FIRE MITIGATION MEASURES

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ABSTRACT

A set of fire scenarios and conditions for evaluation of fire mitigation systems to be used in tunnels are proposed. These scenarios are used for evolution of water spraying systems as part of the UPTUN project. A large number of fire tests have been carried out with water curtains, high and low pressure water mist systems. Currently limited data on the effects of water curtains are available. Test results for high and low pressure water mist systems give a significant reduction of the heat release rate from fires tested, as well as heat and toxic conditions for tunnel users exposed to the fire effluents.

1. INTRODUCTION

1.1 Acknowledgment

This paper presents results from the fire mitigation test program conducted in the EU-project UPTUN[1] (Cost-effective, Sustainable and Innovative Upgrading Methods for Fire Safety in Existing Tunnels). Acknowledgement is given to European Commission (Research Directorates) and the entire 41 partner participants in UPTUN. Special thanks are given to the UPTUN partners Fogtec and Semco, which have provided the high pressure water mist system. Thanks are also given to VID, which has provided the low pressure water mist system, as well as APT for the water curtains mitigation system. These partners have participated in the experimental validation of their suppression system. The last test series for APT was conducted in April 2006 and these conclusions are not jet available and therefore only brief presentation of the APT water curtains is provided. In the UPTUN project also inflatable tunnel plugs are introduced and the scope of application as well as validation is not yet available.

2.2 Background for the study

The dramatic increase of the traffic density in European countries during the last decades has resulted in an increase in the number of tunnels and overloaded traffic in existing road and rail networks. Both the increasing traffic density and the increasing number of tunnels have again resulted in increasing number of serious fire accidents in tunnels. The length of the tunnels and the frequency of traffic jam are increasing, which makes fire extinguishing from the fire services and rescue operations more difficult. To improve the fire safety in tunnels, the European commission have launched the UPTUN project. Innovative technologies are developed and verified within UPTUN. Some of the results from the experimental verification tests conducted in UPTUN Work Package 2 (WP2) are presented in this paper.

2.3 Validation fire protection equipment in general

A lot of different safety measures to cope with fires in tunnels have been proposed, but before a system is adopted, its utility value has to be documented for relevant fire scenarios. The following methods may be used to document the characteristics of fire safety measures:

- Large or full scale fire tests
- Small scale tests
- Fire simulations (only to a limited extent)

The definitely most reliable method of documenting the properties of a safety measure is to carry out full scale tests in which the system is exposed to a realistic fire under realistic conditions, e.g. tunnel shape and ventilation conditions. Small scale tests are less expensive, but not as reliable as full scale tests due to unreliable scaling rules of the fire physics. Small scale test objects (fire protection equipment) are also rarely available with comparable properties of real objects.

Fire simulations are significantly less expensive provided a fully developed and reliable computer codes are available. Fire simulation is normally conducted by use CFD (Computational Fluid Mechanics) and they may to some extent be rather accurate for ventilation and movement of fire effluence for predefined fire scenarios. Several codes have capability to include water spray systems which give such codes capability to demonstrate general affects. However, it is still far from being able to predict the interaction between real water based spray systems and fires. Even calculation of the fire development in a specific vehicle is still out of range of the capability of current CFD codes. Validation of any products to provide fire suppression or fire resistance is still limited to full scale testing. This applies not only for tunnels, but for the fire safety in general.

However, large scale tests are often expensive to carry out. It includes access to a tunnel with some basic installations. Large scale fire tests with heat release rates of 100MW or more requires normally modifications and protection of the lining and installations. Measuring the fire size in terms of the heat release rate (HRR), needs advanced instrumentation and data analysis.

2. FIRE SCENARIO FOR VALIDATION OF THE FIRE SUPPRESSION SYSTEM

2.1 Fire scenario for risk analysis

In the UPTUN project, documentation principles follow the Fire Safety Engineering (FSE) approach. To be able to judge and compare the mitigation systems, a series of fire scenarios are recommended. For risk assessments in general, the fire scenarios should always be evaluated and replaced with more suitable scenarios when more knowledge about the fires is available.

