CETU

Information document

WATER MISTS IN ROAD TUNNELS

State of knowledge and provisional assessment elements regarding their use

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Ministère de l'Écologie, de l'Énergie, du Développement durable et de la Mer

June 2010

Tunnels Study Centre (CETU)

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INTRODUCTION

Since the late 1990s and the catastrophic fires of the Mont Blanc, Tauern and Gotthard tunnels, which were particularly striking for the public, road tunnel safety has become a major concern for authorities. The latest events, which took place in the Frejus tunnel and in the Channel tunnel, highlight an increasing need for tools to improve the safety of tunnels in case of fire, from both life safety and asset protection points of view. Beyond regulatory requirements, which are progressively enforced, new means are constantly being named to raise the safety level in tunnels.

Amongst these new means, fixed fire fighting systems (abridged as FFFS in this document), and particularly those using water as an extinguishing agent, are an example which is more and more cited by rescue services and tunnel owners alike, each having different objectives regarding their use. However, such a device can have an interest only if it is correctly integrated into a general approach of safety. Some characteristics, especially aeraulic, of these underground infrastructures are indeed very different from those of closed spaces which are more traditional applications of FFFS: compartments, ship machinery rooms, warehouses, etc. France, following other European countries, has always been reserved regarding the installation of such systems in its tunnels. Indeed, the action of FFFS may, under certain conditions, create additional risks for the exposed people. Moreover, the efficiency of FFFS for controlling vehicle fires in tunnels has not, to date, been demonstrated with sufficient certainty and accuracy.

The present document is based upon research work carried out by CETU, as well as in the framework of European projects on tunnel safety. It aims at reviewing the current knowledge and propose some help with the assessment of the relevance of FFFS, particularly those using the “water mist” technology, in road tunnels.

First, the general problem of tunnel fires and data regarding the current use of FFFS in the world are exposed. Then the various available technologies are presented. In the third part, the effects of water mist systems on a tunnel fire are analysed. Finally, assessment elements for water mist-based FFFS in tunnels are suggested.

1

CONTEXT

1.1 PARTICULAR CONTEXT OF ROAD TUNNEL FIRES

1.1.1 Nature and size of the fires

Most tunnel fires are caused by spontaneous ignition of vehicles due to a technical failure (overheating, short-circuit, etc.). However, almost all fires having caused fatalities followed an accident (with the very notable exception of the Mont Blanc fire in 1999, and also the Frejus fire in 2005). The dangers which exist in a tunnel fire generally appear in the following order:

- first, the visibility is reduced by smoke and affects considerably the self-evacuation process;
- then the users who could not evacuate because of smoke may be intoxicated, sometimes fatally, by the fire smoke which becomes more and more toxic over time;
- finally, the heat from the fire makes the temperature rise considerably, which can be a threat to people but also to vehicles or tunnel equipment which is vital to the users' safety.

The heat release rate (HRR) of a vehicle fire in a road tunnel may vary from a few megawatts to 200 MW, or even more, depending on the type of vehicle (car or HGV) and the nature of its cargo, especially the presence of dangerous goods. So the HRR of a tunnel fire can be far higher than the values encountered in buildings, for example, where it rarely exceeds 10 MW. Moreover, a vehicle fire in a road tunnel may involve both the combustion of solid materials and liquid hydrocarbons.

1.1.2 Life safety strategy and related equipment

When a fire breaks out in a tunnel, the objectives of the life safety strategy are:

- to allow self-evacuation of users;
- to allow survival until the arrival of rescue services, for the people who could not evacuate;
- to ease the action of rescue services for, on the one hand, assisting users in the evacuation process and, on the other hand, fighting the fire;
- to protect the infrastructure.

Thus, tunnels are built and equipped taking into account specifications which aim at:

- detecting abnormal situations and allow communication with the tunnel users (CCTV, automatic incident detection and other detection equipment, signs, emergency phones, etc.),
- allowing protection and evacuation of the tunnel users, as well as rescue services access (emergency exits, shelters, lay-bys, safety lighting, ventilation, etc.),
- preventing and fighting fires (fire reaction and resistance, fire-fighting means, communication devices for rescue services, smoke control ventilation, etc.)

Among these elements, the smoke control ventilation system plays an essential role, since it is the only device acting directly on the ambient conditions in the tunnel. Its action delays the occurrence of untenable conditions for users and rescue services. Two main strategies can be distinguished:

- pushing all smoke on one side of the fire by creating a sufficient longitudinal air flow, provided that no users are present on that side,
- or keeping the longitudinal air flow at a minimum to preserve the natural stratification of smoke and extract it through the ceiling.

In the latter case, the aeraulic specificities of tunnels (pressure difference between the portals, piston effect of the vehicles) require numerous anemometers to control, almost in real time, the longitudinal air flow. This possibility has a strong influence on the efficiency of the life safety strategy.

Despite this crucial role, the safety level of a tunnel cannot be assessed only through the performance of the smoke control system. Safety can indeed be assessed only by a general approach of the system.

1.2 CONTEXT OF THE USE OF FFFS IN TUNNELS

1.2.1 Position of PIARC

Since 1983, the World Road Association (PIARC) has dealt with the use of FFFS in road tunnels. The latest PIARC recommendations on the subject dated back to 1999 [1] before being recently updated [2].

The "historic" position of PIARC is developed in [1]. It states that FFFS can cool down the burning vehicle(s) and reduce the HRR of the fire, and prevent or limit the fire spread to other vehicles.

Nevertheless, in spite of these advantages, PIARC recommended not to use fixed water sprays:

- to save lives, that is to say during the self-evacuation and assisted evacuation phases, because the use of a fixed water spray system causes:
  - a risk of burns to users through the water vapor from the vaporization of droplets,
  - cooling and destratification of smoke, reducing the visibility in the tunnel;
- to protect the tunnel after the evacuation of users, except in tunnels of outstanding importance, because of:
  - high maintenance costs,
  - low efficiency of these systems to extinguish the fire when it is confined inside the vehicles.

Moreover, the report [1] states that the use of a fixed water spray system in tunnels may also create:

- a risk of explosion through the projection of chemicals from boiling water at the combustible surface, if no appropriate additive is used,
- a risk of explosion through the production of flammable gases despite the fire being extinguished.

Finally, it highlights the difficulties created by automatic activation of those systems through thermofusible devices, while the possibility of human control of the system at all times is necessary.

This unfavourable position regarding FFFS was strongly related to the technology available at that time. Indeed, the difficulties referred to in [1] are linked to the so-called "sprinkler" systems available in the late 1990s. Those systems, close to those installed in some buildings, are automatically activated by thermofusible devices and produce large diameter droplets (of the order of 1 mm). In the last decade, though, technological innovations and improvements in the FFFS led PIARC to reconsider its position.

In its latest report on the subject [2], PIARC states that the main objectives of such systems are to reduce:

- the rate of growth of the fire,
- the heat release rate of the fire,
- the ultimate size of the fire,
- the risk of fire spread from one vehicle to another

Nonetheless, even if each of these objectives can contribute to the improvement of user safety, fire brigade access to the fire and protection of the structure, installing a FFFS remains one of the numerous options available to increase the level of safety in a road tunnel. The other options are ventilation, emergency exits, detection systems, etc. The assessment of such a system should therefore be carried out considering not only its intrinsic performance, but its integration as an element of a safety system at tunnel scale and analysing the efficiency of the whole system.

To achieve this, PIARC underlines that before installing a FFFS, it is necessary:

- to ensure its reliability and to assess the operating costs,
- to analyse and understand its interdependency with other safety elements,
- to pay special attention to the operational decisions regarding its activation, that is to say when, where and by who the system should be activated,
- to have an effective fire detection system in order to operate the system appropriately.

1.2.2 Examples of FFFS use in the world

The use of FFFS in compartments such as buildings or ship machinery rooms is now widespread throughout the world. However, their use in road tunnels remains marginal since only Japan, and to a lesser extent Australia, fit some of their tunnels with such systems, in a prescriptive manner. In the rest of the world, where their installation is decided on a case-by-case basis, there are only about 20 tunnels where a FFFS is installed or where the installation is planned in the near future (see fig. 1).

This limited use of FFFS in road tunnels around the world may be explained by the specificity of road tunnel fires due, on the one hand, to the aeraulic characteristics of underground infrastructures, and on the other hand, to the nature and size of the fires which are likely to occur in tunnels.

