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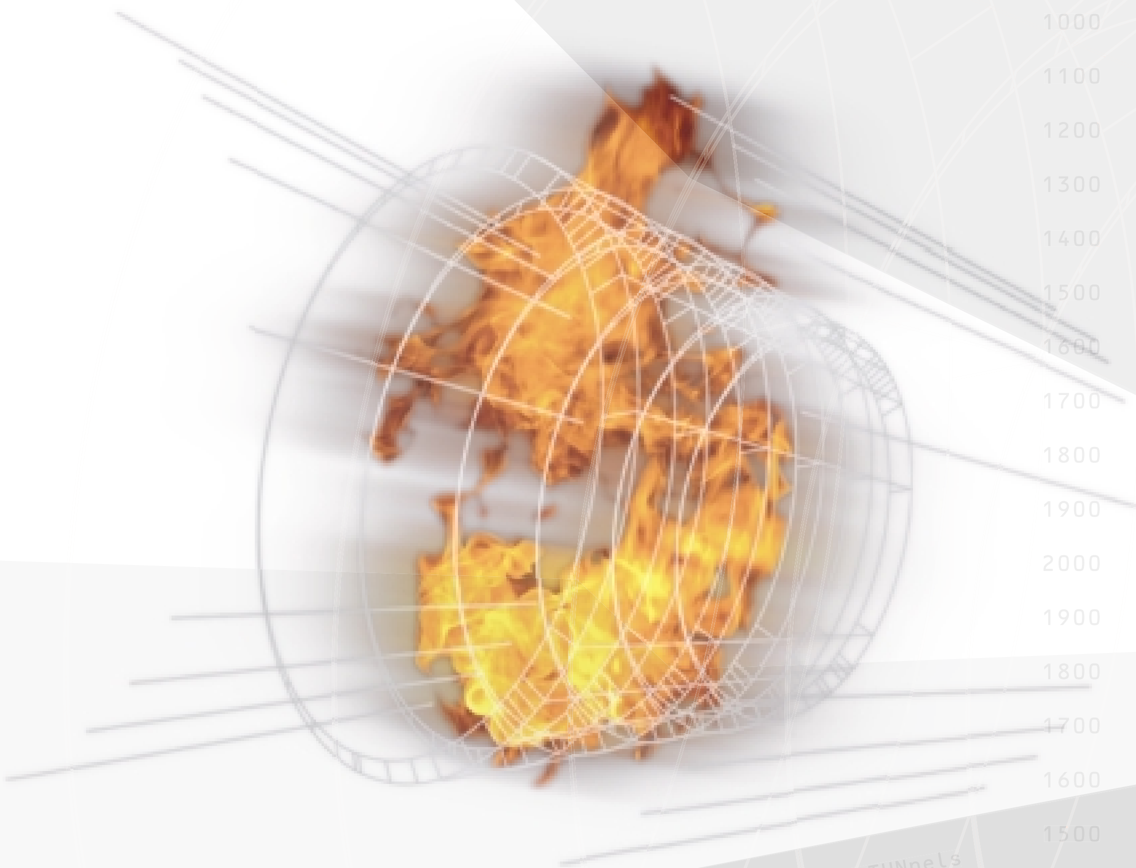
Summary of Large Scale Fire Tests in the

RUNEHAMAR

Tunnel in Norway,
conducted in association with the UPTUN Research Program



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

Contributions from:

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

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Content

Foreword

As co-ordinator of the UPTUN project, I am pleased to present this publication on important results of tunnel safety research work. This work was carried out in the framework of a Swedish national and a European research program on tunnel safety. Comprehensive large-scale fire tests have been conducted in the abandoned Runehamar road tunnel in the Western part of Norway in September 2003.
The measurements and preliminary analyses are such that the results will definitely contribute to increase tunnel fire safety levels in Europe. Therefore the initiative for the actual publication of this document was taken by Promat International with the aim to inform tunnel related, interested parties, by means of this summary document.
The work presented would not have been possible without the effort and financial contribution of the Swedish Road Administration, the Norwegian Road Administration, the Swedish Rail Administration, the Swedish Rescue Services Agency, the Swedish Fire Research Board, the Directorate General Research of the European Commission, the UPTUN partners (especially SP, NBL and TNO) and the industrial partners, especially the partners who supplied and installed the passive fire protection system: Promat International N.V., GERCO Beveiligingen B.V.
This document is based on the presentations and papers of the Boras conference on Catastrophic Tunnel Fires, in November 2003.
I would like to thank René van den Bosch (Promat) and Jan Brekelmans (TNO Building and Construction Research) for their editorial work.

