SOLIT Safety of Life in Tunnels

Engineering Guidance for a Comprehensive Evaluation of Tunnels with Fixed Fire Fighting Systems

Scientific Final Report of the SOLIT² Research Project prepared by the SOLIT² Research Consortium

Annex 7: Fire Tests and Fire Scenarios for Evaluation of FFFS

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This document was produced with best knowledge and with great care. These documents and its annex documents are for the use of experienced fire protection engineers. A case by case evaluation of the application of this document for a specific case must be done by the reader.

Classification:

The scientific research project SOLIT² - Safety of Life in Tunnels was promoted by the German ministry of economics and technology (BMWi; Code No. 19S9008) based on a decision of the German Bundestag. All members of the consortium have set up separate scientific reports related to their aim of study. Most outstanding outcomes have been concluded in the present Guidance. The Guideline has been set up jointly among the consortia members and presents the common final report. The Guideline is part of the work package. All individual reports are available on behalf of the project coordinator.

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Engineering Guidance for a Comprehensive Evaluation of Tunnels with Fixed Fire Fighting Systems.

Annex 7: Fire Tests and Fire Scenarios for Evaluation of FFFS

This document is based on the main document „Engineering Guidance for a Comprehensive Evaluation of Tunnels with Fixed Fire Fighting Systems". The following other Annex documents are available:

Annex 1: State of the Art
Annex 2: Selected Results of Full Scale Fire Tests
Annex 3: Engineering Guidance for Fixed Fire Fighting Systems in Tunnels
Annex 4: Application Example for a Risk Analysis
Annex 5: Safety Evaluation of Technical Equipment
Annex 6: Life Cycle Costs of Technical Equipment

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Table of contents

1. Introduction

1.1 Foreword

This document was prepared by the research consortium of the SOLIT² (Safety-of-Life-in-Tunnels) research programme. This is an Annex of the main document ***"Engineering Guidance for a Comprehensive Evaluation of Tunnels with Fixed Fire Fighting Systems"*** which focuses in particular on FFFS as a compensatory measure for life safety and the protection of the infrastructure.

This document focuses on the fire tests and test scenarios with FFFS in tunnel. The literature available is limited, but available information is collected in chapter 2 of this document. The design fires are summarised from both a standardisation and previous research point of view. Later chapters define design fires, measurements and minimum acceptance criteria. Only heavy goods vehicle fires are included in this document since they represent normally the major risk in most tunnels.

This document is produced exclusively for appropriately qualified and experienced people who understand tunnel safety systems and their interfaces, in particular for fire protection measures. The content of the document shall only be applied in the context of the main document "*Engineering Guidance for a Comprehensive Evaluation of Tunnels with FFFS"* with all annexes.

1.2 Purpose

The purpose of this document is to provide information on the fire tests, in particular design fires, fire scenarios and related minimum measurement systems for the reliable and realistic testing of FFFS. The fire tests are needed as type testing for FFFS and authorities having jurisdiction shall examine fire test protocols and results in a fire test report before giving a permit for the installation of FFFS. The design and installation shall in all cases comply with the relevant national standards.

1.3 Application and Scope

This document refers primarily to using FFFS in road tunnels. If cargo is the main fire load in rail tunnels, fire test results can also be used for this application within certain limits. The assessment of the suitability of presented fire scenarios shall be done individually and together with authorities having jurisdiction. The passenger vehicles on rail roads have normally significantly lower potential HHR than proposed design fires in this document.

This document does not cover dangerous goods, such items need to be assessed separately. Only Class B fires are included in this document, see further details in chapter 2.5.4. of main document.

This document is solely meant for describing fire testing. Components tests are not included; however see *"Annex 3 Engineering Guidance for Fixed Fire Fighting Systems in Tunnels"* for further details about components designs.

It is the responsibility of the designers and authorities having jurisdiction to examine the suitability of this guidance for a specific application and whether any deviating or additional measures not being described herein should be applied.

This document does not cover any other fire fighting equipment in tunnels such as hydrants, wall cabinets and portable extinguishers.

Unless otherwise stated, the rights for figures in this document belong to the partners of the SOLIT² consortium. For all other figures a link to the full source is given. The usage is based on the German UrhG §51 Nr.1.

1.4 Related documents

Relevant standards, codes and guidance shall be considered where appropriate. These include, but are not limited to:

2004/54/EC, Minimum safety requirements for tunnels in the Trans-European road network.

EN 1363-1 - Fire resistance tests - Part 1: General requirements

EN 54-4, Fire detection and fire alarm systems.

EN 60584-(1-3):2008, Thermocouples etc.

ISO/IEC 17025:2005 "General requirements for the competence of testing and calibration laboratories"

NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways.

UPTUN R251, Engineering Guidance for Water Based Fire Fighting Systems for the Protection of Tunnels and Sub Surface Facilities – Report 251, UPTUN WP2.5, 2006.

1.5 Definitions

AFFF — Aqueous Film Forming Foam

Authority Having Jurisdiction (AHJ) — An organisation, office or individual responsible for enforcing the requirements of a code or a standard or for approving equipment, materials, installation or a procedure.

Center point — Middle of mock-up that is the zero point of all measurement equipment.

CFD — Computational fluid dynamics is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyse problems that involve fluid flows and combustion.

Deluge system — Deluge systems are water-based FFFS, discharging water at low pressure in the form of a spray. Often referred to as sprinkler systems with open nozzles.

Design fire — An idealization of the realistic fire being used as a design basis for fire testing and system design

Design nozzle flow rate — Flow rate of a specific nozzle used during type testing

Design parameters — Parameters defining the detailed design of FFFS.

Design pressure — Maximum working pressure expected to be applied to a system component

Downstream — Downwind side of fire mock-up in direction of ventilated air stream

Fixed fire fighting systems — Systems being permanently installed in tunnels for fire fighting purposes and having automatic or semi-automatic operation via a remote control system. Examples include water mist, deluge and foam systems.

Full scale fire test — Experimental fire tests organised in test facilities that are in similar scale with dimensions of tunnel as well as fire size.

Heat release rate (HRR) — The rate at which heat energy is generated by burning, expressed in BTU or megawatts (MW).

HGV — Heavy Goods Vehicle (truck)

High-pressure water mist — Water mist system applying nozzle pressures above 35 bar.

