural design, permissible stress in structural members is assumed to be within the range of 30% - 50% of the compressive strength of concrete by the suitable scale of fire with comprehensive risk assessment.

According to Figure 5.3, if the initial strength is maintained at the level of 100%, temperature of concrete is set to be in order of 350°C as the limit. This way of thinking agrees with RWS and the research findings of TNO[63, TNO].

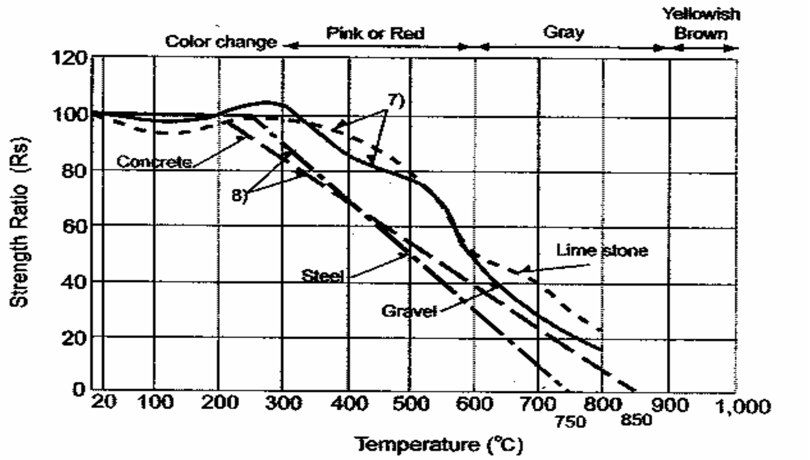


Figure 5.3 Compressive strength of concrete after temperature increase

The temperature at which spalling can occur will vary depending on a number of factors such as, the concrete strength, cement water ratio and the quality of aggregate. The relationship between temperature and strength, showed in Figure 5.3, does not indicate any reduction in the strength of the concrete up to 200°C.

Regarding to the effect of temperature on concrete, the RWS described as next[66, TNO]. Figure 5.3 shows the effect of temperature on the strength of concrete and steel. The strength of concrete is still 100 % at a temperature of approximate 200°C and ends at 750°C. The effect of temperature on high tension steel is worse than on reinforced steel. Before 1992 we only had one safety coefficient to calculate the safety of concrete structures built in the Netherlands, and this was 1.7. This means that if the strength of the concrete is reduced to 100% / 1.7 or 59%, the safety of a structure is 1.0, in other words it is no longer a safe structure (very simplified). The graph shows that the temperature of concrete and steel can rise to approximately 450°C before a structure fails.

However, based on experience, the accepted maximum temperature of 380°C is applied to concrete and 2500°C to steel for the following reasons:

- Both concrete and lining have a high thermal capacity. They hold the heat and even after the fire ahs been extinguished, the temperature within the concrete continues to rise;
- To prevent the concrete so badly damaged that too much concrete has to be replaced after the fire;
- Large shear forces are concentrated near the supports (walls), at places where there is no shear reinforcement, which occurs especially in the older tunnels;
- Still to have a certain safety, as 450°C is a very simplified temperature limit.

Steel:

- It is true that the strength of steel is not reduced at 250°C, but deflections occur. Due to the permanent load on the roof of the tunnel, the chance is high that the defections will be permanent.

According to Figure 5.3, it can bethought that hair crack or spalling already exists over the concrete surface, which has already been affected by high temperature, in the area of temperature where initial strength gets lower (decreases). Therefore, certain maintenance is required for the part which has lost some strength if it is affected by the heat over 350°C for a short period of time. Therefore, it is necessary to limit the temperature that the concrete is subjected to a range within 350°C - 400°C. In any of these cases, if the temperature concrete is subjected to in a fire is between 1000ºC and 1350ºC (RWS standards), set at planning or design stages, it is required to provide materials that shield an approximate maximum temperature of 1,350ºC. (Figure 5.3 and Figure 5.5).

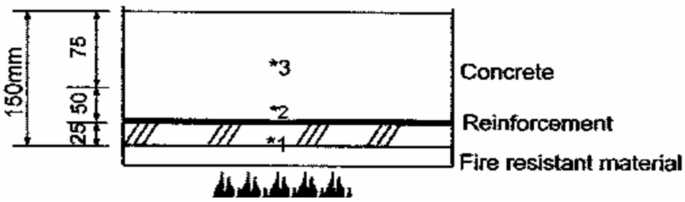


Figure 5.4 Schematic Cross Section of Concrete Member With Fire[62, Bundersrepubli Deutchland]

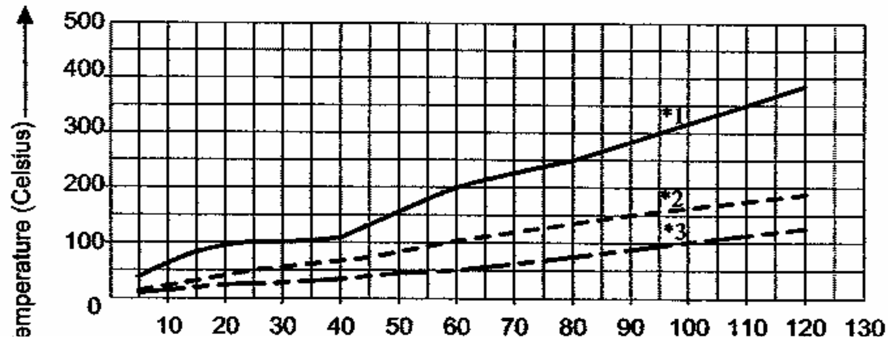


Figure 5.5 Time Temperature Curve at Concrete Surface and inside when Fire Prevention materials are Used[62, Bundersrepubli Deutchland]

when fire prevention materials are used

The following 4 types are the most fundamental types of protecting concrete against fire;

1.Method where fire preventive materials are fixed or wrapped on structural surface for strength protection
2.Upgrading fire resistance of concrete itself
3.Method that delays heat transfer to concrete surface
4.Secondary lining

5.14.6 Mitigation measures for protection of ceilings

In road tunnels ceiling ventilation ducts are installed for transverse ventilation, semi-transverse ventilation and some kinds of longitudinal ventilation lateral flow, semi-lateral flow, or partially in longitudinal flow systems.

There are two different cases in the structure of this ventilation duct. The one is a part of the tunnel's structure itself, which basically receives stress and strain, and the other is not apart of the structure in terms of live loads. The former one should be well heat resistant as the ceiling duct is a part of the structure and the entire structure would be influenced in case the duct is damaged. This is mainly the case for immersed tunnels and tunnels of rectangular cross-section with cut and cover construction method (Figure 5.6).

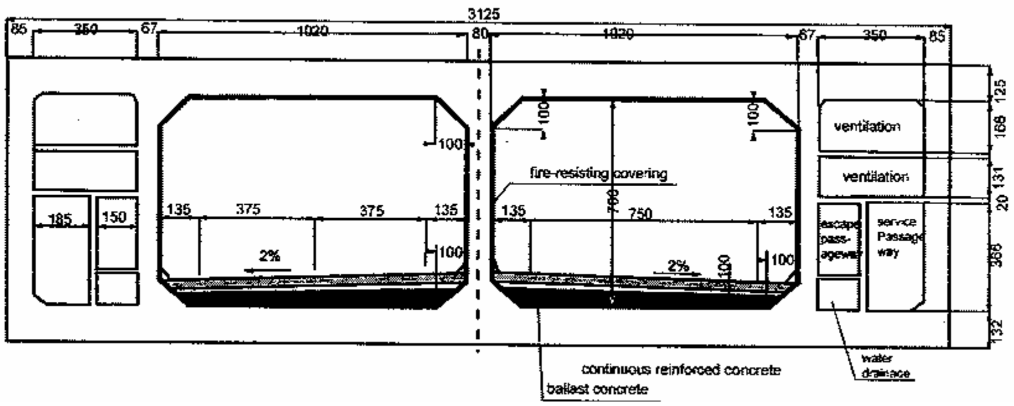


Figure 5.6 Cross section of Liefkenshoek Tunnel, Antwerp, Belgium

On the other hand, it is the popular (standard or general) way of design and construction, which supports structure of the entire tunnel with the entire horse shoe and also resists against the weight of itself and the aerodynamic load, for the one such as the bored tunnel with horse shoe section as shown in Figure 5.7.

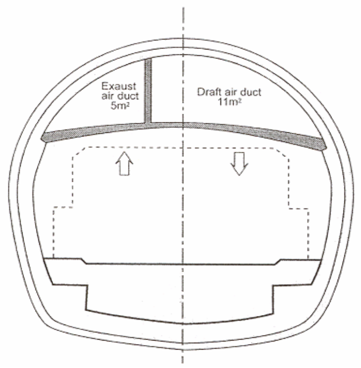


Figure 5.7 Typical Cross section of horse shoe, transverse ventilation tunnel

The ventilation duct is very important for the function of smoke and flame control especially in case of fire the top part of the fire may reach the maximum temperature temporally. We should have more examination (investigation) how the function of exhaust should be ensured in case of fire if it is considered that exhaust is more important than normal ventilation.

It is well known among the engineers of tunnel's ventilation that large exhaust ports is very useful in order to control the fume in case of fire. This large exhaustion part is usually equipped with damper and it is built to be activating (working) when the temperature is under 2500°C to 4000°C

Therefore, it is considered to have heat resistance material for the inner duct as well as for the underneath of the ventilation duct (road side) in order to make the ventilation equipment and the ventilation duct work properly. The reason is that we can expect some damages over the tunnel structure when the temperature within the duct heats up over 400°C, which is the limit of the collapse of concrete structure.

The basic concept for fire protection methodology could be applied same systems for tunnel lining. However, at the lower surface of ceilings at fire point, will be maximum temperature within short period, in the mean time, inside of exhaust air ducts also increase to high temperature.
The mitigation measures of exhaust duct for fire protection, the sandwich structures by fire protection material should be considered.

5.14.7 Mitigation measures for protection of the supported floor/deck

Due to the buoyancy energy of heated air in the case of fire, the thermal conditions of supported floor/deck is lower than ceiling in tunnel space. However if in the case of exhaust air duct is located at below of floor/deck, it will be heated up by the exhaust air, and also flammable spillage should be expand on the pavement, then to get into the drainage system.

In the case of fire, supported floor/deck and related facilities should be checked for their behaviour during in fire, if necessary execution of fire protection will be implemented.

5.14.8 Mitigation measures for protection of Anchorages in traffic space

Regarding to fire protection for suspending structures and other systems attached to the ceiling or walls, PIARC described below.

All the fittings used for the fixing of equipment to the structures should be considered in relation to the fire situation. This means that use of the usual plastic plugs and similar devices should be prohibited. This material will either soften or melt at high temperatures, resulting in flames. Further research will have to demonstrate to what extent special plastic is suitable for fixing equipment inside the tunnel.

Also steel plugs and anchors should be checked for their behaviour during a fire situation. The tensile stress reduces at high temperatures. The calculation of these anchors should be based on the maximum temperatures at which the anchoring should be still properly working.

A distinction must be made between major equipment, which should remain in function during an emergency situation, and equipment whose functions may not be needed during or after a major disaster.

The minimum requirement is that heavy equipment should not fall down when evacuating users or rescue personnel are in the tunnel. This means that no heavy item must fall under 400°C--450°C during the time necessary to fight fire (in a tunnel, such temperatures can produce a radiation level of about 5 kW/M2. which is the maximum tolerable value for firemen).

As aluminium loses its strength at a temperature of approximately 550°C, is it recommended to consider the use of aluminium materials in a tunnel critically. Alternative materials are steel stainless steel.
Especially, jet fans which located at tunnel ceiling or side wall for ventilation and smoke control, which are one of the heaviest equipments.
In the case of fire, the fixing part at the top of ceilings for fans will be loose and equipments will be fall down to carriageway due to high temperature and weaken of anchorage.

Therefore, these heavy equipments should be mounted on the crossbeam which are fixed at side wall. Because of temperature distribution at side wall is slightly lower than temperature at ceiling (Figure 5.8).

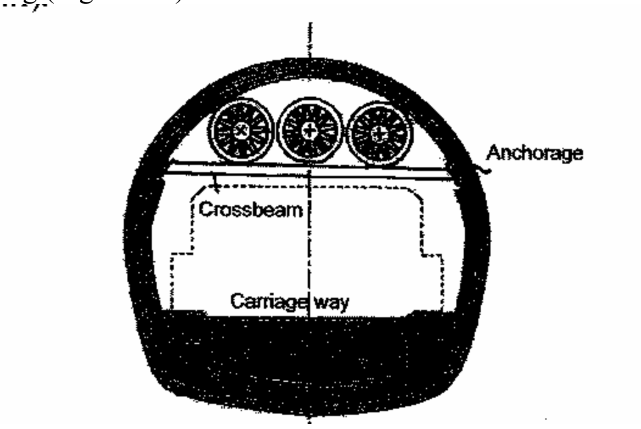


Figure 5.8 Typical support system for ventilation fans

5.14.9 Protection of Structural Elements

The following are the most fundamental methods for protecting concrete against fire.

