Testing active fire protection systems for engine compartments in buses and coaches - a pilot study

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Fire Technology

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Abstract

This report forms the basis for the development of a test standard for fire suppression systems in engine compartments in buses and coaches. An introductory overview of recent statistics shows the need for and efficiency of such systems. This is followed by a detailed introduction to bus engine compartments, with emphasis on fire risks. A detailed review is also presented of current test methods which are similar to or partly overlap the field of application studied here, that is bus engine compartments. Based on these market and technology overviews one chapter is devoted to the identification of relevant parameters for consideration in the design of a final test method. Finally an outline of a test rig geometry is presented and discussed.

Key words: fire, bus, coach, engine compartment, fire suppression, test, standard

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Preface

This project was sponsored by the Norwegian Public Roads Administration and by the Swedish Transport Agency. Their financial support, as well as their participation in the work, is gratefully acknowledged.

Summary

In Sweden alone, an average of three fires in buses and coaches are reported each week. Most of these fires occur in the vehicle’s engine compartment. The engine compartment is often located at the rear of the bus or coach. This makes it difficult for the driver to discover a fire. Thus, the installation of an active fire protection system is an important safety measure. However, no international standard for establishing the performance of fire extinguishing systems in buses is currently available. The aim of this report is to create a basis for a method of testing extinguishing systems intended for bus engine compartments to ensure that adequate system performance can be established.

Fires may occur due to several different reasons. Some engine parts, e g manifold and turbocharger, may reach temperatures high enough to cause leaking fuel or oil to ignite. Fires may also occur due to electrical wiring short-circuits or overheating of engine components. The conditions in the engine compartment are challenging for any extinguishing system, e.g. ventilation fans in the engine compartment often produce high levels of airflow and many compartments have large openings. This can lead to efficient oxygen supply to a fire and the suppression agent may be rapidly removed with the air flow. Furthermore, bus engine compartments are often geometrically complex and/or very compact, making it difficult to ensure that extinguishing agents actually reach the fire source. Additionally, fuel and lubricants are not the only flammable materials present. Fires may also reach solids, like plastics, rubber and insulation materials. This complexity must be accurately simulated in any test method devised to evaluate the performance of extinguishing systems for engine compartments.

A method for testing fire suppression system in this complex environment also needs to be repeatable and reproducible, i.e. it must be possible to repeat at any time and in any place, while still yielding consistent results. The test must also be realistic and capable of simulating different scenarios. Additionally, it should be internationally applicable and must not erroneously qualify or disqualify any specific extinguishing agent.

The suggested method outlined in this report simulates warm and hot surfaces, an airflow-producing fan, a complex geometry as well as a range of fire sources. These components are placed in a test chamber with several apertures. The extinguishing system being tested is installed in the chamber, after which the fire sources are ignited, individually or in concert. Several different scenarios are set up and studied with various fire sources, airflow strengths, aperture sizes, and hot-surface temperatures, but with a fixed position of the system’s extinguisher nozzles for all test scenarios. The test results indicate the strengths and weaknesses of the system, as well as whether or not the minimum standard requirements have been met.

The process of developing a test method presents several challenges, the greatest being establishing a realistic degree of complexity assuring that an extinguishing system that passes the test will also be able to fight a real fire in a real engine compartment. Thus, finalizing the test design will require extensive trials and analyses.

Definitions used in the report

Auto-ignition temperature
Is the lowest temperature where ignition occurs spontaneously, without an external source of ignition, such as a flame or spark.

Class A fire
Fires in solid materials, mainly organic materials. Wood, textiles, rubber and some plastics belong in this category.

Class B fire
Fires in liquids. Typical examples are oil, diesel, and ethanol.

Class C fire
Fires in gases, such as in natural gas and biogas.

Flash point
Is the lowest temperature where the vapours from a liquid form an ignitable mixture in air.

Inerting
Use of an inert gas or vapor that prevents chemical reactions by limiting the oxygen concentration in order to extinguish flames. “Inert” in this sense means that the gas or vapor does not participate in chemical reactions.

Nozzles
The parts of the extinguishing system from which the extinguishing agent is discharged.