In general, fire scenarios can be distinguished between A) fire scenarios with respect to the risk to users of the tunnel, rescue teams and installed equipment necessary to provide safe evacuation and rescue operations (human safety), and B) protection of the tunnel boundary to avoid structural collapse, unwanted fire and smoke spread by ventilation ducts or fire doors (fire resistance), see Figure 1.

In tunnel fires, human safety as well as heat exposure to equipment (cable gates etc.) close to the fire will normally be the first critical issue. Type A) fires are assumed to be significant less severe than type B) fires, which may result in unbearable conditions for humans and significant thermal exposure to constructions (see Figure 1). Small fires (Type A) are often limited to the first object burning and can be ranked by the heat release rate measured in MW, while more severe fires after significant flame spread can also be measured in terms of time-temperature curves (fire resistance). There are several publications on fire scenarios and HRR of various burning objects and recommended time-temperature curves. Publications of Ingason[2], EUREKA[3] 1995, Piarc[4] and FIT[5] among other are evaluating these matters.

Well ventilated tunnel fires with heat release rates larger than 10MW may give significant smoke exposure to human beings if they are exposed to the smoke. For the UPTUN fire mitigation test programme, the main focus has been on Type A) fires to protect human beings, to avoid flame spread and to provide conditions for unhindered escape and rescue. Type A), fires can be considered as fires with a HRR up to 30 MW, while higher HRR can be considered as type B) fires, see Figure 1 and Table 1.

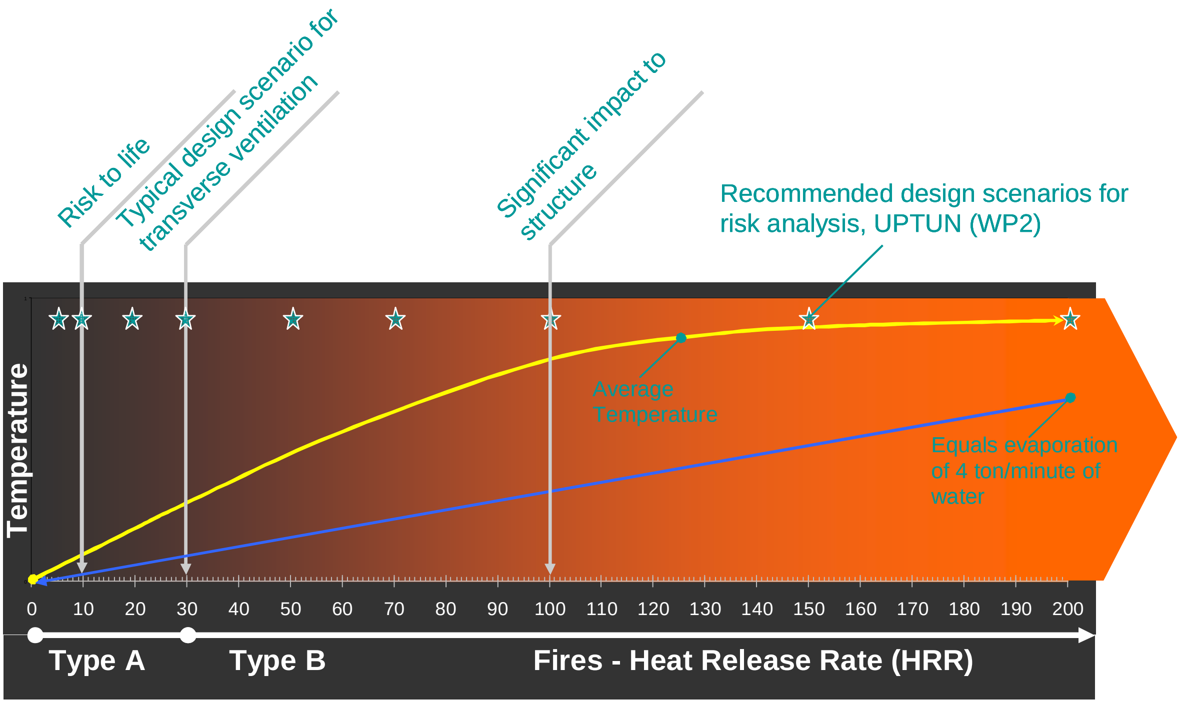

Figure 1. shows the Type A) fires where mitigation action should be provided, while Type B) often represents fires out of control and may provide significant heat exposure to the structure. For risk analysis several scenarios are recommended, her shown by stars[15].