Kees Both, PhD
Coordinator UPTUN project

1 INTRODUCTION

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

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

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

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

UPTUN

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

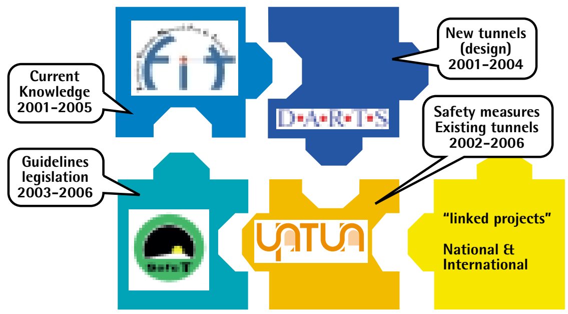
The 41 partners of UPTUN originate from 17 European countries. Several disciplines and professions are incorporated as owners, consultants, universities, research organisations and manufacturers. The partners from Eastern countries take part of the work for some 10%.
It is important to look at tunnels as a system in an environment. Measures to improve fire safety will therefore be studied as a system rather than sub-optimised. Positive as well as adverse interaction should be identified. Socio-economic aspects on the wider region have to be taken into account.
The UPTUN project will play a pivotal role in linking up with:

- various national and international investigations, such as the EC funded research projects and networks: FIT, Darts and SafeT *(see Figure 1)*
- important tunnel associations, such as: International Tunnelling Association (ITA), World Road Association PIARC and the United Nations Economic Commission for Europe

and last but not least,

- national projects, such as the Runehamar tests.

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



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

2 OBJECTIVES

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

2.1 European Commission

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

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

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

2.2 Technical objectives Runehamar tests

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

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

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

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

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

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

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

3 PREPARATION

3.1 Laboratory tests to predict Heat Release Rate (HRR)

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

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

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

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

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

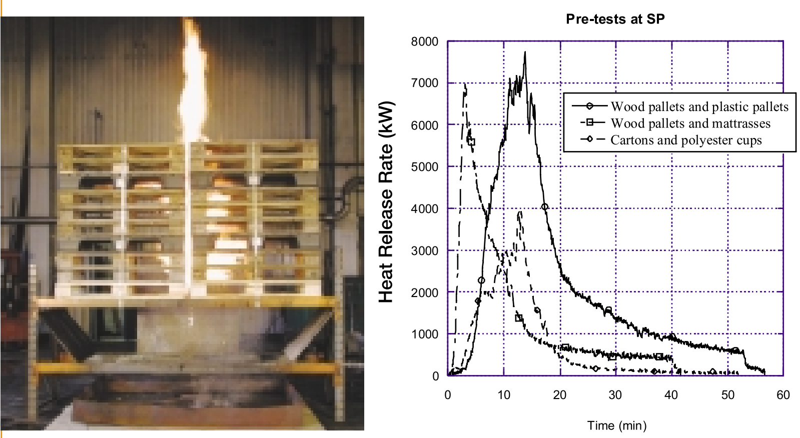


Figure 2 Pre-tests SP.
A Free-burning pre-tests under Industry Calorimeter with wood pallets and plastic pallets.
B Measured HRR.

3.2 Thermal protection boards

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

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

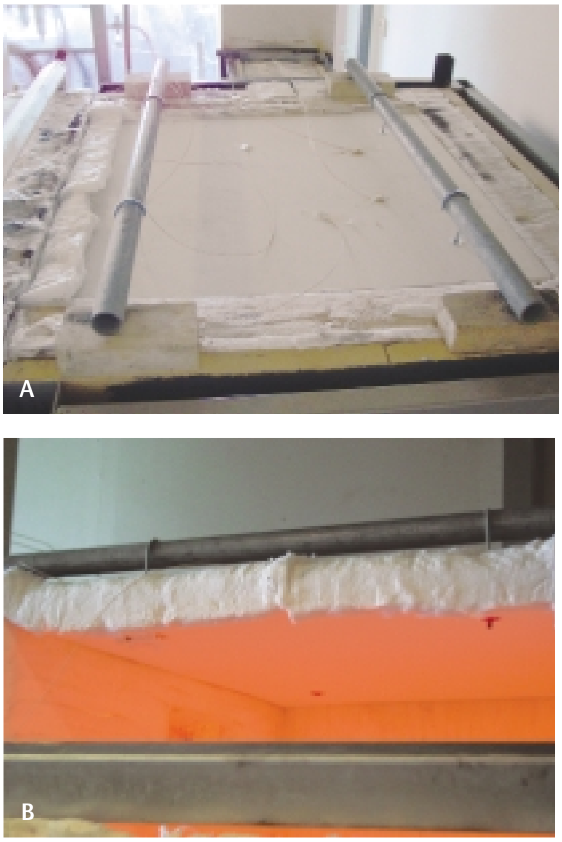
The challenge for the PROMATECT® -T panels can be described as follows:

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

3.2.1 Boards

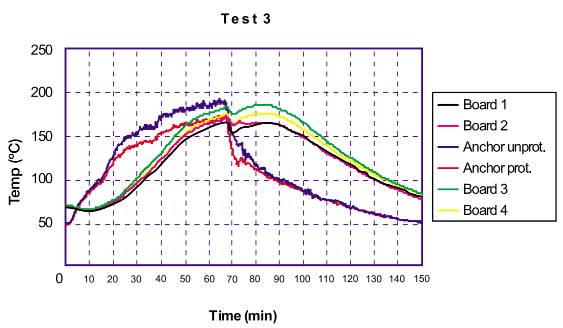
To enable more than one test, the boards were constructed using two thinner boards (20 and 25 mm), glued together with intermediate reinforcement *(see further, Figure 5)*. This is not a standard practical solution but in this case it was chosen to guarantee the integrity of the panel over more than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

Figure 3 Pre-qualification tests Promat and GERCO.



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

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



3.2.2 Pre-qualification of the intended system

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

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

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

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

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

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

3.2.3 Conclusions of the pre-qualification tests

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

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

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

3.3 Steel structure

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

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

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

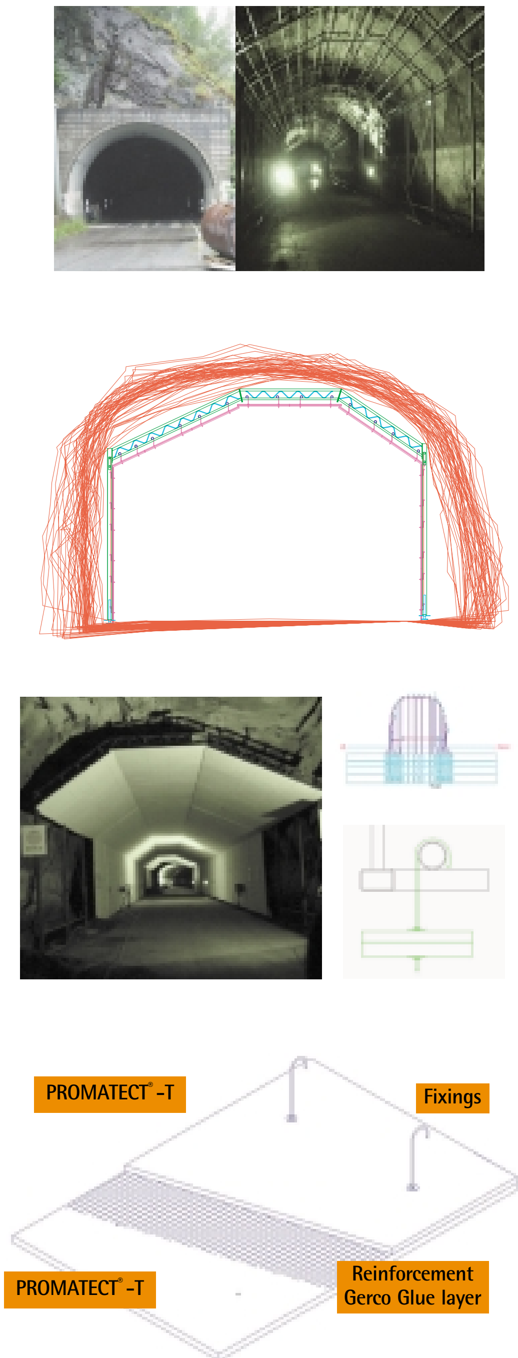
The starting points for the design of the structure were based on the following assumptions:

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

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

Figure 5

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



4 TESTS

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

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

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

Table 6 Commodities used as fuel in the four tests.

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

4.1 Test 1

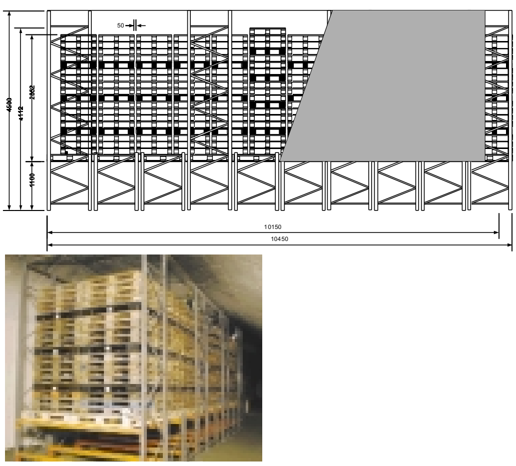


Figure 7 Commodity set-up for test 1 (wood pallets and plastic pallets).