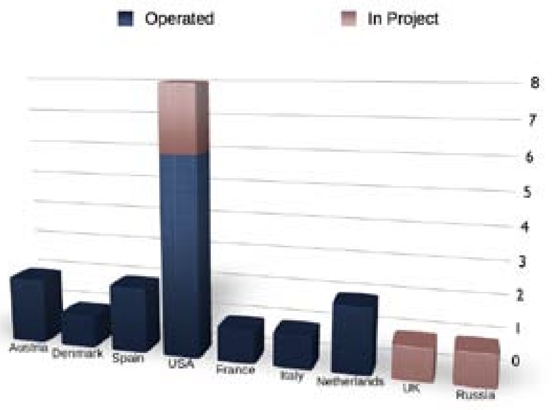

Figure 1: Number of tunnels with FFFS in operation and in project in the world de lutte (outside Japan and Australia)

1.2.3 Research work

European project UPTUN

Following the catastrophic fires of the Mont Blanc and Tauern road tunnels in 1999, and that of the Gotthard tunnel in 2001, numerous research projects aiming at improving safety in road tunnels were launched at European scale.

Among these research projects, UPTUN (cost-effective, sustainable and innovative UPgrading methods for fire safety in existing TUNnels) investigated, among other tasks, the possibility of using water spray systems in tunnels. This project, worth some € 13 million, was carried out from 2002 to 2006 and involved 41 partners from 14 countries. Two large-scale test programs were performed in the framework of this project.

In addition to these programs, other tests were conducted in the Runehamar tunnel in Norway (out of service) and in the Virgolo tunnel in Italy (in operation). These tests were carried out with high-pressure water mist-based FFFS.

• 1st series: current mitigation technologies existing in road tunnels [3].

This series was performed in the test gallery at Deutsche Montan Technology (DMT) in Dortmund, Germany. The gallery has a 9.7 m² cross-section and is 150 m long. The aim of this test series was to assess the performance of three existing fixed water spray systems for use in a tunnel:

- a water curtain system,
- a water spray with droplets of the order of 1 mm, generally referred to as sprinkler,
- a low-pressure water mist system.

The tests were performed with, on the one hand, a fire consisting in heptane pools allowing a maximum HRR of 20 MW, and on the other hand, a longitudinal air flow of 1 or 3 m/s

• 2nd series: new innovative technologies for fire-fighting in tunnels [4]

This series was performed in the gallery of the insurance company IF, located in the outskirts of Oslo, Norway. the gallery has a cross-sectional area of 40 m² and is 100 m long. The aim was to assess the performance of two types of innovative fixed water spray systems for use in a tunnel:

- a fixed low-pressure water mist (< 12.5 bar),
- a fixed high-pressure water mist (> 35 bar).

The tests were performed with, on the one hand, a fire consisting in heptane pools or wood pallets allowing a maximum HRR of 20 MW and 15 MW respectively, and on the other hand, a longitudinal air flow of 1 or 2.5 m/s.

SOLIT project

The Safety Of Life In Tunnels (SOLIT) project is a research project funded by the German federal ministry for Economy and Technology whose objectives were to test and assess the efficiency of a high-pressure water mist-based FFFS to improve safety in tunnels.

In the framework of this project, a test series was conducted in the test gallery of San Pedro de Anes (Spain). This gallery was built by the regional government of Asturias and is operated by the company Tunnel Safety Testing SA. Its geometrical characteristics are the following: width 9.8 m, height 5.2 m, length 600 m. Longitudinal and semi-transverse ventilation can be simulated (in the semi-transverse case, there is only smoke extraction, no fresh air supply). The tests were performed with either heptane pools similar to those used in UPTUN or wood pallets covered or not with tarpaulin.

Hagerbach tests - A86 West tunnel

In order to assess the efficiency of the projected water mist system in the A86 tunnel (open only to light vehicles), the builder and operator Cofiroute conducted a test campaign with and without FFFS in the test gallery of Hagerbach (Switzerland) [5].

Two test series were carried out in order to test two water mist FFFS, one being a medium-pressure system (between 12.5 and 35 bar), the other being a high-pressure system (over 35 bar). These tests aimed essentially at measuring the efficiency of such systems to limit the spread of a fire between light vehicles close to each other. The problem of a HGV fire in a normal height tunnel was not dealt with.

1.2.4 Research program carried out at CETU

In order to properly qualify FFFS for use in road tunnels, additional knowledge proves to be necessary. This is the reason why CETU committed itself, from 2002, into a specific research program. This has led, as a first step, to identify two objectives for FFFS [6], namely:

- to improve the self-evacuation conditions for non-incapacitated users,
- to extend the tenability in time for non-evacuated users and rescue services in the intervention phase.

The second step in the research consisted in a pragmatic approach targeting the case of a bi-directional tunnel. This study was carried out for CETU by BG Consulting Engineers [7][8][9]. It comprised two parts, the first regarding the assessment of the feasibility and investment and operating costs of FFFS, the second dealing with the efficiency of such systems on reference fires in order to compare the safety levels in various configurations. The conclusions of this study confirm the need for further research in this field.

In order to obtain more information on the effects of FFFS on a tunnel fire, several approaches can be considered. The experimental approach is the most obvious option and the one chosen by CETU. A two-phase test programme was planned. The first phase used a reduced-scale tunnel (with a scale factor of 1/3 approximately) on the premises of CSTB (French scientific institute for building), and the second phase is intended to consist in real-scale tests.

So far, only the first phase has been carried out. It consisted in an ambitious 30-test programme with CSTB as a partner [10]. These tests were performed on open or semi-hidden fires consisting in heptane pools, wood cribs or pallets. They aimed at improving our understanding of the physical phenomena at stake, on the one hand, and assessing the efficiency of a FFFS, on the other hand. They also aimed at qualifying the measurement methods for physical quantities such as temperature with probes that are, or are not, protected from water droplets, and more importantly opacity. This latter quantity was measured using different techniques (laser, white light transmission, scattering), since reliable data regarding visibility in the presence of water was still missing. Meanwhile, a theoretical approach using three-dimensional modelling of the reduced-scale fire tests was developed in a PhD thesis [11].

1.3 SAFETY EXPECTATIONS

Given the specificity of tunnel fires in terms of aerodynamics, heat release rates, fire confinement and types of fuel, one should be cautious about the gains in safety which could be expected from the use of a FFFS in a road tunnel.

The assessment of the efficiency of such a system in a tunnel requires a thorough analysis. It is necessary to know and understand better the phenomena at stake, along with their impact on ambient conditions in the tunnel and life safety strategies.

Indeed, the fulfillment of each of the objectives of the life safety strategy depends on the ambient conditions in the tunnel, that is to say visibility, gas toxicity, temperature and radiation. However, these variables do not have the same importance depending on the objective being considered. Unlike the tunnel users, firemen know how to move inside the tunnel without visibility and are equipped with a breathing apparatus. Their action is therefore less sensitive to visibility and toxicity. The protection of the tunnel infrastructure is not at all sensitive to visibility and toxicity since it depends only on the tempertaure and radiative effects.

The following table sums up the relative importance of ambient conditions within the tunnel regarding the various objectives of the safety strategy.

By its action, the FFFS can improve or deteriorate some of the ambient conditions and thus the self-evacuation capacity of users, the action of rescue services of the protection of the tunnel infrastructure.

	visibility	toxicity	temperature[1]
allow self-evacuation	+ + +	+ +	+
improve the tenability time	+	+ + +	+ +
ease the action of rescue services	+ +	+	+ + +
protect the infrastructure	o	o	+ + +

+ + + : very important + + : important + : less important o : no impact

Table 1: Relative impact of the ambient conditions in the tunnel regarding the objectives of the life safety strategy

1 : and radiation effects.

2 CONSTITUENT ELEMENTS OF A FIXED FIRE-FIGHTING SYSTEM IN A TUNNEL

In order to assess which FFFS is the most suitable for road tunnels, it is necessary to take into account, on the one hand, the specificity of fires in those tunnels, and on the other hand, its integration as a safety device in the framework of a safety system approach.

2.1 CHOICE OF THE EXTINGUISHING AGENT

The standard NF EN 2 distinguishes between four classes of fires depending on the nature of the fuel:

- Class A fires are solid material fires, generally producing embers when burning.
- Class B fires are liquid or liquefied solid fires.
- Class C fires are gas fires.
- Class D fires are metal fires.

In order to fight a fire efficiently, one must use the extinguishing agent which is the most appropriate for the class of fire being considered. Indeed, several types of extinguishing agents exist including inert gases (carbon dioxide, argon, nitrogen or blend of these three gases), inhibiting gas (halon, banned since 2004), powder, pure water and water with added tensio-active. The principles of the action of these extinguishing agents is extensively described in [12].