In case of risk analysis of tunnel fires, several fire scenarios have to be studied. Smaller fires may provide other problems than large fires. In risk analysis, it is important to be aware of how different fire scenarios contribute to the overall fire hazard of a tunnel. This approach is according to generally accepted fire safety principles of buildings[6].

For tunnels, the contribution of fire mitigation systems to improve safety would normally be documented by means of a risk analysis, where the mitigation effects by the fire suppression system are considered. For the fire mitigation study, a set of scenarios (fire sources) are recommended as shown in Table 1.

The duration of the fire is to be determined by the amount of available combustible materials. The amount of fuel can for instance be a considerable amount in case of stationary traffic in the tunnel.

Suppression system in tunnels was introduced in Japan based on fire tests from the seventies[7]. The system used was deluge systems which require a significant amount of water[8]. A test program studying suppression depending on fire scenario and wind conditions for sprinklers are done in the 2nd Benelux Tunnel prior to the opening of the tunnel[9]. More recently also a test series using water mist system is published[10]. Successful use of automatic fire suppression systems requires a reliable fire detection system. Several detection systems are on the marked and some public information is available[11, 12]. The UPTUN work has chosen a set of scenarios and carefully measured the exposure after activation of suppression. That includes visibility, toxicity and thermal exposure.

	HRR MW	Road, examples vehicles	Rail, examples vehicles	Metro, examples vehicles	Fire test sources
Risk to life	5	1-2 cars			1 Liquid pool ($2.2\ m^2$)
	10	Small van, 2-3 cars, ++	Electric locomotive	Low combustible passengers carriage	2 Liquid pools ($4.4\ m^2$)
	20	Big van, public bus, multiple vehicles		Normal combustble passengers carriage	3-4 Liquid pools ($6.5\text{-}8.5\ m^2$)
	30	Bus, empty HGV	Passengers carriage	Two Carriages	80-100 wood pallets (1600-2000kg) or 6 liquid pools ($13\ m^2$)

Table 1. Fire sources (Type A) used in validation of fire mitigation systems

3. TYPE A) FIRE SCENARIOS FOR VALIDATION OF MITIGATION SYSTEMS

3.1 The test much-up

For the UPTUN project, three types of fire sources were chosen to experimentally verify the mitigation efficiency (Type A) fires). Scenario Type 1 was a fire in an open liquid pool (diesel fuel), scenario Type 2 was sheltered pool fires and scenario Type 3 was fires in partly sheltered solid fuel (wood pallets). The size of the pool was varied in four steps, where scenario Type 1 and scenario Type 2 were combined. Additionally, the longitudinal ventilation velocities were varied from 1 m/s to 2.5m/s as average over the cross-section area upstream of the fire.