- Upgrading fire resistance of concrete itself
- Application of a coating that delays heat transfer to concrete surface
- Secondary lining
- Installation of fire protection materials

(1) Required performance

As for the methods of protecting concrete structure In case of fire, these are the most popular. The basic installation types are, panel and spray types.

The characteristic of this method of construction is that it can be applied for both new and old tunnels. Especially, it is very useful in order to improve the fire resistance of the tunnels which was constructed in the past.

When installing fire prevention material in road tunnels, it is necessary to consider the following requirements apart from the most important aspect of fire prevention qualities.

(A) Installation strength

Interior of traffic tunnels face severe pressure differential due to passing traffic.

Numerous tunnels have had face pressure differentials measured in the order of 25 kgf/ff. On the other hand, it is reported that rail tunnels experience approximate pressure differentials of 600 kg FM2 when high speed trains pass the tunnel. Therefore, reciprocal differentials of this nature should be withstood by the fire protection material including the fixation materials and sub-frames. Test evidence by an authorised lab should be presented.

(B) Prevention of secondary effects
As tunnel temperature is extremely high, fires, smokes and toxic gases may occur. Hence it is necessary to use materials that do not give rise to such effects.

(C) Harmful effects of material
It is necessary to assure that the material is free from harmful effects to humans during tunnel construction. Materials that are produced in production facilities, having an NEN-ISO 14001 (environmental) certificate are therefore preferred.

(D) Construct ability
As far as construction cost and quality assurance of fire prevention material are concerned, it is necessary to minimise loss in installation, control of rebound water volume, consideration for adjustment of standard measurements in panel-type fixation are exercised. Further, to prevent hindrance to fire resistance qualities, construction standardisation is adopted.

(E) Freezing and thawing resistance
Especially when the fire prevention materials are fixed in tunnels where temperature differentials year around are severe, they are subject to reciprocal effects of drying (thawing) and wetting (freezing) due to precipitation outside the tunnel. Therefore, it is important that freezing and thawing resistance in these materials is evaluated.

(F) With reference to point (E), fire protection materials in tunnels can get wet due to (minor) leaks in the structural concrete tunnel lining, which will cause a situation where the fire protection materials will get fully saturated with water. High relative humidity or water spray due to passing vehicles (in case of wet road surface) will also cause water absorption of the fire protection material.
It is reported that some water saturated fire protection materials will not be able to withstand a fire anymore. This is due to the fact that the water evaporates (expansion ratio from water to steam is 1:1700) and the vapour can not escape through the pores, creating pore pressure build up in the material itself, causing a spalling effect and decomposition of the material, just like concrete will spall.
Test evidence by an authorised lab should be made available, proving that fire protection materials can meet the fire protection requirements with <5% (by weight) humidity and also when fully saturated with water.

(G) Repair and Maintenance

(H) Vandalism, terrorism and explosion measures

It has also been reported that the water-cement ratio and thereby the strength of the concrete may influence the shape of the strength reduction curve. Finally the load condition during the heating may influence the strength reduction.
It is reported that the strength may decrease until a week after the fire has ceased. As the reduction of strength is partly due to dehydration, some of the strength can be regained by rehydration. However, the fire resistance can only to a limited extent benefit from this phenomenon. Direct cooling of the heated concrete will in most cases have a detrimental effect.
The first estimations of fire resistance must in most cases be made during design and based on

assumptions on the characteristics of the concrete. For segmental lining there might be the chance to confirm or to update these assumptions during the construction process. Segments may be rejected for reasons not related to the concrete quality (e.g. out-of-tolerance geometry). Samples can be taken from these segments and tested at different temperatures. The cost of this exercise is small compared to other site tests. As the fabrication of segments is often very controlled and homogeneous relatively few samples will suffice. The observed uncertainty in strength and stiffness reduction can be used actively in the subsequent analyses.
See also state of the art papers on the subject of strength and stiffness reduction in [42, Schneider], [43, Bažant], and [41, Phan] as well as reference text books as [18, Anderberg].
As the concrete on the intrados, the centre and the extrados experience very different temperatures the combination of reduced stiffness and reduced strength must be determined at suited intervals during and after the fire.
Due to the reduced stiffness the maximum strength of heated concrete will be achieved at higher strains. It is worth to mention that strain compatibility must be maintained, the remaining strength may hence not be utilised fully, depending on the load and the deformations. Due to strain compatibility the concrete which has been subjected to the highest temperatures will be further reduced in strength. It will be necessary to estimate the stress-strain relationship for an estimate of the applicable remaining strength.

5.14.10 Type of Fire Resistance Materials

As far as the fundamental concept of fire resistant policies are concerned, considering the temperature rise of between 1,000ºC – 1,350ºC within a short period by vehicle fire, it is common to allow for temperatures as high as the permissible temperature of fire resistant materials of around 1,350^{o}C, in case of concrete and reinforcements.

On the other hand, when concrete is heated slowly during a considerable length of time, thereafter cooling it slowly, it is said that the loss of strength in concrete due to heating is small. Recently, a new technological innovation [14)] has been introduced where punch metal studs are inserted into concrete structure at regular intervals on the surface, thereby controlling the loss of concrete strength through delaying the heat dissipation into concrete surface. It is expected that there would be less (only little) drop in the strength of concrete in case of general building fire compare with road tunnel fire.

From this background, it is the way that we improve the level of decrease in the concrete strength by delaying the heat transfer towards concrete material in case of tunnel fire and it should be improved more.

Spray Type

Fundamental performance of the spray type is as follows:

A. Major characteristics

- Even in case of complicated cross-sections, construction is simple
- At narrow locations like pipe sleeves, construction is very appropriate
- Renovations are simple at places where concrete is damaged after the concrete surface has been cleaned to create a proper bond

B. Cases needing improvement

- It is necessary to do make adjustments if the adhesion of concrete lining varies due to surface conditions. This may mean that a mechanically fixed wire mesh, made out of stainless steel or plastic coated steel, has to be installed

- Since the finished surface is not flat, cleaning is troublesome, and again if flat surfaces are needed for certain cases, then special considerations should me made
- To ensure a homogenous finish and resistive effects at required level, then it is necessary to maintain a consistent level in technical standards
- Thickness control of the applied material must be carefully controlled

C. Basic performance

1. Organic coatings [58, EUREKA; EU 499]

- They produce toxic fumes and dense smoke under fire conditions, which make them unsuitable for use in any situation where life safety is an important consideration.

2. Inorganic coatings[66, TNO]

- They are produced as factory controlled cement/ vermiculite premixes, which are spray, applied directly to the internal surfaces of the tunnel lining.
- Vermiculite cements are essentially inorganic materials and therefore will not bum.
- The can therefore produce no smoke or toxic fumes and are certified non-combustible.
- This means that they can be used in areas where life safety must be considered.
- They can be spray applied quickly to the tunnel surface and if damaged, can be easily repaired (by hand in small areas) after the surface has been properly prepared
- Their fire performance is very predictable and often provides protection to the concrete substrate for periods of time in excess of its intended fire rating.
- Instances have been documented where vermiculite cements have prevented concrete substrates from spalling under extreme fire conditions for periods of up to 24 hours, at which time the concrete / fire proofing interface has reached an equilibrium.

Panel / Board systems

Specific properties of board systems for the fire protection of concrete structures:

- Board materials can easily be checked for thickness and thus the application can be guaranteed to meet with the specifications as per the tested constructions.
- Being mechanically fixed board systems can cope with the dynamic loads from passing vehicles (pressure / de-pressure loads)
- In general, cement based board materials are unaffected by water ingress in the tunnel and combustion gasses.
- Board systems in general require no maintenance. In the case that the concrete substrate needs to be inspected, the boards can be easily and quickly removed and reinstated, thus maintaining the fire protection layer at all times.
- Board materials are produced in factories, ensuring the quality of the material and a correct composition. Most board materials are produced in NEN-ISO 9001 and NEN-ISO 14001 certificated factories.

Two methods of installing boards systems can be defined:

(1) Lost shuttering method: the boards will be installed in the form-work, on top of the load bearing plywood. Screws are partly inserted into the fire rated boards to create a bond between the panel and the concrete. After the reinforcement is installed the concrete can be poured. After the extraction of the form-work the fire rated boards will stick to the concrete thus creating the fire protective layer. The screws are anchored into the concrete creating a firm bond. Due to the very low labour costs of this system, it's intensively used in cut & cover and immersed tunnels, rather then having to apply a fire protection layer afterwards.

(2) Post installation: in both new and existing tunnels the post installation method can be chosen. The boards can be installed, either directly to the concrete or on a subframe.

- Calcium silicate boards are suitable for installation on flat concrete substrates.

- Calcium silicate aluminate boards may be installed on curved concrete substrates and have an improved thermal performance over conventional board systems.

5.14.11 Development of Fire Resistant Concrete

With the objective of protecting the tunnel structure from high temperatures in case of fires, fire resistant concrete has been developed, having upgraded the quality of concrete. In one such method, it has been attempted to increase the fire resistance of concrete by mixing chemical compounds to those existing in concrete, however, this method is yet to be executed in reality. It is expected to meet new innovations of these fire resistant concrete types, thereby minimizing the cost of new tunnels to be constructed in future.

5.15 Current Production Lists of Fire Resistant Materials

Many materials are currently manufactured for the protection of structural elements in a tunnel structure. Many materials are similar to those used for the traditional protection of buildings in providing a certain fire rating as required by local codes and ordinances. These local regulations should be consulted in the selection and type of material to be used for protection of the structural elements of a tunnel system.

MATERIAL	TYPE MATERIAL	TYPE CONST.	ATTACHMENT
Calcium silicate board	Panel	Pre-manufactured panel	Anchor bolts
Light weight concrete	Light weight aggregate	Attached to surface	Spray applied
CIP Concrete	Cement	Cast-in-place	Integral with structure
CIP Concrete/fibers	Cement with Poly fibers	Cast-in-place	Integral with structure
Shotcrete	Cement/additives	Spray	Spray
Shotcrete /fibers	Cement/ additives/ poly fibers	Spray	Spray
Mineral wools	Mineral wool in cement matrix	Spray	Spray
Ceramic Refractory	Refractory cement/ceramic mix	Spray	Spray

Table 5.1 Typical Fire protection materials for tunnels

6. Summary and Recommendations

After extensive deliberation the Working Group has determined that road tunnels should be protected from the influences of a high temperature fire. This is necessary to provide safe evacuation of the public, working time for fire and rescue personnel, reduce non-operational time and economic loss after a fire and to prevent the catastrophic collapse of the structure. The Working Group has also acknowledged that many of the member nations have already in place strict guidelines for the protection of underground structures, and the Working Group hopes to enhance those standards by providing the following recommendations to be used as guidelines for the protection of road tunnels. These recommendations were developed by an extensive review of codes, regulations, ordinances, research and case studies of tunnel fires. These guidelines are intended to provide criteria for the protection of existing as well as new road, (highway) tunnel construction. The information provided herein, may be applicable to other types of tunnels, providing careful consideration is made as to the tunnel usage, and types of materials that are transported within the tunnels. These guidelines are not intended for passenger rail tunnels, which will be covered in a parallel document to be developed by the Working Group in the future.

In agreement with PIARC, the Working Group recommends that the design criteria presented in table 6.1 be used according to the type of structure and traffic in the tunnel.

Traffic Type	Main Structure				Secondary Structures[4]			
	Immersed or under/inside superstructure	Tunnel in unstable ground	Tunnel in stable ground	Cut & Cover	Air Ducts [5]	Emergency exits to open air	Emergency exits to other tube	Shelters[6]
Cars/ Vans	ISO 60 min	ISO 60 min	[2]	[2]	ISO 60 min	ISO 30 min	ISO 60 min	ISO 60 min
Trucks/ Tankers	RWS/ HC_{inc} 120 min[1]	RWS/ HC_{inc} 120 min[1]	RWS/HC inc 120 min[1]	RWS/HC inc 120 min[1]	ISO 120 min	ISO 30 min	RWS/ HC_{inc} 120 min	RWS/ HC_{inc} 120 min[7]

Table 6.1: Joint Recommendations of PIARC and ITA

[1] 180 min maybe required for very heavy traffic of trucks carrying combustible goods

[2] Safety is not a criteria and does not require any fire resistance (other than avoiding progressive collapse). Taking into account other objectives may lead to the following requirements:
- ISO 60 min in most cases
- No protection at all if structural protection would be too expensive compared to cost and inconvenience of repair works after a fire (e.g. light cover for noise protection)

[3] Safety is not a criteria and does not require any fire resistance (other than avoiding progressive collapse). Taking into account other objectives may lead to the following requirements:
- RWS/HC_{inc} 120 min if strong $_{\text{protection is}}$ required because of property (e.g. tunnel under a building) or large influence on road network
- ISO 120 min in most cases, when this provides a reasonably cheap protection to limit damage to property
- No protection at all if structural protection would be too expensive compared to cost and inconvenience of repair works after a fire (e.g. light cover for noise protection)

[4] Other secondary structures should be defined on a project basis

[5] In case of transverse ventilation

[6] Shelters should be connected to the open air

[7] A longer time may be used if there is a very heavy traffic of trucks carrying combustible goods and the evacuation from the shelters is not possible within 120 min

The majority of this document is also relevant to rail tunnels and for this reason, a short study for rail tunnels is recommended to form Part B.