Layout parameters — Parameters defining the general layout of a FFFS, e.g. distance between nozzles, maximum nozzle height, etc.

Length of tunnel — The distance from face of portal to face of portal measured using the centreline alignment along the tunnel roadway.

Low-pressure water mist — Water mist system applying nozzle pressures of less than 12 bar.

Maximum and minimum pressures — The maximum pressure and the minimum pressure measured at the nozzle. The maximum pressure is measured at the nozzle which is installed at the location with the least pressure loss (typically the nozzle closest to the pump). The minimum pressure is measured at a nozzle at the location with the highest pressure loss (typically the nozzle furthest from the pump).

Medium pressure water mist — Water mist system applying nozzle pressures between 12 and 35 bar.

Portal — The interface between a tunnel and the outside atmosphere and through which vehicles pass; a connection point to an adjacent facility.

Protection area — The total area covered when the maximum number of sections that the pump system is able to supply at the minimum nozzle pressure is activated.

Section — An area covered by a set of nozzles, all of which are supplied through the same section valve.

Shall — Indicates a mandatory requirement.

Should — Indicates a recommendation which is advised but not required.

Upstream — Upwind side of fire mock-up against direction of ventilated air stream

Water mist system — FFFS applying water as small droplets as the fire fighting agent. The mean diameter of sprays Dv0,90 measured in a plane 1 m from the nozzle at its minimum operating pressure is less than 1 mm

Water-based FFFS — A system permanently attached to the tunnel which is able to distribute a water-based extinguishing agent through all or part of the tunnel.

2. Tunnel design fires

Design fires are an idealization of a real fire that can occur. As commonly known, tunnel fires are relatively complicated and dependent on many variable factors; tunnel geometry, fire load, impact of fire safety measures, motorist, etc. Therefore it is very hard to predict an exact fire scenario that will happen, but a design fire scenario being realistic enough shall be used. Fire scenario should be created as part of the tunnel safety analysis to match fires expected to happen.

The variables with design fires mainly refer to the following aspects:

- Tunnel geometry, e.g. dimensions
- Fuel, e.g. type, amount, dimensions
- Interaction with other safety systems, e.g. detection, ventilation
- Fixed fire fighting system, e.g. lay-out parameters, nozzle characteristics.

Design fires are used for both design of passive fire protection and ventilation systems as well as dimensioning of FFFS. See main document *Chapters 2.5.2 Design fires to determine the size of passive protection measures, 2.5.3 Design fires to determine the size of fire ventilation systems and 2.5.4 Fire scenarios for dimensioning FFFS*. These parameters will be discussed in later chapters.

It is important to understand also the purpose of the FFFS in tunnels when evaluating different fire scenarios and acceptance criteria. The protection targets of FFFS are discussed in detail in main document *Chapter 2.2. Protection targets and current technology*.

2.1 HRR of real fires

A number of real incidents have occurred during the past decades. These have been collected by number of authors. Fires are collected extensively for example by Beard and Carvel [1]. The aftermath studies have revealed that HRR over 100MW have occurred in many fires where heavy goods vehicles (HGV) have been involved. The following list of the most well-known European catastrophic fires can be given as an example.

Table 1. Peak HRR in real fires with HGVs [2][3]

Tunnel	*Peak HRR*	*Fuel*
Eurotunnel (96)	370 MW	10 HGV
Mont Blanc	380 MW	14 HGV, 9 cars
Tauern	300-400 MW	16 HGV, 24 cars
St. Gotthard	100-400 MW	13 HGV, 10 cars

The positive effect of FFFS to fire and life safety has also been noticed in a few real fires. The most well-known latest fire happened in the Burnley tunnel on 23rd of March, 2007. A fast operation of FFFS together with effective control of ventilation resulted to minimum tunnel damage, no non-crash fire related injuries and rapid reopening of the tunnel [1]. The fire size was suppressed effectively and the fire service was able to extinguish although it was a multiple HGV fire. Another famous fire occurred in Nihonzaka tunnel, Japan, in 1979. In this fire FFFS systems suppressed the fire development that long that over 200 people were evacuated from the tunnel. No casualities resulted from fire at this stage. However, the FFFS system failed after reservoirs ran out of water after about 90 minutes of operation and the fire grew significantly. This resulted in the blaze that lasted several days and destroyed 173 vehicles [4].

On the basis of the catastrophic fires experienced it is very realistic to have over 100MW HRR fires when HGVs are involved. In particular serious fires have always been experienced when fire has spread from one vehicle to another. The real fires with FFFS have demonstrated that fire can be suppressed and life safety is significantly improved.

2.2 View of standardisation

The view of standardisation for the design fires has changed a lot during the last decade. Previously design fires were considered much smaller in terms of HRR size. There were also some misunderstandings about possible danger of FFFS for example having water vapour. The current view of standardisation has been explained in more detail in *Annex 1. State of art, Chapters 3.4 International standards and guidelines* and *3.5 National guidelines*.

The majority of governing standards a decade ago required maximum 30MW HRR for HGV fires. Also PIARC *(World Road Association)* and NFPA502 *(Standard for tunnels and limited access bridges)* recommended 20-30MW design fires for HGVs in the past [7][8]. However, this has changed completely, mainly due to real fires explained in chapter 2.2.1. and fire testing explained in chapters 2.2.3 and 2.2.4. Many national standards require minimum 100 MW HRR nowadays for HGV design fires. Also NFPA502 and PIARC have changed their view. NFPA502 has recommended since 2008 a range of 70-200 MW for HGVs [9]. PIARC will soon publish new design fires that are listed in table 3 [10].

Table 2. NFPA502 list of fire data [9]

Vehicle Type	*Peak HRR [MW]*
Passenger car	5 – 10
Multiple passenger cars	10-20
Bus	20-30
Heavy goods truck	70 – 200
Tanker	200 - 300

Table 3. New PIARC recommendations for peak HRR [10]

Vehicle Type	*Peak HRR [MW]*
Passenger car	5 – 10
Light duty vehicle	15
Coach, bus	20
Lorry, heavy-goods vehicle up to 25 tons	30 – 50
Heavy-goods vehicle, typically 25-50 tons	70 – 150
Petrol tanker	200 – 300

Although standardisation has changed becoming more demanding with design fires sizes, some countries allow at least certain amount of flexibility in fire protection design. This applies also to design fires when FFFS are used. There are cases where design fire has been reduced by deploying FFFS in tunnel. Such are for example the Alaskan Way Viaduct Tunnel in Seattle and the San Francisco Presidio Parkway Tunnels [10].