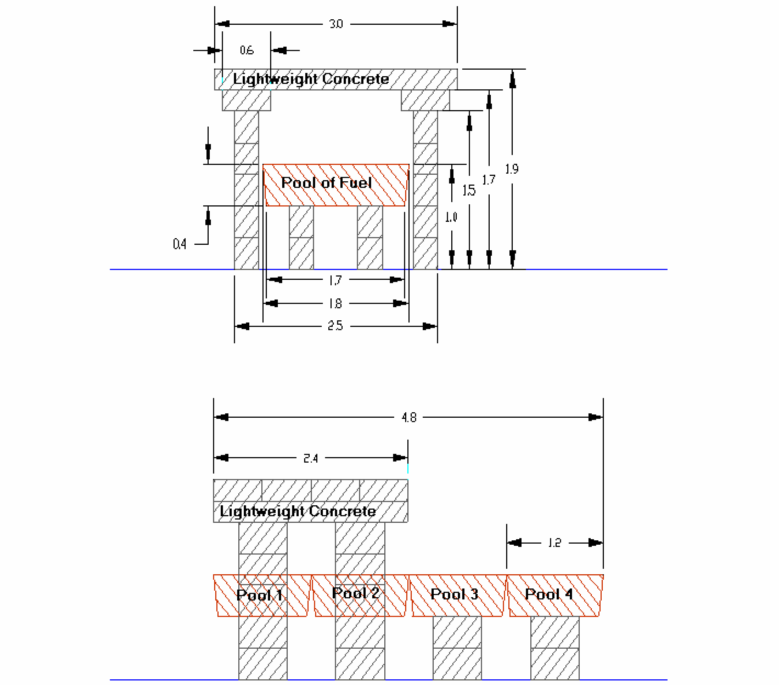

Figure 2 *The drawing shows the experimental setup of sheltered pool fires. The fuel was diesel and the ventilation direction was from left to right (all dimensions in meters)*

Scenario Type 1 and scenario Type 2 fire were provided by a test mock up to provide easy repeatability of the test fires as shown in Figure 2 and Figure 3. The shelter is constructed from lightweight concrete (Siporex) blocks as shown in Figure 2. Figure 2 shows the pools constructed from steel and placed in the shelter in such way that two out of four were covered by the roof. Pool fires were arranged by filling the vessels by water and adding the liquid fuel on top.

Each pool fire represented a HRR of about 4-5 MW. Somewhat higher heat release rates were recorded in the case of sheltered pools and when several pools were burning together. In most of the tests, the suppression system was activated at HRR close to the peak (i.e. after more than 2 minutes after ignition for pool fires and significant more for solid fuel fires). Long activation time increases demands on the suppression systems in general, while for water spraying systems it might be different at least to a certain fire size. For the solid fuel fire scenarios, the pools were replaced with wood pallets (80 standard Euro pallets) see Figure 3, i.e. 80 wood pallets generating a HRR of about 20 MW - 25 MW.

The solid fuel test commodity consisted of 80 wood pallets (1600 kg of wood) measuring 1.6 m x 4.8 m x 1.5 m. A single pallet is measuring 0.8 m x 1.2 m x 0.15m (W x L x H). The pallets were placed under the lightweight concrete mock-up as shown in Figure 2.

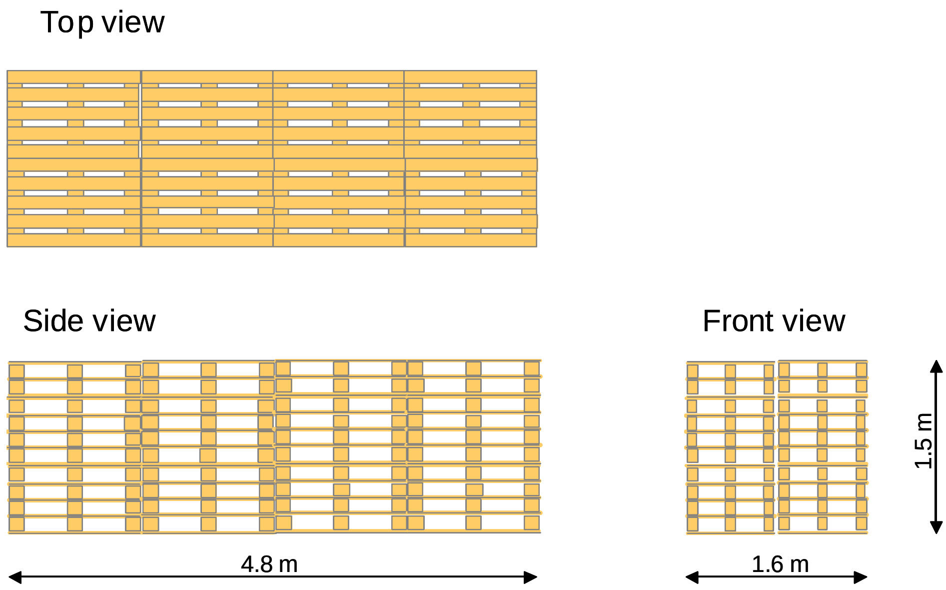

Figure 3. The drawing shows the solid fuel test commodity

The test mock-up was placed in the middle of the tunnel at ground level in every test as shown in Figure 3.