The Working Group decided that the best method of protecting road tunnels is to provide guidelines for the thermal protection of the various elements of a tunnel. This was decided due to the fact that there are so many tunnel sub systems and types of interior structural elements, it would be impossible to identify each and every type and provide a specific fire protection system for them. Therefore the Working Group established two-hour temperature thresholds for the protection of various materials and specific elements as follows:

- Concrete: Typical structural elements wall, ceilings, partition walls, cast-in-place concrete etc: should be protected to limit their concrete surface from a maximum heat rise at surface of 380° C
- Precast concrete elements: including high strength concrete segments, precast planks etc should be protected to prevent spalling and collapse
- Concrete Ceilings shall be suitably protected from collapse for a minimum of two (2) hours with a maximum temperature rise at the surface of 380°C
- Clay brick masonry and dimension (asher) stone are not considered critical and do not need protection.
- Segmental Steel liners shall be protected at the surface for a maximum temperature rise of 550°C
- Segmental Cast Iron liners shall be protected at the surface for a maximum temperature rise of 550°C
- Leaded Joints in segmental liners shall be protected for a maximum heart rise of 200° C
- Ceramic fired tile finishes of tunnels shall be protected from explosive spalling to a maximum temperature rise of 200°C. (Note the use of ceramic fired tile finishes in new tunnels should be avoided)
- Steel structural elements and ceiling hanger rods shall be protected for a maximum temperature rise of 550°C
- Cast Iron structural elements and ceiling hanger rods shall be protected for a maximum temperature rise of 550°C

  More sophisticated assessment methods could be used to develop more economical solutions taking into account other factors influencing:

  - Temperature Gradients
  - Heating Rates
  - Structural Load levels

- Stainless steel structural elements and ceiling hanger rods shall be protected for a maximum temperature rise of 800°C

- Anchorages must be designed for a minimum factor of safety of 3.5 for fixity of anchor. Fixity is described as the bond/ attachment to the substrate

- Epoxy resin anchors shall be protected for a temperature heat rise at a depth of 6 cm from the surface of 200°C. (Note: France prohibits the use of epoxy anchors in environments that may be above 300°C)

- All epoxy anchors shall be designed with the bond zone not less than 6 cm from the surface of the concrete or material that the anchor is being installed within.

- Lead shield anchors or anchors with lead components are not permitted for structural or emergency equipment supports, (i.e. dampers, fans, etc.).

- Brass, zinc or other low melting point anchors are not permitted for structural or emergency equipment supports, (i.e. dampers, fans, etc.)

- All fireproofing materials shall not be degraded in regard to bond to the substrate or in fire resistance rating from the presence of water.

- All materials incorporated in tunnel structures or within tunnels shall be non-toxic and non-flammable.

- All emergency equipment to be installed shall conform to PIARC Guidelines and local codes, ordinances and regulations

- Emergency access/escape areas shall be designed not to exceed a maximum temperature of 40°C in areaways as per PIARC Guidelines and local codes, regulations and ordinances.

The information provided here is intended to act as a guideline and is for informational purposes. Specific measures for the protection for each structure is site specific and must be designed on an individual basis Any inquiries in regard to the information presented here should be sent to the International Tunnel Association Working Group 6 via its web site at www.ita-aites.org or to the Animateur of the Working Group. Mr. Henry A. Russell c/o Parsons Brinckerhoff Quade & Douglas Inc., via e-mail at Russell@pbworld.com.

7. Road Tunnel Fire History

Fire Accident's in the World's Road Tunnels

Year	Tunnel Length	Location Country	Vehicle Where Fire Occurred	Most Possible Cause of Fire	Duration of Fire	CONSEQUENCES Conse-quences People	Damaged Vehicles	Structures and Installations
1949	Holland 2,550 m	New York USA	Lorry with 11 tons of carbondisulfide	Load falling off lorry explosion	4 h	66 Injured smoke inhalation	10 lorries 13 cars	Serious Damage Over 200 m
1974	Mont Blanc 11,600 m	France-Italy	Lorry	Motor	15 min	1 injured		
1976	Crossing BP-A6 430 m	Paris France	Lorry with drums of 16 tons poly-ester film	High Speed	1 h	12 light injuries (smoke)	1 lorry	Serious damage over 150 m
1978	Velsen 770 m	Velsen Nederland	4 lorries 2 cars	Front-rear Collision	1 h 20min	5 dead 5 injured	4 lorries 2 cars	Serious damage Over 30 m
1979	Nihonzaka 2,045 m	Shitzuoka Japan	4 lorries 2 cars	Front-rear collision	159 h	7 dead 1 injured	127 lorries 46 cars	Serious Damage Over1,100 m
1980	Kajiwara 740 m	Japan	1 truck with 3600 litres of paint in 200 cans	Collision with side wall and overturning	n/a	1 dead	1 truck, 4t 1 truck 10t	Serious Damage Over 280 m
1982	Caldecott 1,028 m	Oakland USA	1 car, 1 coach, 1 lorry with 33000 litres of petrol	Front-rear colli-sion	2 h 40min	7 dead 2 injured	3 lorries 1 coach 4 cars	Serious Damage Over 580 m
1982	Salng 2,700 m	Mazar-e-Sharif-Kabul Afghanistan	Soviet Military column. At least one petrol truck	Unknown, probably mine explosion	n/a	>200 dead	n/a	n/a
1983	Pecorila Galleria 662 m	Gênes Savone Italy	Lorry with fish	Front-rear colli-sion	n/a	9 dead 22 injuries	10 cars	Little Damage
1986	L'Arme 1,105 m	Nice France	Lorry with trailer	Braking after high speed	n/a	3 dead 5 injured	1 lorry 4 cars	Equipment de-stroyed
1987	Gumefens 343 m	Berne Switzerland	1 lorry	Front-rear collision	2 h	2 dead	2 lorries 1 van	Slight damage
1990	Røldal 4,656 m	Røldal Norway	VW transporter With trailer	n/a	50 min	1 injured	n/a	Little damage
1990	Mont Blanc 11,600 m	France-Italy	Lorry with 20 tons of cotton	Motor	n/a	2 injured	1 lorry	Equipment de-stroyed
1993	Serra Ripoli 442 m	Bologne-Florence Italy	1 car+lorry with rolls of paper	Collision	2 h 30min	4 dead 4 injured	5 lorries 11 cars	Little damage
1993	Hovden 1,290 m	Høyanger Norvay	Motor cycle 2 cars	Front-rear colli-sion	1 h	5 injured in the collision	1 motor-cycle 2 cars	111 m insulation material de-stroyed
1994	Huguenot 3,914 m	South-Afrika	Bus with 45 pas-sengers	Electrical fault	1 h	1 dead 28 injured	1 coach	Serious damage
1995	Pfander 6,719 m	Austria	Lorry with trailer	Collision	1 h	3 dead in the collision 4 injured	1 lorry 1 van 1 car	Serious damage
1996	Isola Delle Femmine 148 m	Palermo Italy	1 tanker with liquid gas + 1 little bus	Front-rear colli-sion	n/a	5 dead 20 injured	1 tanker 1 bus 18 cars	Serious damage, tunnel closed for 2.5 days
1999 14 July	Mont Blanc 11,600 m	France-Italy	Lorry with flour and margarine	Oil leakage Motor	n/a	39 dead	23 lorries 10 cars 1 motorcycle 2 fire engines	Serious damage, tunnel reopens 22.12.2001
1999	Tauern	A10 Salz-	Lorry with paint	Front-rear colli-	n/a	12 dead	14 lorries	Serious damage

Year	Tunnel Length	Location Country	Vehicle Where Fire Occurred	Most Possible Cause of Fire	Duration of Fire	CONSEQUENCES Conse-quences People	Damaged Vehicles	Structures and Installations
	6,401 m	burg-Spittal Austria		sion 4 cars and 2 lorries		49 injured	26 cars	
2000	Seljestad 1,272 m	E134 Drammen-Haugesund Norway	The trailer truck that caused the multiple collision had a diesel fire in the engine room before collision	Front-rear collision A trailer- truck pushed a car into 4 cars that had stopped behind another truck	45 min	6 injured	1 lorry 6 cars 1 motorcycle	Serious damage. NOK 1 mill. Tunnel closed for 1 ½ days
2001 28 May	Prapontin 4,409 m	A 32 Torino-Bardonecchia Italy	Romanian truck, loaded with beets	Mechanical problem	n/a	19 injured by smoke	n/a	Closed until 6 June in westerly direction
2001	Gleinalm 8,320 m	A 9 near Graz Austria	Car	Front collision Lorry-car	n/a	5 dead 4 injured	n/a	n/a
2001	St. Gotthard 16,918 m	A 2 Switzerland	Lorry	Front collision 2 lorries	2 days	11 dead	13 lorries 4 vans 6 cars	Serious damage Closed for 2 months

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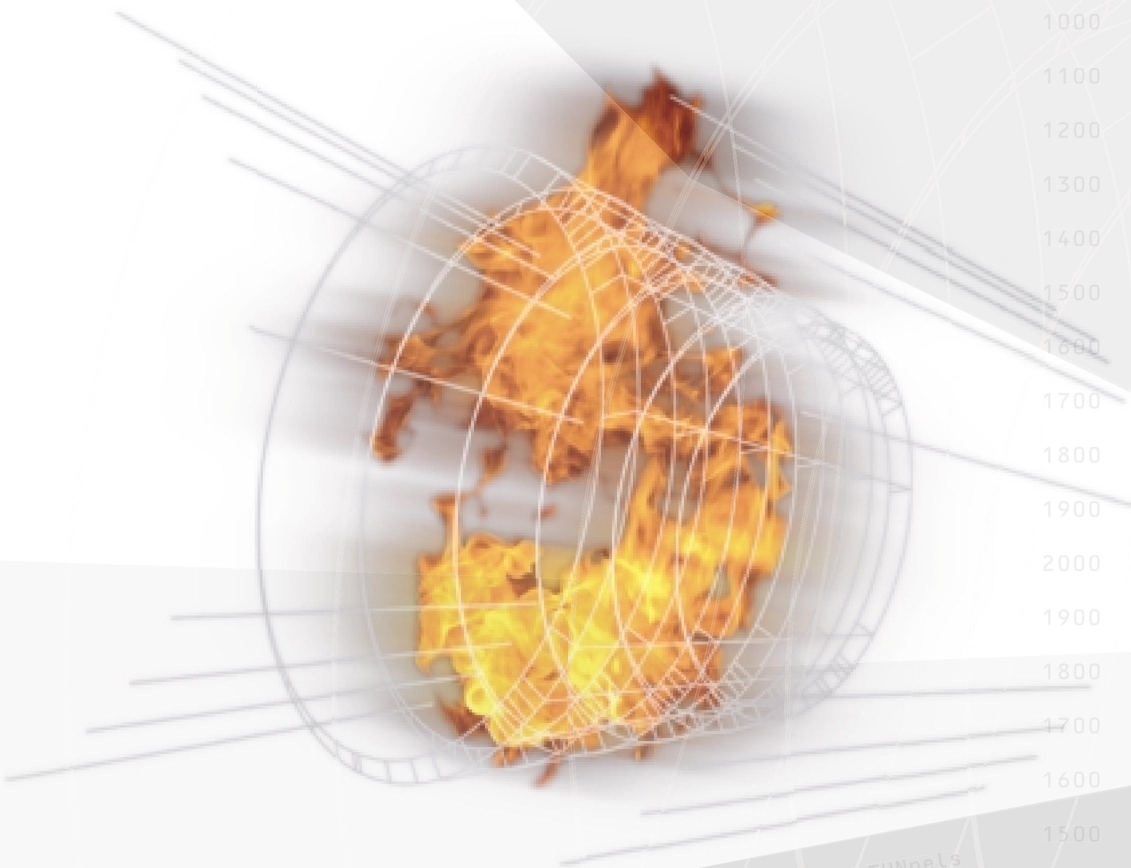
APPENDIX A

RUNEHAMAR FULL SCALE FIRE TEST REPORT - SEPTEMBER , 2003

Edited by:
Jan Brekelmans BSc (TNO Building and Construction Research, Centre for Fire Research)
René van den Bosch BSc (Promat, Tunnel Fire Protection)

RUNEHAMAR

Summary of Large Scale Fire Tests in the Runehamar Tunnel in Norway, conducted in association with the UPTUN Research Program



cost effective, sustainable and innovative UPgrading methods for fire safety in existing TUNnels

Contributions from:
- SP Swedish National Testing and Research Institute, Fire Technology
- SINTEF/NBL, Norwegian Fire Research Laboratory
- TNO Building and Construction Research, Centre for Fire Research
- Promat International NV, Belgium
- Gerco Beveiligingen BV, The Netherlands

Published by:
UPTUN TNO Promat

Content

Foreword

As co-ordinator of the UPTUN project, I am pleased to present this publication on important results of tunnel safety research work. This work was carried out in the framework of a Swedish national and a European research program on tunnel safety. Comprehensive large-scale fire tests have been conducted in the abandoned Runehamar road tunnel in the Western part of Norway in September 2003.

The measurements and preliminary analyses are such that the results will definitely contribute to increase tunnel fire safety levels in Europe. Therefore the initiative for the actual publication of this document was taken by Promat International with the aim to inform tunnel related, interested parties, by means of this summary document.