2.3 Full scale fire tests and HRRs

There has been a number of free burning tests with various vehicles as it has been listed in the *Annex 1. State-of-art, Part 4 – Fire tests.* As a summary it can be concluded that most of the recent fire tests with FFFS and HGV design fires have been conducted at minimum 100MW HRR as unsuppressed. Figure 2 presents photos from various fire tests. The standard fire load material has mainly been wood pallets and sometimes plastic pallets or passenger vehicles or tyres are added. Most recent fire tests have had a cover to make fire development more realistic than without. Additionally many fire test programs with FFFS have included also Class B fires, which normally are more limited in size compared to Class A fires.

Figure 1. HGV fire loads from various test series [18]

3. Fire testing with FFFS

3.1 Suitability of design fire

Fire testing should be based on the results of risk analysis for every tunnel. The risk analysis defines the vehicle types and related design fire sizes that shall be considered for the tunnel *(Notice! This document focuses only on HGV fires).* The risk analysis will define in detail whether some special risks shall be considered or normal HGV fire scenarios can be used. The authorities having jurisdiction shall approve the suitability of the design fire scenarios. Similarly the authorities having jurisdiction shall decide what the minimum acceptance criteria is and whether the tunnel being studied requires some additional criteria.

3.2 Interfaces to other safety measures

Fire testing of FFFS does not test only the performance of FFFS but includes the overall safety concept with other parts. Therefore ventilation conditions of real tunnels shall have as a minimum the same capacity as used in the tests. Also fire detection/localization systems shall be capable of detecting fires at a minimum in the same time that FFFS is activated in the tests. There can be some other special issues in real tunnels that shall be taken account when testing FFFS. These shall be defined in the fire test protocol.

3.3 Applying results from one tunnel to another

A specific type (make) of FFFS does not require undergoing fire testing for each individual tunnel it may be installed in, as long as the major design parameters of the actual tunnel to be protected are within the parameters of the tunnel used for fire testing.

3.4 Full scale testing or CFD

The latest technology using CFD simulations, depending on the code used and the model assumptions, is only suitable for a limited interpolation or extrapolation of test data for FFFS in tunnels. CFD modelling shall not however replace full scale fire testing. See also main document *Chapter 2.5.4 Fire Scenarios for dimensioning FFFS*.

3.5 Selection of test institutes

Full scale fire testing in tunnels is very specialized and requires extensive special knowledge. Therefore it is recommended to use only test institutes with previous experience with full scale tunnel fire testing. The amount of measurement instruments is also very high and limits available test institutes.

Although a standard for recognized test laboratory exists (ISO/IEC 17025), the focus should be given to the experience of the test institute.

3.6 Selection of test tunnel

Test tunnel shall be suitable for the testing purposes having proper ventilation, geometry, equipment, temperature tolerance and safety. Geometrical minimum dimensions are a cross-section of 40 m^2, minimum height of 4,5 m and minimum length of 400 m. Authors having jurisdiction might allow using different values in the case where test or real tunnel have smaller dimensions.

3.7 Repeatability of the tests

There has been criticism raised why real HGVs (trucks) or also cargoes have not been used as fire loads [32]. Normally fire tests have budget constraints to burn real vehicles. Also real fires have shown transported goods being more risky than vehicles. Cargo compositions vary a lot, which creates a need for standardized fire load material as for all other fire tests. Euro wood pallets have been used since the Runehamar free burning tests as the main standardized fire load that allows easy repeatability. Such a fire load is easily available, standardized and cost-effective to use in tests. Euro wood pallet fire loads also present very significant fire risk due to their open structure that allows entrance of oxygen well into the fire seat. An example of Euro wood truck in real life and as simulated in fire tests is shown in figure 3.

Figure 2. Euro pallets in transportation and as fire load in tests

3.8 Safety during testing

Full scale fire experiments always have risks. In particular fire tests in tunnels create risks due to the confined space and fire sizes. Tests have shown that if FFFS system fails or is turned off during the test, controlled and suppressed fires can develop very severely within minutes. Two photos in figure 4 show how an HGV size fire which is under control by FFFS develops within 1 minute to a blaze that fire services are unable to fight.

Figure 3. Example of fire after FFFS turned off [18]

Due to the risks and fire size, only trained personnel shall participate in the tests. The institute carrying out the tests shall do safety induction for all external personnel visiting or witnessing the fire tests. A part of the safety induction is introduction to the evacuation plan of the test tunnel. All major tests shall be secured with professional fire fighters.

4. FFFS for fire tests

FFFS tested with design fires shall have same design parameters as to be used in the tunnel. The nozzle type, K-factor, pressure, spacing, etc. shall be recorded as part of testing. The FFFS shall preferably be installed in the test tunnel with same connecting method and materials as will be used in the real installation. The activation length of FFFS may be shorter in fire tests than in real installation.

The layout of the system should be the most unfavourable conditions as would be used in the real tunnel. The system should be tested with the minimum pressure and minimum application rate. The difference in the whole test installation (last nozzle to first nozzle) should be less than 10% for pressure and application rate.

5. Design fires for FFFS

5.1 General

The design fires and fire scenarios presented in next chapter are defined on the basis of previous knowledge about tunnel design fires, *see chapter 2 Design fires and Annex 1. State-of-art*. The main focus in the following is in HGV fire loads which typically is the realistic severe fire scenario instead of absolute worst cases. The suitability of fire scenarios shall be proven in every real tunnel with the risk analysis and authorities having jurisdiction. Two fire scenarios are given in this document: A. Class A *(solid fire)* and B. Class B *(pool fire)*. Both test scenarios are easily repeatable and cost effective to be carried out.

Other smaller design fires e.g. passenger cars, vans, buses, etc. are not as demanding as HGV; so these will be covered also with the testing. *See chapter 2.5.4. in the main document*.

5.2 Class A HGV design fire

5.2.1 Design fire size

The design fire size should be realistic corresponding to common knowledge and standardization, *see Chapter 2 of this document and main document Chapter 2.5*. Minimum fire load with the potential HRR of 150 MW or higher as unsuppressed fires shall be used to simulate a severe HGV fire. The test set-up shall represent a HGV trailer.