The test tunnel used for the water mist systems (IF- Assurance, Safety Centre at Hobøl, Norway) is made from concrete and placed above the ground. It has a 40 m^2 cross-section, a total length of 100 m and the width of the roadway was 8.07 m. More detail about the test arrangement and instrumentation can be found in the UPTUN reports[13, 14, 15].

4. FIRE MITIGATION IN TUNNELS

4.1 Mechanical ventilation

In general there are several means to reduce the risk for fire accidents in tunnels as well as reducing the hazard from the fires itself. This study is limited to present the innovative fire mitigation tools studied within the UPTUN project. Even though ventilation is the most used and probably the most important fire mitigation system for current tunnels, it is defined outside the scope of UPTUN, since the technology is more or less developed to an acceptable level. Mechanical ventilation is a method used in tunnels to supply fresh air and to provide for evacuation of the smoke gases from the tunnel in order to reduce the smoke exposure of persons trapped in case of a fire in a tunnel. The smoke is the greatest killer in most fires, and tunnel ventilation systems mainly concern with control and extraction of smoke in case of fire.

- Prevent backlayering, or ‘control’ the smoke in order to provide a smoke free escape route.
- Reduce the effects of smoke exposure (temperature, toxic gases, reduced visibility etc.) of the occupants as well as tunnel structure and equipment (temperature only)

Ventilation is important for fire safety in tunnels, but it has a limited capacity to provide safety in case of large fires. When adding additional fire mitigation systems in a tunnel, it would always be advantageous if the systems work together with the ventilation system and especially if it can increase the safety capacity of exiting systems.

4.2 Sprinklers and Water Spraying Systems in general

Sprinkler and water spraying systems can be divided into the following systems:

- Wet pipe sprinkler is permanently filled with water under pressure
- Dry pipe sprinkler is usually filled with air or an inert gas under pressure, downstream the dry alarm valve
- Pre-action sprinkler is a combination of a dry sprinkler and an alarm installation
- Deluge system involves application of water with open nozzles, which disperse the water over a predetermined area

The suppression agent of water spraying can be water with additives (e.g. foam). The pressure and the nozzle design provide the water discharge rate, droplet distribution and droplet size along with location and density of nozzle. For tunnels, deluge type systems will be preferred, which also require systems for manual or automatic activation of the system.

4.3 Water curtains

Water curtains were mainly introduced for shielding thermal radiation from fires. In tunnels, such systems can also reduce the gas smoke temperature and to some extent also work as a smoke curtains. Water curtains is assumed to be very efficient in terms of avoiding flame spread through the “wall of water”.

Water curtains may work well in combination with the ventilation system and it will only have minor effect to pressure distribution in the tunnel. It will therefore have limited capability to block longitudinal smoke spread, but it can to some extend delay, cool the hot gases and mix the layers especially towards the fire in low ventilated tunnels. The final results within the UPTUN project are not jet available and it will not be further discussed here.

4.4 Inflatable tunnel plugs

Inflatable tunnel plugs are already in use in metro tunnels to minimize the spread of dust from construction and maintenance work. The concept is also introduced as a concept for fire suppression and to reduce smoke spread from tunnels fires. Limited testing and validation of the concept is available. The test carried out in Virgolo[16] tunnel in 2005 indicates that such system has limited capacity in terms of maintaining significant pressure difference over the tunnel plug, which normally occurs if the fire is locked in an enclosed space for oxygen starvation.

Inflatable tunnel plugs may well be efficient for blocking smoke spread with limited pressure differences, e.g. to guide smoke in metro systems in different directions than the station area. This matter is still under evaluation in the UPTUN project and it will not be further discussed here.