4.2 Test 2

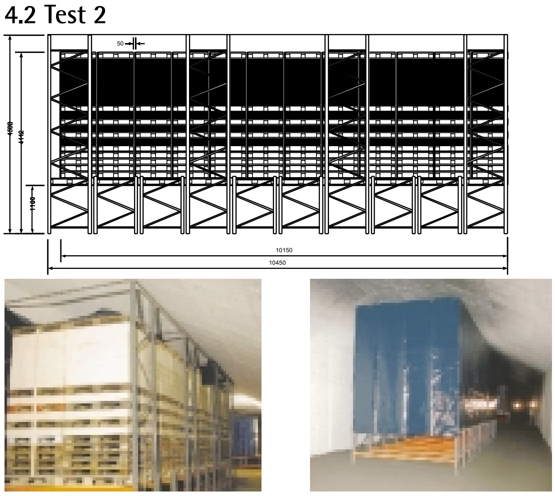


Figure 8 Commodity set-up for test 2 (wood pallets and PUR mattresses).

4.3 Test 3

Figure 9 Commodity set-up for test 3.

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

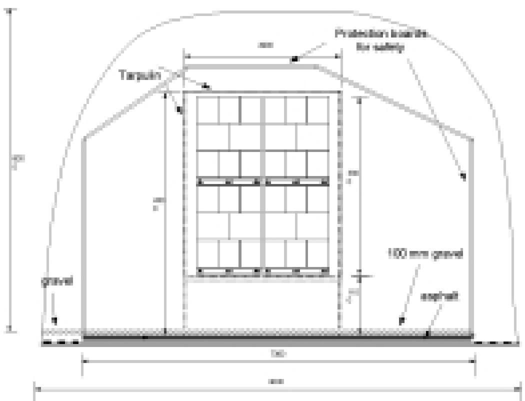


Figure 11 Cross section of the tunnel at the trailer set-up.

4.4 Test 4

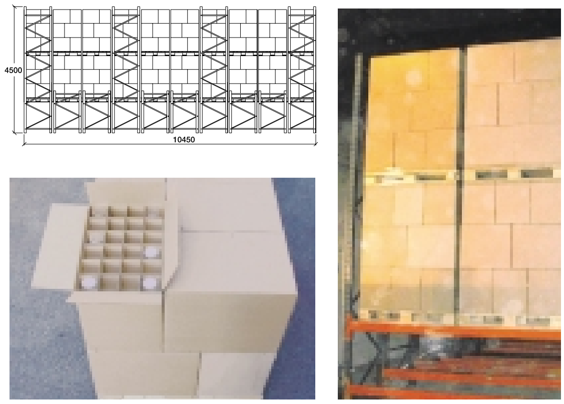


Figure 10 Commodity set-up for test 4 (plastic cups in cardboard boxes on wood pallets).

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

5 MEASUREMENTS AND INTERPRETATION

5.1 Overview of fire development

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

Figure 12 Overview of fire development.

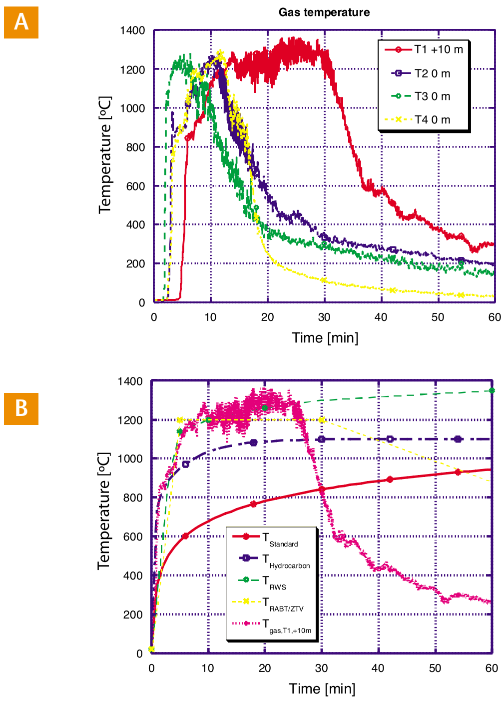
A After 5 minutes

B After 30 minutes

5.2 Gas temperatures

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

Figure 13 Gas temperature.