5.2.2 Mock-up dimensions

The geometry of the mock-up shall correspond to a typical HGV or especially the trailer. Figure 5. gives an example how HGVs are simulated in fire tests.

Figure 4. Real trailer and simulating mock-up [31]

Euro wood pallet stacks shall be used as fuel. A minimum of 400 pallets corresponding to a minimum HGV design fire size of approximately 110-140 GJ. Euro wood pallets shall be stacked on the platform representing the trailer floor.

The minimum dimension shall follow typical dimensions of HGVs in Europe:

- Height: Minimum 4,0m *(having minimum 2,5m height for the fuel part)*
- Width: 2,4m
- Length: 10,0m

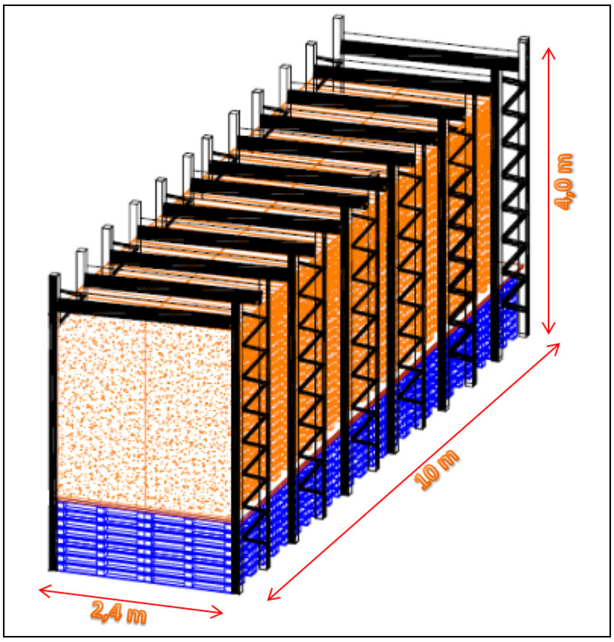


Figure 5. Mock-up dimensions

Euro wood pallets shall be stacked with steel frames preventing them falling and so having larger surface and improved effect of FFFS. Steel frames shall survive the test without collapsing, but they should not cover more than 10% of the sides or top of fuel. *Notice! It has been noticed in previous tests that the falling of fuel might cause a temporary high peak to HRR due to larger surfaces.*

But also, FFFS has fought fire better since water can affect a much larger surface instead of in a deep seated fire. So keeping fire load together is much more demanding for FFFS.

The back and front of the mock-up shall be covered with a steel plate representing the truck or trailer doors blocking the access of the air straight inside the mock-up.

A PVC tarpaulin shall be used for covering the fire load. The tarpaulin shall not be fire retardant. The tarpaulin shall be fixed properly that forced ventilation will not remove or open it. *Notice! Tarpaulin or other covers have been noticed to have an impact on fire development but especially on FFFS capabilities to fight fire. If a cover is not used, water has immediate access to seat of fire which is normally not a realistic scenario with most real HGVs.*

Figure 6. HGV mock-up with tarpaulin [18]

Additionally, a comparison test with uncovered mock-up can be done. The dimensions of the mock-up shall be similar otherwise.

Figure 7. HGV mock-up without tarpaulin [18]

5.2.3 Position of the fire mock-up

The mock-up shall be eccentric to the centre line of the test tunnel. The distance from the side wall shall be less than 1,5m. Often centre line has been used for positioning mock-up in previous tests, but this is normally a very unlikely situation in real tunnels. Additionally such a position is often most effective for FFFS since the fire fighting medium is properly delivered on both sides.

Figure 8. Eccentric position of mock-up in cross-section

5.2.4 Fuel specification

As mentioned in chapter 4.2.2., Euro wood pallets shall be used as a fuel. These are standardized and easily available.

The dimensions of the standardized Euro wood pallets are following [33]:

- Height: 144 mm (-0/+3mm)
- Width: 1200 mm (-0/+3mm)
- Length: 800 mm (-0/+2mm)
- Weight: approx. 22-25 kg *(depending on the moisture content)*

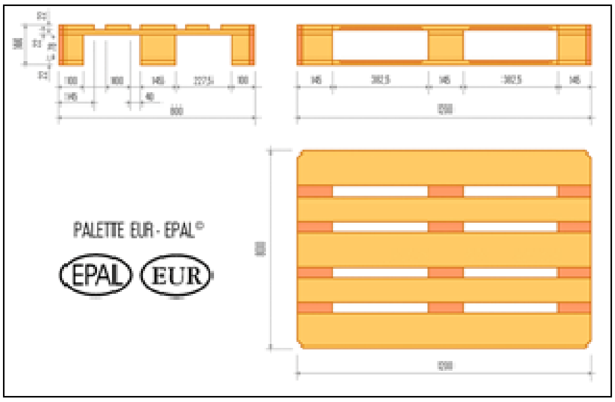


Figure 9. Dimensions of Euro wood pallet [33]

The moisture content of pallets normally varies and depends on the storage conditions as well as on the age of them. Only pallets with a moisture content of 18 % or less shall be used. Random probes shall be measured from the pallets in the set up before each test. The measurements shall be included in the test report.

Notice! Plastic pallets are not recommended to use since they have more variation in properties. Secondly plastic pallets lose their structure integrity (melting) at a relatively low temperature, which causes the collapsing of the fire load in early *stage. Also HRR is less dependent on ventilation with plastic pallets than with porous wood pallets, which does not give so much variation to test different ventilation conditions [35]. Additionally plastic pallets are ten times more expensive than hard wood pallets [34].*

5.2.5 Ignition

Ignition shall be done at least with two small pans, each having size of 600 mm x 150 mm x 50 mm filled with 2 litres of gasoline. Pans shall be placed inside the first pallets on the side of the mock-up (second stack of pallets on the upstream front). Following figure shows the place in more detail.