4.5 General for water mist systems

All tests gave a significant temperature reduction close to the fire as well as downstream from the fire. No significant heat exposure to tunnel user was measured after activation of the suppression system. In this paper focus will be addressed on all fire effluences causing toxic and thermal effect for users trapped in the smoke. These are evaluated in chapter 5 (acceptance criteria).

4.6 Low Pressure Water Mist System

A total of 19 successful tests were carried out, as well as 8 reference tests (i.e. tests without any mitigation actions). The peak HRR was ranging from about 2 MW to about 28 MW (peak HRRs were depending on the time of activation). Four different pool fire scenarios were included with two ventilation conditions. One solid fuel scenario and one demonstration test with real vehicles are reported. The tests showed that the effectiveness of the water mist system was dependent on the burning object, time to activation and water discharge rate. For the low pressure water mist system, the discharge rates varied from 1 to 3.5 litre/(m^2·minute)

Fire in	HRR before suppression (MW)	Reduction in the HRR (%)	Equivalent to a fine in a:
One pool:	2 - 5	0 - 60	1-2 cars
Two pools:	5 – 13	0 - 80	Small van, 2-3 cars
Three pools:	17	80	Big van, public bus, multiple vehicles
Four pools:	22 – 24	70 - 80	Big van, public bus, Multiple vehicles
Wood pallets:	17 – 25	40	Big van, public bus, multiple vehicles

Table 2. An overview of the test results in terms of reduction of the HRR (%) from the tests with the low pressure water mist system

It seems as if the higher the heat release rate was prior to activation of the system, the higher was the effectiveness of the fire suppression. For the 'one pool tests' the suppression efficiency was up to 60 % reduction in the HRR. For two and four pools the suppression efficiency was up to 80 % reduction in the HRR.

For 80 stacked wood pallets, the reduction in the HRR was approximately 40 %. The test results from the low pressure water mist test are summarized in Table 2. Table 1 includes equivalent real tunnel fires with respect to the heat release rate.

The effect of the mitigation system is strongly dependent on type and location of nozzle as well as the water discharge rate used in the test. It is less depending on the activation time of the fire mitigation. For some fires, the mitigation effect was not measurable, while for the best test results, the mitigation of the heat release rate was down to 20 % of free HRR. The smallest fires (2-5 MW) were less affected by the suppression system and the best results were achieved for the largest fires (22 MW). It can be concluded that expected mitigation of the test fires with HRRs in the range 10-22 MW was about 40-60 % for an optimized suppression system compared to the free burning rates.

4.7 The High Pressure Water Mist System

A total of 56 successful tests were carried out, as well as 8 reference tests. The peak heat release rate (HRR) was ranging from about 2 to 25 MW before activation of the water mist system. Activation of the suppression system was after 2-3 minutes for the pool fires and significant more delayed activation in case of the solid fuel fires. Four different pool fire scenarios were included with two ventilation conditions. One solid fuel scenario and one demonstration test with real vehicles were also included in the tests. The high pressure water mist system provided a water discharge rates in the range 0.6 – 2.3 litre/(m^2·minute)

Higher heat release rate before activation of the water mist system provided higher fire suppression effectiveness. For one pool only minor reduction in heat release rate was measured, while for three and four pools fires the corresponding effectiveness was up to 70 %. For 80 stacked wood pallets, the effectiveness or reduction in the heat release rate was about 50 %. Table 3 shows an overview of the test results from the tests with the high pressure water mist system.

