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SESSION 3

Fire – Prediction and mitigation

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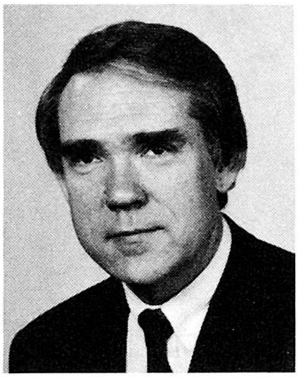
Fire Protection in Traffic Tunnels: Resu of EUREKA Research Project EU 499 FIRETUN"

Alfred Haack
Prof. Dr.-Ing.
STUVA e.V.
Cologne, Germany



Alfred Haack, born 1940,
received his civil engineering degree 1966 at TU Hannover, his professorate 1996 at TU Braunschweig; Executive Board member of STUVA; ITA Executive Council Member

Summary

Against the background of increasing problems concerning the safety in underground transport facilities 9 European nations cooperated in the EUREKA project EU 499 FIRETUN. Their common efforts formed the basis for a remarkable condensed instrumentation of a 2300 long test tunnel. Altogether 21 tests were conducted between 1990 and 1992 and evaluated during 1993 through 1995. Many important results were gained and published inbetween. They form a strong basis for international discussion on fire safety concepts.

1. Introduction

Fire in traffic tunnels (road or rail), are an international problem. They are characterised by the danger they present to the persons affected and, in many cases by the considerable amount of material damage that they cause (see Fig. 1). Serious accidents resulting in injuries have been individually reported from France, Great Britain, Japan, Canada and the U.S.A. Various major fire accidents have also occurred in tunnel facilities in Germany. These cases have served to draw attention to the possibilities of escape and rescue, which are made more difficult in a tunnel scenario.

Serious fire cause considerable material damage, not only to rolling-stock or vehicles, but often to the tunnel facilities as well. This damage is brought about by the massive development of heat and aggressive combustion gases, among other causes. Although the effects of fire seldom threaten the stability of a tunnel structure, they often reduce the availability of the tunnel for traffic, at least for a certain length of time.

The effects of this latter aspect should on no account be underestimated. In some cases, redevelopment can take weeks or months. If as a result, service in important tunnel sections of a metro or urban commuter network has to be discontinued, the inevitable result will be serious disturbances in their everyday operation in built-up areas (such as Berlin, London, Paris or Vienna). As a consequence, in Germany the "Guidelines for Furnishing and Operating Road Tunnels" [1] expressly point to the effects of a case of fire and consequently call for suitable measures already within the scope of preventive fire protection.

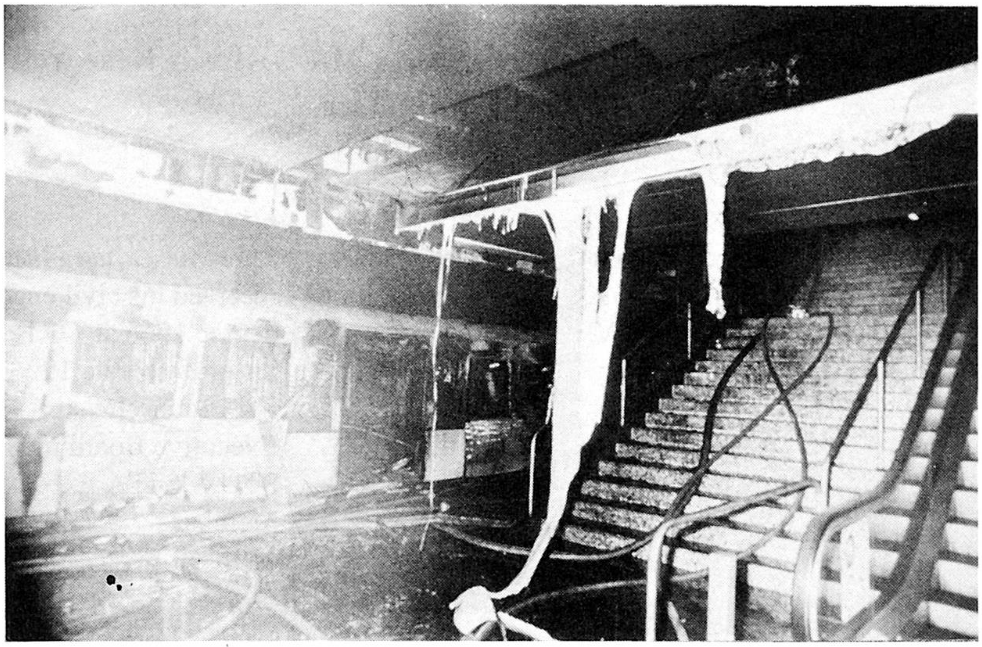


Fig. 1 Destroyed vehicles and interior furnishings at a stop following an urban commuter train fire on April 8, 1980 in Hamburg, Germany

2. Rate of Risk

According to statistics of the late eighties the probability of a fire accident in traffic tunnels can be assumed as follows: 1 case per 10^{10} km regarding road traffic and 1 case per 0,5 x 10^{9} km regarding railway traffic. In the field of passenger transport the risk with car traffic can be assumed as being about 20 to 25 times as high as that of railway traffic. Additionally and generally speaking, it has been determined that the risk of fire in traffic tunnels is on the increase. The reasons for this are:

- The growing density of traffic, especially on the roads.
- The increasing travelling speeds in rail traffic.
- The already high (Table 1) and steadily growing number of tunnels, with ever greater individual lengths.
- Increasing of vandalism, including increasing a trend towards terrorism (witnessed, e.g., in cases of arson).

Such developments must be taken into consideration in developing a safety concept for tunnel traffic.

3. Amount of Tunnels

This becomes still clearer by looking closer to the situation of recent and future tunnelling in Europe:

Numerous rail and road tunnels are in operation (Table 1) or are being built in various European countries. As examples, the following major projects are either in operation, under construction or in the planning stage:

- The Channel Tunnel (rail) between Britain and France, which is approximately 52 km long.
- The Great Belt Tunnel (rail) in Denmark, between the islands of Funen and Seeland, which is about 7 km long.
- The Alpine transit routes for rail traffic in Austria/Italy (the Brenner Base Tunnel) and in Switzerland (where the Gotthard Base Tunnel and the Lötschberg Tunnel are being contemplated), each approximately 40 to 50 km long.
- Mt. Cenis Tunnel as an additional Alpine transit between Lyon (France) and Turin (Italy) with an estimated length of 54 km.
- A recently discussed special tunnel for transport of goods between South-Germany and North Italy (Tunnel Tyrol) with a total length of about 150 km.
- A tunnel undercrossing the Oresund between Denmark and Sweden with a length of 4 km.
- A tunnel between France and Spain undercrossing the Pyrenees along the route between Narbonne and Barcelona with a total length of about 12 km.
- The Gibraltar Tunnel between Spain and Morocco, which will prabably be about 50 km long.
- A large number of tunnels within the framework of the planned pan-European high-speed rail links, scheduled to be completed by the year 2015 [2].
- Various tunnels planned in Norway beneath straits in order to connect islands with one another or with the mainland; the overall length will be greater than 100 km. A number of these tunnels will be more than 10 km long and will be constructed at depths of 600 m and more below sea level [3].

Taking all these new construction measures into account, the pan-European traffic tunnel network is likely to far exceed 10,000 km by the year 2000.

	Traffic tunnels (route km)			
	Metro	Rail	Road	Total
Austria	15	105	210	330
Switzerland	-	360	140	500
Germany	550	380	70	1000
France	270	650	180	1100
Great Britain	200	220	30	450
Italy	60	1150	600	1810
Norway	20	260	370	650
Spain	200	750	100	1050
Total	1315	3875	1700	6890

Table 1 Rail and road tunnel operations in various West European countries (status 1990)

4. Generalities of the EUREKA-Project

Against the background described above, and in consideration of the fact that subsurface traffic facilities are increasing in number, length and number of users, ministries in Germany and other countries have commissioned a comprehensive survey in order to improve fire protection in subsurface traffic facilities - something urgently required throughout Europe.

In Germany, iBMB (Institut für Baustoffe, Massivbau und Brandschutz) at the Technical University of Braunschweig started about 1970 first theoretical studies into the fire process in tunnels and continued its efforts in midth of the 80ies in cooperation with STUVA (the Research Association for Underground Transportation Facilities, Inc., Cologne) by planning and preparing experimental tests. After strong rejection by the environmentalists in Germany the tests were conducted in an abandoned transport tunnel in the north of Norway.

The Technical Research Centre of Finland, Fire Technology Laboratory at Espoo and the Norwegian Road Research Laboratory in Oslo were also involved in the project. Finally, other European countries such as Austria, France, Great Britain, Italy, Sweden and Switzerland joined the project and supported it. Their contribution consisted of additional tests and back-up technical equipment for test tunnel measurements within the scope of a jointly sponsored project.

The EUREKA-project EU499 FIRETUN (in the following: EUREKA tests) can be seen in a certain sense as a continuation of former European full scale tests in the 60ies and 70ies as they were conducted in the Ofenegg Tunnel (Switzerland) in 1965 [4] and in the Zwenberg Tunnel (Austria) in 1976 [5]. In both cases petrol pool fires were performed to investigate the smoke movement along a tunnel dependent on the air velocity. They gave important answers to the question of dimensioning mechanical ventilation systems especially in road tunnels. Directly continued are the Ofenegg-Tunnel and the Zwenberg-Tunnel Tests by those conducted in the Memorial Tunnel, West Virginia, USA, during 1993 to 1995. In these tests the main modes of mechanical ventilation systems (longitudinal, semi-transverse and transverse) are simulated with tremendous financial efforts [6]. Again, here are used petrol pool fires, in this case with a fire load up to 100 MW, so, taking all these full-scale test series, the EUREKA tests were the only ones using real today's vehicles as fire load.

5. Most Important Findings

The evaluation of the international test programme was finished in 1995 and published in an international English written report. The most important findings have been established as follows [7, 8]:

1. The influence of damage both to the vehicles and the tunnel lining, especially in the crown area, depends on the type of car. This fact, already derived from numerous fire accidents was entirely confirmed by the tests in Norway. The roof of those vehicles constructed of steel resisted the heat, whereas the roofs of the public bus and of a metro car both made of aluminium were completely destroyed at a rather early stage of the test fire. The same happened, as expected, to the roof of the private car with a plastic body (see Fig. 2).

2. The temperatures during most of the rail car and bus fires reached maximum values of about 800 to 900 °C, in one case about 1000 °C. Against this the temperature during the test with the heavy good vehicle loaded with 2 t of modern furniture climbed up to more than 1300 °C (Fig. 3). Along the tunnel, temperatures decrease over a relatively short section. For escape, the situation is worse downwind than upwind.

3. The size of the fires has been recalculated on the basis of the Swedish and Norwegian measurement of heat release. The rail car fires mostly amounted to between 15 and 20 MW, the burning of the heavy good vehicle was measured more than 100 MW. This leads to the values given in Table 2.

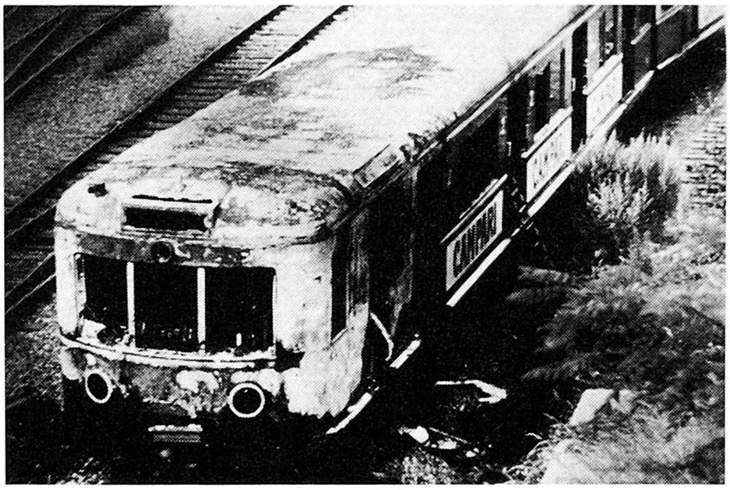


Fig. 2a
All-steel body; fire accident on July 24, 1979, on the Hamburg urban commuter system

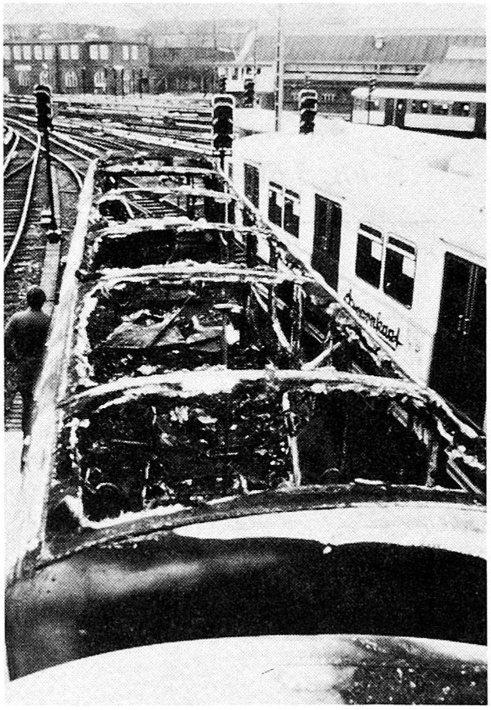


Fig. 2b
Fiber-glass-reinforced plastic in the roof section; fire accident in the Hamburg metro on April 11, 1979

Fig. 2c
Aluminium body; fire accident on April 8, 1980, on the Hamburg urban commuter system

Fig. 3 Fire test on a heavy good vehicle loaded with 2 t of modern furniture

Type of vehicle	Max. temperature [°C]	Max. calorific power release [MW]
Passenger car	400 - 500	3-5
Bus/lorry	700 - 800	15-20
Heavy lorry (HGV) with burning goods (not petrol or other harzardous goods)	1000 - 1200	50-100
railway coaches	800 - 900	15-20

Table 2 Most important results: maximum temperatures and maximum momentary rates of heat release [7]

4. All the rail and road car fires registered a fast development during the first 10 to 15 minutes. So, seen from the aspect of temporal development and heat emission, the hydro carbon curve of RABT covers the reality much better than the unit temperature curve of DIN 4102 (see Fig. 4). But, in this connection, there is one question not yet answered. The European countries have to discuss and think it over, if the Dutch design curve - especially taken for the static calculation of underwater tunnels - with its maximum temperature value of 1350 °C, is closer to reality than the RABT curve in Germany with its highest temperature value of 1200 °C. This question arose as a consequence of the test with the heavy good vehicle.