The work presented would not have been possible without the effort and financial contribution of the Swedish Road Administration, the Norwegian Road Administration, the Swedish Rail Administration, the Swedish Rescue Services Agency, the Swedish Fire Research Board, the Directorate General Research of the European Commission, the UPTUN partners (especially SP, NBL and TNO) and the industrial partners, especially the partners who supplied and installed the passive fire protection system: Promat International N.V., GERCO Beveiligingen B.V.

This document is based on the presentations and papers of the Boras conference on Catastrophic Tunnel Fires, in November 2003.

I would like to thank René van den Bosch (Promat) and Jan Brekelmans (TNO Building and Construction Research) for their editorial work.

Kees Both, PhD
Coordinator UPTUN project

1 INTRODUCTION

Fires in European tunnels in recent years have clearly shown the risks and consequences of fires in large vehicles. Over 20 semi-trailers, for example, were destroyed in a single fire in the Mont Blanc tunnel in 1999. Over 50 people died in these recent fires in road tunnels. Nevertheless, knowledge of the growth and spread of fires in semi-trailers is very limited. The most recent fires in the Eurotunnel (1995), the Mont Blanc tunnel (1999), the Tauern tunnel (1999) and the St. Gotthard tunnel (2001) showed that such fires can develop very high energy releases (150-600 MW), involving a dozen or so vehicles.

Besides the destruction of the tunnel construction and trailers involved in recent tunnel fires, the tunnel tubes themselves were severely damaged by the intensive heat. Due to this, tunnels have been out of service for months and even years after a fire, causing economic loss for the (surrounding) area. There is still a huge gap between the outcome of real fires and of small scale tests. There is a need for more detailed knowledge on how and why various semi-trailer cargos burn so strongly and why they spread so quickly. The high heat exposure from the semi-trailers to the tunnel linings also needs more focus. The only reasonable way of finding an answer to these questions is to carry out systematic large scale experiments that can provide a better basis for the design of technical systems in road tunnels.

The accidents that have occurred in recent years have also revealed the problems facing the fire and rescue services: they have not been able to reach the fire due to the enormous amount of heat and the dense smoke. The discussions after these accidents have included consideration of equipping fire and rescue services with mobile fans that can drive the smoke in a particular direction in order to assist their work. However, this in turn requires improved knowledge of the effects of such fans. What is the effect on the fire of increasing the ventilation? What is the effect on the spread of fire between vehicles? The situation for the fire services was considered in these tests, especially the effects of radiation in the vicinity of the fire, on their ability to approach and fight the fire.
In the frame of a Swedish national and a European research program on tunnel safety, comprehensive large scale fire tests have been carried out in the abandoned Runehamar road tunnel in the Western part of Norway in September 2003.

Semi-trailer fires, similar to the size of the recent fires in Mont Blanc Tunnel (France/Italy) and St Gotthard Tunnel (Switzerland), have been particularly considered. The tests have been conducted by the Swedish National Testing and Research Institute (SP) in collaboration with the UPTUN partners: TNO Building and Construction Research from the Netherlands and the Norwegian Fire Research Laboratory (SINTEF/NBL).

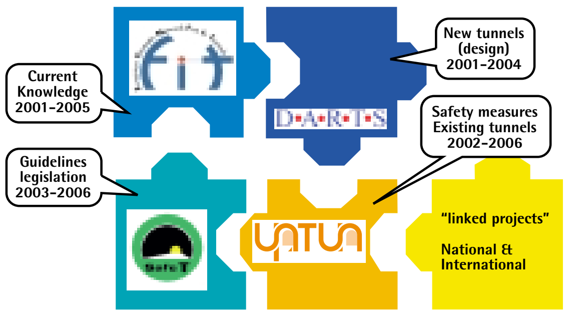
UPTUN

The UPTUN project concerns the improvements with regard to existing tunnels. UPTUN is an abbreviation for 'cost effective, sustainable and innovative UPgrading methods for fire safety in existing TUNnels'.
The UPTUN project was initiated in September 2002 and is co-ordinated by TNO (Netherlands). It is a four year research and development project.

The 41 partners of UPTUN originate from 17 European countries. Several disciplines and professions are incorporated as owners, consultants, universities, research organisations and manufacturers. The partners from Eastern countries take part of the work for some 10%.
It is important to look at tunnels as a system in an environment. Measures to improve fire safety will therefore be studied as a system rather than sub-optimised. Positive as well as adverse interaction should be identified. Socio-economic aspects on the wider region have to be taken into account.
The UPTUN project will play a pivotal role in linking up with:
- various national and international investigations, such as the EC funded research projects and networks: FIT, Darts and SafeT *(see Figure 1)*
- important tunnel associations, such as: International Tunnelling Association (ITA), World Road Association PIARC and the United Nations Economic Commission for Europe

and last but not least,
- national projects, such as the Runehamar tests.

Figure 1 European research projects and networks "fit" well together.



See further: [7] (Paper7), [8] (Paper8), [10] (Ref.1)

2 OBJECTIVES

The objectives of carrying out large scale fire tests in the Runehamar tunnel can be described from a political and technical point of view.

2.1 European Commission

From a political, social and economical point of view tunnels in the Trans-European transport network are very important. In a political sense mobility is of utmost importance for a competitive, open European market. This can only be fulfilled if we can rely on the sustainable growth of a durable and reliable transport system. For the end-users it is important that these tunnels are safe. In case the transport network is obstructed, it will have an enormous economic and socio-economic impact. Apart from the direct costs associated with reconstruction, wider regions could be out of business for extended periods of time.

Due to a growing population and mobility, European transport networks are extending and more often run through various road and railway tunnels than previously. Recent fires in traffic tunnels, such as Mont-Blanc, Tauern, Gotthard and Channel tunnel, obstructed the open European market and growth. People lost faith in a safe Trans-European road and rail network. These fires in road and rail tunnels caused serious loss of life and significant structural damage with serious socio-economic impacts on the wider regional economy.

Beside the fires in traffic tunnels, fires in public transport tunnels and underground areas also endangered the faith in tunnel safety, such as the fires in the funicular tunnel in Kaprun and in the King's Cross metro station in London.
To avoid these incidents in the future and to improve tunnel safety, the relevant Directorate Generals from the European Commission took the initiatives to draft legislation and to start up EC funded research projects and networks.
All relevant national and international knowledge has been brought together in one of these networks (FIT).

2.2 Technical objectives Runehamar tests

From a technical point of view the project aims to obtain new knowledge about fire development and fire spread in semi-trailer cargos and the heat exposure to the tunnel linings in the vicinity of the fire. There is a lack of systematic studies of the fire behaviour of semi-trailer cargos. Only two large scale fire tests using semi-trailer fire loads have been performed in a tunnel. These tests were performed in 1992 in the EUREKA 499 test program performed in Repparfjord in Norway and sponsored by European partners. A historic overview of large scale tests, carried out in the past, is given in [1] **(Paper 1)**, included on the attached CD-rom.

Consequently, a scientifically performed study of semi-trailer cargo fires, including systematic variation in the commodity types, commodity configurations and ventilation conditions as well as the risk for fire spread between these vehicles would provide information of great importance that is presently lacking to tunnel authorities, tunnel designers and fire services.

See further: General, [12] (Ref.2), [13] (Ref.3)

By conducting these full-scale tests the UPTUN partners wanted to obtain additionally detailed information about:
- the influence of ventilation on the peak Heat Release Rate and fire growth rate,
- the production of smoke and toxic gasses from various goods and
- the possibility for rescue services to fight heavy good vehicle (HGV) fires.

Part of the results of these tests can be found in this document. Detailed information is available on the attached CD-rom or in the full Proceedings of the International Symposium on Catastrophic Tunnel Fires, see http://www.sp.se/fire/Eng/default.htm.

Regarding toxic gases and possibility for rescue, reference is made to [3] (paper 3)

Regarding other activities of UPTUN Work Package 2 (fire suppression systems), reference is made to [4] (paper 4)

3 PREPARATION

3.1 Laboratory tests to predict Heat Release Rate (HRR)

Pre-tests consisting of free burning tests under a large hood system (Industry Calorimeter) at SP's Fire laboratory were performed prior to the large-scale fire tests. These tests were carried out in order to obtain some preliminary knowledge about the fire development and to estimate the peak HRR of the commodities used in the large-scale test program.

The set-up of the pre-burn tests is shown in Figure 2a. Three tests were carried out using two pallet piles of the commodity.

The height of the piles was 1.5 m, which is about half the height of the large-scale fire load. Following type of commodities were tested under the hood system:

1 wood pallets and plastic pallets (82/18 %)
2 wood pallets and PUR (polyurethane) mattresses (82/18 %)
3 cartons with PS (polystyrene) cups (81/19 %)

Reference is made to: [1] (paper 1) and [12] (Ref.2)

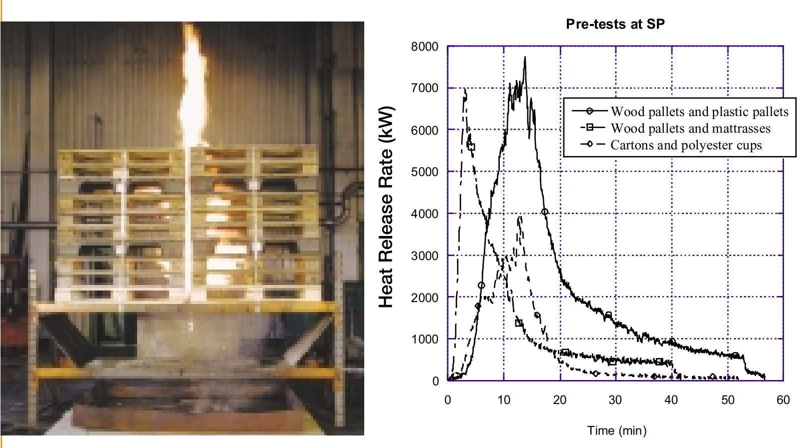


Figure 2 Pre-tests SP.
A Free-burning pre-tests under Industry Calorimeter with wood pallets and plastic pallets.
B Measured HRR.

3.2 Thermal protection boards

The tunnel had to be protected with high temperature resistant materials because of the expected high thermal output. The decision was taken to apply PROMATECT® -T panels, rather than for instance a spray mortar.

The effects of the intended fire loads on the heat release rate and the time temperature curve were unknown, prior to the Runehamar tests. Therefore TNO advised to fire test the intended construction to the Dutch RWS fire curve, exposing the panel to multiple fires. This RWS fire curve is still seen as the most severe hydrocarbon type of fire, due to its rapid temperature rise in the first 5 minutes, creating a thermal shock to the tunnel lining and reaching a maximum temperature of 1350° C.

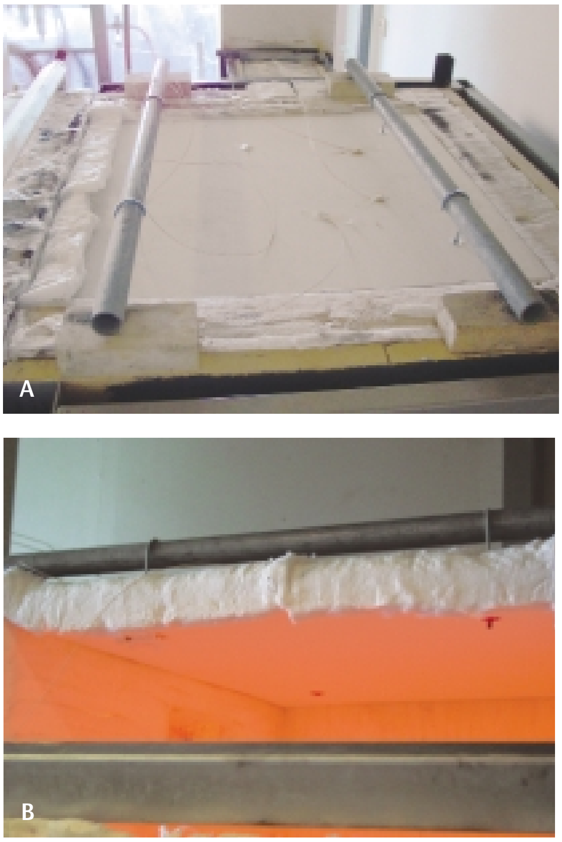
The challenge for the PROMATECT® -T panels can be described as follows:

- The system should be able to withstand 4 fires with maximum temperatures going up to approximately 1400° C.
- The temperature criterion on the rock structure of the tunnel was set to be 250° C. This was perceived to be a safe temperature for the rock material to minimise damage.
- The system was not allowed to show any integrity failures. This was applicable to the PROMATECT® -T panels and the sub-frame including the fixation materials.
- The system should be easy to install to reduce the installation time required to install the whole system, and to facilitate replacement of panels in the unlikely event of damaged panels (mechanical impact). Promat also wanted to have the possibility to extract fire exposed panels from the tunnel, to investigate these in the Promat Research and Technology Centre (PRTC).