Fire in	HRR before suppression (MW)	Reduction in the HRR(%)	Equivalent to a fire in a
One pool:	4 – 5	minor	1-2 cars
Two pools:	10 – 11	10 - 70	Small van, 2-3 cars
Three pools:	15 – 20	10 - 70	Big van, public bus, multiple vehicles
Four pools:	18 – 25	10 - 70	Big van, public bus, multiple vehicles
Four pools with AFFF:	18	50	Big van, public bus, multiple vehicles
Wood pallets:	17 – 20	50-80	Big van, public bus, multiple vehicles

Table 3. The test results from the tests with the high pressure water mist system

The effect of the mitigation system was strongly dependent on the type of nozzle used as well as the water discharge rate. The results achieved were also affected by location of nozzles and the type of fire scenario. For some fires, the mitigation effect was not measurable, while for the best test results, the mitigation of the heat release rate was down to 20 % of free burning rate (i.e. a 80 % reduction in the HRR). For the smallest 5 MW fires the reduction in the HRR was generally minor. The best results were achieved for the largest fires. Expected mitigation for the test fires between 10 MW to 20 MW is 50% -70 % for an optimized system compared to free burning rate.

5. THE ACCEPTANCE CRITERIA

5.1 Tunnel users

The accept criteria will be assessed according to convective heat exposure (temperature exposure) of the occupants of the tunnel. The following target criteria for heat exposure, toxic gases and reduced visibility of the occupants of the tunnel are proposed by UPTUN WP2 (TG2 – Target Criteria).

- Visibility ≥ 10 m
- Convection (temperature) ≤ 60 °C
- Convection (temperature) ≤ 50 °C when activation of water based suppression
- [Radiation ≤ 2 kW/m^2]
- Toxic gases: The model of Purser: $FI_{tot} < 1$

The following values are proposed by UPTUN for fire fighters fighting fires in tunnels:

- Gas temperature ≤ 100°C
- [Radiation ≤ 5 KW/m^2]
- Toxic gases : no limitation due to BA apparatus
- Visibility : No limitation due to infra-red cameras

5.2 Fulfilment of the Accept Criteria

Toxicity assessments of the low and high pressure water mist tests show that the toxicity with respect to CO and O_2 was acceptable, when including the development of the CO and the concentrations of O_2 after activation of the water mist systems.

The accept criterion with respect to visibility was, however, not in an equal degree fulfilled in the low and high pressure suppression tests. It seemed as if the visibility was not improved by activation of the water mist system. The visibility was generally reduced to 0.5 m - 1 m in most of the tests with the fire suppression system. The reduced visibility was due to the increased steam production at activation of the water mist systems. However, these phenomena were most prominent during the first minutes of the fire suppression and downstream of the fire. The visibility was generally increased as the fire size and the heat release rate were reduced during fire suppression.

The problem of backlayering (i.e. smoke spread upstream of the fire) and the visibility upstream were significantly improved for the largest fires, more than 10 MW.

5. CONCLUSIONS

The following conclusions may be drawn on the basis of the fire tests with the fire mitigation systems:

- Validation of performance of fire safety equipment like water spraying systems requires full scale fire testing and can not be trusted by for example simulations
- The final conclusions from the UPTUN project for water curtains and inflatable tunnel plugs are not yet available

- A mock-up for conducting A) type fires (Up to 30MW) is proposed for validation
- The efficiency of the water mists systems was satisfactorily
- However, the efficiency was strongly dependent on the size of the fire (or heat generation rate), nozzle type, location and the water discharge rates.
- For the smallest fires (less than or equal to 5 MW) the mitigation effect was minor
- The best results were achieved for the largest fires (i.e. a heat release rate at or above 20 MW). The mitigation of the heat release rate was down to 20 % of the free burning rate, i.e. a maximum reduction of the heat release rate of 80 %.
- A rapid reduction of the temperatures downstream of the fire was noticed after activation of the suppression system. The efficiency of both water mist systems was satisfactorily with respect to heat stresses as well as the toxicity of the fire effluents on human beings.
- The visibility was not improved downstream of the fire during the first minutes after activation of the suppression systems, but the visibility was generally increased as the fire size and the heat release rate were reduced during fire suppression.
- The problem of backlayering (i.e. smoke spread upstream of the fire) and the visibility upstream were also significantly improved after activation of the water mist systems.
- High pressure water mist systems are using less water and suppress the fire to a higher degree in the gas phase of the flames, while for the low pressure systems the fire extinguishing effect is mainly cooling of the fuel surfaces

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