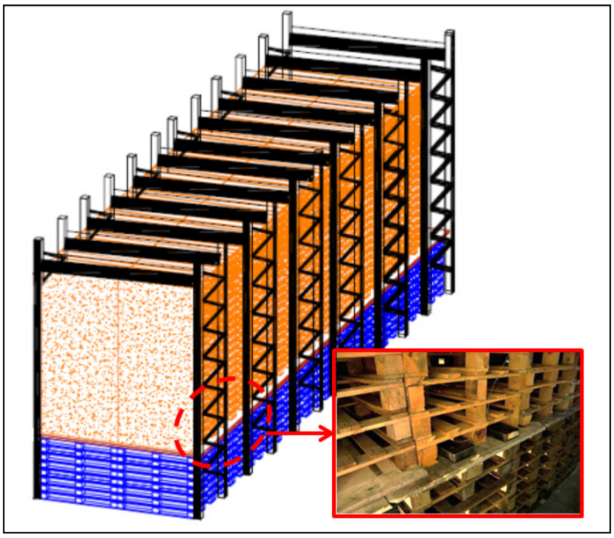


Figure 10. Ignition location and pans

5.2.6 Fire target

Fire target is very practical way to study the capability of FFFS to prevent fire spread from one to the other HGV. Fire target shall be used with Class A fires having it placed 5m downstream behind the mock-up. The fire target should have the same width, height and combustibility as the mock-up, Euro wood pallets shall be used.

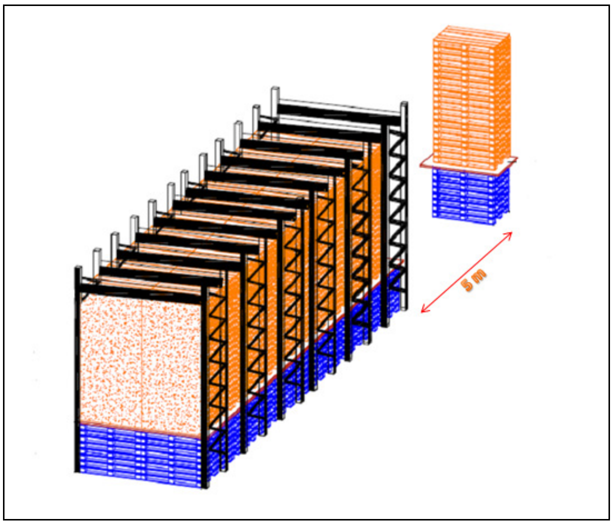


Figure 11. Location of fire target 5m downstream of the mock-up

Figure 12. Example of undamaged target after a fire test [31]

Notice! Water filled barrels or any other non-combustible targets shall not be used, because they do not demonstrate the fire spread directly.

5.2.7 Ventilation

The air velocity should be measured 45 m upstream of the position of the fuel and be checked for plausibility prior to the start of each test.

Ventilation shall correspond to the test values given or as defined by authorities having jurisdiction. For longitudinal velocity, minimum1,5 m/s and 3 m/s shall be tested.

5.2.8 Activation and deactivation

The activation of FFFS shall happen manually and be delayed compared to the detection systems. Triggering values for a Class A HGV fire shall be as follows and as defined by authorities having jurisdiction:

A. Minimum 1 minutes after ignition or
B.

The System shall discharge continuously for a minimum of 30 minutes after activation or longer if required by authorities having jurisdiction. FFFS shall be deactivated manually.

The activation area shall be defined by the manufacturer, but it shall be minimum 3 times the length of the mock-up. *Notice! Activation area in real tunnel is normally longer due to risk of inaccuracies of detecting and localizing the fire.*

5.3 Class B liquid fire

5.3.1 Design fire size

The design fire size with Class B fires is limited on the size of the surface area of pools used in the tests. The minimum size should be 50MW representing very serious scenario having diesel spread over a large surface, see main document *Chapter 2.5.4 Fire scenarios for dimensioning FFFS*. *Notice! Class B fires in real tunnels are expected to be completely different to the tested scenarios. The thickness of the fuel layer is several centimetres, compared to a very thin layer on the road level in a real tunnel. This makes the fire test scenario worse than real life and even HRR per area is higher since no cooling of the road surface exists.*

5.3.2 Mock-up dimensions

Large pools shall be used as the mock-up for Class B HGV test fires. The minimum dimensions of the mock-up are the following:

- Width: minimum 2,5 m
- Length: minimum 6,5 m

The pool shall be placed on the road level so that the maximum height of the pool is 0,5m above it.

The mock-up can have either one large pool or separate smaller ones. The minimum size for one pool is 4 m^2.

5.3.3 Position of the fire mock-up

The mock-up shall be eccentric to the centre line of the test tunnel. The distance from the side wall shall be less than 1,5 m. Often centre line has been used for positioning the mock-up, but this is normally a very unlikely situation in a real tunnel. Additionally such a position is often most effective for FFFS since water is properly delivered on both sides of fire.

Figure 13. Eccentric position of mock-up in cross-section

5.3.4 Fuel specification

Light diesel oil shall be used as fuel. The volume shall be equal to a minimum of 7 minutes burning time as unsuppressed fire.

5.3.5 Ignition

Ignition shall be done with just enough gasoline and torches to ensure that all pools are ignited within 60 seconds.

Figure 14. Example of ignition of a large 100MW pool fire [18]

5.3.6 Ventilation

The ventilated air velocity should be measured 20 m upstream of the position of the fuel and be checked for plausibility prior to the start of each test.

Ventilation shall correspond to the test values given or as defined by authorities having jurisdiction. For longitudinal velocity, minimum 1,5m/s and 3m/s shall be tested.

5.3.7 Activation and deactivation

Activation of FFFS shall happen manually and be delayed compared to the detection systems. Triggering of FFFS shall happen within 2 minutes after ignition.

System shall discharge continuously until the fire is extinguished or the fuel is consumed completely. FFFS shall be deactivated manually.

The activation area shall be defined by the manufacturer, but it shall be minimum 3 times the length of the mock-up. *Notice! Activation area in real tunnel is normally longer due to risk of inaccuracies of detecting and localizing the fire.*

5.4 Summary of minimum tests

The following tests shall be carried out for FFFS as a minimum requirement.

Table 4. Summary of minimum tests

Number	*Type*	*Test*	*Ventilation*
1.	Class A - HGV	With tarpaulin cover	1,5m/s
2.	Class A - HGV	With tarpaulin cover	3,0m/s
Optional	Class A (optional) – HGV	Without tarpaulin cover	1,5m/s
Optional	Class A (optional - HGV)	Without tarpaulin cover	3,0m/s
3.	Class B – min. 50MW		1,5m/s
4.	Class B – Min.50MW		3,0m/s

It is strongly recommended to carry out a separate test fire series for calibration of the measurement system before the official tests. Smaller size Class B fires can be used for this purpose. Also free burning tests with Class B fires should be used for calibration purposes.