5. Modern outfitting of rail cars makes them much more resistant against ignition than that of earlier vehicle generations. This could be proved by the fire tests with two halves of German Federal Railway passenger coaches, which both had all-steel bodies but with different lining materials for their walls and roof. The two latter-mentioned test vehicles were stripped off seats and other internal furnishings in order to obtain a true comparison of the influence of the roof and wall lining materials.

   The coach lined with materials based on fibre-glass reinforced, unsaturated polyester, in accordance with the latest state of technology, developed a considerable fire. However, the other coach, lined with materials based on a phenol resin basis, which releases energy at a lower rate, proved to be flame-resistant. In both cases, an ignition energy of approximately 6 l isopropanol (= 7,293 cm^3, corresponding to 200 MJ = fire load of a seat) was applied. The phenol resin lining did not catch fire, even after the ignition energy was doubled.

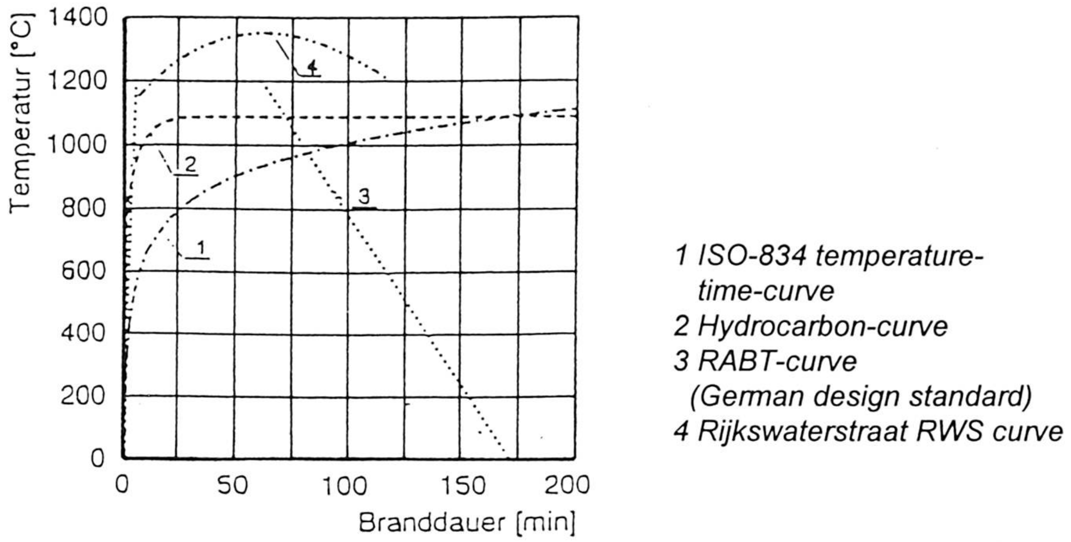


Fig. 4 Comparison between the time-temperature curves of RABT, the Dutch RWS, a hydrocarbon fire and ISO-834/DIN 4102

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Full-Scale Fire Tests as part of Risk Analyses

Niels Peter Høj
Project Manager
COWI
Lyngby, Denmark

Lars Pedersen
Project Engineer
COWI
Lyngby, Denmark

Niels Peter Høj, born 1959, M. Sc. in 1983 at Aalborg University. Since 1989 with COWI. His main occupation has been research, risk analyses and tunnel design. Mr Høj has been the prime responsible for analyses of Great Belt Tunnel after the 1994-fire. Further he was involved in analysis of the fire-damage of the Channel Tunnel after the 1996-fire.

Lars Pedersen, born 1966, M. Sc. in 1991 at Aalborg University. Since 1991 with COWI. Engineering specialist within structural monitoring and testing. Considerable experience in monitoring of durability and safety. Assisted in the Great Belt Tunnel recovery by specifying monitoring of structural safety of the fire-damaged lining.

Summary

The present paper presents the fire tests carried out in the wake of the fire which occurred in one of the TBMs during construction of the 8 km long railway tunnel under the Great Belt. Along with other investigations the tests formed basis for a general update of models describing the fire-performance of the tunnel lining. The paper describes the fire test design and the analysis of results in the context of Operational Risk Analysis updating.

1. Introduction

For tunnel structures the exposure to fire is a central issue. Fires may result in exposure of the structures to very high fire temperatures and recent in-situ experiences, from the Great Belt Project and from the Channel Tunnel, have shown that damage to concrete resulting from fire may turn out quite severe. Experience which accentuates the need and relevance of taking due account of risks of fires in the assessment of operational risks for tunnels. The implications of fires in hazardous goods may be disruption of tunnel operation and loss of revenue for several months and the structures may ultimately collapse possibly resulting in flooding of the tunnel.

For the bored tunnel under the Great Belt, which opened to traffic spring 1997, both durability and safety were emphasised early in the planning. The concrete was prescribed as a dense concrete containing fly-ash and microsilica, with a cylinder strength of 50 MPa. Extensive risk analyses have been made for managing safety and it was at an early stage decided to integrate the fire considerations in the Operational Risk Analysis, [3]. Design predictions on fire-performance of the tunnel lining, covering a.o. the spalling behaviour, was established based on international standards, literature and experts advice. Modifications of the structural design were made on the basis of these risk studies and an acceptable resistance towards fire in hazardous goods was thereby established.

The fire resistance was later to be reassessed in the update brought about by the fire that occurred in the TBM in 1994. A main part of the update, described in this paper, was the laboratory testing for reassessment of the prediction models on fire-performance. In these tests the spalling behaviour of the lining was the main matter of interest.

2. Failure Mechanism and Fire Design

The elevated temperatures prevailing during a fire will cause moisture in concrete to migrate away from the heated face. At a certain time the escaping moisture will be taken over by the advancing heat front and the restraining forces within the concrete, brought about by the evaporation of water, may cause spalling hereby exposing new concrete to fire temperatures. Thereafter the temperature in the remaining concrete will gradually increase accompanied by a decline of concrete strength and stiffness possibly in combination with continued spalling.

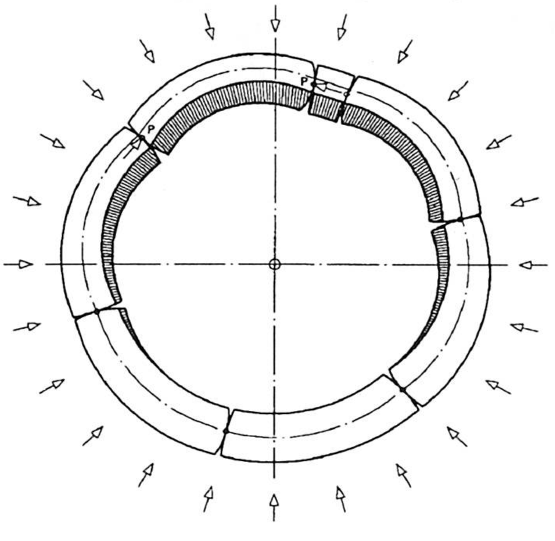

Fig. 1. Principle of damage to lining and deformation under hoop load

For a bored tunnel as the Eastern Railway Tunnel failure takes place when the remaining concrete section no longer can sustain the compressive hoop load. Critical loss of load bearing capacity may occur during the fire or in the cooling phase. In the latter event not because of spalling but as a result of continued loss of strength.

Fire design and the Operational Risk Analysis conducted at the design stage was based on theoretical modelling of fire-performance of the lining. The event of spalling was modelled in the analyses as foreseen to influence the fire-life of the structures. Based on international guidelines, literature reviews and experts advice it was assumed that the inner concrete cover, of size 40 mm, would spall away after 20 minutes of fire and that spalling would then cease. A transient heat equation was assumed for estimating concrete temperatures and thus the current load bearing capacity of the lining. Based on a study of fire scenarios a 1200°C hydrocarbon fire was selected for the analyses. It was, together with experts, assessed that the fire curve of RABT, which indicates a rapid increase in temperature and a constant temperature after 5 minutes, would provide the best representation of a hydrocarbon fire.

Based on the described assumptions and considering the tunnel specific behaviour, taking account of temperature-induced stresses and stress-relieving interaction with the ground as well as deformations in the lining, it was assessed that the lining would sustain the fire for 3-5 hours. With this estimate the risk of service disruption in excess of one month was well within the acceptance criterion, [1].

3. The Fire during Tunnel Construction

A fire in one of the tunnel boring machines took place 11 June 1994, and although the tunnel structure sustained the fire, the spalling damage was more severe than design predictions had suggested, [2].

Whether this could be due to the special conditions for a fire present during tunnel construction was not obvious at the time. Neither was it clear whether the experience would have implications on the operational risks for the tunnel and in the wake of the fire it was thus decided to update design prediction models on fire-performance of the tunnel lining; namely those that could significantly effect the fire-life of the structures.

The major part of the update was the performance and interpretation of full-scale fire tests of segmental lining under realistic loading conditions, but the updating also encompassed small scale laboratory tests carried out in order to confirm models for the concrete strength and elasticity during elevated temperatures, as well as reviews of relevant as-built documentation. Along with the updating, a literature study was conducted and international experts were consulted in order to be up to date with recent conceptions and results of research on the related subjects.

4. Fire Tests with Tunnel Segments at Full Scale

Test Conditions
The main purpose of the tests was to explore the spalling behaviour of the concrete segmental lining when subjected to a severe hydrocarbon fire.

The literature studies and consultations with experts confirmed that the concrete mix, the moisture content of concrete and the external mechanical pressure are important factors for the possibility, and possibly also for the severity of spalling. As to moist it is widely held that the more moist in the concrete the more vulnerable it will be towards elevated temperatures. Presence of compressive normal load may increase the risk of spalling but the magnitude of the load could also be a contributory factor for the risk and severity of spalling.

In the planning of the tests these aspects had to be considered plus the requirement that test conditions were to resemble those expected to prevail in the tunnel in its operation phase. As tunnel segments from the general production were still available these were obvious specimens for testing. The test programme set out comprised two full-scale tests, namely one with a segment at low pressure level (2 MPa) and another with a segment at realistic in-situ pressure level (5 MPa).

Overall, the moisture content of the segments subjected to testing equalled that of the segments already in-place in the tunnel; about 4% by weight. For the latter segments the moisture content is most likely to decline over the years why this test condition tend to be on the safe side compared with future in-service conditions.

The fire exposure was, as in the design calculations, set to an initial climb to 1200°C in 5 minutes, i.e. a fire curve resulting in high rates of heat flow and moisture movements most likely increasing the chance of spalling and accelerating its occurrence in combination with a quite rapid loss of concrete strength. The temperature was kept at 1200°C for 4 hours followed by 2 hours of cooling.

Test set-up and Measurements
The tests, specified and interpreted by the consultants of the Great Belt Link Ltd, COWI-MOTT JV, and undertaking by Swedish National Testing and Research Institute, took place with the segment placed on top of a horizontal furnace as shown in fig. 2. During the testing a purpose-designed loading arrangement provided the specified external load on the segment.

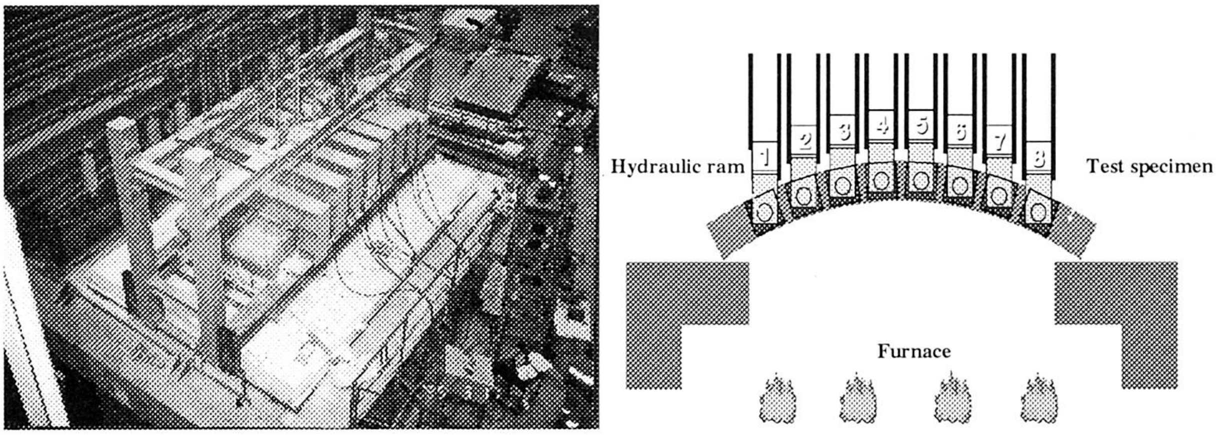

Fig. 2. Test Set-up for full scale fire tests.
External pressures corresponded to forces of 342 and 870 tons in the respective tests.

The destructive effects of the fire were visually observed through dedicated windows situated in the walls of the furnace. Temperatures inside the test specimen were recorded by thermocouples which further provided information on the current depth of spalling.

5. Test Results

Fig. 3. Concrete segment after fire test

Spalling Depths
After 4 hours of fire and 2 hours of cooling the segment was lifted off the furnace and appeared as can be seen in fig. 3. The size of damage that the concrete had encountered in the two tests differed only slightly and in both tests the remaining concrete appeared dome-shaped as was the case in the 1994 tunnel fire.

The contour plot in fig. 4 is produced based on a detailed mapping of the final damages. The virgin thickness of the segment was 400 mm.

The overall trend in the progression of spalling is illustrated in fig. 5. As can be seen the majority of spalling took place within the first 20 minutes of the fire, and the final spalling was more severe (90mm) than the design prediction model (40mm) had suggested. The spalling shown in fig. 5 is the spalling depth (cross sectionally averaged) in the worst affected cross section of the test specimen. As it was only possible to carry out a detailed mapping of damages upon completion of the tests the curve has been established on basis of visual observations made during testing and is thus rather approximative.

The fire resistance of the tunnel is determined by the weakest segment in the group of segments exposed to fire. Due to the random nature of spalling an increase in the number of exposed segments will, from a probabilistic point of view, increase the severity of spalling damage in the worst

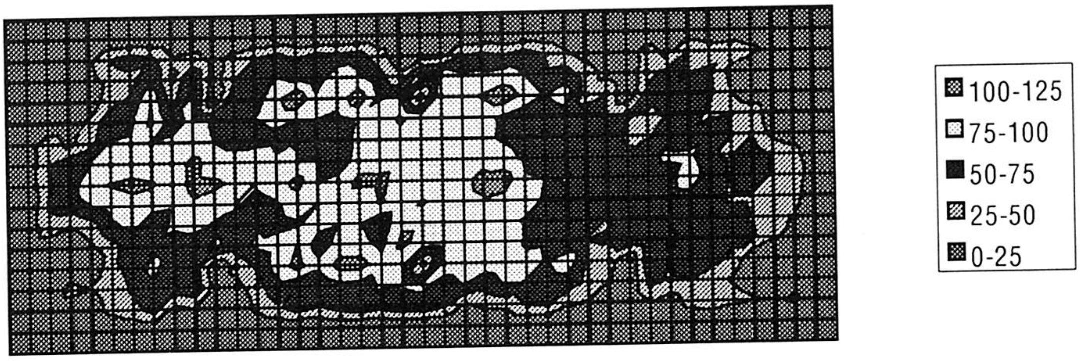

Fig. 4. Spalling depth in mm. Result from test with 5 MPa pressure is shown.