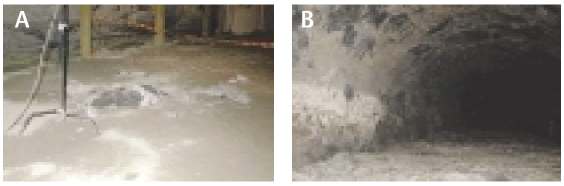
A Measured gas temperatures close to the fire during the four tests.

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

Thermal protection and spalling

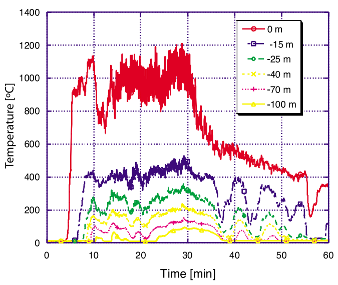
As shown in Figure 11 the tunnel was protected with PROMATECT® -T boards. This was done for safety reasons to avoid rocks falling from the tunnel structure. A distance of 75 m of the tunnel ceiling was protected, while 25 m of the walls (near the fire) were protected with these boards. Downstream of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

Figure 14 Rocks falling down during test 1.



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

Figure 15 Temperature upstream of the fire.



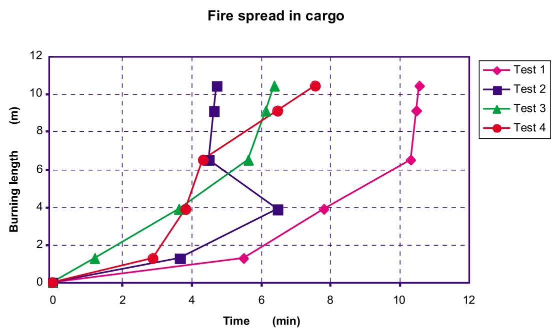
The rocks falling down upstream of the protection was a result of the back-layering taking place in spite of the ventilation. This back-layering was caused by the fact that the velocity decreased when the fire intensity increased, increasing the pressure drop over the fire field. The results can be seen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

5.3 Temperatures in cargo and fire spread

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

Figure 16 presents 'the length of the burning part of the cargo' as a function of time, based on a temperature of 600° C. Test 1 and test 3 show an almost monotonic increase of 'burning length' with time, indicating a constant fire spread of approximately 18 mm/s for a 'burning length' between 1.3 m and 6.5 m. This is not the case in test 2 and test 4. Test 4 suggests an even faster fire spread over the same length. Further analysis of Figure 16 is difficult, because parts of the cargo fell down during the tests. This could for instance be the cause for the unrealistic behaviour in test 3 where a 'burning length' of 6.5 m seems to appear earlier than a 'burning length of 4,5 m.

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



5.4 Thermal load on wall at 1 meter above road level

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

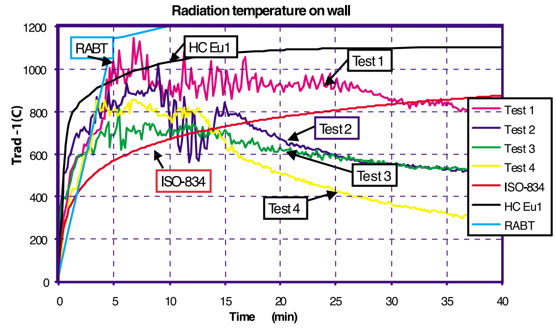
The error in the comparison is relatively low for high heat fluxes and is estimated to be between 20° C and 50° C.