In the usual cases where FFFS are used, namely when the fire is neither confined nor ventilated, the table[2] below sums up the effectiveness of extinguishing agents depending on the class of the fire.

	class A	class B	class C	class D
inert gas	B	G	G	*
inhibiting gas	B	G	G	
BC powder	B	G	G	
ABC powder	G	G	G	
pure water, sprayed	G	L	B	
water with tensio-active, sprayed	G	G	B	
foam	L	G	B	

G : good efficiency L : limited efficiency B : bad efficiency

* on such fires, only specific liquid or powder extinguishers must be used.

Table 2: Extinguishing agents efficiency depending on fire class

In the case of tunnels, the most commonly encountered fires are of classes A or B. Given the specificities of tunnel fires, the most appropriate extinguishing agent seems to be pure water. It is applicable to the fires likely to occur in tunnels; it is also the most widely used and best known agent. Extinguishing agents such as inert gases, inhibiting gases and BC powder are ineffective on unconfined and unventilated class A fires, and even more so on confined and ventilated fires. ABC powder, foam, and to a lesser extent water with added tensio-active need an open fire to be fully effective so they can reach the fuel surface; yet most fires in tunnels are at least partially hidden

So, in the remainder of this document, we shall investigate only fixed fire-fighting systems using pure water as the extinguishing agent.

2 : from the judicial memo reminder TJ 20 on fire prevention at work, INRS (French institute on occupational health and safety), October 1st, 2004.

2.2 DROPLET SIZE

Current technology can generate different droplet sizes by modifying the water pressure and spray nozzle geometry. To date, two types of water spray systems should be distinguished depending on the droplet size distribution: water mist systems and large droplet systems, also referred to as "sprinklers".

According to NBN CEN/TS 14972 (issued May 12th, 2008) and NFPA 750[3] standards, a water mist is a spray made of droplets with a characteristic diameter $D_{V0,9}$ less than 1 mm, which means that droplets smaller than 1 mm in diameter contain at least 90% of the total water volume. If $D_{V0,9}$ is larger than 1 mm, the system is called sprinkler. The NFPA 750 standard distinguishes 3 classes of water mist according to their characteristic diameter $D_{V0,9}$ (see tab. 3).

Class I	Class II	Class III
$D_{V0,9} \leq 200$ µm	200 µm $\leq D_{V0,9} \leq$ 400 µm	400 µm $\leq D_{V0,9} \leq$ 1000 µm

Table 3: Water mists classification according to NFPA 750

Class III water mists and sprinklers are rather suitable for class A fires because the size of their droplets enables them to reach the surface of the solid combustible, provided it is not hidden, and therefore to cool down the solid fire.

However, such water mists are less efficient than Class I mists to cool down the gas phase (air and smoke). Indeed bigger droplets have a lower surface-to-volume ratio, which reduces the heat transfer between the gas and the liquid. The heat absorption by vaporization of droplets and the radiation absorption are therefore lower for bigger droplets.

In the case of tunnel fires the fire is most of the time hidden, which makes direct water spraying onto the combustible surface impossible. The efficiency of a Class I water mist is therefore better than that of a system producing bigger droplets. Moreover, the water consumption of a Class I water mist is lower than that of a sprinkler system. So the following discussions focus only on Class I water mists.

2.3 SPRAY SYSTEM CONTROL BY SECTION

For the whole duration of a road tunnel fire, the operator and the rescue services must keep full manual control of the safety devices of the tunnel in order to define the best life-saving and intervention strategy. This requirement means that the water mist system must be controlled through remote-controlled vanes, and not through thermo-fusible devices which do not allow manual control. The water mist must be operated by section. Such a system consisting in remote-controlled spraying sections is commonly referred to as "deluge".

In order to optimise the efficiency of the water mist, the length of the sections should be limited to those areas where the temperature is high enough to vaporise the water mist droplets, taking into account the uncertainty on the fire location. Outside these areas, the water mist would not be efficient since the droplets would not be vaporised. This is why manufacturers recommend that the system be operated over a tunnel length of 100 to 150 m, comprising two or three sections. This can be compared to the length of the smoke extraction zone for transverse ventilation, which is 400 to 600 m in France, or to the distance between two emergency exits which is 200 to 400 m. For longitudinal ventilation, the distance between two groups of jet fans is about 100 m. So the spraying zone is rather limited in length.

3 : NFPA 750 - standard of water mist fire protection systems, 2006 edition.

2.4 TYPICAL ARCHITECTURE OF A WATER MIST-BASED FIXED FIRE-FIGHTING SYSTEM IN A TUNNEL

The large quantity of water (about 500 m³ for 2 hours of operation) and high pressure required to operate a water mist-based FFFS make it impossible to use the traditional fire hydrant network as a water source. It is therefore necessary to create a dedicated network, which must be protected against freezing, made of non-oxidising materials, equipped with filters and incorporating an anti-bacterial treatment system protecting the users' health.

Nozzles are generally attached to the ceiling. Such a fitting reduces the gas temperature through the vaporisation of the droplets but reduces considerably the direct action of the system on the fire.

Installing the nozzles in the lower part of the sidewalls could be considered to improve the effect of the water mist on the fire. Indeed, due to the temperature gradient, the vaporisation of droplets from nozzles located in the lower part of the sidewalls would be less, making it easier for these droplets to reach the combustible surface. Such a mounting may therefore allow a reduction of the HRR of the fire through a direct action on the combustible surface, provided this surface is accessible to the water mist droplets.

However, no detailed study comparing the efficiency of the various possible nozzle arrangements is available to date; furthermore, most fires in tunnels are hidden. Hence, we retain the recommendations of the water mist manufacturers, who favour setups where nozzles are located under the ceiling only.

In order to ensure effective spraying regardless of the transverse location of the fire, it is necessary to have nozzles on several longitudinal axes, the exact number depending on the width of the tunnel (see fig. 2).

The investment cost for such a water mist system is estimated at € 2M per km of tunnel [8].

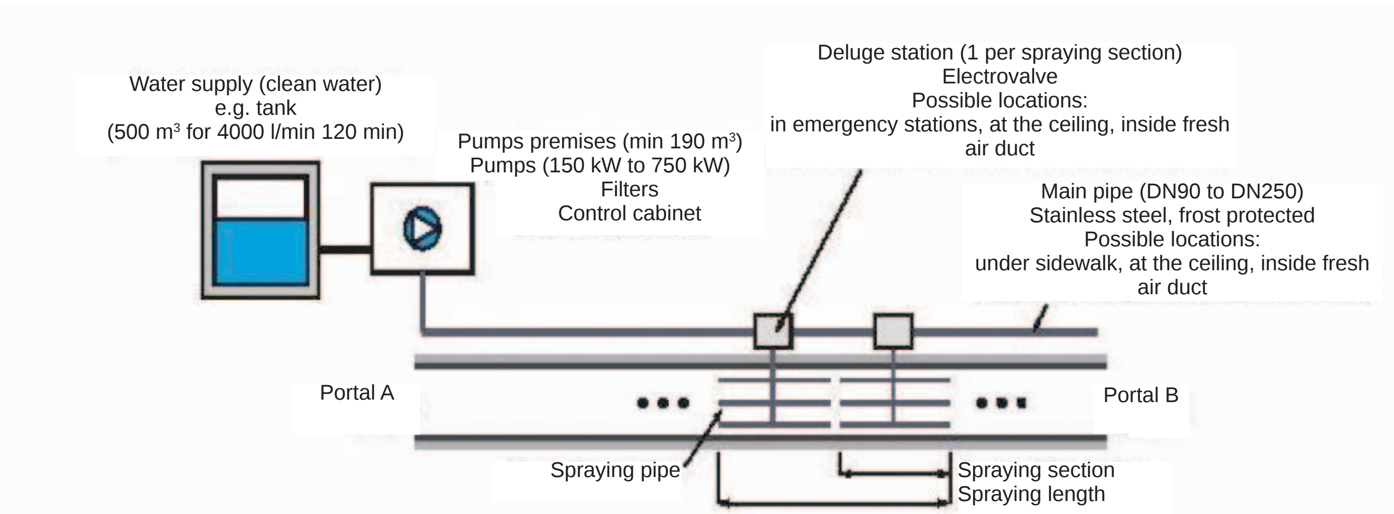

Figure 2: Typical architecture of a water mist-based FFFS and relevant equipments in a tunnel

2.5 MAINTENANCE OF A WATER MIST SYSTEM IN A TUNNEL

The maintenance operations required on water mist-based FFFS in tunnels are relatively similar to those expected for sprinkler systems in buildings. The most important ones are described in good detail in US NFPA 13[4], 15[5] and 750 standards. Among these, the most essential are:

- **monthly basis:**
  - checking that the pumps start properly
  - inspecting visually the equipment in the pump room

- **one to two times a year:**
  - testing the pumps (flow rate, pressure)
  - testing the alarms
  - inspecting visually the condition of piping
  - checking the deluge vanes
  - checking visually the structure of the spray jets
  - checking filters

- **every 5 years maximum:**
  - replacing joints and filters

Ensuring that the nozzles are not blocked up by dirt in a tunnel environment is an important element of the maintenance of a water mist system. Some manufacturers suggest that the nozzles be protected by removable caps which would be expelled by the water pressure at system activation. This solution implies an additional maintenance operation: refitting the caps to the nozzle after each activation. Other manufacturers think it is possible not to use these caps for high-pressure water mist systems, which would wash away dirt particles when they are activated. They are performing experimental studies on the obstructing of nozzles by dirt; the results are not available yet.