6. Measurements

6.1 General instruction

This chapter explains typical minimum measurement instrumentation for full scale fire tests with the fire scenarios explained earlier. All details of the measurement equipment, working principles and their locations shall be included in the fire test protocol that shall be approved by the authorities having jurisdiction prior to the tests.

If FFFS is designed for some special purpose, e.g. primarily only for life safety or asset protection, special measurements shall be considered.

The measurement system described in this chapter is meant for testing FFFS with longitudinal ventilation. The adaptation to other ventilation strategies shall be done together with authorities having jurisdiction. For example the locations of measurement instruments shall be reconsidered.

6.2 Standardisation and calibration

In general, the measurements shall be made by a company which has ISO/IEC 17025:2005 standard accreditation. Other companies can be accepted as well if their competencies and abilities of planning, realization and evaluation of complex measurements in full scale tunnel fire tests are proven. E.g. by demonstrating prior experience.

All measurement equipment shall be calibrated before the fire tests, and the data shall be attached to the test protocol. The calibration shall follow generally accepted codes of practise for each piece of equipment. The calibration reports or certificates shall be part of the fire test reporting.

It is important to carry out some reference tests for the calibration of the measurement system. Class B pool fires are very important for this since they give constant HRR for checking the accuracy of measurement and calculation method. The calibration should be done with small, e.g. 5MW and larger, e.g. 30MW pool fires.

6.3 Positioning and naming measurements

Full scale tunnel fire tests have large dimensions and require many measurement instruments in various positions. Therefore a predefined logic of naming instruments is essential for processing measurement data.

The centre point of the measurement system shall be nominated as virtual zero point 00, which is longitudinally in the middle of the mock-up. Everything upstream shall be marked with Uxx, where xx is the distance from the zero point in meters. Everything downstream shall be marked with Dxx, where xx is the distance from the zero point in meters. For example the ends of the HGV Class A mock-up are located in U5 and D5. Correspondingly the fire target is located at D10.

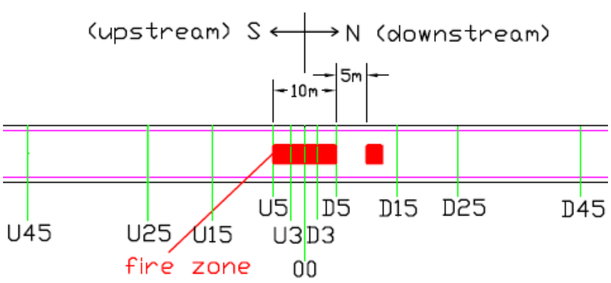


Figure 15. Example of U (upstream) and D (downstream) numbering

Cross-section location shall be given based on numbers. The detailed grid shall be decided based on the cross-section of tunnel. The following is an example of such.

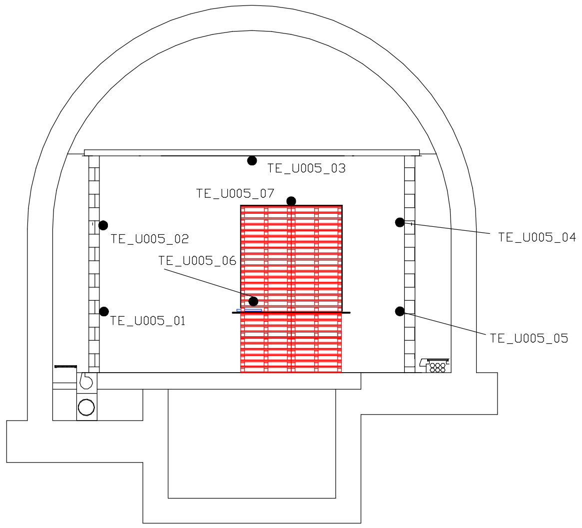
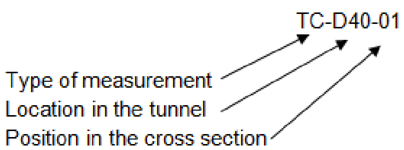


Figure 16. Numbering of equipment in cross-section

It is practical to use abbreviations to mark the type of measurement equipment used in various locations. The following is a list of different measurement types and possible abbreviations.

Abbreviations	*Measurement*
TC	Thermocouple
HF	Heatflux
IR	Infrared camera
CM	Video recording
AN	Anemometer
GA	Gas sampling
VI	Visibility sensor/camera

Logically, given measurements can be located with a simple logic, e.g.



6.4 Measurements

6.4.1 Temperature

The temperatures are used to evaluate the fire characteristics and the exposure in the tunnel.

Thermocouples type K, 1.0 mm diameter, shall be able to measure up to 1300°C and have a minimum accuracy of ±1%.

Thermocouples shall be installed with a minimum grid of having 5 sensors in cross-section and in the locations of U100, U45, U25, U10, U5, U3, D3, D5, D10, D25, D45 and D100.

6.4.2 Heat radiation

Heat radiation is measured to evaluate tenability conditions for people and the exposure of the tunnel structure.

The measurement and calculation method shall be detailed in the fire test protocol. Heat radiation sensors shall be able to measure up to 20 W/cm^2 and have a minimum accuracy of ±3%.

Heat flux sensors of type Gordon (Medtherm) shall be installed with a minimum of having 2 sensors at 1.5m height in the locations of U15 and D15.

It is not recommended to use thermo plates. These sensors are usually to slow to react on fast changes during a fire test with FFFS. Furthermore, due to droplets hitting on the large measurement surface, failures in the measurement might occur.

6.4.3 Gas concentrations

The gas concentrations are measured both for evaluating tenable conditions and for oxygen consumption to calculate the HRR.

Oxygen (0_2)

It is recommended to use electrochemical oxygen sensors because of their high accuracy and their fast response characteristics, which is needed to calculate the HRR in real time. Such sensors need calibration just before the start of each fire test.

Oxygen sensors must support the nominal content in air being able to measure 0-25 Vol. % and have a minimum accuracy of ±0.5%

Oxygen has to be measured with a dense enough grid in cross-section since it can vary a lot within different heights and areas of cross-section. A minimum of 3 sensors with 2 suction points each in the tunnel cross section shall be used. It is important to measure oxygen concentration on both sides of the fire. Such places are U45 and D45.