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

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

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

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

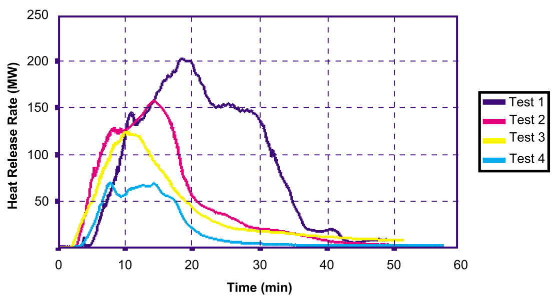


5.5 Heat Release Rate (HRR)

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

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

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

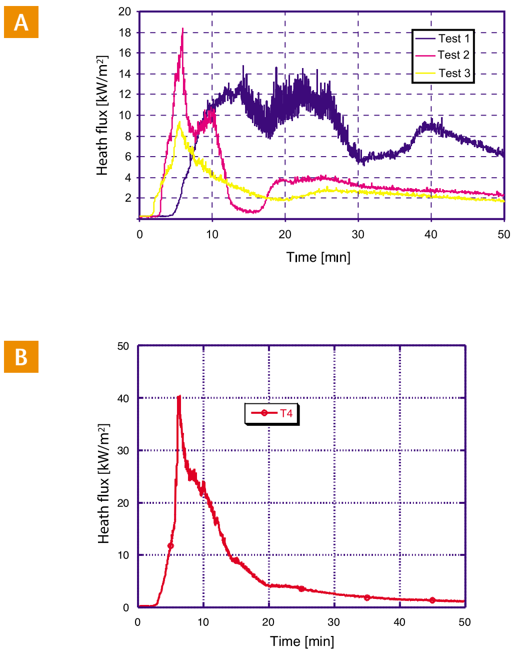


Test nr	Time from ignition to peak HRR (min)	Linear fire growth rate (R=linear regression coefficient) (MW/min)	Peak HRR (MW)	Estimated from laboratory tests (no target – inclusive target) (MW)
1	18.5	20.5 (0.997)	203 (average)	186-217
2	14.3	29.0 (0.991)	158 (average)	167-195
3	10.4	17.0 (0.998)	124.9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

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

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

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



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

5.6 Radiation levels near the fire

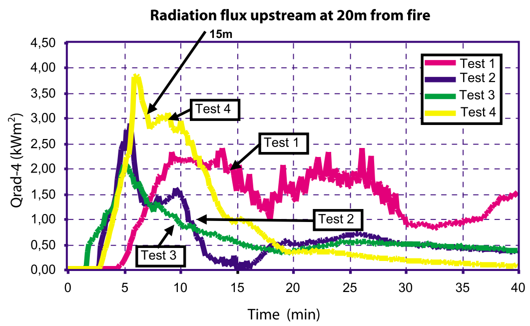
The high temperatures give rise to high radiation, which is important for the fire spread to other vehicles in the tunnel. Another important issue regarding the radiation is how close to the fire the fire fighters can reach before they are stopped by the high radiation. Tests performed with fire fighters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

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

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

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

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



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

5.7 Near fire radiation levels and risk of fire spread

The measured heat fluxes near the fire for all tests together with the critical level for fire spread of 12.5 kW/m^2 are presented in figure 7 in [6] **(Paper 6)**. In test 1 heat fluxes on the floor of 250 kW/m^2 occur during 15 minutes. In the same test peak values of 200 kW/m^2 and average values of about 120 kW/m^2 on the wall can be observed. At a distance of 5 meter behind the fire the heat flux is still 50 kW/m^2.

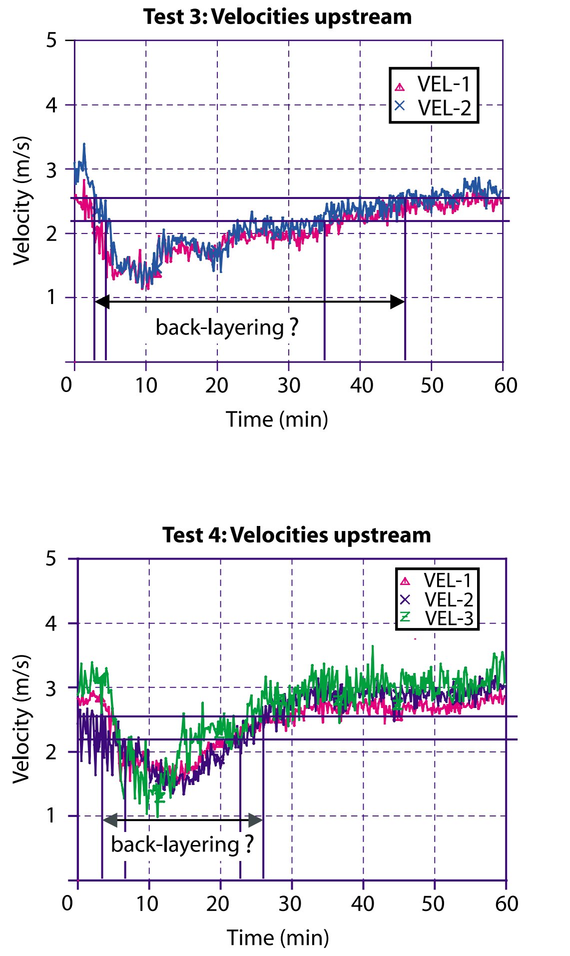
In all tests the critical level for fire spread is exceeded on the location 5 m behind the fire. The risk of fire spread to a vehicle on that location exists therefore in all tests, but for different lengths of time. In test 1 the risk exists for 55 minutes. In the other, less severe tests shorter durations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