Other small-diameter parts of the tunnel may also be prone to obstructing by dirt particles in the water. It is important to maintain the filters carefully to avoid this phenomenon.

The maintenance cost of a water mist-based FFFS is estimated at € 40,000 per km of tunnel and per year [8]. This figure does not include the cost related to closing the tunnel for certain maintenance operations. This cost may be significant in the case of toll roads.

4 : NFPA 13 - standard for the installation of sprinkler systems, 2007 edition. / **5 :** NFPA 15 - standard for water spray fixed systems for fire protection, 2007 edition.

3

EFFECTS OF A FIXED FIRE-FIGHTING SYSTEM

3.1 TEMPERATURE AND RADIATION

3.1.1 Reduction of gas temperature

Spraying water mist droplets has an unquestionable reducing effect on the gas temperature (see fig. 3). This phenomenon was observed in all fire tests with water mist (see [4][5][10]). This decrease is essentially related to the heat transfer between the hot smoke and the droplets which, when they vaporise, absorb a part of the convected energy. The temperature can be further decreased through the decrease in the heat release rate of the fire under the action of the water mist (see section 3.2).

The activation of a water mist system inevitably causes homogeneisation of the gas temperatures over the whole height of the tunnel. It causes smoke destratification in the activated spraying section(s), due to smoke cooling, downward entrainment of smoke particles by the droplets and increase in turbulence. However, this change in the temperature profile does not seem to increase the temperature in the lower part of the tunnel.

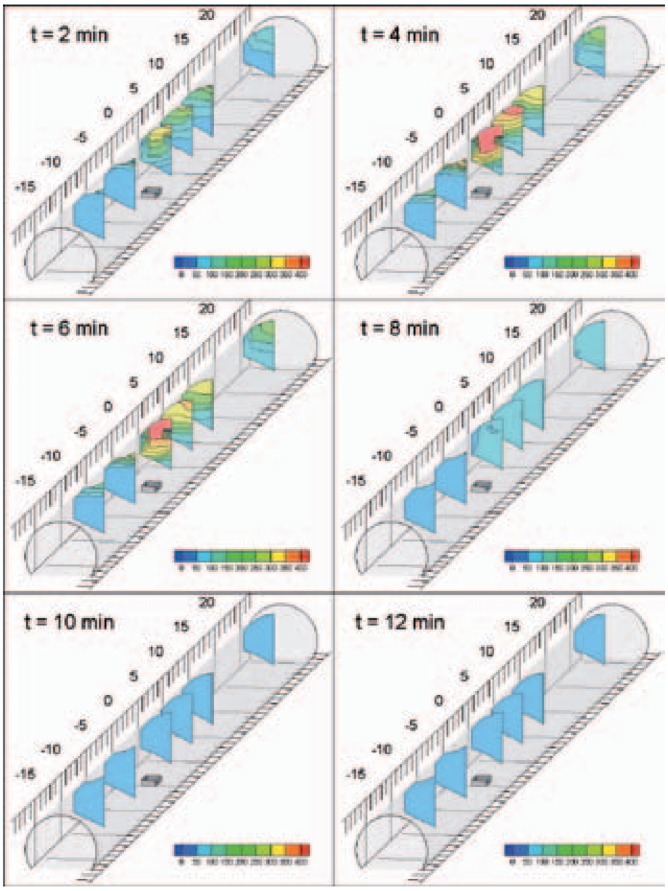

Figure 3: Temperature fields in the 1:3 scale model for a pool fire corresponding to 30 MW at 1:1 scale. Activation time of water mist is 5 minutes [10]

Along with this decrease in temperature under the action of a water mist-based FFFS, an increase in the relative humidity of air is observed. The presence of large amounts of water in the atmosphere affects the tenability conditions in the tunnel. Indeed, the risk of skin or respiratory system burns appears when the temperature exceeds 80°C when the air is saturated with water, the limit being 120°C for dry air. With saturated air, a temperature of 60°C remains nonetheless tenable for about 30 minutes.

3.1.2 Radiation attenuation

The water mist also has an indisputable effect on radiation, which is strongly attenuated. Indeed, spraying droplets creates a screen to the radiant heat flux from the fire, characterised by the absorption of a part of the radiant energy by water droplets. This part is maximum for wavelengths close to the diameter of the droplet[6].

Measurements performed during the fire tests in Hagerbach for the A86 tunnel [5] 10 m downwind of the fire show that the total heat flux (radiant + convective), decreases under the action of a water mist (see fig. 4).

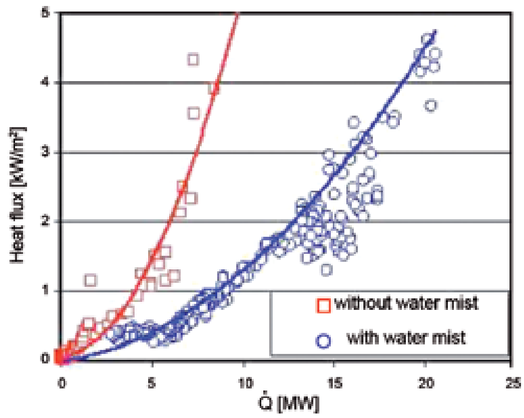

Figure 4: Example of comparison of radiative heat fluxes with and without water mist [5]

6 : for a radiative black body at 1300 K, the wavelength of maximum energy is around 2 µm.

3.1.3 Fire spread

The limitation of fire spread is another important effect of a water mist-based FFFS.

The decrease in radiant heat flux, along with the decrease in gas temperature, reduces the risk of fire spread from one vehicle to another. This effect is unquestionable in the case of a solid fire, but more doubtful for a liquid fire, for which a risk of spread may exist, for example in a sloping urban tunnel. Spraying water onto burning hydrocarbons might indeed increase the quantity of liquid running on the pavement and create a risk of fire spread to another vehicle.

3.2 HEAT RELEASE RATE OF A FIRE

The effectiveness of a water mist-based FFFS to limit the heat release rate of a fire varies depending on the fuel type (liquid or solid), and the confinement of the fire.

3.2.1 Open liquid fire

When the fuel is liquid and the fire is not hidden, the water mist can cause a 50% decrease in the heat release rate of the fire, as shown by the tests performed in the framework of the UPTUN project (see fig. 5).

The main phenomena explaining this decrease are known and can be modelled:

- heat absorption by the droplets when they vaporise in the flame,
- decrease in the incident heat flux on the fuel surface from the flame,
- decrease in the vaporisation rate of the fuel, which is proportional to the heat release rate.

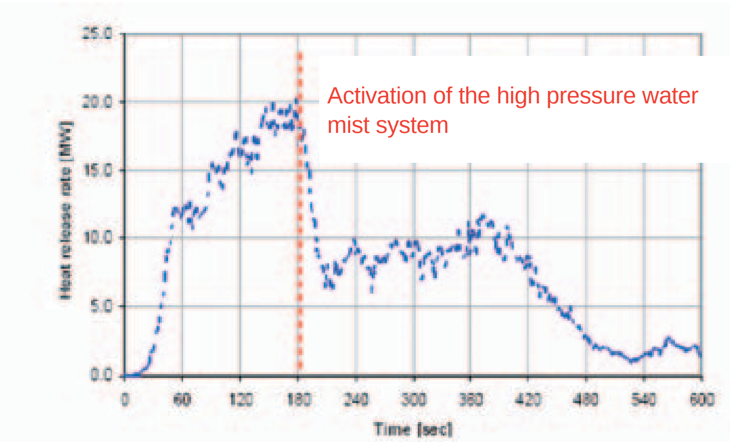

Figure 5: Example of the impact of a water mist-based FFFS on the heat release rate of a fire consisting of three heptane pools [4]

The complexity of secondary phenomena makes their modelling difficult. For example, when a droplet vaporises in the flame, the volume occupied by water vapor is much larger than the volume of the droplet. This expansion generates a small depression within the flame, which increases the entrainment of oxygen and somewhat increases the heat release rate. This effect can be observed mostly just after the activation of the system, but rapidly becomes stable.