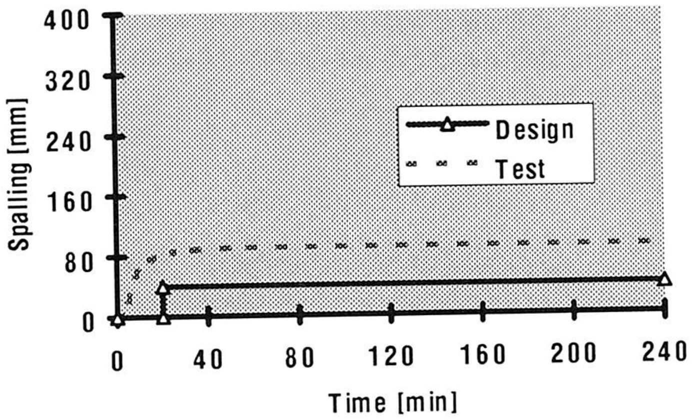

Fig. 5. Approximate rate of progression of spalling observed in tests along with design prediction.

affected segment. Conditioned that 30-300m of tunnel are exposed to fire then the best estimate for the worst affected segment is a spalling damage of 100-110 mm.

Segment Temperatures

The segment temperatures did not rise as rapidly as was predicted by the transient differential heat equation (fig. 6, Theory 1). As the temperature level determines the concrete strength the observation suggests that the decline of capacity of the remaining concrete will take place at a lower rate than originally predicted.

The lack of detailed information on the rate of progression of spalling (in time and space) introduces uncertainty when referring temperature registrations to depths below the exposed surface.

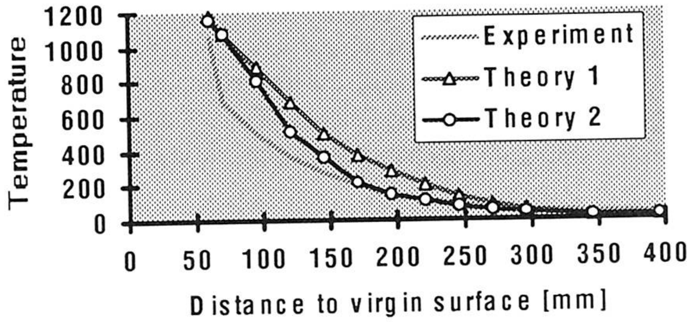

Fig. 6. Concrete temperatures in the remaining concrete.

For the deeper thermocouples this uncertainty plays a minor role as regards the accuracy of the temperature profile, and the tests revealed that a more refined heat flow model (fig. 6, Theory 2) would be more accurate in estimating concrete temperatures than the design prediction model (Theory 1). The heat flow model in question takes account of the energy consumption of decomposing reactions in the concrete during heating, and was, due to its better performance for the particular concrete, applied in the subsequent update of fire resistance.

6. Update of Fire Resistance and Risk Analyses

The fire testing resulted in updating of prediction models for spalling (depth and time of occurrence) and for the heat flow in segments. Additionally, laboratory tests of smaller scale verified the design prediction model describing the concrete strength-temperature relation and a review of quality control documentation from the segment production documented that the cylinder strength of segment concrete was some 50% higher than the design value. In summary, a more refined calculation basis for determination of fire resistance for the particular structure was made available.

Inevitably, an element of uncertainty is associated with updating and for that reason the reassessment of fire resistance involved a sensitivity study in which implications of combinations of worst case and best estimate scenarios were investigated. The study embraced spalling scenarios ranging from 110mm (test result) over 150mm (the spalling recorded after the 1994-fire) to 180mm and fire temperatures of 1200°C as well as 1350°C. Based on the study it was concluded that the fire resistance is 4 hours or longer and as the design prediction was 3-5 hours the result had no implications on the existing operational risk account for the tunnel.

7. Conclusion

For the bored tunnel below the Great Belt the destructive effects of fire on the concrete lining were modelled and considered at the design stage. Subsequent fire testing with full-scale tunnel segments exposed to a RABT 1200°C fire curve provided a more refined model for the spalling behaviour of the particular structure. Additionally, the tests showed that a heat flow model taking account of energy consumption of decomposing reactions in the concrete performed better than the commonly used design prediction model. Testing was carried out with segments with a moisture content equal to that of segments in the tunnel, and under realistic loading conditions. The size of mechanical pressure acting on the test segments showed to have only marginal effect on the severity of spalling.

The subsequent update of fire resistance supported the robustness of the design prediction (3-5 hours), and with this estimate the risk of long-term service disruption is well within the acceptance criterion for the specific structure. For other concrete structures with other structural systems, e.g. immersed tunnels with large span roofs, spalling damages of sizes as those observed after only 10 minutes of fire testing could well result in structural collapse even quite early in a fire. For such structures fire insulation may prove to be very effective. In conclusion, the test results and in-situ experiences, from the fires in the Eastern Railway Tunnel and in the Channel Tunnel, accentuate the need for taking due account of the rather complex structural mechanisms at play during fires in the assessment of operational risks for tunnels.

8. Acknowledgement and References

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Probabilistic Fire Analysis. Limfjordstunnel. Denmark

Jens Vejlby Thomsen
Civil Engineer
Road Directorate
Copenhagen Denmark

Max Karlsson
Civil Engineer
RAMBØLL
Virum, Denmark

Niels Baden
Chemical Engineer
RAMBØLL
Virum, Denmark

Hanne E. Andersen
Civil Engineer
RAMBØLL
Virum, Denmark

Torben Arnbjerg-Nielsen
Civil Engineer
RAMBØLL
Virum, Denmark

Summary

Since its opening in 1969 the Limfjordstunnel has been continuously monitored, and during the latest years it has been inspected, reassessed and repaired. In relation to these activities a probabilistic fire analysis has been performed. Data on traffic and on transported goods in the tunnel has been collected, and a prognosis set up.
A spectrum of possible fire scenarios has been determined. The thermal impact on adjacent structural elements is calculated and their probabilities of occurrence are assessed. A simple structural reliability assessment has been performed leading to a design fire scenario that the Limfjordstunnel shall be able to resist. It is assessed whether the tunnel is able to resist the found design fire without fire insulation. As this is not the case, requirements to a fire insulation are set up.

1. Introduction

Considering road tunnels in various parts of the world, it is seen that some tunnels are fire insulated and others are not. The Limfjordstunnel has not been fire insulated from its opening. The present study which was initiated as a part of the planning of a larger repair of the tunnel gives a rational method for assessing the need for fire insulation. The presentation is based on a description of the analyses performed to assess the need for a fire insulation of the Limfjordstunnel in Denmark.

2. Limfjordstunnel

The Limfjordstunnel is located in Aalborg in the northern part of Jutland in Denmark. It is part of the north-south motorway in Jutland.

The Limfjordstunnel was opened in 1969 by the Danish Road Directorate. It is a 600 m long immersed tunnel. It comprises two tunnel tubes. The total width of each tunnel tube is 13.7 m, the internal width being 10.5 m. The total height of the tunnel structure is 8.25 m, the internal height being 5.4 m.

There are three traffic lanes in each tunnel tube, and 0.70 m wide emergency platforms in both sides of each tunnel tube. Emergency escape doors between the two tunnel tubes are placed for every 50 m.

3. Traffic

As part of the analyses, information on the traffic in the tunnel was collected, especially information on the transport of dangerous goods in the tunnel. The following sources were used:

- General statistics of Danish road traffic
- Traffic census in the Limfjordstunnel
- Statistical information on transportation of dangerous goods in Denmark
- Information from local companies

Based on this information a prognosis of the traffic in the Limfjordstunnel in the year 2010 was established.

The Limfjordstunnel is both used as a local connection between north and south of the city of Aalborg and as the south-north motorway in Jutland. It was concluded that the development of the traffic in the Limfjordstunnel has been very similar to the general development of road traffic in Denmark but less than the development of traffic on typical motorways in Jutland. In future, the traffic in the Limfjordstunnel is expected to increase due to the fact that it has been politically decided to try to move traffic from the nearby Limfjord bridge to the tunnel.

The amount of dangerous goods in the tunnel was found to be more or less the same as the average amount of dangerous goods transported on the Danish roads. In future it is expected that the amount of dangerous goods transported in the tunnel will increase - but the percentage of dangerous goods of the total traffic in the tunnel is expected to remain more or less constant.

Concerning the accident rate, it was concluded that the number of accidents per millions car-km is approximately 0.8 which is approximately 6 times the average for Danish motorways. This can be explained by

- A large traffic intensity especially during peak hours
- The approach systems just before and just after the tunnel

The approach systems before and after the tunnel lead to multiple shifts between the traffic lanes.

4. Frequencies and Consequences of Fire Scenarios

Based on the above mentioned information and analyses of various possible types of accidents, assessment of ignition probabilities, and assessments of fire escalation, the fires in the tunnel were categorised into 5 typical fire scenarios, for which the frequencies were calculated. All frequencies were calculated for a traffic prognosis for the year 2010. The main results are presented in Figure 4-1.

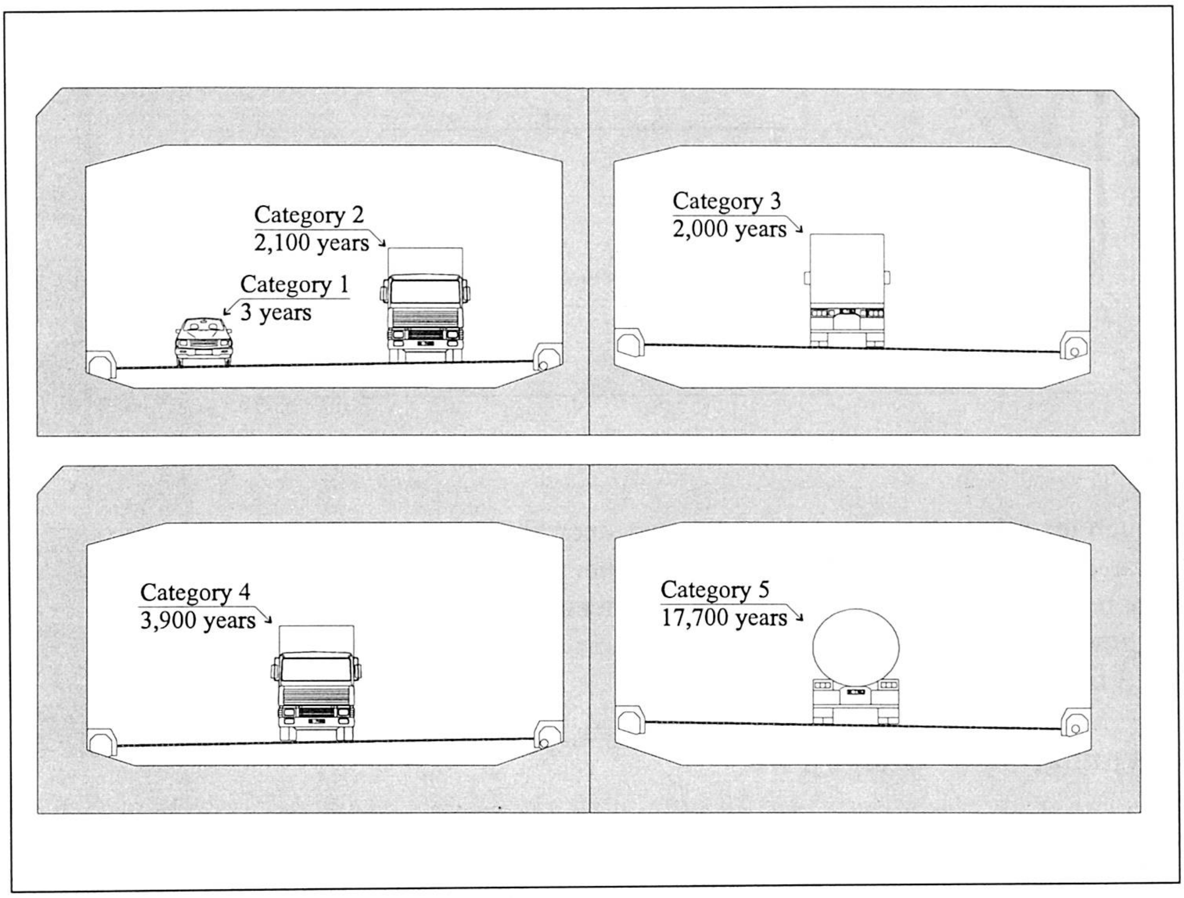


Figure 4-1 Return periods for the 5 main categories of fire scenarios.

The fire categories are described by the following typical fires:

- Category 1: Fire in a car.
- Category 2: Fire in a van with mail bags.
- Category 3: Fire in a van with plastic bottles.
- Category 4: Fire in a van with euro pallets (wood).
- Category 5: Fire in a tank lorry with oil products.

It is seen that a fire in an ordinary car is expected to occur once every 3 years in the Limfjordstunnel, whereas a large fire in a oil road tanker is expected to occur once every 17,700 year.

The consequences of the various fires have been assessed by fire calculations. As the main purpose of the study was to assess the need for fire insulation, the fire calculations have been focused on the calculations of the temperature development near the structural concrete of the Limfjordstunnel. Figure 4-2 shows the temperature development at the roof of the tunnel just above the fire.