3.2.1 Boards

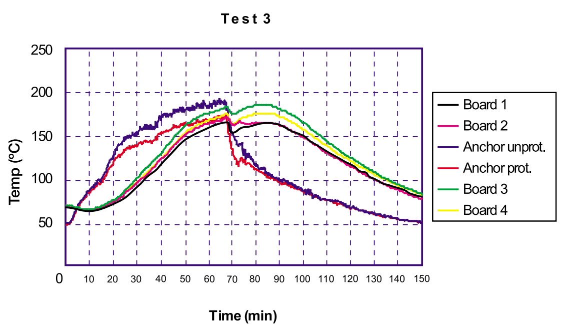
To enable more than one test, the boards were constructed using two thinner boards (20 and 25 mm), glued together with intermediate reinforcement *(see further, Figure 5)*. This is not a standard practical solution but in this case it was chosen to guarantee the integrity of the panel over more than one extreme fire test.

Figure 3 Pre-qualification tests Promat and GERCO.



A Construction set-up during fire test.
B Heated PROMATECT® -T panel and fixations.

Figure 4 Thermocouple recordings during test 3 on the non-exposed face.



3.2.2 Pre-qualification of the intended system

Three consecutive fire tests were conducted at the GERCO laboratory in order to judge:

1 the integrity of the panels after 3 fire tests
2 the integrity of the chosen, easy to install, fixation materials and system.

As shown on the above Figure 3a, the panels were hung on threaded rods (M6), which was also the case in the tested constructions.

Normally such a fixation method is not to be recommended for tunnels, which are in operation.
The heat sink effect through the steel fixation materials (threaded rods) was also investigated. Two out of four anchors were left unprotected *(Figure 3b)* and the temperature rise on the non-exposed face was measured on the protected, as well as the unprotected threaded rod. As can be seen from Figure 4, the temperature difference was perceived to be negligible. The maximum temperatures were 193° C (unprotected) and 174° C (protected) respectively.

In the tests, the maximum furnace temperature was recorded to be 1350° C, which is equal to the maximum temperature of the RWS fire curve. Figure 4 shows the temperature recordings on the non-exposed face during test 3.

Even after three fire tests the non-exposed face of the boards remained well below 200° C, which should be compared to our maximum allowed temperature on the rock surface of 250° C. The heat dissipation in the gap between the PROMATECT® -T boards and the rock should also create some additional cooling effect, leading to the conclusion that the proposed system should correspond to the established design conditions.

3.2.3 Conclusions of the pre-qualification tests

From the pre-qualification tests the following conclusions were drawn:

- During three consecutive fire tests no integrity failures were recorded for the PROMATECT® -T panels and the sub-frame, including the fixation materials.
- The maximum temperature on the non-exposed face of the panels was 186° C, which is well below the criterion of 250° C.
- No major negative influence of penetrations of the threaded rods were found

Based on the above experiences Promat was confident to proceed with the described system and offer it to the Runehamar consortium for use in the full-scale fire test program in the Runehamar tunnel in Norway. As we know now, the described system behaved very well, and all partners were satisfied with the results.

3.3 Steel structure

The tunnel width varies from 8.17 m to 9.40 m with a lowest height of 6.39 m, in the region identified for the fire location. To determine a best fit location and geometry for the test set-up, 2400 positions were measured. For ease of installation a light steel structure was chosen as the support framework of the PROMATECT® -T boards.

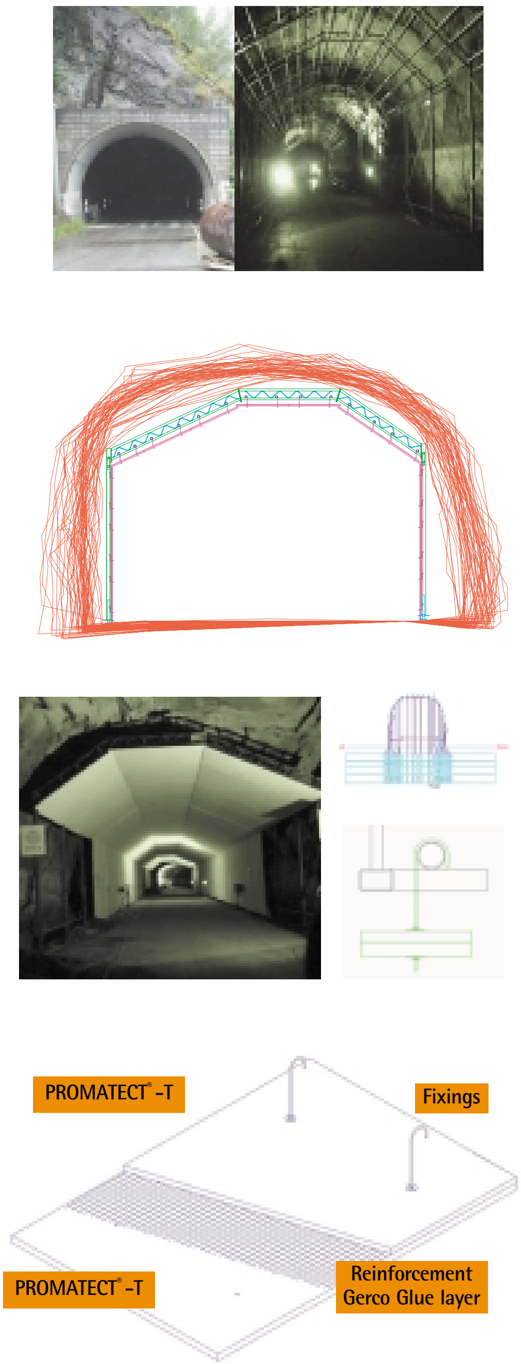
Within 10 weeks, a 16 ton steel structure with 30 tons of PROMATECT® -T boards was produced and built inside the tunnel by GERCO Beveiligingen B.V. from the Netherlands.

The boards were installed with 4 hooks on steel pipes, positioned with their long axis in the longitudinal direction of the tunnel, bearing on the bottom flanges of the truss girders. These kinds of trusses are traditionally used in greenhouses. Originally it was planned to drill anchors in the ceiling of the rock tunnel to install some of these girders. However, due to some doubts about this connection, it was decided to make a free-standing structure based on only portal frames. The length of the thermal isolation is 75 m. Over a part of the walls at both ends of the structure Promat ceramic blankets were used.

The starting points for the design of the structure were based on the following assumptions:

- A maximum of 250° C on the non-exposed side of the thermal board,
- A maximum of 400° C for the protected steel structure and
- A maximum of 600° C the unprotected parts of the steel structure where the ceramic blankets were installed.

Figure 5
Lay-out of steel structure with PROMATECT® -T boards



See further: Video1, Installation, [7] (Paper7), Brekelmans II, [9] Paper9

4 TESTS

In total four tests were performed with a fire in a semi-trailer set-up. In three tests mixtures of different chosen cellulose and plastic materials were used, and in one test a "real" commodity consisting of furniture and fixtures was used. In all tests the mass ratio was approximately 80% cellulose and 20% plastic. A polyester tarpaulin covered the cargo.

The commodities are described in more details in Table 6. The reason for using furniture is that in the past a test was carried out (EUREKA 499) with similar materials and a very high ventilation rate of 6 m/s at the start of the test. This particular test provides a good point of comparison between the data from the Runehamar tests and the EUREKA tests.

Test nr.	Description of the fire load	Target	Total weight (kg)	Theoretical calorific energy (GJ)	Mass ratio of plastic
1	360 wood pallets measuring 1200 x 800 x 150 mm, 20 wood pallets measuring 1200 x 1000 x 150 mm 74 PE plastic pallets measuring 1200 x 800 x 150 mm	32 wood pallets and 6 PE pallets	10911	240	18%
2	216 wood pallets and 240 PUR mattresses measuring 1200 x 800 x 150 mm	20 wood pallets and 20 PUR mattresses	6853	129	18%
3	Furniture and fixtures (tightly packed plastic and wood cabinet doors, upholstered PUR arm rest, upholstered sofas, stuffed animals, potted plant (plastic), toy house of wood, plastic toys). 10 large rubber tyres (800 kg)	Upholstered sofa and arm rest	8500	152	18% (tyres not included)
4	600 corrugated paper cartons with interiors (600 mm x 400 mm x 500 mm; L x W x H) and 15 % of total mass of unexpanded polystyrene (PS) cups (18000 cups) and 40 wood pallets (1200 x 1000 x 150 mm)	4 wood pallets and 40 cartons with PS cups (1800 cups)	3120	67	19%

Table 6 Commodities used as fuel in the four tests.

The commodities were placed on particle boards on a storage rack system (see Figure 7, Figure 8 and Figure 9) to simulate a semi-trailer measuring 10450 mm by 2900 mm. The total height was 4500 mm. The height of the platform floor was 1100 mm.

4.1 Test 1

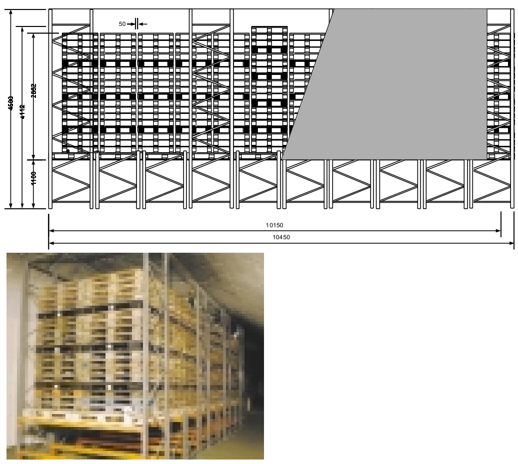


Figure 7 Commodity set-up for test 1 (wood pallets and plastic pallets).

4.2 Test 2

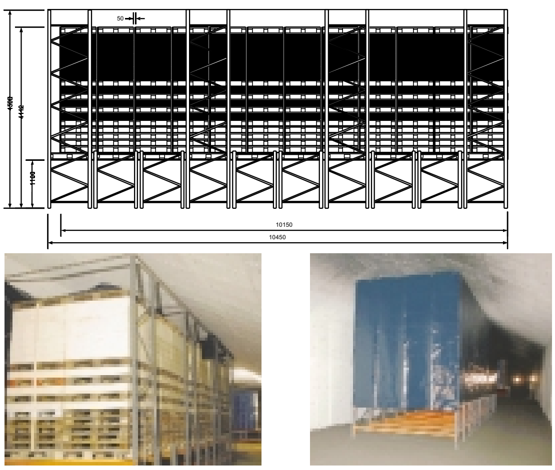


Figure 8 Commodity set-up for test 2 (wood pallets and PUR mattresses).

4.3 Test 3

Figure 9 Commodity set-up for test 3.

4.4 Test 4

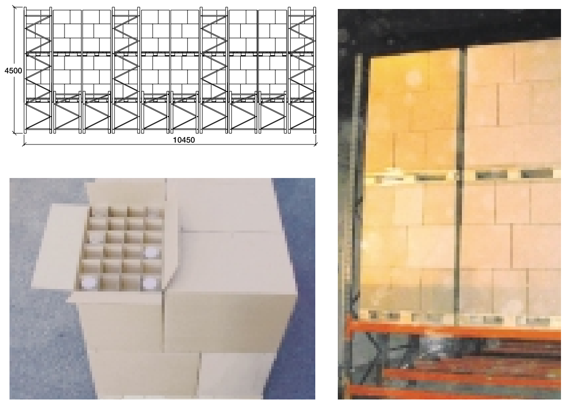


Figure 10 Commodity set-up for test 4 (plastic cups in cardboard boxes on wood pallets).

The fire was located 560 m from the west entrance and the wind direction in the tunnel was from east to west.
The cross-section of the tunnel at the site of the fire is shown in Figure 11. Two small ignition sources, consisting of fibreboard cubes soaked with heptane, were placed within the lowest wood pallets (adjacent to the flue between the two pallets) on the upstream end of the semi-trailer set-up. The tarpaulin was lifted away during the ignition process. Directly after the commodity was ignited the tarpaulin was replaced.
At a distance of 15 m from the downstream side of the test commodity there was a target consisting of the first row of the same test commodity used in actual test.

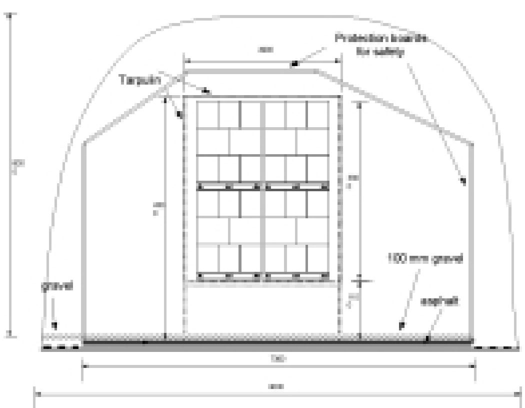


Figure 11 Cross section of the tunnel at the trailer set-up.

See further: Video2, Video3, Video4, Video5, Fire test, [2] (Paper 2)

5 MEASUREMENTS AND INTERPRETATION

5.1 Overview of fire development

Figure 12a and Figure 12b show the fire development for each test after respectively 5 minutes and 30 minutes. In test 1 and test 2 the camera and cargo were on the same position. In test 3 the cargo and camera were moved in the upstream direction over a distance of respectively 5m and 10m. In test 4 the cargo was again moved 5m upstream. According to Figure 12b in all tests the fire is still burning after 30 minutes, but in particular in test 1 and test 3 there is still considerable flaming.

Figure 12 Overview of fire development.