3.2.2 Open solid fire

When the fuel is solid, combustible gases are not generated by the vaporisation of the fuel but through the pyrolysis of the organic compounds in the solid. These compounds are generally made of polymer molecules (plastics, rubber, wood, etc.). Under the action of heat, the polymer chain is broken and volatile molecules are released. They are burnt when they come in contact with oxygen in the air.

In the case of a liquid fuel, the production of combustible gases is due to the incident heat flux on the surface of the combustible from the flame, wheras for a solid fuel it is due to the temperature of the solid, which in turn also depends on the incident heat flux, but also on the heat transfer within the solid. The water mist reduces the incident heat flux from the flame, as it does for a liquid fire, but since almost all droplets are vaporised before they reach the fuel surface, they do not reduce significantly the temperature within the solid. The water mist is therefore less efficient at reducing the pyrolysis phenomenon of solids than it is at reducing the vaporisation of liquids.

Pyrolysis is a physical and chemical degradation of the solid; it is very difficult to model because of its complexity. The assessment of the decrease in heat release rate of an open solid fire under the action of a water mist is therefore delicate. It can be done only by performing tests on calibrated open solid fires with and without FFFS.

3.2.3 Hidden liquid or solid fire

Partial or total confinement of a fire, be it solid or liquid:

- prevents the water from reaching the fuel surface,
- limits the decrease in the incident heat flux on the fuel surface caused by the water mist

The first effect is more important for sprinkler systems because, in the case of the water mist, almost all droplets are vaporised before they reach the vicinity of the fuel surface.

The second effect has a significant impact on the heat release rate through the incident heat flux from the flame onto the fuel surface. Indeed, the water mist cannot act on the whole flame, but only on the parts that are accessible to the droplets, where the heat flux is locally reduced. Although the incident heat flux from the flames decreases at places, the fact that the combustible surface is hidden limits this influence. The heat release rate of the fire is therefore not as significantly reduced as for an open fire.

The impact of a water mist on the heat release rate for a hidden fire, regardless of the fuel type, remains therefore difficult to quantify.

3.3 GAS TOXICITY

The production of toxic gases by a fire is a function of its heat release rate, the ventilation conditions (oxygen supply) and the nature of the fuel. The production of carbon dioxide (CO_2) depends almost exclusively on the heat release rate, whereas that of carbon monoxide (CO) and nitrogen oxides (NO_x) also depend on the vaporisation rate of the fuel, which is related to the fuel type and the oxygen (O_2) supply.

Thus, the use of a water mist system causes a decrease in the CO_2 production caused by the combustion reaction. This decrease is difficult to quantify because it is related to the decrease in heat release rate, which is itself difficult to assess. The qualitative and quantitative assessment of the effect of a water mist on CO and NO_x production is even more difficult.

Moreover, these gases are hardly soluble in water under the temperature and pressure conditions encoutered in fires. The Hagerbach tests [5] have confirmed that they were not diluted under the action of a water mist-based FFFS. Yet, other toxic gases may be released by the fire, for example hydrogen chloride (HCl), sulphur dioxide (SO_2) or hydrogen cyanide (HCN), which are very easily soluble in water. The dissolution of these gases may form hydrochloric acid, sulphuric acid or cyanhydric acid. The analysis of the water on the pavement after the water mist tests in Hagerbach showed a pH of about 2. Current knowledge does not allow a quantification of these phenomena under the temperature and pressure conditions corresponding to a fire.

Finally, the destratification of smoke due to the activation of a water mist system causes an increase in toxic gas concentrations at user level and is therefore harmful to the users during the self-evacuation phase.

3.4 VISIBILITY CONDITIONS

In the presence of smoke, the visibility conditions may be strongly deteriorated in the lower part of the tunnel under the action of a water mist system. This is due to the destratification of smoke in the activated spraying section(s), as shown by the measurements performed on the scale model [10] (see fig. 6).

The visibility conditions depend on the concentration of soot particles and water mist droplets in air, the size of the droplets, and the lighting of the tunnel. This last parameter has not been investigated so far. The possible scrubbing of soot by the water mist is difficult to quantify. It is indeed very uneasy to measure and to model because of the wide range of soot particle and droplet diameters, which depend on the fuel and the nozzle design, respectively. The decrease in visibility caused by the presence of water mist droplets in the air is also difficult to measure and model. Furthermore, the water vapor generated in the vicinity of the fire may condensate downwind of the fire and generate fog.

In the absence of smoke, the visibility conditions are also deteriorated by the activation of a water mist-based FFFS but this does not prevent the tunnel users from evacuating on their own.

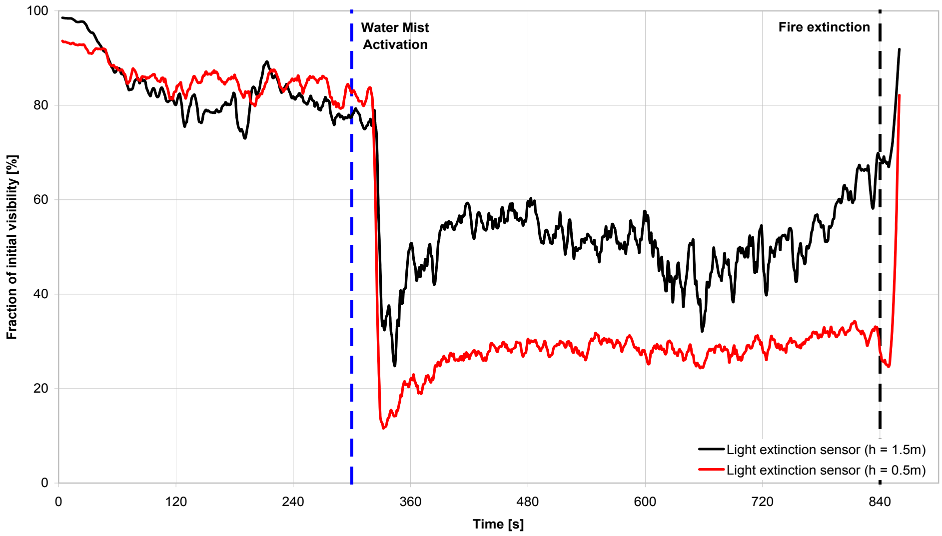

Figure 6: Example of the effect of a water mist-based FFFS on visibility [10]

3.5 FFFS EFFECTS SUMMARY

According to current knowledge, the effects of a water mist-based FFFS on the ambient conditions in a tunnel can be summarised as follows.

	certain improvement	probable improvement	uncertain effect	no effect	certain deterioration
temperature and radiation	decrease in temperature and radiant heat flux *				decrease in the tenability limit for temperature due to increased air humidity
fire spread	limitation of fire spread (solid fuel)		limitation of fire spread (liquid fire in sloping tunnel)		
heat release rate of the fire		decrease in heat release rate **			
gas toxicity		decrease in toxic gas emissions **	risk of acid generation	scrubbing of toxic gases	loss of stratification if initially present
visibility				scrubbing of soot	limited decrease in visibility when no smoke is present loss of stratification if initially present

* but the temperature profile is modified
** do not seem sufficient to ensure tenability in smoke in all cases

Table 4: Effects of a water mist-based FFFS on the environment conditions in a tunnel according to current knowledge

4 PROVISIONAL ELEMENTS FOR ASSESSING THE USE OF WATER MIST-BASED FIXED FIRE-FIGHTING SYSTEMS IN A ROAD TUNNEL

4.1 OBJECTIVES AND ACTIVATION CONDITIONS

Two types of objectives (which can be both relevant for a given case) may lead to considering the installation of a water mist-based FFFS:

- The FFFS may be regarded as a means to fulfill regulatory prescriptions (such as those mentioned in [13] for France), according to the hypotheses and objectives underlying the regulations. Thus, the purpose of installing a FFFS may be to compensate for the insufficient performance of other safety measures which, for example, would raise important feasibility, operational or even financial issues. Another purpose may be to tackle issues which are not related to life safety, for example the protection of the infrastructure to limit the damage in case of fire, thus reducing the duration and cost of repair. In all cases, it is necessary to make sure that the installation of a FFFS does not harm the safety level of the tunnel. This topic is dealt with in more detail in section 4.1.1.
- The installation of a FFFS may also aim at raising the safety level of a tunnel beyond the regulatory prescriptions, in order to handle more severe situations than the normal design cases. This second type of objective is the subject of section 4.1.2.

In all cases, the effects of spraying regarding safety depend strongly on the time when the system is activated. This will be overlooked in section 4.1.3 and will be adressed in the analysis developped in the rest of this chapter (section 4.2 and following).