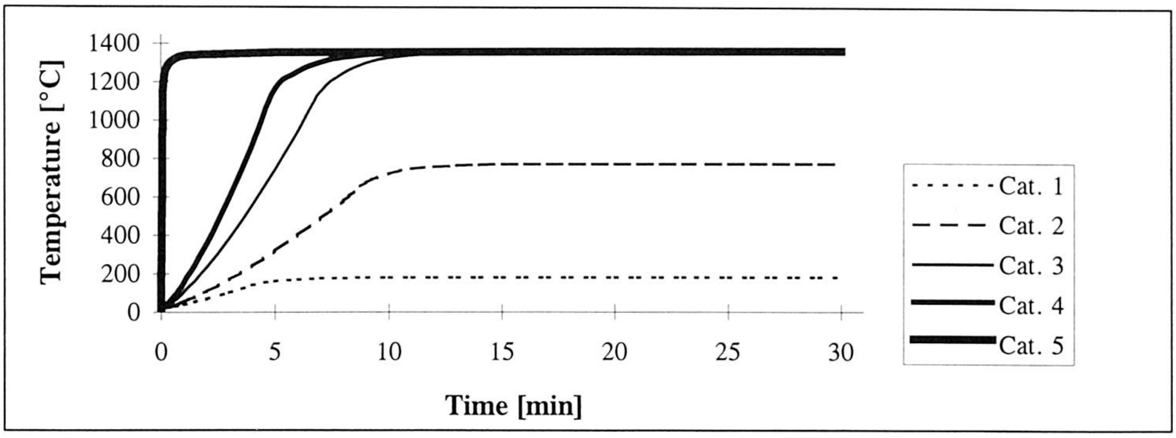


Figure 4-2 Temperatures at the roof just above the fire for the 5 main fire categories.

Even though the calculations are believed to be somewhat conservative it is seen that fires of categories 3, 4, and 5 will all lead to very high maximum temperatures. Furthermore, it is seen that the initial increase in temperature (the thermal chock) is increasing with increasing fire category, and that the initial increase in temperature in category 5 fires may be dramatic.

5. Determination of Design Fire

The purpose of the fire insulation is to protect the structures of the Limfjordstunnel in case of a fire. Consequently, it was decided to base the decision of fire insulation on an assessment of the structural reliability of the Limfjordstunnel. The basic structural reliability requirement for the Limfjordstunnel against fire loading shall be equivalent to high safety class in the Danish code of practice. This overall requirement may be assumed to be equivalent to an annual collapse probability of $1 \cdot 10^{-6}$, ref. /1/.

In an accident situation, as the considered tunnel fire, the structural reliability is the result of two factors:

1. The reliability that follows from a low probability of occurrence of the fire
2. The reliability that follows from the ability of the structure to withstand a certain fire with a certain probability.

Mathematically this may be formatted:

$$P_f = P_0 \bullet P_{f/fire}$$

where P_f is the probability of failure of the structure, P_0 is the probability of occurrence of fire, and $P_{f/fire}$ is the probability of failure of the structure given fire.
By use of this equation and rough structural reliability assessments it is concluded that the return period of the design fire shall be of the order of 20,000 to 100,000 years if the probability of collapse shall be less than $1 \cdot 10^{-6}$.

By use of the frequencies of the various fire scenarios, ref. Figure 4-1, it is concluded that the structures of Limfjordstunnel shall be able to withstand a medium category 5 fire if the structures shall be in high safety class.

6. Requirements to the Fire Insulation

In case of a fire in the tunnel two problems exist:

- Spalling of the concrete cover
- The load carrying capacity of the structure at high temperatures

As mentioned, a category 5 fire may lead to a very high initial temperature rise. The unprotected concrete is unable to withstand this temperature rise without serious spallings.

Whether these spallings are a problem in relation to the load carrying capacity of the structures depends on the structural behaviour of the element in question. The analyses of the structural elements are now ongoing.

The conclusion is that a fire insulation of the Limfjordstunnel is needed, and the extent of the fire insulation will be determined in the ongoing structural analyses. At least the roof of the tunnel is expected to be fire insulated.

Where fire insulation is necessary, the following requirements to this insulation are set up:

- The fire curve defined below shall be used
- The temperature in the contact layer between concrete and insulation must not exceed 380°C
- The temperature in the reinforcement must not exceed 250°C

For engineering reasons it has been decided to specify the requirement by means of a standard time-temperature curve. Especially the ISO 834 curve, the Hydrocarbon curve from the Eurocode ,/2/, and the Rijkswaterstaat (RWS) curve have been considered. These curves are shown in Figure 6-1.

By comparison between the standard curves in Figure 6-1 and the calculated fire curves in the Limfjordstunnel shown in Figure 4-2, is seen that even though the ISO curve may be suitable for lower categories of fires, it can not be recommended in the present case, as neither the initial temperature rise nor the maximum temperature are adequately modelled.

The HC curve seems to model very well the very high initial temperature rise that may occur in a category 5 fire. On the other hand the HC curve has a maximum temperature of 1100°C, whereas a maximum temperature of a category 5 fire in the Limfjordstunnel is expected to be 1350 degrees.

The RWS curve does not fully model the extremely initial high temperature rise but on the other hand the RWS curve has a maximum temperature of 1350 degrees.

Based on these considerations it was decided to use the RWS curve.

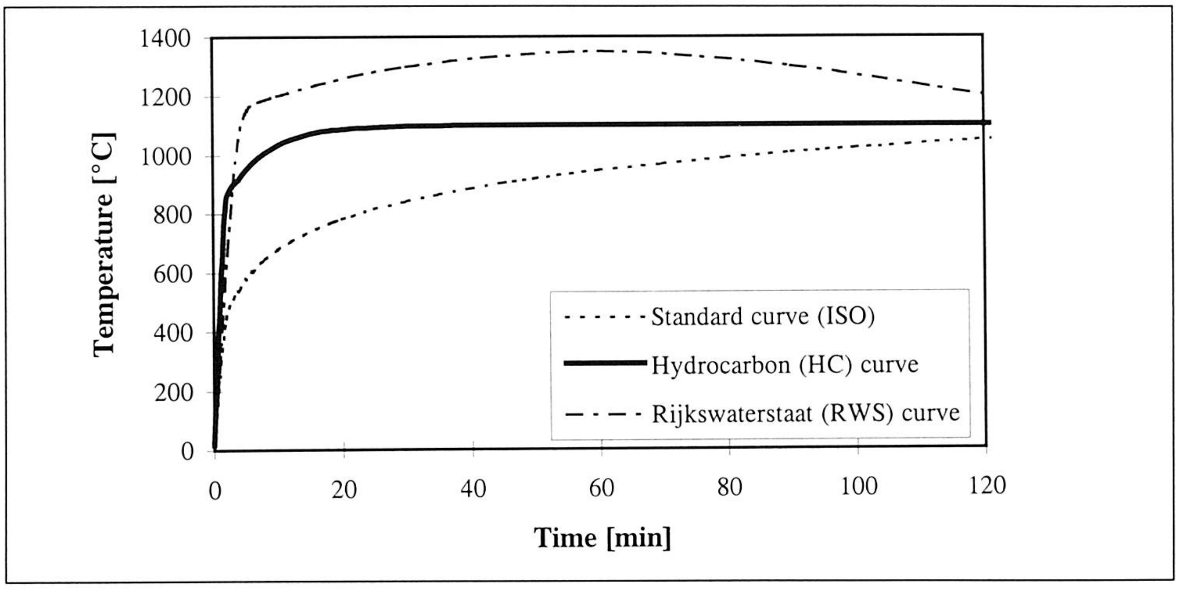


Figure 6-1 Standard Fire Curves

7. Concluding Remarks

In the probabilistic fire analysis of the Limfjordstunnel a rational method for assessing the need for fire insulation of a tunnel is demonstrated. The method can be used both in design of new tunnel structures and in the assessment of existing structures.

The effect of possible restrictions e.g. in the transport of dangerous goods, can be taken into consideration in the prognosis of the traffic population.

Finally, it shall be mentioned that the described method focuses on the structural reliability of the tunnel. However, this is only a part of the problems related to a tunnel fire. Especially assessment of user safety, including analyses of escape routes, have been performed. Concerning the Limfjordstunnel such assessments were performed primarily to assess the requirements to the ventilation system.

8. References

/1/ Nordic Committee for Building Structures (NKB): “Recommendation for Loading and Safety Regulations for Structural Design”, No. 35 and 55, 1987.

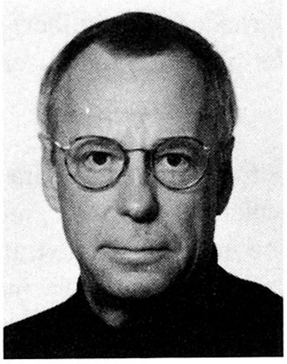
/2/ Eurocode 1: “Basis of Design and Actions on structures, Part 2.7: Actions on structures Exposed to fire, ENV 1991-2-7 April 1993”.

Risk Analysis and Safety Concept

Norra and Södra Länken

(Northern and Southern Link)

Arne Brodin
Fire Engineer
SwePro Engineering AB
Stockholm, Sweden



Arne Brodin, fire engineering degree 1967.
12 years active duty, municipal emergency and rescue services, including the post of deputy chief fire officer.
Since the 1980's, Emergency Service Centre Manager, SOS Alarm AB; Managing Director of Teli Mobitel Trafikledningssystem AB; Consultant in alarm and security systems, tunnel safety specialist.

Summary

The work on safety and security on Norra and Södra Länken has been performed in a number of iterative processes. The aim has been to identify weaknesses in the safety concepts proposed as well as to find cost-effective solutions within the framework of the safety level established. Various solutions have been examined with respect to structural engineering measures, safety engineering installations, restrictions and the organization of rescue services. Through the development of an evaluation model it has been possible to compare and evaluate the alternative solutions. Support for the solutions selected has been established step-by-step with the relevant authorities.

Established Goals in the Field of Road Traffic Safety

There are three supreme goals in the work on road traffic safety in Sweden:

- The total number of people killed or injured on the roads (injury number) shall be continuously reduced.
- The risk of being killed or injured on the roads (risk number) shall be continuously reduced for all categories of road-user.
- The risk of being killer or injured on the roads (risk number) shall be reduced to a greater extent for unprotected road-users than for protected road-users. Special attention shall be paid to children's safety.

The goal incorporated in the safety concept for Norra and Södra Länken is to attain a road traffic environment that is safer than that which otherwise is prevalent today. This can be achieved through both the creation of a more viable and safe traffic environment, and through the installation of systems that limit the severity of any injury incurred in an accident. The safety concept is defined by the technical and organizational measures undertaken, as well as by the regulations and specifications that are intended both to reduce the risk of undesired occurrences as well as to minimize the consequences of such occurrences.

Risk Analysis

A multi-phase risk analysis has been performed based on certain defined objectives. The goal in the initial phases has been to compare the different alternatives:

- in order to be able to judge the level of risk involved in constructing underground tunnels on Norra and Södra Länken in comparison to an above-ground construction of the urban motorway system
- in order to be able to evaluate the efficiency in the different conceivable risk reduction measures through cost-benefit analyses.

The issue of the transport of dangerous goods has been treated in subsequent phases of the risk analysis, when the objectives were:

- to examine the risks involved for people travelling in underground road tunnels as compared to their using roads above ground. This examination was based on information gathered on the quantity of dangerous goods involved as well as on their chemical properties, on information on road and tunnel geometry, etc.
- to evaluate the effect of the alternative protection measures and restrictions on the transport of dangerous goods through the Norra and Södra Länken tunnels.

Results

The acceptance level chosen gives a notable reduction in the accident rate in comparison with today's situation. This acceptance level thereby complies with the Swedish National Road

Administration (SNRA) requirement on a continuous lowering of the accident rate and it is furthermore fully in line with Vision Zero.
The acceptance level presumes 0.004 fatalities per million vehicle kilometres, which corresponds to 2.5 fatalities per year on Essingeleden, Norra and Södra Länken combined.
The following figure presents a compilation of the risks. The graph shows both the analysed scenarios (frequency and consequence) and the acceptance curve.

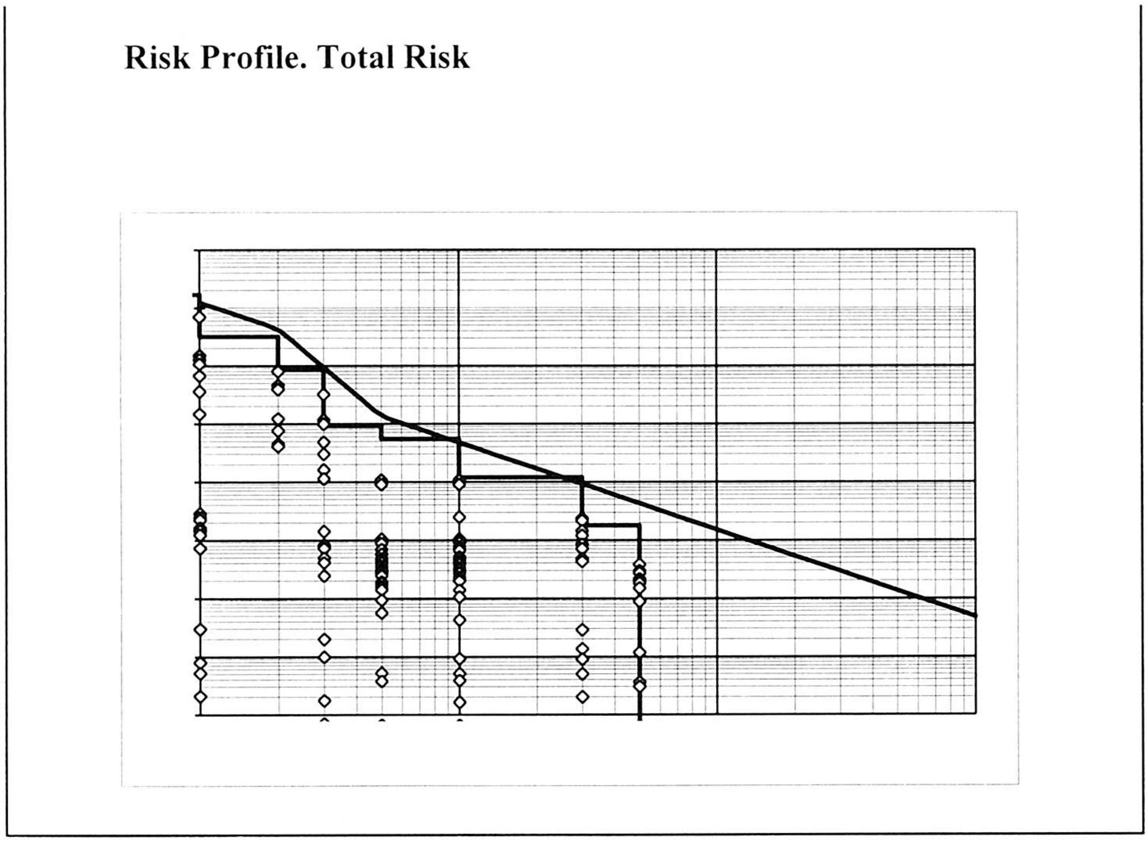


Figure 1: Risk Profile of Norra and Södra Länken

In the work on the risk analysis, what is referred to as aversion factors were used for large-scale accidents. This means that special precautions have been taken against major accidents so that their impact on the risk becomes less and less with an increase in the number of fatalitites per single accident. An example of such precautions could be the installation of sprinklers or escort units in connection with the transport of dangerous goods. In performing the risk analysis, the expected risk has been calculated according to established risk-reducing measures. These calculations include all known risk scenarios but exclude certain risk-reducing measures as presented below. The expected risk has been calculated at 0.0033 fatalities per million vehicle kilometres which corresponds to 2.1 fatalities per year.