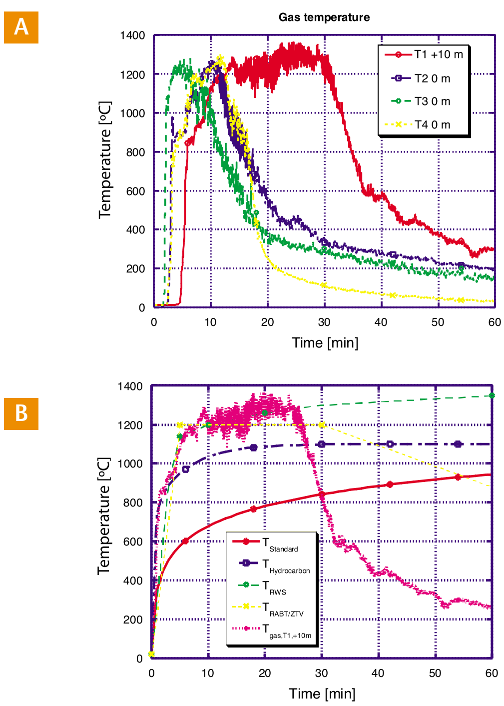
A After 5 minutes

B After 30 minutes

5.2 Gas temperatures

The four commodities used in the tests were chosen to give different fire development and maximum heat release rates. Test 1 with wood pallets and plastic pallets had the highest total energy content and gave the highest maximum heat release rate *(see Figure 13a)*. The large amount of combustible material also gave a longer period of elevated gas temperatures, with the highest maximum temperature of 1365° C.
In Figure 13b the gas temperature near the ceiling in test 1 (at + 10 m) is compared to four different standard fire curves. It can be seen that the increase in gas temperature in the test with wood pallets and plastic pallets is very rapid and almost exactly follows the hydrocarbon-curve for about three minutes. Then the temperature increases even further and more rapidly than the hydrocarbon-curve and instead follows the RWS curve, again almost exactly with exceptions for the fast time variations and for a period around 20 minutes after ignition where the measured temperature is higher than the RWS curve. The RWS curve was developed assuming a tanker fire with petrol or fuel oil lasting for 120 minutes and giving a heat release rate of 300 MW. The heat release rate in the tests in the Runehamar tunnel did not reach 300 MW, but still the temperature followed the RWS curve very well.
In test 4 only 3120 kg of cardboard boxes and polystyrene cups were used, potentially creating the lowest calorific energy output of all tests. However temperatures were recorded to be in the same magnitude of test 1, although for a shorter period of time.

Figure 13 Gas temperature.



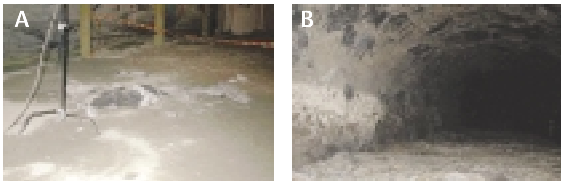
A Measured gas temperatures close to the fire during the four tests.

B Gas temperature in test 1 compared with four different standard fire curves.

Thermal protection and spalling

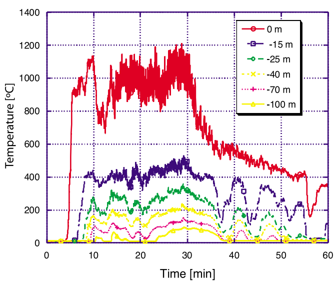
As shown in Figure 11 the tunnel was protected with PROMATECT® -T boards. This was done for safety reasons to avoid rocks falling from the tunnel structure. A distance of 75 m of the tunnel ceiling was protected, while 25 m of the walls (near the fire) were protected with these boards. Downstream of the board walls, the rock was protected using ceramic curtains mainly to minimise the flow of hot gases above the protecting ceiling. Such hot gases could otherwise affect both the rock ceiling and the steel structure on which the boards were hanging. Upstream of the board walls, a distance of 9 m was also protected with ceramic curtains, although not all the way down to the road. This was done to keep the back-layering gases below the protecting ceiling. It was obvious that this protection was needed during and after the first test, when large rocks fell down onto the road both upstream and downstream of the protection (see Figure 14). Downstream of the protection, the tunnel ceiling was affected almost all the way to the western tunnel entrance.

Figure 14 Rocks falling down during test 1.



A upstream of the protected area. *B downstream of the protected area.*

Figure 15 Temperature upstream of the fire.



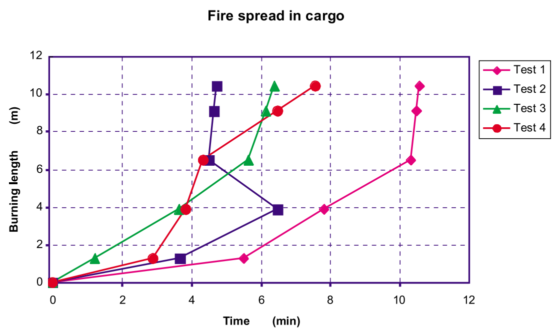
The rocks falling down upstream of the protection was a result of the back-layering taking place in spite of the ventilation. This back-layering was caused by the fact that the velocity decreased when the fire intensity increased, increasing the pressure drop over the fire field. The results can be seen in Figure 15 where the temperatures upstream of the fire during test 1 are presented. It can be seen that 40 m upstream, the temperature is well above 100° C during a long time period and as far away as 100 m upstream the temperature is close to 100° C. For further details and explanation on the back-layering phenomenon see section 5.8.

5.3 Temperatures in cargo and fire spread

Results of the temperature measurements in the cargos are presented in figure 4 in [6] **(Paper 6)**. All tests show temperatures between 900° C and 1000° C during 10 to 15 minutes with peak values up to 1200° C in test 1. In test 1 the first thermocouple near the fire is heated up about 3 minutes after ignition. A mere 7 minutes later the whole cargo is on fire. Test 2 shows an even shorter period of 4 minutes between heating up of the first and last thermocouple. In all tests the whole cargo is on fire within 8 to 10 minutes after ignition.

Figure 16 presents 'the length of the burning part of the cargo' as a function of time, based on a temperature of 600° C. Test 1 and test 3 show an almost monotonic increase of 'burning length' with time, indicating a constant fire spread of approximately 18 mm/s for a 'burning length' between 1.3 m and 6.5 m. This is not the case in test 2 and test 4. Test 4 suggests an even faster fire spread over the same length. Further analysis of Figure 16 is difficult, because parts of the cargo fell down during the tests. This could for instance be the

Figure 16 The length of the burning part of the cargo as function of time.



cause for the unrealistic behaviour in test 3 where a 'burning length' of 6.5 m seems to appear earlier than a 'burning length of 4,5 m.

5.4 Thermal load on wall at 1 meter above road level

In order to estimate the thermal load on the tunnel wall the heat flux is converted to the temperature of a black body radiating with the same flux as received by the wall. This so called radiation temperature can be compared with nominal temperature curves that are controlled with plate thermo-couples. The radiation temperature determined in this way is slightly higher than the temperature that would have been measured with a plate thermocouple on the same spot. This is caused by the colder surface of the heat flux meter resulting in increased convective heat transfer to the sensor.

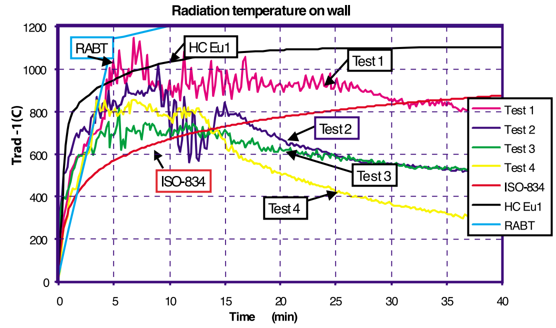
The error in the comparison is relatively low for high heat fluxes and is estimated to be between 20° C and 50° C.

Figure 17 shows the radiation temperatures on the wall and some well known standard fire curves. The curves are shifted to the left in order to facilitate comparison with the fire curves.

In test 1 an average temperature of 900° C occurred during 30 minutes with peak values of 1100° C. In test 2 peak values of 1000° C occur. In test 2 and test 4 an average temperature of 800° C can be seen during 15 minutes. Test 3 shows a lower average over the same period, namely 700° C.

In all tests the thermal load on the wall exceeds the standard ISO-834 curve used for testing of building materials. In test 1 this lasts 30 minutes and in the other tests approximately 15 minutes. Other fire curves seem more appropriate to represent the thermal load on the wall during these periods, as e.g. the hydrocarbon Eurocode 1 curve. Presently tunnel walls are often left unprotected. The test results clearly show the necessity of a fire protective lining for wall applications.

Figure 17 Radiation temperatures on the wall 1m above the floor for all tests.

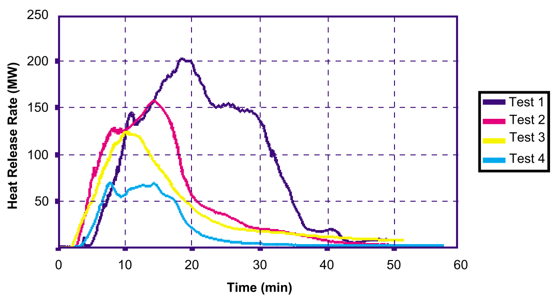


5.5 Heat Release Rate (HRR)

A number of different instruments were used to determine the HRR; 5 bi-directional pressure difference probes, 12 thermo-couples, 3 oxygen (O_2) analysers and 2 carbon dioxide (CO_2) / carbon monoxide (CO) analysers. These measurements are not included in this document. Reference is made to [1] **(Paper 1)**, included on the attached CD-rom.

In the first two fire tests, test 1 and test 2, a pulsation of the fire was experienced during a time period when the fire was over 130 MW. This created a pulsating flow situation at the measuring station, where the measurements showed that the maximum velocity was pulsating in the range of 3 to 4 m/s down to a minimum in the range of 1 to 1.5 m/s. The frequency of the maximum velocities was about 45 seconds during this period. Since the air mass flow rate is dependent on the velocity measurements the HRR measurements also pulsate during this period. The HRR curves presented in Figure 18 are the actual HRR (average for test 1 and 2 during the pulsating period), although a correction has been made for the transportation time.

Figure 18 The HRR from the four large-scale fire tests with HGV-trailer fire load.



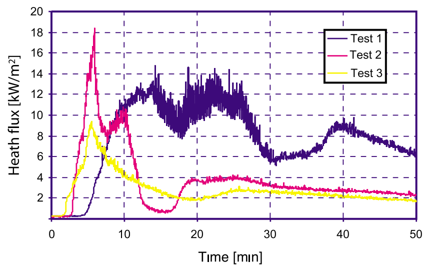
Test nr	Time from ignition to peak HRR (min)	Linear fire growth rate (R=linear regression coefficient) (MW/min)	Peak HRR (MW)	Estimated from laboratory tests (no target – inclusive target) (MW)
1	18.5	20.5 (0.997)	203 (average)	186-217
2	14.3	29.0 (0.991)	158 (average)	167-195
3	10.4	17.0 (0.998)	124.9	-
4	7.7	5 – 70 MW: 17.7 (0.996)	70.5	79-95

Table 19 Peak HRR and fire growth rate from the Runehamar tests.

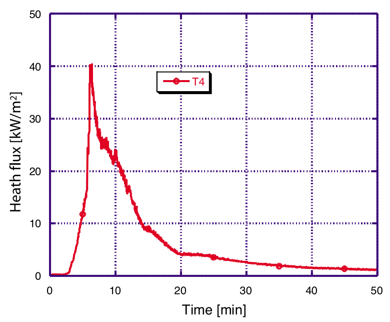
The fire growth rate appears to be relatively linear for all the tests when the fire becomes larger than 5 MW and less than 100 MW except for test 4 which has a peak HRR of 70 MW. Therefore, a linear curve fit for the different tests was used between 5 MW and 100 MW for test 1 to test 3 and between 5 MW and 70 MW for test 4. The linear regression coefficient R is shown in parentheses in Table 19 and is found to be very high in all cases (>0.99), indicating a highly linear behaviour during this period. Table 19 shows that the wood pallets and mattresses (test 2) yield the fastest fire development (29 MW/min), followed by the wood pallets and plastic pallets in test 1 (21 MW/min). Test 3 and test 4 were found to be very similar (17-18 MW/min).

Figure 20 Radiation upstream of the semi-trailer set-up (Note the difference in scale).

A



B



A 10 m upstream of the semi-trailer set-up
B 5 m upstream of the semi-trailer set-up

5.6 Radiation levels near the fire

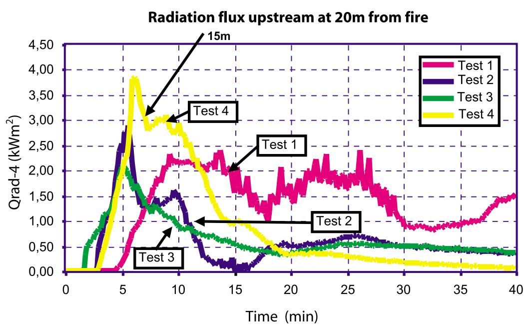
The high temperatures give rise to high radiation, which is important for the fire spread to other vehicles in the tunnel. Another important issue regarding the radiation is how close to the fire the fire fighters can reach before they are stopped by the high radiation. Tests performed with fire fighters in protection clothing indicate that there is a limit approximately 5 kW/m2 exposure above which the fire fighters will have difficulty to work and also feel pain after about 5 minutes.