4.1.1 Reach the prescribed safety level

Through its action, a water mist-based FFFS can improve, but also deteriorate some of the ambient conditions in a tunnel during a fire (see tab. 4). It is therefore necessary, before any installation, to balance the favourable and undesired effects of such a system, taking into account the other safety elements present in the tunnel. One should analyse the capacity of the system, as an element of an integrated safety system, to improve the fulfillment of the safety objectives, namely (see section 1.1.2):

- to allow self-evacuation of the users,
- to allow survival until the arrival of rescue services for people who were not able to evacuate by themselves,
- to ease the action of rescue services in order to, on the one hand, help users evacuate the tunnel, and on the other hand, fight the fire,
- to protect the infrastructure.

The possibility of installing a water mist-based FFFS as a complement to the other safety elements, or even as a compensation for the insufficient performance of some of these elements, may therefore not be analysed without assessing the consequences of its activation on the life safety strategies, which strongly depend on the smoke control strategy and the type of traffic in the tunnel. Hence, the analysis of the interaction between such a system and the ventilation system is the cornerstone of this assessment, which should be performed in the framework of a global approach to tunnel safety.

4.1.2 Increase the robustness of the system

The installation of a water mist-based FFFS may also be considered in order to raise the safety level of the tunnel. Of course, it is necessary not to decrease the safety level, at the very least as described in section 4.1.1. The decision must be based on an analysis integrating the particular situations or events in which the safety strategies are caught out; these situations are beyond the design cases prescribed by the regulations ([13] for France).

Indeed, in the absence of a FFFS, fire safety depends essentially on the smoke control strategy. This can be either a longitudinal or a transverse strategy. Both of these systems may be inefficient in particular situations.

The transverse strategy relies on the capacity to limit the longitudinal air flow to keep the smoke as stratified as possible and extract them through the ceiling, thus tending to create acceptable conditions underneath the smoke layer. However, this strategy is caught out in cases where the heat release rate of the fire exceeds that of the design fires, or the pressure difference between the portals exceeds the dimensioning value:

- In the first case, the volume of smoke to be extracted is such that, despite the use of ventilation devices to extract it through the ceiling, smoke is accumulated in the whole cross-section of the tunnel and spreads to adjacent zones.
- In the second case, the impossibility of controlling the longitudinal air flow makes it difficult to keep the smoke stratified in the extraction zone. More importantly, the smoke is no longer confined within this zone and spreads rapidly along the tunnel, generally destratified.

The longitudinal strategy consists in pushing all the smoke toward one end of the tunnel, ensuring good conditions on the other side of the fire. But this strategy is caught out if the traffic is blocked downwind of the fire because of a traffic incident, accident or congestion. In this case, the smoke control strategy exposes the users downwind of the fire to high temperatures and toxic gases due to the fire.

4.1.3 Activation conditions

The analysis performed to assess the interest of installing a FFFS in a tunnel must tackle the crucial issue of the activation conditions of the system. The system can be activated:

- as soon as the fire is detected,
- after the rescue services have arrived,
- after all the users have left the tunnel, with or without the help of the rescue services.

Depending on the chosen activation time, the use of the FFFS may or may not modify the self-evacuation conditions, the survival conditions or the intervention conditions for the rescue services. In all cases, its use helps limiting the damage to the infrastructure by reducing the thermal solicitation; the earlier the activation, the better this effect.

In order to determine the activation time of the FFFS, one must therefore analyse its effect on the strategy of the rescue services, and more importantly on the strategy used to help the users get out of the tunnel safely. These strategies are based on a two-phase safety process:

- the self-evacuation phase, whose objective is to protect the users' lives when they are on their own in the tunnel,
- the intervention phase, whose main objective is to help save the people who are still in the tunnel before fighting the fire.

The duration of each phase depends on the time needed for the rescue services to arrive, but also on the tenability conditions inside the tunnel for users and firemen. The different tenability times are presented on figure 7.

The following paragraphs examine the effect of a water mist system depending on the moment when it is activated.

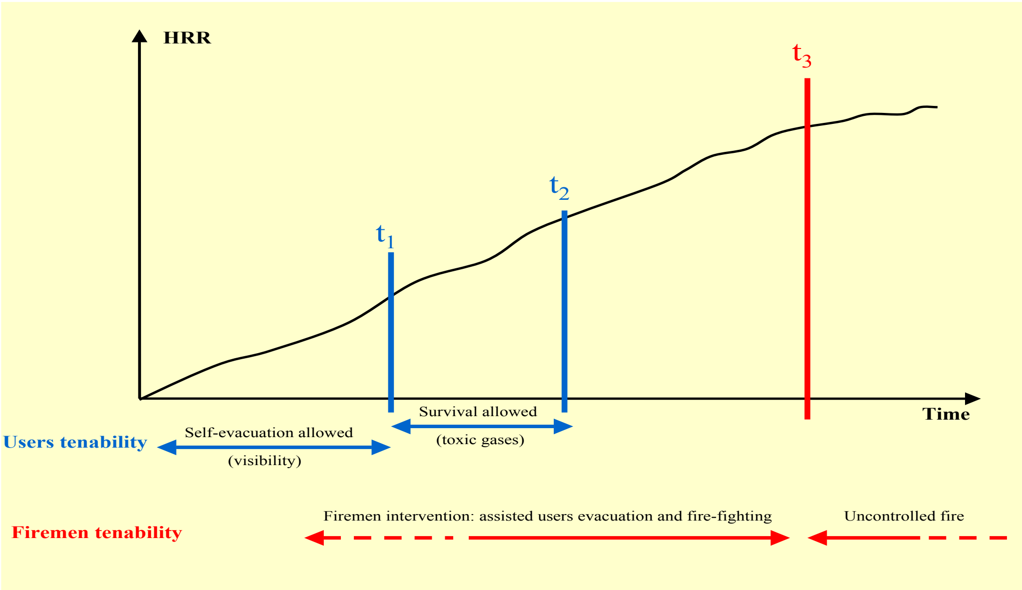

Figure 7: Successive tenability durations representing the ability of human beings to bear unsuitable ambient conditions

4.2 EFFECTS OF SYSTEM ACTIVATION DURING THE SELF-EVACUATION PHASE

The self-evacuation phase begins as soon as the fire is no longer controllable by the users themselves or the operation personnel, and ends when the rescue services arrive.

During this phase, it is crucial to have good visibility conditions for the users to see where the emergency exits are and to evacuate the tunnel (see tab. 1). To this end, the smoke control strategy aim at either favour smoke stratification or push the smoke in the traffic direction toward the end of the tunnel. In the absence of a water-based FFFS, these strategies fulfill the objective of preserving correct visibility as long as the situation remains within the limits of the design scenarios (see section 4.1.2). Indeed, beyond these limits, there may be situations where users find themselves in areas entirely filled with smoke and therefore have limited self-evacuation capacity.

Thus, three self-evacuation scenarios can be distinguished, depending on smoke control strategy:

- the users evacuate in smoke-free zones only,
- the users evacuate under a stratified smoke layer,
- the users evacuate in zones where smoke fills the entire cross-section of the tunnel.

4.2.1 Activation in smoke-free zones

In smoke-free zones, the activation of the water mist slightly deteriorates the visibility conditions in the spraying zone, without making self-evacuation impossible.

4.2.2 Activation in zones with a stratified smoke layer

Users in the spraying zone

In zones where the smoke is stratified, the water mist causes the destratification of smoke, which strongly deteriorates the visibility conditions.

This adds to the deterioration of the tenability conditions for the users since the destratification of smoke increases the concentration of toxic gases at head height. This negative effect should be counterbalanced by a decrease in toxic gas production by the fire, but this remains uncertain in the current state of knowledge.

However, even if the homogenisation of temperatures (related to the destratification of smoke) modifies the temperature at head height, experiments tend to show that the temperature remains tenable for the users, despite a high relative humidity.

Furthermore, in the case of a transverse smoke control strategy, the destratification of smoke related to the downward motion of water mist droplets makes the extraction of smoke more difficult in the spraying zone. As a counterpart, the quantity of smoke is likely to be less due to the descrease in temperature and fire heat release rate.

Generally speaking, the self-evacuation conditions for the users in the spraying zone seem to be deteriorated.

Users outside the spraying zone

For the reasons detailed in section 2.3, the length of the spraying zone is 100 to 150 m, whereas in a transverse ventilation system, the extraction zone is often longer (for exemple, up to 200 m for reduced-height urban tunnels, 400 m for urban tunnels and 600 m for non-urban tunnels, according to the French regulations). This difference raises the issue of the effect of water mist activation on the self-evacuation conditions for users who are outside the spraying zone. Two different cases should be considered:

- the smoke is confined within the extraction zone and stratified, thanks to a very weak longitudinal air flow at the fire location,
- the smoke is not confined but remaisn stratified over a certain distance.