All in all, the chosen design and construction of the tunnels and road system has been considered to provide a high safety level. Using those calculation and analysis methods available, the risk of being killed in this road system has been estimated at 0.0033 fatalities per million vehicle kilometres, 99% of which is the result of a traffic accident while the remaining 1% is due to other causes, such as accidents associated with the transport of dangerous goods.

The risk analysis and modelling of the different scenarios has not taken into consideration the positive effect on the accident rate that the implementation of the Traffic Management Centre (TMC) is expected to have; e.g., through the greater amount of traffic information that will be available to road-users, through the creation of the vehicle assistance patrol and through the effects achieved by introducing the Motorway Control System (MCS). Based on Holland's experience, the effects of the MCS alone can reduce the primary accident rate by 25%, and secondary accidents by 40%. Considering that the risk profile for underground road tunnels indicates extensive repercussions through just rear-end collisions in particular, the implementation of the MCS has great potential for making positive improvements in the picture of the risk presented in the risk analysis.

Evaluation Model

An evaluation model based on the SNRA effect index was developed for Norra and Södra Länken. Different technical, organizational and administrative solutions were tested within the framework of the safety requirements that had been set (acceptance level). In general, if a safety concept fulfils the acceptance level, its comparative cost is calculated. Calculating comparative costs for several concepts can be used to collate different "valid" safety concepts.

Additionally, the economic reliability and the functional certainty of the different technical and organizational solutions were described. These descriptions were compiled in a simulation program that applies the Monte-Carlo principle. As a result, it became possible to adopt the safety concept with the greatest calculated accuracy.

Design Scenarios

Considering the restrictions that will be placed on the transport of dangerous goods, the following design standards have been accepted for the structures and installations on Norra and Södra Länken:

- A burning lorry with an effect of 100 MW represent the design fire scenario for the evacuation and rescue routes.

- The fire ventilation system shall be able to control combustion gases from a burning lorry (100 MW). Tunnel sections with a sprinkler system shall be designed for a fire of 10 MW.

- The supporting structures shall be designed for a burning lorry (100 MW)

- The automatic fire alarm shall be designed to detect a fire in a passenger car (3 MW) at an air speed of 5 metres per second.

The reason for not designing the fire ventilation system and supporting structures for a petrol fire (300 MW) can be summarised as follows:

- The risk analysis has indicated that the probability of accidents with dangerous goods is low.

- Considering the initial rapid development of the fire, a combustion control system cannot be designed in such a way as to be able to guarantee safety. In other words, modern technology is not capable of providing a fire ventilation system with sufficient capacity for larger petrol fires. The measures planned are therefore those which first and foremost reduce the risk involved; i.e., restrictions, sprinkler systems and escort activities.

Considerations

Evacuation and Rescue Routes

The smoke ventilation in the design fire scenario shall be able to maintain a smoke-free tunnel upstream from the fire.

The traffic control system shall normally be able to divert and dissipate the traffic that is downstream from the fire so that those road-users are not affected by combustion gases.

The information and warning systems placed at the disposal of the Traffic Management Centre shall be sufficiently well developed so as to ensure that information on a commanded emergency evacuation will reach the road-users concerned.

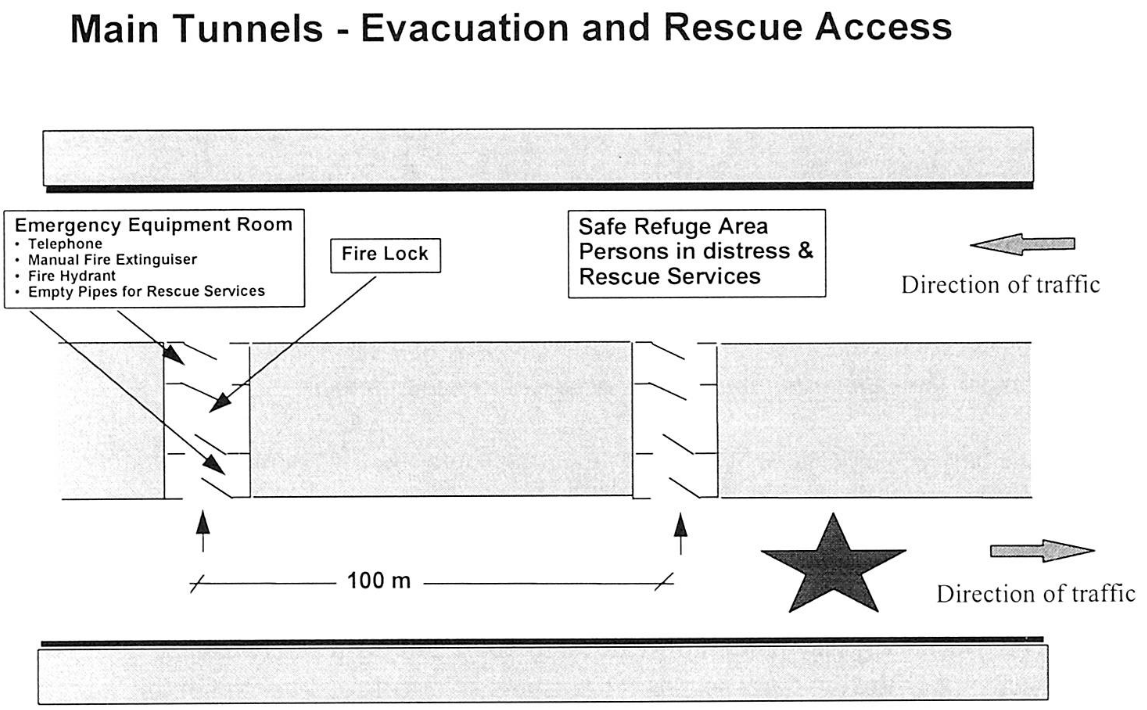


Figure 2: Principles for the evacuation and rescue accesses in main tunnels

Adaptations will be made in the design to ensure that disabled persons can make their way to the safety area without assistance, while simultaneously ensuring that these adaptations do not jeopardize the overall evacuation possibilities or interfere with the rescue services being able to perform their task efficiently.

So-called rescue rooms will be constructed in those parts of the evacuation routes where inclines are too steep.

The evacuation from the ramp tunnels will occur according to the same principles as for the main tunnels; i.e., primarily through tunnel connections to other ramp tunnels but these cross-connections can also lead to main tunnels as well.

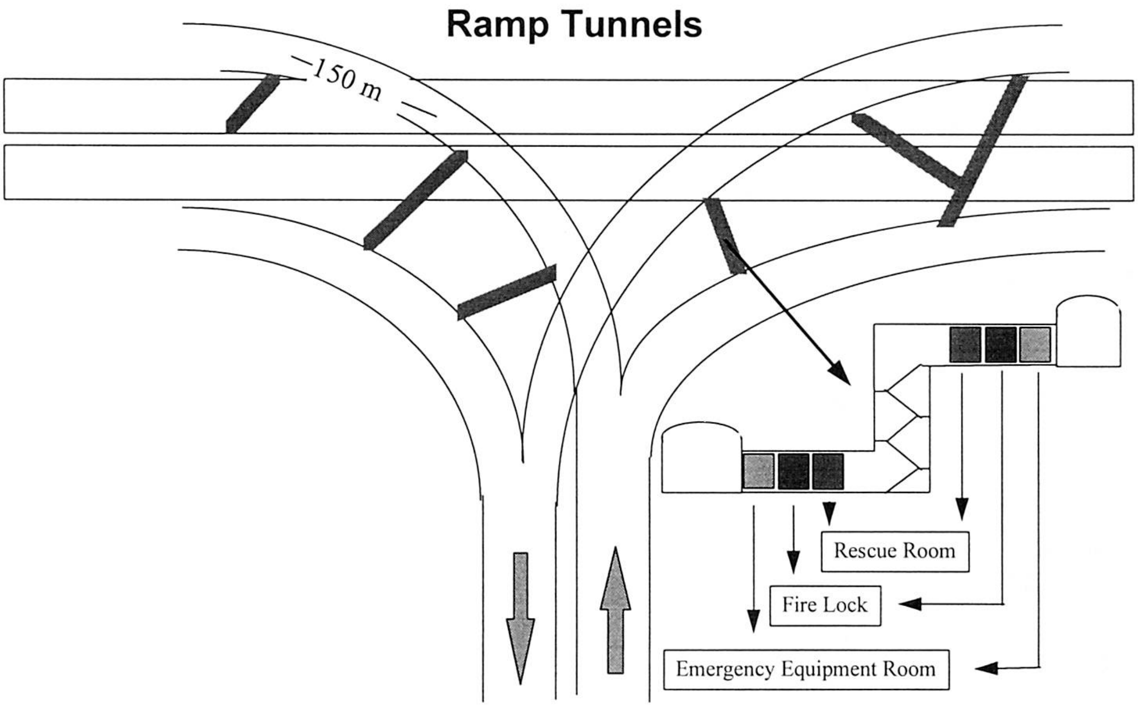


Figure 3: Principles for the evacuation and rescue accesses in ramp tunnels

The longest distance between emergency exits to evacuation routes that lead either to a safety refuge area or out in the open air shall be **100 metres for main tunnels** and **150 metres for ramp tunnels**.

Different distances between exits were tested before making the final decision. Analyses showed that from an evacuation viewpoint, intervals up to 200 - 250 metres between emergency exits were not critical with respect to the personal safety of road-users. On the contrary, the critical factor was the perception times; i.e., the time from when an incident occurs until the evacuation is actually set in motion. In other words, it is more effective to concentrate on systems that draw road-users' attention to the need for evacuation than to shorten the distance between exits. The distance finally set was based on the fire brigade's requirements on access routes.

Consignment Accidents - Fire and Explosion

According to the foregoing, a burning lorry loaded with 20 tonnes of furniture in cartons has been chosen as the design fire scenario.

The amount of energy released in connection with this has been calculated at 300,000 MJ. This fire has been estimated to last about 90 minutes.

The load-bearing main system in the road tunnels shall be calculated on the basis of a temperature cycle in accordance with the HC-curve with a 120 minute heating phase but without a cooling phase.

The fittings and fixtures in the road tunnels, including the lining, doors as well as the main bearing structural elements and the fire-sealing walls in the evacuation routes and sub-stations shall be designed according to the standard fire curve ISO 834.

Ensuring human safety is the prime consideration. As far as the protection of property is concerned, the requirements are limited so that it is only cave-ins, collapse and progressive landslides that shall be prevented in case of fire. Reparable damage to localized supporting structures is acceptable. Examples of such damage are cracking, permanent deformations, spalling concrete and individual load-bearing structural elements that have been totally destroyed.

Calculations that have been performed for an alternative solution without fireproofing have shown that there is no risk for collapse in the supporting structures as a direct result of a fire. However, due to the risk of spalling in connection with a longer fire, either fireproofing or reinforcement measures have been introduced for these concrete structures.

According to the risk analysis calculations, the design fire scenario can be expected less often than once every 150 years. Furthermore, fires larger than this can be expected less than once every thousand years. Despite this, it has been assessed that these incidents have been effectively limited by the restrictions taken (escort units and the sprinkler system).

Fires in flammable liquids that have leaked onto the roadway, will be extinguished quickly since the wastewater system has been designed to discharge 80 litres per second thereby limiting the area covered by the liquid to 250 m^2. The effect of such a fire can temporarily exceed the design fire effect. However, the released energy, which forms the basis for the design criteria for the structural elements, will probably be less than the design criteria according to the HC curve.

In practice, it shall be possible to completely restore the bearing capacity of the entire structure after the occurrence of a design fire.

The foregoing opinion has been based on the risk analysis that was performed. This shows that special measures for property protection in the case of fire are, generally speaking, not profitable, considering the expected frequency and extent of the damage.

As far as the false ceiling in the tunnels is concerned, a concrete construction has tentatively been decided upon with a partitioning capacity corresponding to EI 60.

The design scenario chosen consists of a vehicle loaded with 30 kilograms of dynamex (a brand of dynamite) that has exploded. Thirty kilograms of dynamex is the maximum consignment that may be transported without either a special permit or without being specially labelled.

According to the risk analysis calculations, such an accident can be expected less than once per 1000 years. Calculations also show that there is no risk for a collapse of the supporting structures or in a functional failure in the partitioning capacity in the evacuation routes. It has been estimated that an explosion in an illegal load (exceeding 30 kilograms) would occur less than once per 10,000 years.

Remaining Issues

Safety in the transport of dangerous goods in tunnels

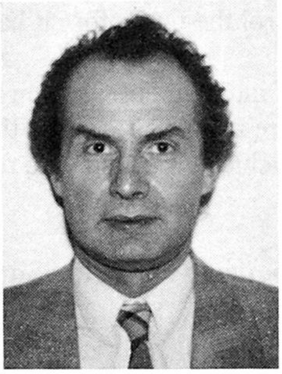
There are five different alternatives for handling the transport of dangerous goods in tunnels:

1. Registration of vehicles entering and exiting the tunnels
2. Escorts
3. Sprinkler systems
4. Transport through a tunnel closed to other traffic
5. Prohibition

Escort activities and the installation of a sprinkler system are equivalent from a personal safety point of view. The alternative to these methods would be that dangerous goods would continue to be transported on the above-ground road network (instead of through underground tunnels) according to instructions from the authorities. This is not considered to be an alternative at the present time.

Fire Safety Checking of Tunnels based on Probabilistic Analysis

Pierre SPEHL
Civil Engineer
SECO
Brussels, Belgium



Pierre Spehl, born in 1945, received his civil engineering degree in 1969 from the Brussels Free University. Lecturer at this University since 1993. Civil engineer since 1972 at SECO, the technical control office for the construction, he is in charge of special missions in the field of fire safety, dynamic effects and structural reliability, and is also active in standardization work (CEN) in this field.

Summary

The fire safety regulations, standards and codes of practice, traditionally based on descriptive requirements deriving from experience of authorities and experts, are more and more including performance requirements expressed independently of the building solutions.
The probabilistic fire analysis is a new step forward to represent more closely the global fire safety really obtained : any possible cause of failure (accidental actions, fire scenarios, structural defect, human error, ...) is considered and its probability of occurence is assessed by methods based on available statistical data about real fires.
The feasibility of standards and regulations based on probabilistic analysis is discussed and practical problems raised by this approach for tunnels are detailed.