The measurements during the large-scale fire tests, presented in Figure 20 show that this limit is exceeded in all of the tests at a distance of 10 m from the set-up. The fire fighters not only need to be able to withstand the radiation, they must also be able to work in the heat.

The radiation level 20 m upstream of the fire is an important quantity to determine whether or not the fire brigade can reach the fire with their water jets. Figure 21 shows the measured heat fluxes at this distance.

It appears that all heat fluxes remain below the critical level of 5 kW/m2. The fire brigade will therefore be able to approach the burning cargo up to 20 m and attack the fire.

Figure 21 Radiation flux upstream 20m behind the fire for all tests.



However, 20 m upstream, in the area were the rock was not protected against the fire, at 80-100° C, spalling rock has been recorded, resulting in large blocks of rock falling down in the area where the fire brigade would be expected to attack the fire. This would endanger the fire fighters and hamper their ability to do their work.

5.7 Near fire radiation levels and risk of fire spread

The measured heat fluxes near the fire for all tests together with the critical level for fire spread of 12.5 kW/m² are presented in figure 7 in [6] **(Paper 6)**. In test 1 heat fluxes on the floor of 250 kW/m² occur during 15 minutes. In the same test peak values of 200 kW/m² and average values of about 120 kW/m² on the wall can be observed. At a distance of 5 meter behind the fire the heat flux is still 50 kW/m².

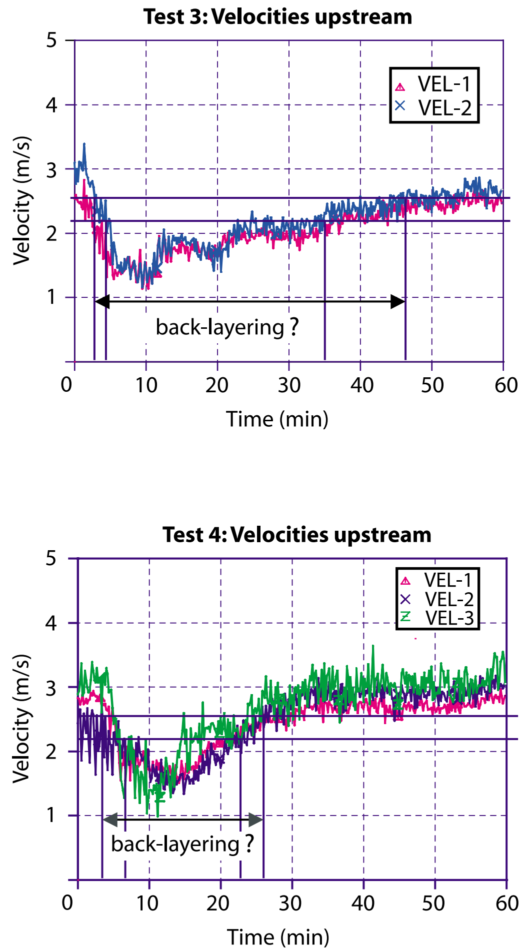
In all tests the critical level for fire spread is exceeded on the location 5 m behind the fire. The risk of fire spread to a vehicle on that location exists therefore in all tests, but for different lengths of time. In test 1 the risk exists for 55 minutes. In the other, less severe tests shorter durations of about 7 to 10 minutes occur. More accurate estimations of the risk of fire spread in case of a heavy good vehicle fire will be made in the near future, using more sophisticated radiation models.

5.8 Back-layering

The back-layering of heat and smoke can cause several problems. It can decrease the visibility both for the people inside the tunnel and for the rescue personnel. The gases are toxic for people without proper breathing equipment. The hot gases radiate, which can affect both the people escaping from the fire and the fire fighters trying to reach the scene of the fire. As discussed above, the hot back-layering gases can make rocks fall down and possibly make concrete start spalling. This can pose a serious safety problem for the people inside the tunnel.

Upstream velocities and temperatures were measured in order to correlate the occurrence of back-layering with the ventilation velocity. The velocities were measured with hot sphere anemometers located 150 m upstream, 2.5 m above the floor in both lanes. In addition a bi-directional probe was placed in the middle of the tunnel, 50 m upstream at a height of 3 m. According to Atkinson [1 4] the critical velocity to prevent back-layering should be 2.2 m/s for wide tunnels and 2.5 m/s for small tunnels for a fire with a heat release rate greater than 10MW.
In Figure 22 the velocities measured in test 3 and test 4 are shown together with the predicted period of back layering according to Atkinson.

Figure 22 Velocities upstream the fire in test 3 and test 4 with predicted period of back layering.



Temperatures have been measured with thermocouple trees on 3 upstream locations in the tunnel. In test 1 these trees were placed in both lanes and in the middle of the tunnel 100 m upstream of the centre of the fire. In the other tests the trees were positioned 25m, 50m and 75m upstream in the middle of the tunnel. Each tree consisted of 5 type K thermocouples located 1m, 2m, 3m, 4m and 5m above the road surface.

Figure 13 in [6] **(Paper 6)** presents the upstream temperatures for test 3 and test 4 together with the same predicted period of back-layering indicated in Figure 21. From these figures it can be concluded that there is a good correlation between the measured and predicted occurrence of back-layering. In all tests a velocity of 2.5 m/s is sufficient to prevent back layering.

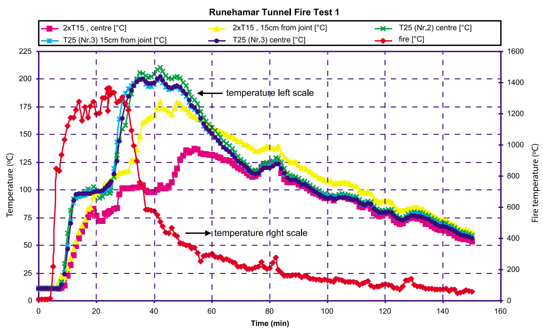
5.9 Results and behaviour of the protective lining

Due to irregular shape of the Runehamar tunnel, the PROMATECT® -T boards were installed suspended on a metal frame; there is no direct contact between the board and the rock *(Figure 23)*. The objective of these tests was to determine the performance of a range of fire protection in different fire conditions when no concrete structures were present (concrete contributes generally to fire resistance of products by a cooling effect), no joint protection exists and when the boards were submitted to multiple exposures in successive fires.

Figure 23 Designed fire protection system for the Runehamar tunnel fire tests.

Note: The metal frame on which the PROMATECT®-T boards were fixed, is shown in red.

Figure 24 Temperatures in the tunnel and on the boards, measured during the most severe test 1.

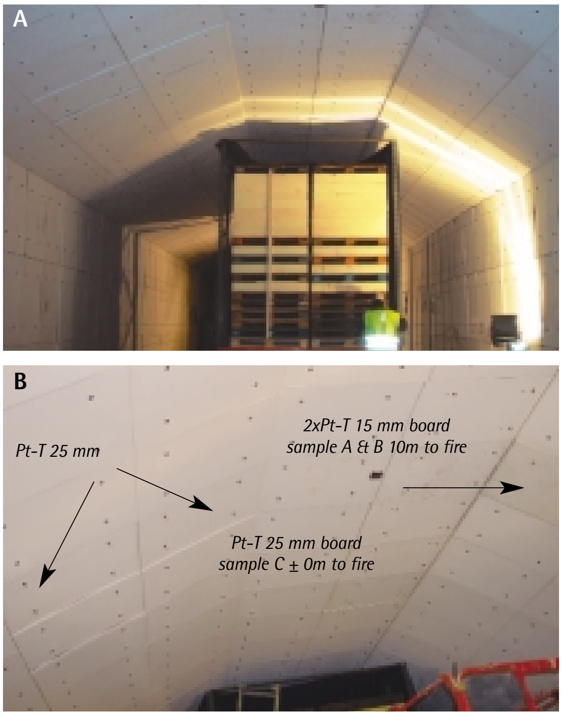


The Figure 24 illustrates the temperatures developed in the tunnel during the first fire test (the red curve, temperatures indicated on right side) and the temperatures measured on the cold side of the boards (temperature values indicated on left side of the graph).

These results demonstrate that the fire temperatures reach 1365° C in a normal cargo truck fire, no liquid hydrocarbon fuel being used. The curve overlaps the hydrocarbon curve (first few minutes) and RWS fire curve (up to 30 minutes) very well. With this extreme tunnel fire, the maximum temperatures registered on the cold side of the PROMATECT® -T 1x25 mm boards and 2x15 mm boards were 210° C and 179° C respectively.

The locations for the different thicknesses of the boards are indicated in Figure 25. These temperatures are far below the design-limit of 250° C, agreed by the partners of this project. This confirms the results from the laboratory testing of the proposed system *(see 3.2.2)*.

Figure 25 Stability and locations PROMATECT® -T boards.



A PROMATECT®-T stability after the test 1.
B Locations of board sample collection.

Some boards were collected *(Figure 25b shows the locations)* for detailed investigations on the matrix behaviour after exposure to most intensive fire (test 1) or to successive fires (total of 4). Samples A and B are from overlapped 15 mm boards situated above the vertical side of the fire load, 10m downstream, where the temperature has reached 1365° C. Sample A was on fire side, sample B on the protected side. These samples were exposed only to the fire test 1 and will be discussed further.

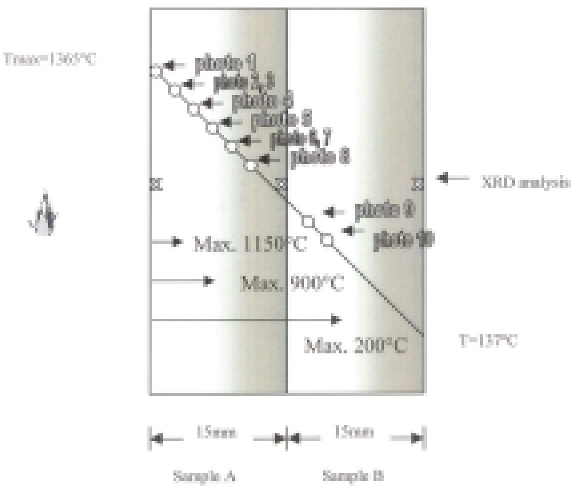
Scanning Electron Microscopy (SEM/EDX) and X-ray diffraction (XRD) were used to investigate the matrix details and to establish the profile of temperature evolution inside the product during the fire tests; the matrix integrity was examined by SEM on polished sections, using back-scattered conditions.

Thanks to mineral engineering technology, PROMATECT® -T has "mineral tracers" (a kind of on-site thermometers), that can provide information about the evolution of the temperature at any place on the board. Figure 29 illustrates the evolution of temperature from the hot to the cold side through the thickness based on mineral phase transformations and modified engineered crystal morphologies. Some details are shown in Figure 26, Figure 27 and Figure 28. A temperature profile can be established with a maximum of 1150° C at 3 mm depth from the exposed surface, a maximum of 900° C at 7 mm and a maximum of 200° C at 20 mm from the exposed surface inside the boards. Note that the board was exposed up to 1365°C in this test.

X-ray diffraction analysis from hot to cold side of the boards demonstrates that on the exposed face, at a thickness of 3 – 4 mm, a layer of a ceramic insulator was formed at temperatures between 1150° C and 1350° C. No defects are created into the matrix during this process *(see photo 1 in Figure 26)*.

As for the other samples, the SEM/EDX and XRD analysis demonstrates the perfect stability of the matrix of the boards that preserves intact the necessary functions for fire protection.

Figure 29 Position of the sample A and B.



Note : the numbers on each picture correspond to the photo number on Figure 29.

See further: [1] (Paper1), [2] (Paper2), [5] (Paper5), [6] (Paper6), [9] (Paper9)

Figure 26 Sample A.

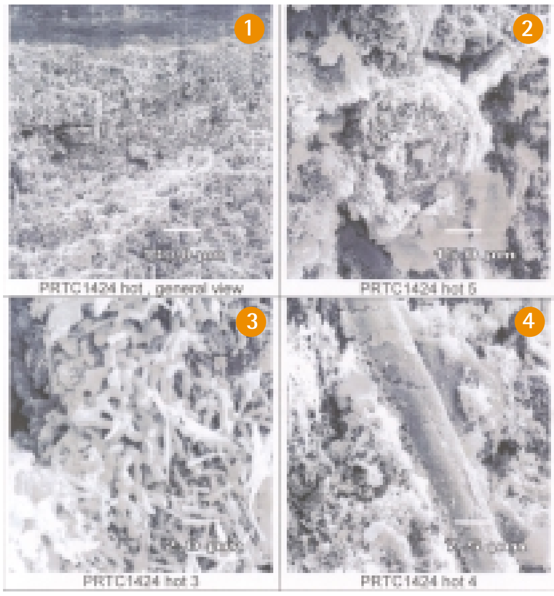


Figure 27 Sample A.