• Case 1: confined smoke

This corresponds to a situation in which the velocity of the longitudinal air flow is almost zero at the fire location (see fig. 8), either because the pressure difference between the portals is weak or because an efficient air flow control system has been installed.

When a water mist-based FFFS is activated in such a situation, the vaporisation of water reduces considerably the air temperature in the spraying zone (see zone A on fig. 8). Experiments seem to show that smoke destratification does not occur outside the spraying zone in this case.

Indeed, the decrease in temperature in the spraying zone reduces significantly the “driving force” and volume flux of smoke. Its density remains less than the ambient air density. If the difference is large enough, the smoke may spread outside the spraying area as stratified layers (zone B, fig. 8). The thickness of those layers would probably be less than without spraying.

The spraying of unvaporised water might also contribute, by its dynamic effect, to the limitation of smoke spread beyond the spraying zone.

The self-evacuation conditions outside the spraying area are therefore probably improved.

• Case 2: unconfined smoke

This case often takes place in tunnels with transverse ventilation, but with a longitudinal air flow which is insufficiently controlled and entrains the smoke beyond the extraction zone (situation described by figure 9). On one side of the extraction zone, there exists a relatively strong air flow (to the left of the figure) directed toward the fire. At the other end, the longitudinal air flow is either in the same direction or directed toward the fire, but too weak to confine the smoke. This case may also appear when a longitudinal ventilation system is used at a reduced regime, for example in case of congestion downwind. In this situation, the longitudinal air flow has the same direction everywhere in the tunnel.

As in the previous case, the activation of a water mist-based FFFS tends to reduce the volume flux of smoke “feeding” the smoke layer outside the spraying zone (see zones B and C on fig. 9). However, unlike the previous case, the longitudinal air flow entrains destratified smoke toward the exit of the tunnel. If no change in the direction of the longitudinal air flow occurs (middle sketch of figure 9), the stratification of smoke which has been destroyed by spraying cannot be recovered downwind. The smoke is then entrained toward the portal and fills the whole cross-section.

If the direction of the longitudinal air flow changes (bottom sketch of figure 9), a variable level of stratification may reappear, provided the air flow inversion is sufficiently marked and stable. However, this phenomenon and the conditions for its existence are difficult to quantify. The activation of a spraying system may also help obtain the confinement of smoke because the driving force of smoke is reduced and so is the minimal air velocity required for smoke confinement.

Users who found themselves under the stratified smoke layer before the activation of the water mist (see zone B, fig. 9) probably experience a deterioration of their visibility conditions and an increase in toxicity of the gases they breathe during self-evacuation. The toxicity level should be limited by the decrease in toxic gas production by the fire, which remains uncertain.

The situation is quite different for users located further downwind of the fire, in zones where the smoke was already destratified before the system was activated (see zone C, fig. 9). After the activation, the situation may evolve in different ways depending on the quality of the longitudinal air flow control: the smoke may re-stratify to a variable extent, or even disappear completely from the zone; it may also remain destratified.

In the first case, the self-evacuation conditions get better. In the second case, the water mist effects is similar to the one described further in section 4.2.3 for a destratified smoke layer (case a).

Conclusion from the users’ point of view

Activating a FFFS in the presence of stratified smoke as soon as the fire is detected, during the self-evacuation phase, may or may not cause deterioration of the self-evacuation conditions depending on the the users’ location and the fire situation.

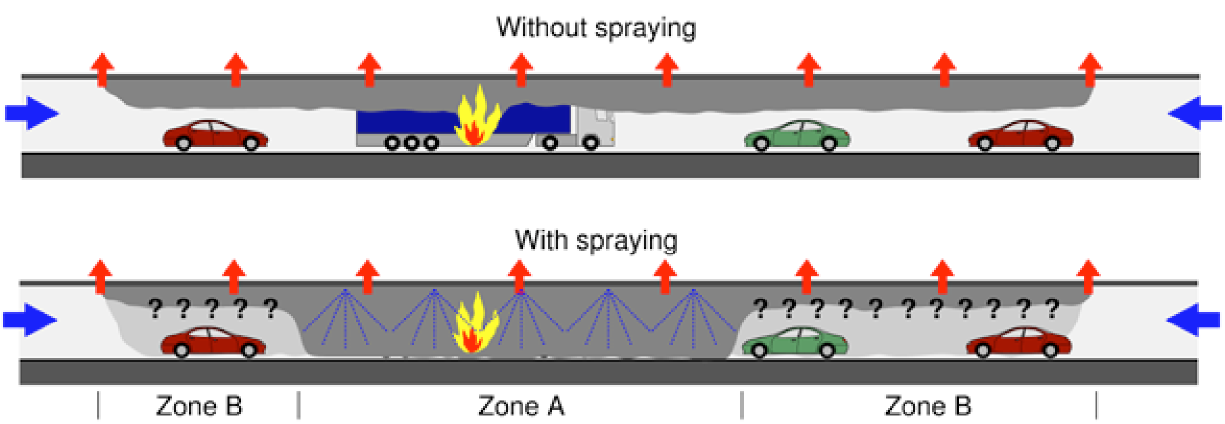

Figure 8: Stratified and confined smoke

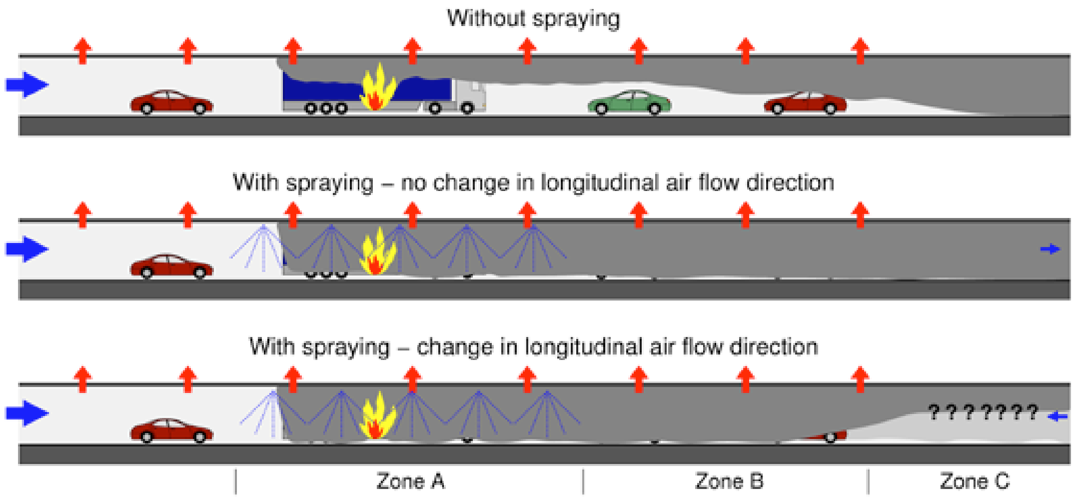

Figure 9: Unconfined smoke with stratification in the fire zone

This deterioration is certain for those users who find themselves in the spraying zone. It is more difficult to assess for users who are outside this zone. Indeed, the deterioration of their self-evacuation conditions seems to depend essentially on the existence of an uncontrolled longitudinal air flow.

4.2.3 Activation in zones with destratified smoke

When a water mist-based FFFS is activated in a zone where smoke is not stratified, they remain of course destratified.

Outside the spraying zone, smoke may be present under one or both of the following conditions:

- **a.** The longitudinal air flow pushes the smoke out of the spraying zone. This is systematically the case for longitudinal ventilation because there is no other way out for the smoke. This can also happen with transverse ventilation if the longitudinal air flow control is not sufficient. In this case, the visibility conditions outside the spraying zone are not modified by the spraying upwind and remain bad. The smoke remains destratified.
- **b.** The heat release rate of the fire exceeds the design value for a transverse ventilation system. Then, the smoke extraction capacity may not be sufficient despite the decrease in the fire heat release rate and the limitation of fire spread under the action of the water mist. Part of the smoke then spreads beyond the spraying zone. If the longitudinal air flow velocity is close to zero at the fire location, a restratification of smoke may occur outside the spraying zone. This would improve the visibility conditions outside the spraying zone. However, in the current state of knowledge, it is impossible to know whether this phenomenon actually occurs in practice and under which conditions. If restratification does not occur, the situation is similar to the previous case.