1. General objectives of fire safety

The general objectives of fire safety in tunnels are usually :

The safety of persons : *occupants :* passengers, drivers, train personnel, ...
rescue teams : fire fighters, medical assistance, ...

The protection of goods : *properties :* vehicles, loads, structure of the tunnel
environment : smoke, surface and underground pollutants

2. General performance requirements

From these objectives of fire safety, general performance requirements are usually derived, such as those defined by the European Commission for the construction products (1) :

2.1 Fire prevention strategy

To minimize the risk of an outbreak of fire.

2.2 Loadbearing capacity of the tunnel

In case of fire, to guard against collapse and to provide for the safety of occupants and rescue team.

2.3 Limitation of generation and spread of fire and smoke within the tunnel

To enable occupants near and remote from the origin of fire to have sufficient time to escape and to enable the fire brigade rescue teams to control the fire before it has grown too large.

This requirement includes the prevention of initial ignition within the technical installations, the limitation of the generation and spread of fire and smoke within the vehicles circulating in the tunnel (trucks, railways, cars, ...) and beyond the vehicle of origin (fire resistant compartmentation, control of hot gases and smoke between zones).

2.4 Limitation of spread of fire to neighbouring construction works.

To ensure safety of occupants in other construction works nearby and remote from the tunnel.

2.5 Safety of evacuation of occupants, by provision of means of escape and of access for rescue teams :

- to allow occupants anywhere within the tunnel to be able to evacuate to a place of safety
- to allow rescue teams to have access to, search, and get out of the tunnel safely

The required safety measures concern the design and layout of escape routes, their separation from the surroundings, the control of smoke and other equipments (lighting, signs, ...).

2.6 Safety of rescue team, by additional provisions :

- to ensure possibility for rescue operations to be carried out
- to allow fire fighting to be carried out effectively
- to enable rescue teams and fire fighters to operate with a reasonable level of safety and leave the site safely.

The additional safety measures include extinguishing installations and equipments, emergency communication installations, control of utilities and safety systems, fire protective systems, marking and signs to assist fire fighters, ...

3. Traditional prescriptive approach

These general performance requirements are traditionally expressed in the fire safety regulations, standards and codes of practice by prescriptive requirements based on a conventional fire development, usually the temperature growth over time defined by the international standard ISO 834 (2), and on specific design solutions which have proved to be satisfactory by experience.

This traditional approach doesn't take into account the variability of fire developments and imposes design concepts which are often limiting artificially the freedom of search for design solutions.

4. The natural fire safety concept

One step forward to a more realistic fire assessment is to consider the various possible developments of real fires which may occur, associated with their probability of occurence, based i.a. on statistics of real fires.

This approach needs to identify the different fire origins and their possible scenarios, in order to check the fire safety against the most unfavourable developments of temperature over time. These temperature developments over time are calculated in each case of fire from a combustion model which takes into account the oxygen available to adapt the curve of Rate of Heat Release over time obtained from full scale tests (3).

From the total development of the temperature over time in the tunnel (temperature increase and decrease), the temperature evolution within the tunnel walls and its consequences on the properties of the materials and the stability to fire of the structure of the tunnel may be assessed.

Imposed and constrained expansions and deformations caused by temperature changes shall be considered not only within the members exposed to fire but also in any other member and part which may be affected.

5. The global fire safety concept

5.1 General principles

The next step forward is to express and assess directly and quantitatively the performance requirements, independently of the building solutions, in order to give more freedom to the designers and to allow a better optimization of the combinations of safety measures.

5.2 Loadbearing capacities

5.2.1. Probabilistic approach

As suggested by J.B. SCHLEICH and his European research team (4), the probabilistic approach described in EUROCODE 1 (5) (6) may be used in order to quantify the influence of safety measures. The safety condition to be checked is that the failure probability of the structure Pf_S is lower than a target failure probability Pt :

$$Pf_S \leq Pt$$

where $Pt = 10^{-6}$/year or 10^{-4} over a working life of 100 years
is the level of structural safety standardized by EUROCODE 1

$Pf_S = Pfi \,.\, Pacc$
Pfi = failure probability in case of fire
Pacc = probability of fire

The probability of a fire in a tunnel may be derived from statistical analysis of real fires having occured.
For railway tunnels, an order of magnitude of Pacc is 6.10^{-4}/year per km of tunnel (7).
For roadways, an order of magnitude of Pacc for one civil engineering structure (tunnel or bridge)

has been established for example for France (8) :

- any fire : $1{,}5.10^{-3}$/year
- fire from trucks : 4.10^{-4}/year

A target value of the failure probability in case of fire Pt,fi may then be obtained :

$$Pt{,}fi=\frac{Pt}{Pacc}$$

The analysis may be further developped if alternative fire scenarios may lead to failure; in this case, the failure probability of the structure will be obtained by the addition of the probability of occurence of each alternative fire scenario multiplied by the failure probability in case of this fire scenario :

$$Pf_S=\sum_j Pfi{,}j.Pacc{,}j$$

The probability of occurence of each fire scenario Pacc, j may be derived from statistics of real fires.

The failure probability in case of one specific fire scenario Pfi, j is depending on the safety factors applied in the checking of the design against the effects of this fire, considered as an accidental action.

When a part of the failure probability is allocated to each fire scenario, a target value of the failure probability in case of each fire scenario may be established and safety factors may be derived as described in EUROCODE 1.

5.2.2. Safety factors

If the resistance R and the stress or sollicitation S in a structural section are represented by their statistical distributions defined by their standard deviation σ and mean value m, the failure occurs when S > R and the failure probability Pf is given by the hatched area under the probability density function of the variable z = R - S for which z < 0 (figure 1).

ill. 1

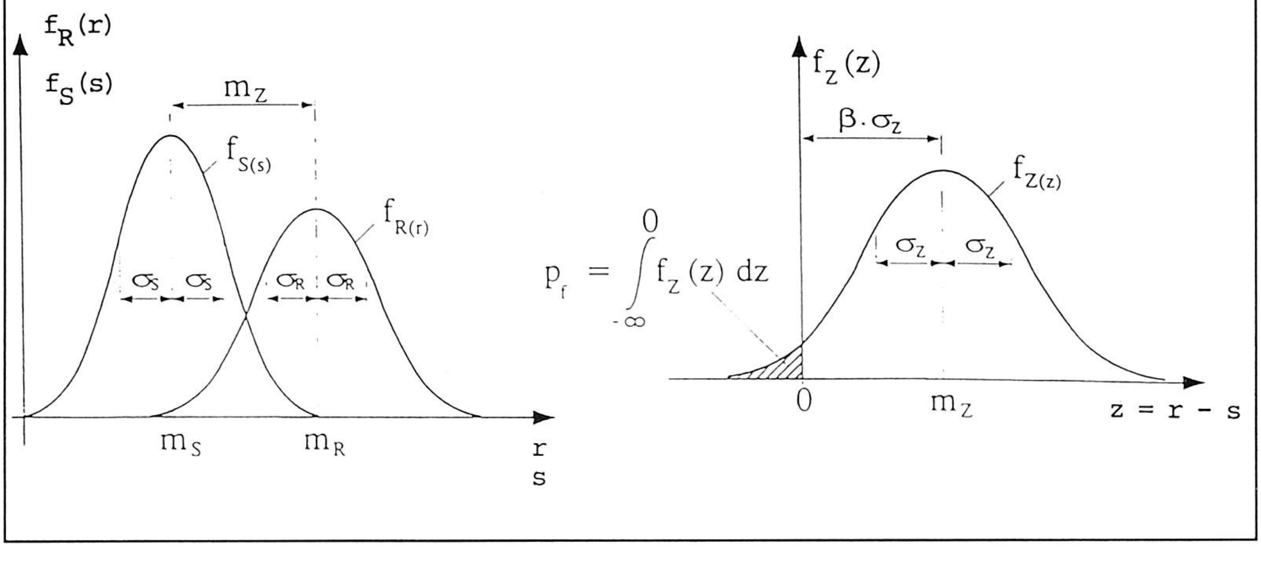


Figure 1

In order to simplify the verification, EUROCODE 1 has adopted a semi-probabilistic approach, the FORM (First Order Reliability Method), based on the following assumptions :

ASSUMPTION 1 :
The two variables R and S may be represented by equivalent normal distributions, so that $z = R - S$ is also a normal variable defined by its mean value $m_Z = m_R - m_S$ and its standard deviation

$$\sigma_z = \sqrt{\sigma_R^2 + \sigma_S^2}$$

The value z having a probability P of not being exceeded is given by $z = m_Z - \beta \sigma_Z$ where β is the value of the standard normal variable ($m_\beta = 0$, $\sigma_\beta = 1$) having the same probability of not being exceeded.
For $z = 0$, $\beta = m_Z/\sigma_Z$ and the probability of failure $Pf = \phi(\beta)$ can be read from standard normal distribution tables (Table 1). Conversely starting from a value of Pf, the corresponding value of β, called the safety index, may be obtained.

ill. 2

Pf	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
β	1,3	2,3	3,1	3,7	4,2	4,7	5,2

Table 1

ASSUMPTION 2 :
The failure condition may be written : $R_d < S_d$
where $R_d = m_R + \alpha_R \beta \sigma_R$ = design value of resistance
$S_d = m_S + \alpha_S \beta \sigma_S$ = design value of stress or sollicitation
and $\alpha_R = \sigma_R/\sigma_Z = 0{,}8$
$\alpha_S = \sigma_S/\sigma_Z = -0{,}7$

By considering constant (simplified) values for the weighting factors α_R and α_S, the design values R_d and S_d may be defined independantly of each other : each design value depends only on the safety index β and on the statistical distribution of the variable represented.

As a consequence, it is possible to define safety factors $\gamma_R = Rd/Rk$ and $\gamma_S = Sd/Sk$ where Rk and Sk are the standardized characteristic values of the variables R and S.
The safety factors γ_R and γ_S depend on the nature of each variable and the safety index corresponding to the target value of the failure probability.

5.3 Limitation of generation and spread of fire and smoke

For each possible fire scenario, the ability of the tunnel ventilation systems to control air flows has to be checked in order to provide for the safety of occupants along their escape routes for the time needed to evacuate, and for the safety of rescue teams along their access routes to the fire area.

The performance requirements to be checked may be expressed in terms of air toxicity, temperature and obscuration, and will depend from the concept for evacuation of occupants and for access of rescue team.

5.4 Safety of evacuation of occupants

This requirement may be expressed by a maximum evacuation time to be assessed by calculation models, and by additional performance requirements regarding functional geometry of escape routes, emergency lighting, guidance signs, etc ...

5.5 Safety of rescue teams

This requirement may also be expressed by a maximum access time for fire fighters, medical teams, etc ... together with additional performance requirements.

5.6 Global probability of casualties

One could think ultimately to look for a safety objective expressed as a global probability of casualties not to be exceeded, which would include the influence of all the above mentionned causes. To achieve this objective, a quantitative risk analysis has to be performed, which balances the consideration of an accident's consequences with an estimation of its frequency.

This approach mixes together technical factors, which may be quantified, and human factors, which are much more difficult to evaluate.

A fire prevention strategy with regard to training, inspection, maintenance, testing, fire fighting exercices, etc ... is required to minimize the risks but it would not be wise to rely on it completely for fire safety assessment of civil engineering design. Therefore, we would recommend to maintain two criteria : a target value for the structural failure probability and a target value for the global probability of casualties.

6. References

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Fire Hazard Mitigation for the Øresund Link Immersed Tunnel

Steen Lykke
Contract Director
Øresundskonsortiet
Copenhagen, Denmark

Erik Skotting
Design Manager
Øresundskonsortiet
Copenhagen, Denmark

Jan Ebben
Team Leader, Mech. & Elec.
Øresund Link Consultants
Copenhagen, Denmark

Mikael W Braestrup
Chief Adviser
RAMBØLL
Copenhagen, Denmark

Summary

The 3.8 km immersed tunnel for motorway and railway under the Drogden Channel, currently under construction and scheduled to open in the year 2000, is a significant component of the Øresund Link, connecting the Danish capital Copenhagen with the Swedish city Malmö. The toll-funded link will be owned and operated by Øresundskonsortet, a Swedish-Danish joint venture, which is also responsible for the construction of the 16 km coast-coast section of the link. The Drogden Tunnel accommodates two tubes for the dual track railway, two tubes for the four lane motorway, and a central installation and escape gallery. The latter is a major feature of the safety concept, by providing a safe and smoke-free escape route in case of accident or fire. The fire hazard mitigation includes fire insulation of the structure, and hydrants for fire fighting, but no automatic sprinkler system.

1. Introduction

The toll-funded motorway and railway link across Øresund will connect the city centers of Copenhagen in Denmark and Malmö in Sweden. The approximately 16 km coast-to-coast section comprises the following key components (see Fig. 1):

- An artificial Peninsula extending 430 m from the Danish coast at Kastrup
- An immersed Tunnel 3,510 m long under the Drogden navigation channel
- An artificial Island 4,055 m long south of Saltholm
- A western Aproach Bridge 3,014 m long between the Island and the High Bridge
- A cable-stayed High Bridge 1,092 m long over the Flintrännan navigation channel
- An eastern Approach Bridge 3,739 m long from the High Bridge to the Swedish coast at Lernacken
- A terminal area with toll station and Link Control Center located at Lernacken.

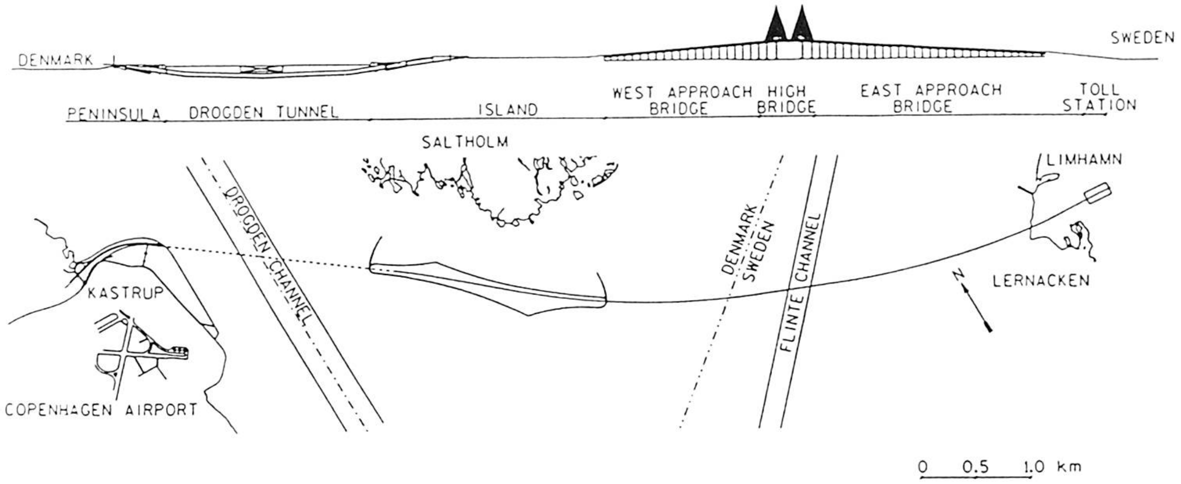

Fig. 1: Coast -to-coast section of the Øresund Link

The Drogden Tunnel is motivated by the proximity of the link to the Copenhagen airport at Kastrup, which precludes a high bridge over the busy navigation channel. The tunnel cross-section accommodates two tubes for the dual track railway, two tubes for the four lane motorway, and a central installation and escape gallery (see Fig. 2). The outer cross-sectional dimensions are 8.6 m by 38.8 m.