5.8 Back-layering

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

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

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



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

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

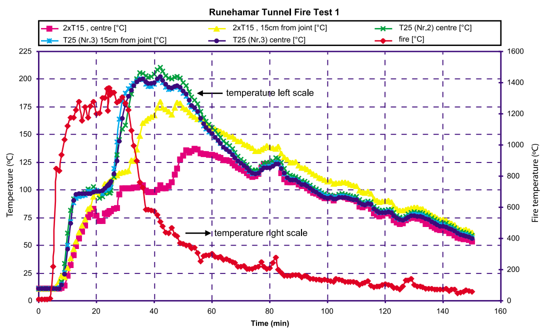
5.9 Results and behaviour of the protective lining

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

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

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

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

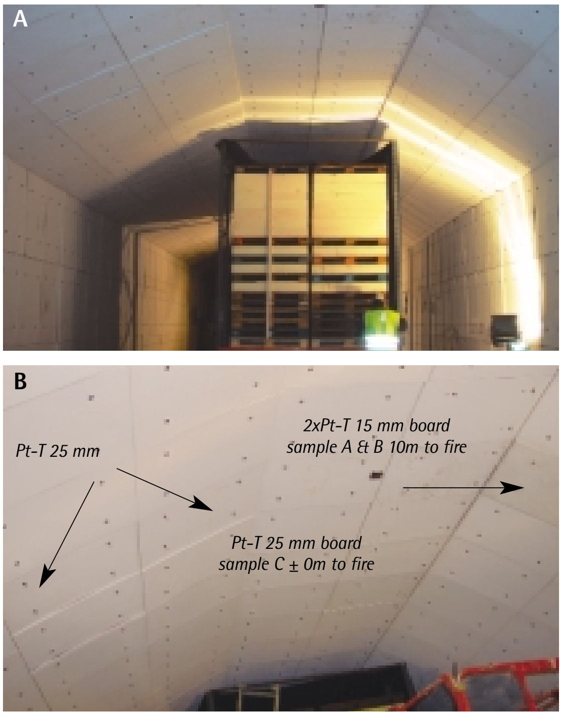


The Figure 24 illustrates the temperatures developed in the tunnel during the first fire test (the red curve, temperatures indicated on right side) and the temperatures measured on the cold side of the boards (temperature values indicated on left side of the graph).

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

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

Figure 25 Stability and locations PROMATECT® -T boards.



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

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

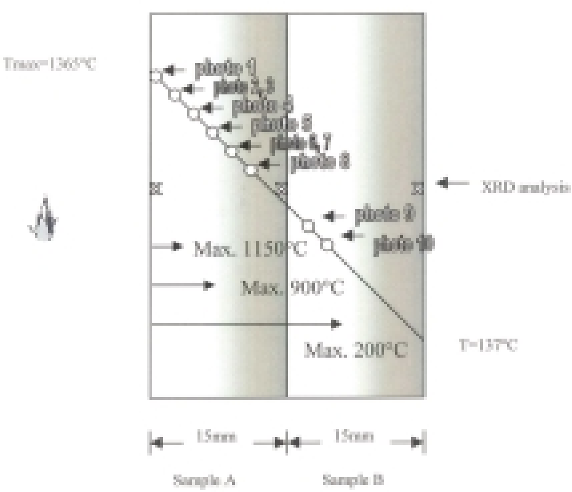
Scanning Electron Microscopy (SEM/EDX) and X-ray diffraction (XRD) were used to investigate the matrix details and to establish the profile of temperature evolution inside the product during the fire tests; the matrix integrity was examined by SEM on polished sections, using back-scattered conditions.

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

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

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

Figure 29 Position of the sample A and B.



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

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

Figure 26 Sample A.

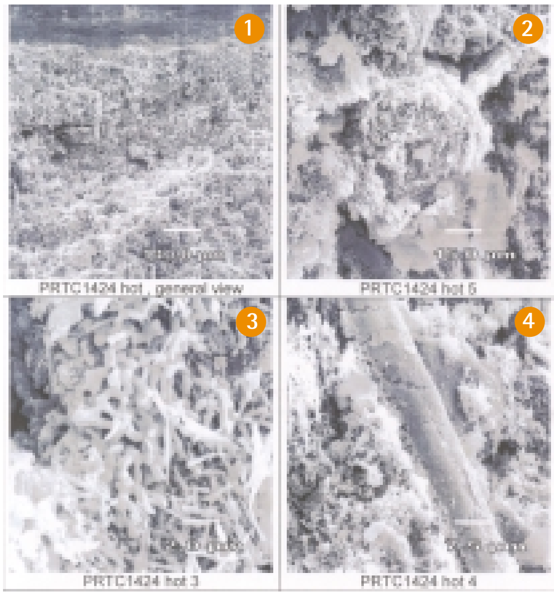


Figure 27 Sample A.