In the absence of good visibility conditions, the important parameters for users who try to evacuate or wait for the rescue services are the tenability conditions, especially the toxicity of gases. In such cases, water mist systems seem capable of reducing gas temperatures to an acceptable level despite the high humidity. Moreover, provided it reduces significantly the production of toxic gases,water mist spraying certainly improves and prolongs the tenability conditions for users inside and outside the spraying zone alike.

4.2.4 Summary

The decision of activating a water mist-based FFFS during the self-evacuation phase is extremely delicate because it must take into account the level of smoke stratification at the time of fire detection, and the smoke control strategy. Indeed, by examining every possible situation, we have shown that depending on the users' location and the stratification of smoke, the self-evacuation conditions may be improved, deteriorated or remain unchanged after the activation of the FFFS. Unfortunately, the operator is generally incapable of knowing the exact state of the smoke when the fire is detected, which would be crucial to assess the opportunity of activating the system during the self-evacuation phase.

Moreover, one of the issues in this phase is to let users know they have to evacuate, in particular those users who have no physical perception of the fire and the related risks. One can therefore wonder what the users' reaction would be when the system is activated. Spraying might lead them into thinking that the situation is dangerous and they must leave their vehicle, or that the fire should soon be out or under control thanks to spraying. The discomfort of being under the water mist might also deter them from getting out of their vehicles. In the absence of knowledge about the users' behaviour in such a situation, the question remains open.

For all these reasons and in the current state of knowledge, it does not seem judicious to activate a water mist-based FFFS during the self-evacuation phase for tunnels with a transverse ventilation system, in which the smoke control strategy consists in favouring smoke stratification. This applies if the arrival of firefighters is quick enough (10 to 15 minutes). If the self-evacuation phase is longer, the FFFS could be activated because the visibility conditions are very likely to become insufficient and the risk of a very quick deterioration of the tenability conditions becomes very high. The system could also be activated earlier if it turned out that the fire size or the pressure difference between the portals make the conditions untenable in the tunnel before the fire-fighters' arrival.

The conclusion is identical for tunnels with a longitudinal ventilation system operated in two phases when the traffic is congested – first the longitudinal air flow is set at a small velocity in order to keep the smoke somewhat stratified, then the velocity is increased to ease fire brigade intervention. For this kind of tunnels, the FFFS activation could be decided before the arrival of the rescue services if it is clear that the tenability conditions are no more satisfied.

On the contrary, for tunnels with a longitudinal ventilation system operated in a single phase, the FFFS may in theory be activated as soon as the fire is detected. This would improve the tenability conditions for users who would be stuck downwind of the fire due to an accident or a similar event.

4.3 EFFECTS OF SYSTEM ACTIVATION DURING THE INTERVENTION OF RESCUE SERVICES

The phase of rescue service intervention begins upon their arrival at the fire site. It consists in two stages which may, depending on the circumstances, be simultaneous:

- assisted evacuation,
- fire fighting.

4.3.1 Activation to help the users evacuate

When they arrive, the rescue services' priority is to help the users who are still in the tunnel. The self-evacuation phase ends at this time, but the visibility condition may still be suitable for the self-evacuation to continue (see fig. 7).

If they are, the acrivation of the spraying system may then deteriorate, improve, or not modify the conditions for ongoing evacuation. However, unlike in the self-evacuation phase, the rescue personnel can try to assess the stratification of smoke and the opportunity of activating the water mist system.

In the case of insufficient visibility conditions, the tenability conditions become essential for the survival of users who cannot evacuate on their own. The activation of a water mist system may then be favourable because it probably can lower the toxicity of inhalated gases by reducing the emission of toxic gases by the fire, and almost certainly bring the temperature down to an acceptable level despite the high humidity. These effects are also favourable to the rescue services and can ease their action in assisting the users.

In such situations, the rescue services could therefore request activation of the FFFS, if there is one.

4.3.2 Activation after the evacuation of all users

The ability of firemen to fight a fire depends essentially on the temperature and radiation level which, if they are too high, prevent them from approaching the fire. Indeed, they are used to moving without visibility and are equipped with breathing apparatus which protect them from toxic gases, even though their action is obviously easier with good visibility and a breathable atmosphere.

The activation of a water mist system after all tunnel users have been evacuated can indisputably ease fire fighting since it reduces the gas temperature, the radiation level, the heat release rate and the spread of the fire.

4.3.3 Summary

The activation of a water mist-based FFFS during the intervention of rescue services can ease their action, but the activation time must be carefully chosen. The decision must be made by the rescue services.

Indeed, even if the priority for the fire brigade is to assist the users who are still in the tunnel, they generally start fighting the fire at the same time. Activating the FFFS immediately after their arrival might make the evacuation of valid users more difficult, in the case where the visibility is still sufficient for self-evacuation. In the opposite case, the activation of a water mist is helpful to the rescue services because it prolonges the tenability for tunnel users and firemen alike.

For tunnels with a longitudinal ventilation system operated in a single phase, section 4.2.4 states that the FFFS, if it exists, may theoretically be activated as soon as the fire is detected. It may, to greater reason, be activated after the arrival of rescue services if this has not been done before.

4.4 INFRASTRUCTURE PROTECTION

Through its action on temperature, radiation, heat release rate and fire spread, a water mist-based FFFS reduces the heating of the tunnel structure. Early activation of the system makes the system more effective regarding the protection of the structure.

However, its activation must not compromise the fulfillment of the objectives of the life safety strategy (self-evacuation and assisted evacuation of the users). The protection of the infrastructure is generally not a safety objective, or at least, not the most important one. The activation criteria related to the safety of users or rescue personnel must prevail over those linked to the protection of the infrastructure.

4.4.1 Single-phase longitudinal ventilation

For tunnels with a longitudinal ventilation system operated in a single phase in case of fire, the activation of the water mist immediately after the fire has been detected is compatible with the safty objectives.

4.4.2 Transverse or two-phase longitudinal ventilation

In tunnels where transverse ventilation is used, or where a longitudinal system is operated in two phases in case of fire, the immediate activation of a water mist system does not seem likely to improve the fulfillment if the safety objectives in all fire situations. The difficulty of qualifying the fire situation, especially the stratification of smoke, as soon as the operator has detected the fire, requires particular caution before taking the risk of activating a spraying system during the self-evacuation phase. The same caution may be required during the first minutes of the intervention of rescue services to allow localisation of the users who would still be inside the tunnel. This latency, which is necessary to fulfill the life safety objectives, requires the system have a certain resistance to fire, so it remains functional if the temperature increases strongly before activation.

4.4.3 Level of protection from a water mist-based FFFS

Even though a water mist-based FFFS represents a significant protection of the tunnel infrastructure, it does not have the same reliability as passive protection. It cannot therefore be regarded as an alternative to passive protection in zones which must be protected to fulfill regulatory requirements. To be such an alternative, one should guarantee that the system can be fully operational at any time, which is not easy; this would require extremely careful maintenance and frequent tests. Indeed, the system may face several types of malfunctions, such as the breakdown of a pump or vane, the deterioration of wall-mounted elements due to vehicle impacts, the obstruction of nozzles by dirt, freezing, etc. It is also necessary to ensure good localisation of the fire and adequate activation of the spraying system, which means a perfectly functional detection system and adequate reaction of the operator. If the spraying system has an essential role regarding safety in the tunnel, in case of breakdown, the impact on the tunnel operation may be serious and the operator may have to close the tunnel depending on the minimal operation conditions.

CONCLUSION

The possible use of fixed fire-fighting systems (FFFS) in tunnels, especially water mist-based FFFS, raises a strong interest because of the additional safety they could provide.

As shown by the present document, the architecture of such systems can be defined quite precisely, even if their sizing needs to be adjusted through real-scale tests. However, their effects on the various parameters of a tunnel fire are known with variable accuracy. For example, the reduction of gas temperatures and solid fire spread are certain, whereas the effect on the heat release rate of a hidden fire, and more importantly on the production of toxic gases, remain difficult to quantify. Moreover, some effects of water spraying may be either favourable or unfavourable depending on the circumstances.

These are the reasons why analysis elements have been provided in order to analyse more globally the effects of water mist spraying on smoke, depending on its stratification, the ventilation situation and the time of activation of the system. These elements are incomplete and often uncertain due to the limitations of current knowledge. They are only partial elements which must be taken into consideration in the framework of a global assessment.

Therefore, the effectiveness of a water mist-based FFFS in a tunnel must be assessed on a case-by-case basis, in the framework of a global analysis of the safety system of the tunnel. All characteristics and equipment of the tunnel should be taken into account, as well as its operational conditions. Such an approach requires a clear definition of the safety objectives and an appropriate choice of the time of activation of the FFFS. Due to the large uncertainties which remain in such studies, one should be cautious before making a decision.

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