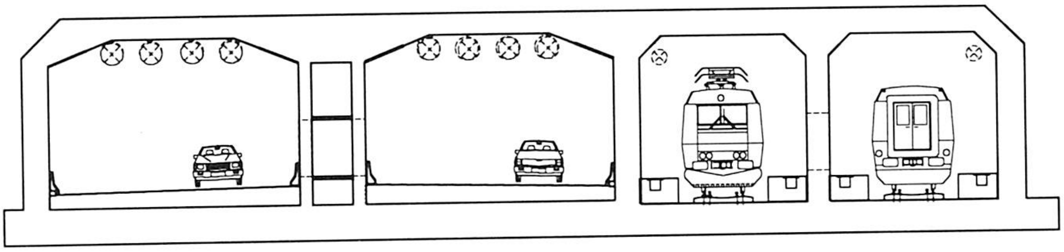

Fig 2: Cross-section of Tunnel

The approximately 3.8 km long tunnel consists of three main components (see Fig. 3):

- Ramp and portal building on the Peninsula
- Immersed Tunnel under the Drogden navigation channel
- Ramp and portal building on the Island

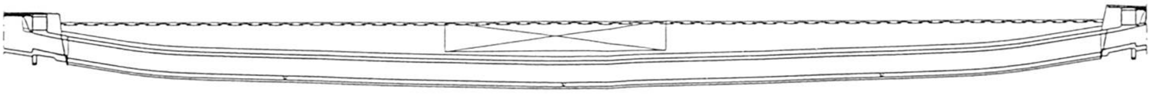

Fig. 3: Longitudinal Section of Tunnel

The portal structures accommodate underground service buildings with rooms allocated for tunnel installations, ie road lighting, ventilation, drainage, communications and energy supply.

The 3.5 km immersed part of the tunnel is constructed from 20 elements that are floated out and installed in the predredged trench. Each element is composed of 8 segments, which are match-cast and joined by injectable waterstops. During tow-out and immersion the integrity of the element is provided by temporary prestressing.

The first element was installed at the peninsula portal in early August 1997, and construction is proceeding on schedule (se Fig. 4). Thus six elements had been placed at year-end 1997, and the last element is due to be installed in December 1998.

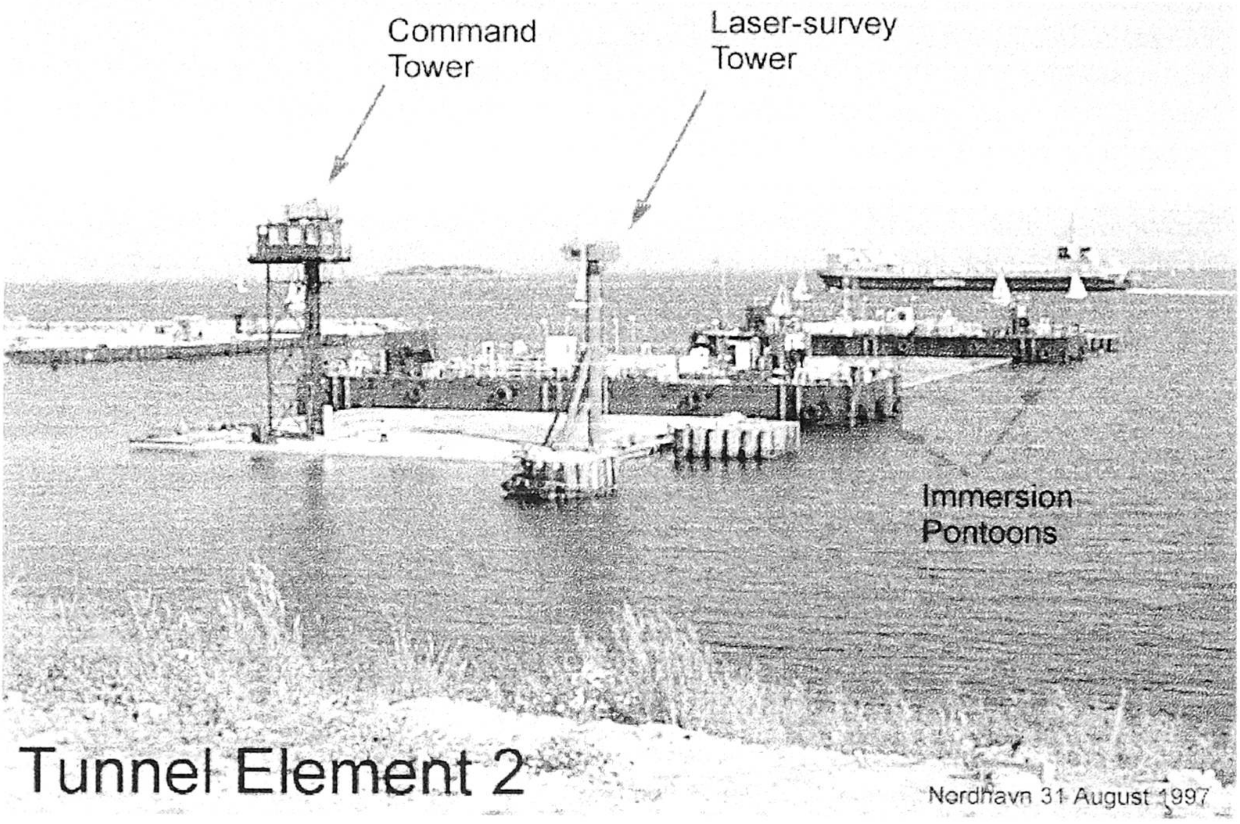

Fig. 4: Tunnel element moored at production facility north of Copenhagen, ready for towing to construction site for immersion

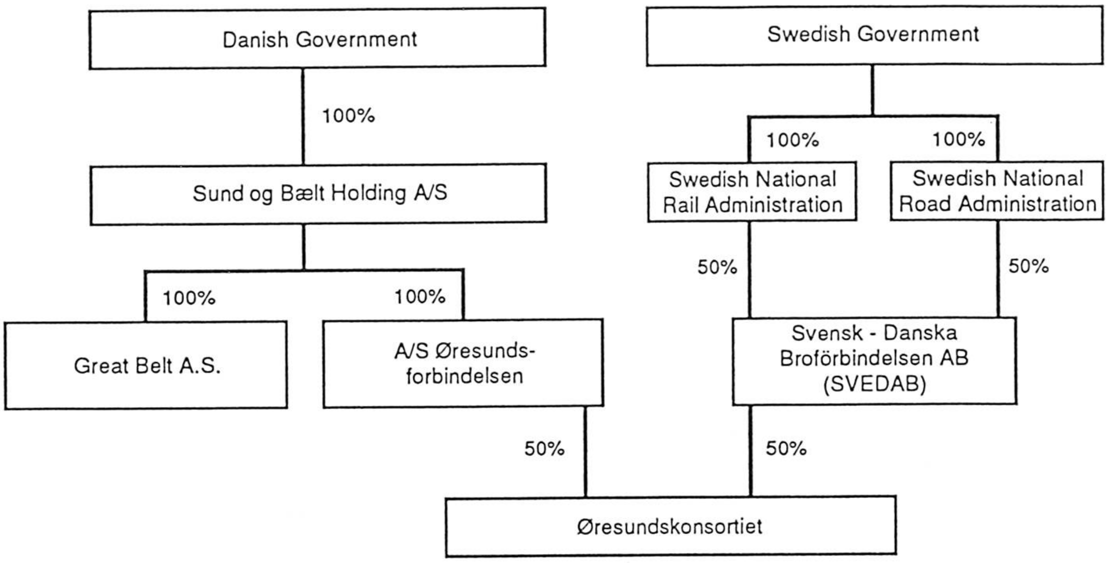

Fig 5: Øresund Link Ownership Organization Chart

The Øresund link shall be owned and operated by Øresundskonsortiet, a Swedish-Danish joint venture, indirectly owned by the two governments (see Fig 5.) The two partners - Øresundsforbindelsen and SVEDAB - are directly responsible for the Danish, respectively the Swedish, landworks, ie the traffic infrastructure connections to the city centres, whereas Øresundskonsortiet is in charge of the coast-to-coast section.

The major construction works are covered by three contracts tendered in 1994: Dredging & Reclamation, Tunnel, and Bridges. In July 1995 the USD 670 million Tunnel contract was awarded to the Øresund Tunnel Contractors, a joint venture between NCC Contractors (Sweden), Dumez GTM (France), John Laing (UK), Pihl & Søn (Denmark) and Boskalis Westminster (Netherlands).

The tunnel construction was tendered as a design-and-construct contract, implying that the contractor is responsible for the detailed design, based upon a conceptual design prepared by the Øresund Link Consultants (ØLC), acting as house consultant to the owner. ØLC is a joint venture between RAMBØLL (Denmark), Scandiaconsult (Sweden), Halcrow (UK) and Tunnel Engineering Consultants (Netherlands), in association with architects Dissing + Weitling (Denmark). Contracts for coast-to-coast installations, including the provision of control and communication systems and equipment, were tendered in 1997.

To ensure the owner's control of the environmental and aesthetic qualities of the Link the conceptual design is quite specific regarding geometry, dimensions, and major features. Furthermore, it is required that the design be performed in accordance with the Eurocodes, which is made possible by means of a Project Application Document, prepared by ØLC.

2. Safety Concept

2.1 Risk Analyses

It is the policy of the owner to ensure that the risk to users of the Øresund Link is reasonable and comparable to those associated with similar traffic installations in Denmark and Sweden. To examine various scenarios which could lead to fatalities or disruptions of the Link operational risk analyses have been carried out, including individual as well as societal risks. The individual risk is measured in eg the fatality risk per billion passages of the Link. The societal risk may be expressed in a risk profile (see Fig. 6). The frequency is plotted on the vertical axis, and on the horizontal a measure of the consequences (user fatalities, third party fatalities, days of disruption). The risk is traditionally calculated as the product of frequency and consequence, thus in a double logarithmic plot a constant risk level corresponds to a straight line with negative slope. Risks in the lower left hand corner are acceptable, whereas the upper right hand region is clearly unacceptable. In between is a region where the risk shall be As Low As Reasonably Possible. For designs in the ALARP region risk mitigation measures are introduced on a cost-benefit basis.

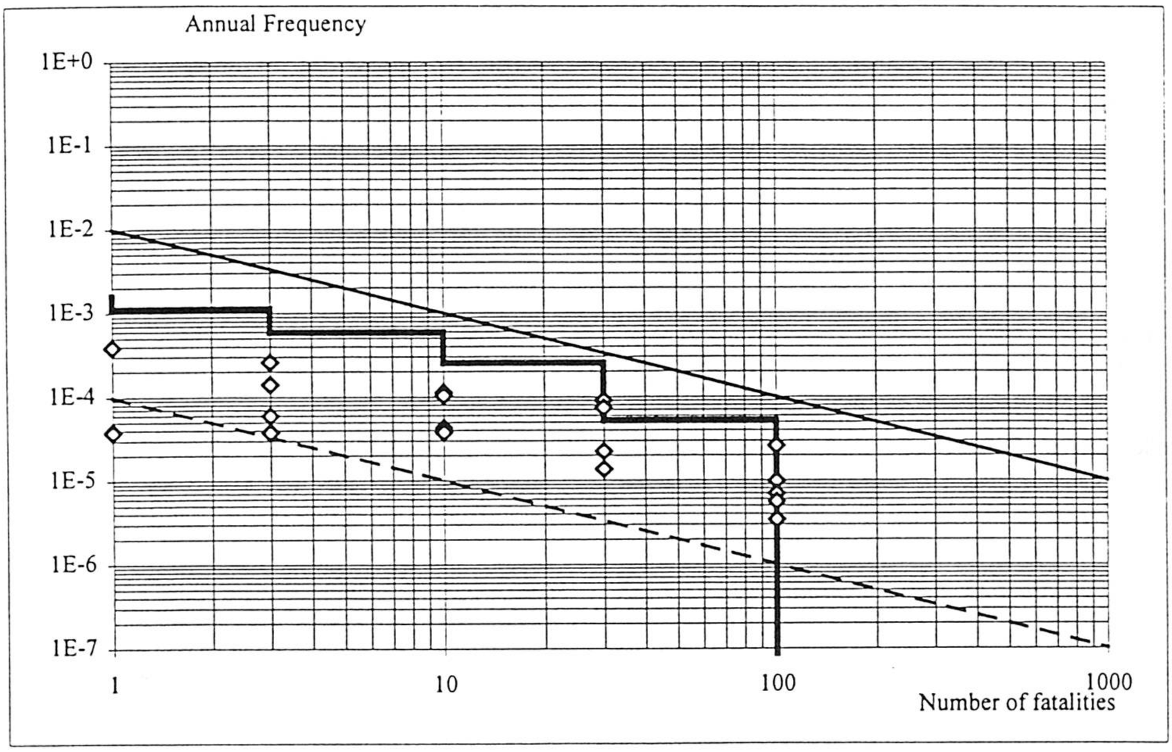

Fig. 6: Typical Risk Profile, showing the ALARP Region

For the Øresund Link a special study has been carried out concerning the transport of dangerous goods, and the operational risk analysis concluded that no restrictions need be imposed. Further risk reducing measures are, however, considered, such as the operational restraint of not allowing freight trains with dangerous goods in a tunnel tube simultaneously with passenger trains.

The following fire scenarios have been analysed:

Motorway

- Car
- Truck
- Heptane
- LPG

Railway

- Passenger train
- Freight train
- Heptane
- LPG

Thus scenarios with and without dangerous goods are included.

The evaluation of the structural consequences of fires take account of the fire insulation and the fire fighting, cf chapter 3 below. The human consequences are based upon the assumption that the ventilation system is operating to reduce the heat and the smoke.