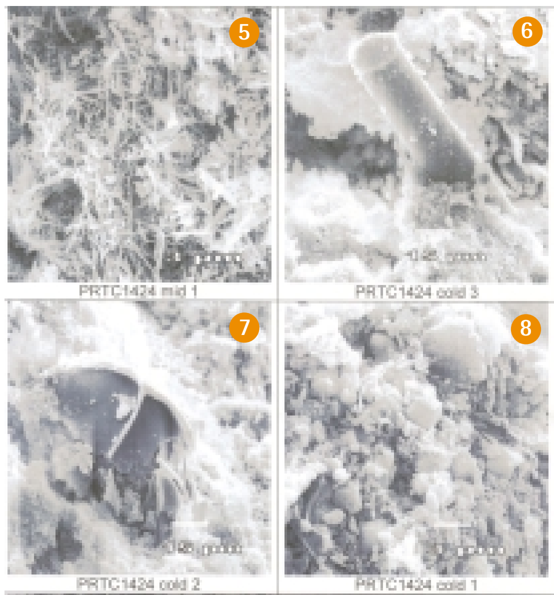
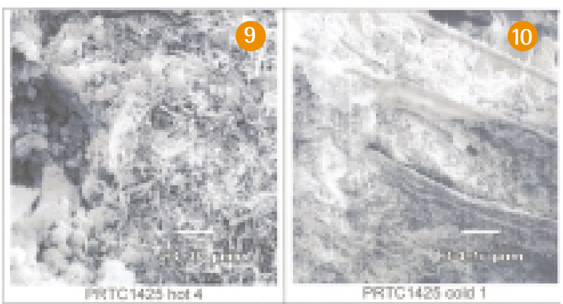


Figure 28 Sample B.



6 CONCLUSIONS AND RECOMMENDATIONS

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

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

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

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

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

7 ACKNOWLEDGEMENT

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

The publication of this report would not have been possible without the financial support of Promat International N.V., TNO Building and Construction Research and UPTUN.

8 REFERENCE LIST

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

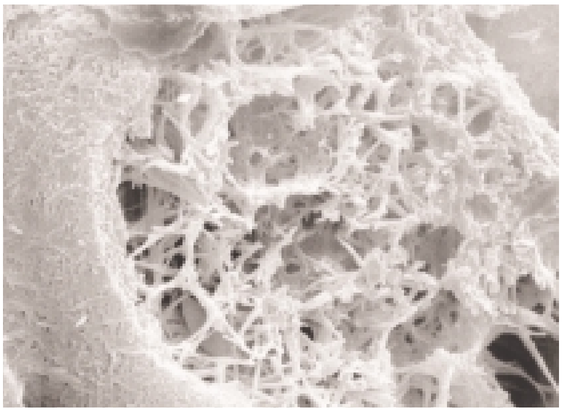
ANNEX A: PROMATECT® -T MATERIAL DESCRIPTION

Mineral engineering and products with engineered matrix :

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

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

Figure 30 Controlled crystal growth technology for engineered matrixes.

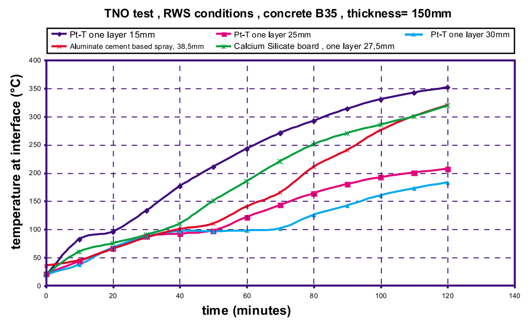


High performance product:

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

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

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



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

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

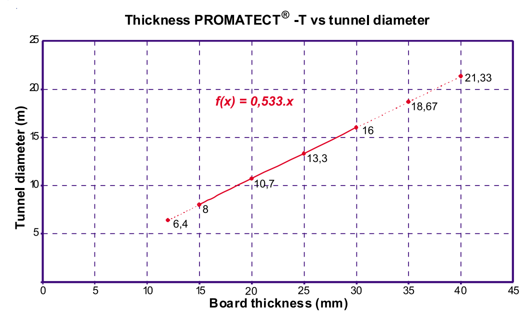


Figure 33 Toulon tunnel protected with the PROMATECT® -T boards for ceiling, escape routes , smoke extraction ducts and fire doors.