Carbon dioxide ($C0_2$)

Carbon dioxide sensors are used to evaluate the life safety and tenable conditions within the tunnel as well as to calculate the HRR.

Carbon dioxide sensors must support the typical range of 0-25 Vol. % and have a minimum accuracy of ±10%.

Carbon dioxide shall be measured at different heights, but especially at the breathing level of tunnel. A minimum of 3 sensors with 2 suction points each in the tunnel cross section shall be used. It is important is to measure carbon dioxide concentration on both sides of the fire. Such places are U45 and D45.

Carbon monoxide (C0)

Carbon monoxide sensors are used to evaluate the life safety and tenable conditions within the fire.

Carbon monoxide sensors must support the typical range 0-10 Vol. % and have a minimum accuracy of ±5%.

Carbon monoxide shall be measured at different heights, but especially at the breathing level of the tunnel. A minimum of 3 sensors with 2 suction points each in the tunnel cross section shall be used. It is important is to measure carbon dioxide concentration on both sides of the fire. Such places are U45 and D45.

In case of a semi- or transversal ventilation, such measurement must be carried out in any cross-section behind the last ventilation flap of the downstream area as well.

6.4.4 Air velocity

Air velocity is used for evaluating the functioning of the ventilation system and calculating the air mass flows in HRR determination.

Since air velocity can vary a lot in different parts of the tunnel, it shall be measured over whole cross-section either with ultrasonic sensors to get a mean value or, more commonly, using bidirectional probes. Sensors shall be able to measure at minimum 15m/s…+15m/s and have a minimum accuracy of ±1%.

Air velocity needs to be measured on both sides of fire load, at minimum in U340, U45, D45 and D215.

6.4.5 Visibility

Visibility measurements are used for evaluating the life safety and self-evacuation possibilities.

The subjective, visual evaluation of the visibility shall be carried out on the upstream and on the downstream side of the fire. Different kinds of methods can be used for the evaluation.

1) The visibility can either be measured by using opacimeters in different positions and at a height of 1.5 m. With a combination of a spot light with suitable wave length and a photo sensor, the extinction of light will be calculated.

Type:	Phototransistor
Halogen spotlight:	500 W (adjustable)
Method:	Extinction
Range:	1/m
Accuracy:	1 %

2) Or the visibility can be measured by recording self-lighting LED lines with a video camera. Those LED lines shall be positioned in different heights of 1, 2, 3, 4 and 5 m at the tunnel wall. A recording video camera is placed perpendicular to the tunnel longitudinal axis.

Visibility needs to be measured at minimum in U045, D045; D100, D215.

6.4.6 Pressure FFFS

The pressure of FFFS shall be recorded as documentation of operating parameters. The System pressure shall be recorded since this is the minimum pressure nozzles shall be operated in the real installation.

Measurement shall be done with the pressure transducers having at minimum absolute ±1% accuracy. The pressure shall be measured from hydraulically the last nozzle in the system.

6.4.7 Flow rate

Flow rate of FFFS shall be recorded as documentation of operating parameters. Flow rate should correspond to the value calculated using the nozzle K-factor, the number of nozzles and the minimum nozzle pressure. Due to pressure losses of FFFS the measured flow rate is normally a bit higher, but there shall not be more than 5% difference. If difference is higher than 5% water will be distribute too unevenly in the activated area.

Flow rate shall be measured with a flow sensor having minimum ±1% accuracy. The flow sensor shall be located between the pump unit and the activated sections in the test tunnel.

If different fire fighting agents are used together, flow measurement shall be taken for each of them.

6.4.8 Video recordings

Video recordings shall be used for evaluating other measurements together with visual recordings. Both normal and thermal video cameras shall be used. The recommended locations are minimum 1 normal camera upstream U10. Additionally 1 camera shall be based downstream at D25. Cameras on the downstream side should be installed below 1,5m height and have thermal insulation. A thermal video camera shall be used on downstream side in D25. All cameras should be pointed to the mock-up and cover the whole cross-section.

6.4.9 Queries and empirical data

Queries to fire fighters and other personnel can be used for collecting empirical experiences with different tests. These shall be done together with authorities having jurisdiction to collect additional information. Visibility conditions or difficulty level of manual fire fighting are examples of such.

6.4.10 Summary of measurement locations

A summary of different longitudinal measurement locations and related instruments are collected in the following table. These shall be considered as minimum. The authorities having jurisdiction may limit or increase instruments, especially if some special risk is related to the real tunnel to be protected.

Table 5. Summary table of different measurements and their longitudinal locations

Location	*Number and type of sensors*
U340	2 thermocouples 2 air velocity (ultrasonic)
U100	5 thermocouples
U45	7 thermocouples 5 bidirectional probes 3 oxygen 3 carbon dioxide 3 carbon monoxide 1 relative humidity 1 thermocouple visibility
U25	5 thermocouples
U15	5 thermocouples 1 heat flux sensor
U05	7 thermocouples
U03	7 thermocouples
D03	7 thermocouples
D05	7 thermocouples
Target	3 thermocouples
D15	5 thermocouples 1 heat flux sensor
D25	5 thermocouples
D45	5 thermocouples 5 bidirectional probes 3 oxygen 3 carbon dioxide 3 carbon monoxide 1 relative humidity 1 thermocouple visibility
D100	5 thermocouples visibility
D215	2 thermocouples 5 bidirectional probes 2 air velocity (ultrasonic) visibility

6.5 Heat release rate

Heat release rate is relatively complex to measure in fire tests and therefore needs special attention. It can be basically measured as a mass loss during the combustion process or by the oxygen consumption of the fire. Only the latter is suitable for the tests with FFFS, because the fire fighting medium will be applied to the fire load. Furthermore the HRR is used as the triggering point for activation of FFFS, *see chapter 4.2.8.* The maximum delay of HRR measurement should be 60 seconds in order to get timely activation of FFFS. A fast response of the HRR measurement is also important for safety reasons.

The mass loss based HRR calculation can only be used in free burning fires and especially with Class B fires. These can be used for the calibration of oxygen based HRR measurement. The mass loss can be used also with Class A fires for verifying the HRR over the whole time.