In the motorway tubes the most severe scenario is a heptane fire with a catastrophic release of fuel. Depending on the time of day the number of fatalities is 3 - 30, and minor spalling could lead to the closure of one lane for a week.

For the railway tubes the consequences of fire could be more severe due to the larger concentration of people. Thus a pool fire with a large release of heptane could cause up to 300 fatalities, and close a track for 1 - 2 weeks. An LPG flash fire with a catastrophic release of fuel, which is highly unlikely, could lead to collapse of the tunnel.

2.2 Authorities' Requirements

In order to incorporate safety requirements in the design at an early stage Øresundskonsortiet in October 1993 instigated the formation of an advisory group, known as KKSURR (the Danish acronym for coast-coast safety, accident, rescue and clearance). KKSURR comprises representatives from road and railway authorities, as well as police, fire brigades, rescue organizations and municipalities from both countries, together with the owner and his consultants, thus involving all stakeholders in the operation of the road and railway link.

The work of the group is collated in the 'KKSURR Report', and the conclusions are incorporated into the 'Design Basis - Safety', which is part of the internal project Technical Design Basis (TDB). The requirements of the TDB are included in the relevant contract documents for the construction works.

For the tunnel the KKSURR report includes numerous recommendations regarding fire prevention and detection, but there are no requirements to fire insulation. This feature has been adopted by the owner in the tunnel design as regards fire hazard mitigation, which is summarized in the section below and detailed in the subsequent chapters.

2.3 Tunnel Design

A major feature of the safety concept is the central gallery between the motorway tubes, which serves as a safe and smoke-free escape route in case of emergency.

The outer walls, the roofs and the upper part of the internal walls of the four traffic tubes are protected with fireproof insulation material, and emergency installations containing fire-fighting equipment and telephones are placed at intervals of 88 m. At the same spacing safety doors are provided between the two railway tubes, between the railway and the motorway tube, and in the walls giving access to the escape gallery, which constitutes a safe exit for all tunnel users in case of emergency.

In case of a fire the ventilation system can be directed to control the smoke and the heat, facilitating the work of the fire brigades and rescue teams. It also serves to provide oxygen to avoid the accumulation of unburned gasses, which might impose an explosion risk. The ventilation will remain operational for at least an hour at a temperature of 250°C. Fire hydrants with connectors for both Danish and Swedish fire fighting systems are placed at the walls to the central gallery, next to the escape doors (see Fig. 7).

The tunnel is provided with a drainage system to remove water and any liquid spillage from the road and the railway. The 2% cross-fall of the carriageways leads liquids to drain pipes with inlets and water locks every 22 m. The tunnel tubes have separate pump sumps with spare pump capacity, fire detectors, and automatic foam extinguishing systems. The pump sumps are equipped with seals as well as oil and sediment separators.

The entire coast-to-coast link is supplied with high-voltage power, which can be fed from Danish as well as Swedish high-voltage grids. This ensures a high reliability of supply, and loss of high-voltage power would require at least two consecutive failures.

All essential power consumers are connected to Uninterupted Power Supply (UPS) units with battery back-up. The batteries of the UPS are automatically charged during periods of normal power supply, and the UPS systems take over immediately in case of public power supply failure.

The lighting system for the road tubes is designed to make the roadway and all objects on it sufficiently visible at the required distance.

The Øresund Link is provided with a supervisory control and data acquisition (SCADA) system to monitor the road traffic and control all installations. The SCADA communicates via an optical fibre system (a 'data highway'), and can be operated from control centres as well as locally.

3. Fire Protection and Materials

3.1 Fire Insulation

The main purpose of the fire insulation is to ensure the structural safety of the tunnel in case of fire. The functional requirements to the insulation is that it shall prevent spalling of concrete and deterioration of segment joints as well as immersion joints by offering protection during a two hour hydrocarbon fire.

The adopted material is Fendolite MII, applied by spraying to a thickness of 21 mm. Fendolite MII is a proprietary, cementitious material, the main ingredient being vermiculite 'aggregate' which provides resistance to thermal shock by allowing expansion to take place within the material, without inducing internal stresses. Application is by shotcreting technique, where water is added to the dry mix at the spraying nozzle. The fire insulation is applied to the tunnel roof and at the complete outer walls above the New Jersey barriers. The internal separation walls are only covered over approx.1m below the haunch of the bores (see Fig. 7).

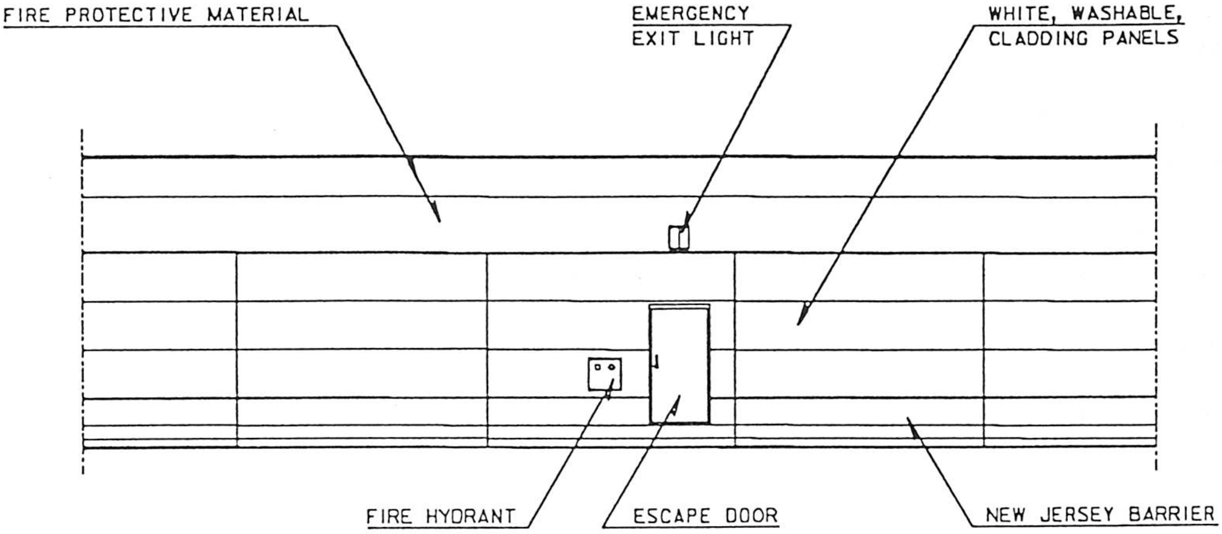

Fig. 7: Longitudinal section of roadway tunnel, showing the wall to the escape gallery

The fire insulation material has been used in tunnels in the Benelux and in Hong Kong, and the efficiency in preventing concrete spalling has been verified by laboratory testing. For the Øresund Link dedicated fire testing of segment and immersion joints is planned.

3.2 Fire Fighting

The need for a sprinkler system in the roadway and railway tubes has been discussed in the KKSURR group, and the recommendation was against deployment. The reason is that in case of fire sprinkling could force the smoke down, creating poor visibility and air quality, which would endanger evacuation and rescue actions. The main purpose of a sprinkler system would be protection of the structures, which is achieved by the fire insulation, cf the preceding section.

In the service gallery, however, a water spray system will be provided to protect the electrical system cabinets, cables and accessories. The water spray system consists of:

- A main plant in each portal building, including water storage facilities, pumps and control panel
- A main water pipe connected to both main plants, and running in the lower part of the central gallery
- Approximately 64 sections (at about 60 m spacing) connected to the main water pipe through a diverting valve, and feeding a dedicated section of spray nozzles.

The water storage capacity at each portal is sized to supply a maximum of one section for 10 min action at any time, resulting in capability of supplying two adjacent spray sections for 10 min.

Each main plant is equipped with a programmable unit located in the control panel, which ensures the local automatic control of the system. Information is transmitted via the overall SCADA system. An automatic fire detection system activates the water spray system, and sends general information to the SCADA.

For fire fighting in the traffic tunnels pressurised water is provided in fire hydrants located next to the emergency doors to the escape gallery (see Fig. 7). The main components of the fire hydrant system are:

- A fire main run in the central gallery, with branches every 88 m to the fire hydrant in each motorway tube
- A pumping plant and reservoir at each portal building.

The emergency panels, placed at 88 m distance in all four traffic tubes, are equipped with fire alarm push buttons and dry powder fire extinguishers.

The fire hydrants are placed in recesses, protected by a door, and fitted with couplings corresponding to Danish and Swedish fire fighting systems. Fire hose reels are located in each portal building. In addition the fire hydrant system is used to supply water to the water spray system reservoirs at the portals (cf above), and to the foam extinguishing systems at the mid-point pump sumps.

The water reservoir at the peninsula portal is supplied with municipal water from Copenhagen, whereas the island reservoir is supplied via the fire hydrant piping. The concrete reservoirs are placed in the immediate vicinity of the fire hydrant pumping stations to minimise connection piping. Each fire hydrant pumping station will be fitted with two main pumps, one being a stand-by. Under normal operation the main pump is designed to supply, on one half of the fire hydrant network, a 800 kPa maximum and 450 kPa minimum pressure at hydrant head, with two hydrants in operation (216 m^3/h).

A water treatment system is provided upstream of the peninsula reservoir for the addition of hypochlorite or similar to reduce scaling deposits in the pipes.

4. Safety Provisions for Users

4.1 Escape and Access Routes

To give the tunnel the same safety standard as a public building it is necessary to provide an escape route such that people can leave an accident area as soon as possible, and enter an environment which is physically separated from the accident, and from where they can safely leave the structure.

The Drogden Tunnel escape system is based on the escape gallery located between the motorway tubes. Access to the escape gallery is by emergency sliding doors placed every 88 m, and marked with emergency signs above the doors (see Fig. 7). For the railway tubes the escape routes are in the other tube, via the elevated foot paths. Consequently, emergency doors are located in the separation wall between the railway tubes. The doors are situated at the same chainages as for the motorway tubes, and emergency panels are placed adjacent to the doors.

The escape gallery is provided with an over-pressure system to prevent the entering of smoke. Internal signs give the direction of the way out. The gallery is split into two parts by the mid-point installations rooms, so the accessible portal is also the nearest.

When the evacuees reach the portal building they continue along the escape gallery out of the structure into the median strip between the New Jersey Barriers in the open air. Using the portal building itself as a way out is not feasible in a situation with many people under traumatic circumstances.

Depending on the severity of the accident in one of the tunnel tubes the complete tunnel may be closed. In that case rescue organisations like police, fire brigade, etc. are able to use the free motorway tube as an access route to the accident. Flashing emergency signs will give the position of the door to be used to cross the escape gallery and enter the accident area.

4.2 Lighting

The railway tubes are provided with a minimum lighting level which is sufficient for maintenance, and for finding the way out in case of accidents.

The purpose of the motorway lighting system is to give guidance to the driver regarding the alignment, and to show objects on the surface of his lane. The approach roads have a middle verge lighting system of low pressure sodium lamps. This lighting is the continuation of the lighting of the connecting roads.The tunnel structure is provided with a dedicated lighting system. The long tube will be extremely dark during day hours, and to prevent the so-called "black hole" effect the entrance lighting can be regulated in the right proportion related to the outside levels. Six different levels are available, and the switching will be done automatically, based on information from sensors under the daylight louver.

The tunnel structure is divided into 4 zones, the threshold zone, the transition zone, the interior zone and the exit zone. In each zone the lighting level will be adapted to the preceding zone. The threshold zone is provided with a daylight louver to gradually lower the level of the daylight so it can be continued by artificial light. Then in the transition zone the level will be reduced again until a level which is sufficient to recognise everything happening in the tube, and which also creates a relaxed driving situation. The interior zone lighting will continue at this level until the exit zone, where the level will be increased as preparation to the open air area.The level of the exit area is designed in such a way that in cases of two way traffic in one tube the zone is able to act as an entrance lighting system as well.

4.3 Ventilation

The design criteria for the ventilation are as stated below.

Wind velocity at the portals	12 m/s
Maximum air velocity created by fans at centre tunnel	10 m/s
Maximum NO_2 value	800 $\mu g/m^3$
Maximum CO value during free floating traffic	50 ppm
Maximum CO value during congested traffic	100 ppm
Maximum CO value during maintenance	35 ppm
Visibility during free floating traffic	0.005 m^{-1}
Visibility during congested traffic	0.007 m^{-1}
Visibility during maintenance	0.003 m^{-1}
Fire load	100 MW
Maximum temp. the fans shall withstand and transport air for at least one hour	250 °C
Maximum A-weighted sound pressure level of fans	95 dB(A)

Traffic characteristics

Traffic flow in each direction per annual average day	10,000 v/ad
Peak hour traffic flow in each direction	1,300 v/h
Congested traffic flow in each direction speed 20 km/h	2,000 v/h
Maximum peak traffic flow in each direction	65 v/min

Traffic composition during Peak Hour and Basic Traffic Emission

Traffic composition during peak hour	%	Basic traffic emission at 60 km/h		
		Ox	CO	Smoke
		g/(km, vehicle)	g/(km, vehicle)	M^2/(h, vehicle)
Cars	88.0	0.23	1.01	-
Heavy trucks, Diesel < 7 tons	4.2	0.81	3.24	50
7-18 tons	3.2	3.60	2.09	120
> 18 tons	4.6	11.63	3.09	180

The ventilation of the motorway tubes has been designed to create a maximum air velocity of 10 m/s at the centre of the tubes. This velocity is necessary to blow out, under all circumstances, possible smoke in case of fire.

The ventilation system will also be used to keep the polluted air within acceptable limits. A detection system of CO and visibility sensors will be installed, which switches on the fans as needed to keep the pollution level acceptable.

The fans are fixed in niches in the ceiling in 3 sections in the tunnel, located at the entrance, the mid-point, and the exit of the tunnel. Each section consists of 5 rows of 4 fans each (see Fig. 2).

The ventilation system is completely reversible, providing the option of blowing in the most convenient direction in case of accidents. During normal conditions the air flow will be in the traffic direction.

The railway ventilation system is in principle the same, except that there is only 1 fan in each of the 5 rows (see Fig. 2).

4.4 Emergency Panels

Emergency panels are located in all four traffic tubes in the exterior walls of the motorway tubes and in the wall separating the railway tubes. The spacing is 88 m, the same as that of the emergency doors giving access to the escape gallery between the motorway tubes.

Each emergency panel contains a hand fire extinguisher, a telephone which is directly connected to the central operator, an alarm push button, two electrical socket outlets, and lighting connected to the UPS. The door of the panel can be opened and the alarm push button can be used as well as the telephone. In that way the Link operator will be informed immediately in case of accidents. Simply opening the door will give a signal to the operator by means of a built-in switch, alerting the operator to the fact that the door is open.