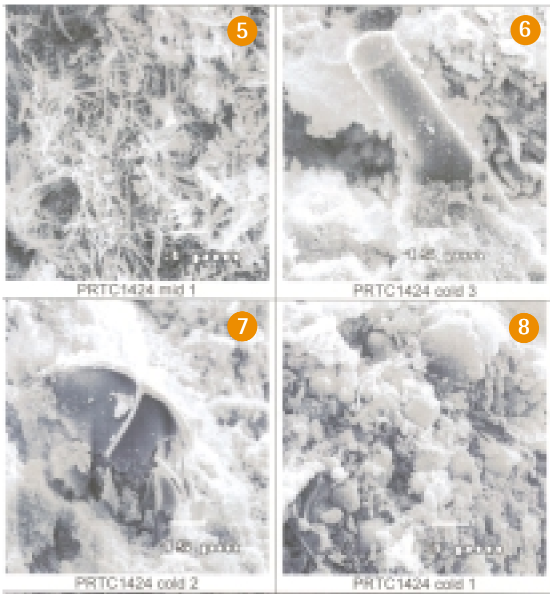
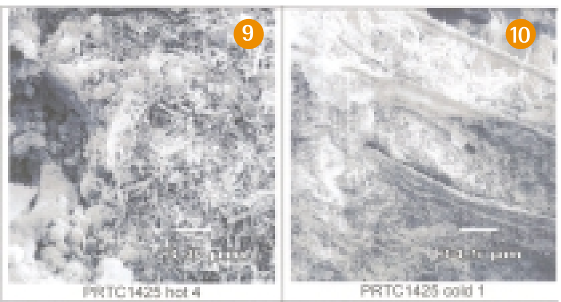


Figure 28 Sample B.



6 CONCLUSIONS AND RECOMMENDATIONS

Gas temperatures and radiation:

Four large scale fire tests were performed simulating fires in the cargo of semi-trailers inside a tunnel. The cargo was simulated using different mixtures of cellulose and plastics *(about 80/20 mass ratio)*. This represents ordinary cargos transported daily on the roads and thereby also often passing through tunnels. The type and amount of combustible materials varied between the tests, but all four combustible mixtures showed very fast increase in temperature after an initial delay. The results also show that the tunnel construction and protections need to withstand very high temperature. The standard fire curve best representing the test results is the RWS curve.

Heat Release Rate (HRR):

The heat flux measurements indicate that it can be difficult for the fire fighters to come close enough to the fire to be able to fight the fire. Without back-layering it is probably possible to fight the fire at 20 m distance with water jets.
The HRR from four large-scale tests in a heavy good vehicles (HGV) -trailer mock-up in a road tunnel with longitudinal ventilation were measured. Peak HRRs in the range of 71 to 203 MW (average) were measured. The time to obtain the peak HRR was found to be in the range of 8 to 18.5 minutes from ignition. In two of the large-scale tests *(test 1 and test 2)* pulsation of the fire and the smoke upstream of the fire were observed during a period when the fire was larger than approximately 130 MW. The fire growth rate in the range of 5 to 100 MW (70 MW in test 4) is linear for all the tests.

Fire spread and thermal load on the wall at 1 meter above road level:

In all tests a rapid fire spread occurs: within 5 to 10 minutes the whole cargo is on fire. A first attempt to estimate the fire spread was partly successful for test 1 and test 3. In test 1, there is a great risk of fire spread to other vehicles at a distance of 5 m behind (upstream) the burning cargo during a period of 55 minutes. This risk also exists in the other tests, but for a shorter duration of 7 to 10 minutes. More accurate estimations of the risk of fire spread in case of a heavy good vehicle fire will be made in the near future.
A first attempt was made to correlate the heat flux to the wall with the intensity of the fire, but more sophisticated modelling is required. In all tests the thermal load on the wall exceeds the standard ISO-834 temperature curve for building materials for a duration of 15 to 30 minutes. Other fire curves seem more appropriate to represent the thermal load on the wall during these periods, e.g. the hydrocarbon Euro code 1 curve.
It should be noted that all measurements were taken 1 meter above road level. Presently tunnel walls are often left unprotected. The test results clearly illustrate the necessity of a fire protective lining for wall applications.

Back-layering and spalling:

Back-layering of heat and smoke was registered both visually and using temperature measurements. The observed velocity at which back-layering occurs is in good agreement with the values predicted by Atkinson [14]. Above 2.5 m/s no back-layering was observed. The back-layering caused rocks to fall down upstream of the passive fire protection *(ceiling)*. This can pose a risk to both the people trying to evacuate the tunnel and for the fire fighting and rescue personnel. It also shows the importance of a suitable protection of the tunnel ceiling and other installations inside the tunnel. A similar problem can occur with spalling of concrete used inside tunnels when exposed to high temperatures. Downstream from the ceiling protection the road was covered by rocks that fell down from the tunnel ceiling.

PROMATECT® -T Boards:

The tests clearly demonstrated that:
- the product is capable of resisting the high intensity and high temperatures developed in a tunnel fire *(maximum 223 MW, 1365° C)*;
- the mineral engineered matrix, a totally new approach in fire protection materials, improves the cooling and thermal protection of the tunnel structures and components.
- temperatures below 200°C can easily be kept for long periods of time, on the tunnel structures side with the calculated thickness applied;
- the integrity of the boards was demonstrated, even down to micron scale, after successive fires;
- the boards are easy to install and replace when necessary after a fire from the exposed part of the tunnel, securing a low cost and short time for repairs and re-opening of the tunnel.

7 ACKNOWLEDGEMENT

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8 REFERENCE LIST

Papers [1] – [9] presented at the International Seminar on 'Catastrophic Tunnel Fires (CTF)', Borås, Sweden, 20-21 November 2003, see http://www.sp.se/fire/Eng/default.htm for the full Proceedings.:

[1] Ingason, H. and Lönnermark, A., **LARGE SCALE FIRE TESTS IN THE RUNEHAMAR TUNNEL** – Heat Release Rate (HRR), SP Swedish National Testing and Research Institute, Sweden. **Paper1, Haukur Ingason I, Ingason II, Ingason III**

[2] Lönnermark, A. and Ingason, H., **LARGE-SCALE FIRE TESTS IN THE RUNEHAMAR TUNNEL** - Gas temperature and radiation, SP Swedish National Testing and Research Institute, Sweden. **Paper2, Anders Lönnermark**

[3] Brandt, A.W., **PRESENTATION OF TEST RESULT FROM FULL SCALE FIRE TESTS AT RUNEHAMAR TUNNEL**, SINTEF, Norwegian Fire Research Laboratory (NBL), Norway. **Paper3, Are Brandt**

[4] Opstad, K. and Wighus, R., **FIRE SUPPRESSION SYSTEMS FOR ROAD TUNNELS (UPTUN)**, SINTEF, Norwegian Fire Research Laboratory (NBL), Norway. **Paper4**

[5] Anton, O. and Wu, X., **RUNEHAMAR TUNNEL FIRE TESTS – UPTUN – FIRE PROTECTION**, PROMAT International NV, Belgium. **Paper5, Octavian Anton**

[6] Lemaire, A., **RUNEHAMAR TUNNEL FIRE TESTS** – radiation, fire spread and back layering, TNO Building and Construction Research, Centre for Fire Research, The Netherlands. **Paper6, Tony Lemaire**

[7] Brekelmans, J.W.P.M. and Goudzwaard, D. van, **RUNEHAMAR tests as part of the UPTUN** project, TNO Building and Construction Research, Centre for Fire Research, The Netherlands **Paper7, Jan Brekelmans I, Brekelmans II**

[8] Nelisse, R.M.L, **THE FIRST YEAR'S RESEARCH RESULTS OF THE EUROPEAN PROJECT UPTUN**, TNO Building and Construction Research, Centre for Fire Research, The Netherlands. **Paper8, Mirjam Nelisse**

[9] Olst, D. van and Bosch, René van den, **PROTECTING THE RUNEHAMAR TUNNEL IN NORWAY WITH PROMATECT"-T AGAINST MULTIPLE FIRES, AS PART OF THE UPTUN RESEARCH PROGRAMME, PROMAT BV**, Tunnel fire protection, The Netherlands. **Paper9, Donald van Olst**

[10] Brekelmans, J.W.P.M. **TUNNEL SAFETY-RELATED RESEARCH PROJECTS AND NETWORKS FUNDED BY THE EUROPEAN** COMMISSION, PIARC World Congress 2003, September, Durban. **Ref.1**

[11] Persson, H., **BASUTRUSTNING FÖR SKUMSLÄCKNING** – Försöksresultat och rekommendationer som underlag för dimensionering och utförande, SP RAPPORT 1990:36, SP Swedish National Testing and Research Institute, Borås Sweden, 1990 (in Swedish).

[12] Ingason, H. and Lönnermark, A., **PROJECT DESCRIPTION AND PLANNING OF LARGE SCALE TESTS IN RUNEHAMAR TUNNEL**, SP Swedish National Testing and Research Institute, Borås Sweden, August 2003. **Ref.2**

[13] Ingason, H. and Lönnermark, A., **LARGE SCALE TESTS IN RUNEHAMAR TUNNEL**, SP Swedish National Testing and Research Institute, Borås Sweden, September 2003. **Ref.3**

[14] Atkinson, G.T. et al, **FIRE TESTS AND CFD MODELING OF CRITICAL VELOCITY BEHAVIOR**, ITC seminar Smoke and Critical velocity in tunnels 1996, London, p13 - p24.

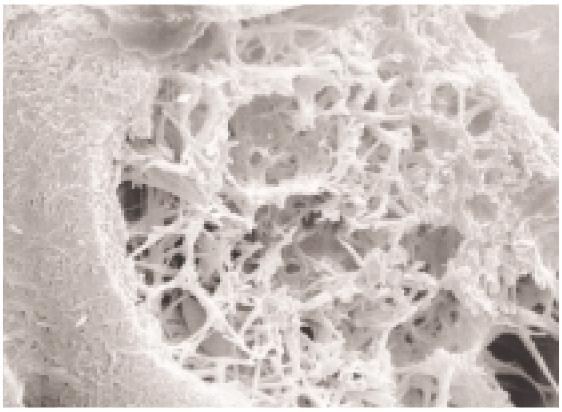
ANNEX A: PROMATECT® -T MATERIAL DESCRIPTION

Mineral engineering and products with engineered matrix :

The traditional, commonly used, development and manufacturing technique for a product aimed at fire protection is the combination of different inorganic raw materials in order to obtain a non-combustible, fire resistant product with the required physico-mechanical characteristics.

Promat's Research and Technology department developed a new approach to products' manufacturing. Selected mineral phases are synthesised by a controlled crystal growth technology. This mineral engineering applied by specific manufacturing technologies enables the achievement of the best performance for a given application. Not only is the crystallo-chemistry controlled but also the morphology and the crystals assembling mode *(Figure 30)*, thus creating a product with specially designed porosity, density, mechanical performance, thermal conductivity, dimensional stability in diverse humidity and temperature conditions; a product with an *engineered matrix.*

Figure 30 Controlled crystal growth technology for engineered matrixes.

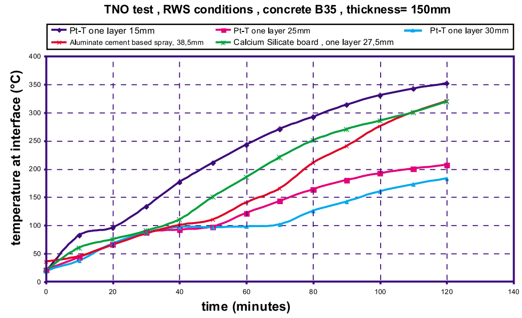


High performance product:

A new generation of high performance products - PROMATECT® -T - was launched with numerous advantages for the protection of concrete structures, construction of escape routes, fire doors, cable systems and ventilation systems.

Designed to satisfy all needs, including the most severe fire situation as described by the RWS fire curve, this product is not only a barrier to fire or a kind of ceramic protection, but for a certain period of time can provide an intensive cooling effect, by cooling down in pre-designed steps the environment near the board. Afterwards, the board becomes an efficient thermal insulator at fire temperatures up to 1300° C - 1400° C.

Figure 31 The performance of matrix engineered product : thickness / fire rate compared with known, standard type of products.



The engineered matrix products can easily secure the same interface temperature with a concrete structure, with only 50% of the thickness of the other products *(Figure 31)*. Although designed as panels, the engineered matrix allows curving on-site of a board to cover surfaces with a curvature down to 8 meters diameter *(Figure 32)*. Easy to install by simple, efficient techniques *(Figure 33, Toulon tunnel)*, the application of the engineered matrix products can be achieved on existing tunnels without total prohibition of the traffic.

Figure 32 Maximum on site curving capabilities of the PROMATECT® -T board.

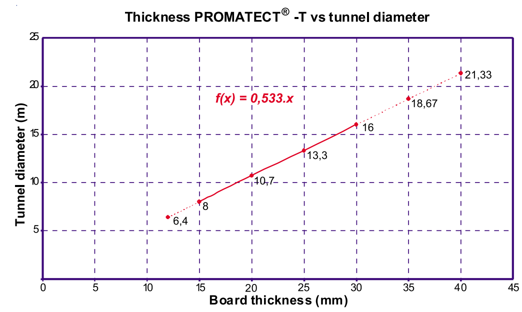


Figure 33 Toulon tunnel protected with the PROMATECT® -T boards for ceiling, escape routes , smoke extraction ducts and fire doors.