The oxygen consumption based HRR method shall be documented in detail in the fire test protocol and report. Its accuracy shall be tested by Class B reference tests with and without FFFS. The authorities having jurisdiction shall approve the method being used, *see chapter 4.*

7. Minimum acceptance criteria

7.1 General

The acceptance criteria of fire tests shall be documented in advance of the fire test protocol. The acceptance criteria can vary a lot depending on the primary purpose of the system. There are tunnels where FFFS is meant primarily for life safety and others where the structure protection is more important. The detailed acceptance criteria shall be defined by authorities having jurisdiction based on the risk analysis of every individual tunnel.

This chapter gives some guidance for selecting minimum acceptance requirements but do not specify in detaild absolute values. The requirements are divided into four main categories, These also support the general protection targets as listed in the main document *Chapter 2.2*

1. Fire development and suppression,
2. Personal (life) safety,
3. Fire services safety and,
4. Tunnel structure protection.

Much previous research work as well as other literature has been used as a basis for defining the minimum acceptance criteria [7][9][22][36][37]. But as mentioned above and also in other documents, every tunnel shall be evaluated separately to define acceptance requirement.

7.2 Class A fires

7.2.1 Fire development and suppression

FFFS shall be able to slow the development of fire in terms of measured HRR. The given limit for HRR shall be in line with the capacity of the ventilation system and other fire size dependent systems.

Prevention of fire spread is essential in every case and fire target shall not have ignited during the test. FFFS has failed if fire spread has spread to the target 5 m downstream behind the mock-up (D10). The target shall be studied after extinguishing fire to see if there were fire damages that would indicate ignition of target material.

Also measured temperatures at target location shall be evaluated for preventing fire spread. The criteria shall be defined by authorities having jurisdiction. The main document and annex 1 give some references about real measurements with similar fire loads.

7.2.2 Personal (Life) safety

Tenable conditions for life safety on upstream side of fire shall be provided by FFFS. This refers to temperatures, heat radiation, visibility and gas concentrations. The limitations for these values shall be defined by the authorities having jurisdiction.

Also corresponding limits shall be given for more critical downstream side of the fire. Especially special notice shall be given to the gas concentrations, CO and CO_2 values. The main document and annex 1 give some references about real measurements with similar fire loads.

7.2.3 Fire services

Fire services have protective clothing and breathing apparatuses, which puts them in a different condition to people in self-evacuation. Normally acceptance criteria given for personal (life) safety enables fire services operate in fires. But fire services may require some special requirements in addition if tunnel has some special features. The decision of such is made by authorities having jurisdiction.

7.2.4 Tunnel structure

The acceptance criteria for the tunnel structure may vary depending on the tunnel method, construction and materials used. The minimum criterion is that high temperature exposure areas will be limited to a small area, directly above fire loads or slightly downstream.

The absolute limit values, and more importantly time they are allowed, has to specified by the authorities having jurisdiction. This is typically defined by the tunnel structure type, construction or some special parts e.g. joints/seals. For example concrete structure with 6 cm deep reinforcement is much more tolerant if compared to cast iron lined tunnels. It must be also noted that even high temperatures, e.g. over 500℃ are allowed if exposure time is short and area is small. The acceptance criteria shall be defined by authorities having jurisdiction.

7.3 Class B fires

7.3.1 Fire development and suppression

FFFS shall be able to suppress the fire significantly. It is the obligation of the test institute to show the suppression abilities using the collected data. *Notice! If the ventilation system is designed for certain unsuppressed fire size, FFFS shall be able to suppress increased design fire under this size.*

7.3.2 Life safety

Tenable conditions for Class B fire shall remain same as for Class A fires. *See chapter 7.2.2.*

7.3.3 Fire services

Acceptance criteria for fire services shall remain same as for Class A fires. *See chapter 7.2.3.*

7.3.4 Tunnel structure

Acceptance criteria for tunnel structure shall remain same as for Class A fires. *See chapter 7.2.4.*

7.4 Time delay in activation and achieving target values

Chapters 7.2 and 7.3. listed some basics for minimum acceptance criteria. However, it is important to notice that FFFS systems normally need a certain response after getting a triggering signal. During this time pumps start to run and water pressure increases to the designed level. This also means that FFFS might have some delay before taking over thermal conditions, e.g. measured temperatures. Authorities having jurisdiction shall define which is time limit all acceptance criteria e.g. temperatures shall be under limits.

8. Reporting

8.1 General

Good reporting is essential to ensure that all parties involved in the fire tests have common understanding about the intention of tests and required performance. There are two main documents that cover both preparation and final documentation of the fire tests. These are the fire test protocol and the fire test report.

8.2 Fire test protocol

The fire test protocol is a predefined document identifying clearly the tests to be done with all technical details.

The fire test protocol shall cover as a minimum the following aspects:

- Description of referred to test standards and variations if any
- Description of the test tunnel
- Description of test setup (instruments, methodology, measurement grids)
- Description of system calibration
- Description of fire load and target in all tests
- Description of fire ignition
- Activation times
- Geometry of the test tunnel
- Ventilation conditions
- Categorization of the intended FFFS
- Intended system parameters
- Fire test program schedule

The fire test protocol has to be approved well prior to the tests by the authorities having jurisdiction.

8.3 Fire test report

The fire test report summarises all tests with detailed results as planned according to the fire test protocol.

8.3.1 Summary of FFFS

The fire test report shall describe in detail tested design parameters such as lay-out parameters, design pressure of nozzle, design flow rate of nozzle.

Additionally one sample nozzle shall be delivered together with the fire test report for? the records of the authorities having jurisdiction.

8.3.2 Summary of measurements

The fire test report shall summarise all measurements in the acceptance tests. By special agreement data files can also be delivered in an electronic format.

8.3.3 Summary of acceptance criteria

The fire test report shall summarise all acceptance criteria and whether these were passed or not in the tests. A reference to fire test measurements shall be done with each acceptance criteria.

8.3.4 Summary of other recordings

Other recordings shall be included also in the fire test report. The content of the other recordings shall be agreed with the authorities having jurisdiction.

8.3.5 Summary of empirical values

A summary of various observations can also be included in the fire testing. For example, experiments of fire fighters can be collected for qualitative evaluation of system operation.

8.3.6 Copies of original log file

Copies of fire test log files of approval tests shall be attached to the fire test report. These shall have the signature of the witness from the authorities having jurisdiction or their representatives in the fire tests.

8.4 Authorities having jurisdiction

Authorities having jurisdiction have a very important role in all stages of the reporting process. These are for example approving the fire test protocol, witnessing the fire tests and approving the fire test report.

9. References

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