Rear of the engine compartment
In a vehicle with a rear-mounted engine this is the section of the compartment at the extreme rear of the bus, closest to the engine compartment door.

1 Introduction

Each year, a large number of fires occur in buses and coaches [1]. In 2009, a total of 153 bus/coach fires were reported in Sweden [2]. This equals an average of three fires per week. Figure 1 shows the increase in the number of reported fires since the end of the 1990’s. However, the statistics do not define the extent of the reported fires, i.e. they include everything from small self-extinguishing fires to cases where the fire has consumed the whole vehicle. Furthermore, the statistics do not distinguish between fires originating inside the cabin and those occurring outside, e.g. in the engine compartment, brakes, etc.

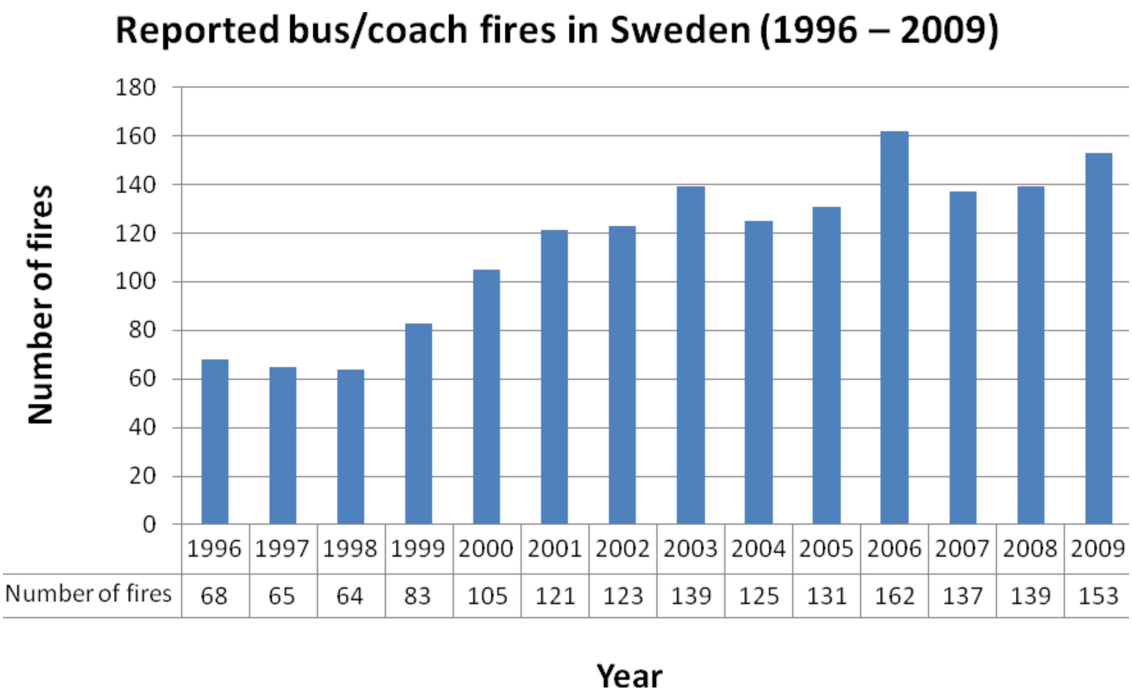

Figure 1 Reported bus/coach fires in Sweden 1996-2009 [1, 2].

Between 2000 and 2009, an average of 1 242 new buses/coaches entered the Swedish registry each year. During this period, an annual average of 13 710 such vehicles were in use, see Appendix 1. Based on this, the mean service life of a bus/coach in Sweden is assumed to be approximately 11 years.

During the period of 1999 to 2009, fires were reported in approximately 0.9% of Swedish buses/coaches annually. In 2009 alone, the figure was 1.1%. Taking the vehicles’ service life into account, fire has been reported in 10% of all buses and coaches based on the 1999 - 2009 statistics.

There is also an unknown number of unreported bus and coach fires. One reason is that certain larger bus/coach companies do not take out fire insurance with insurance companies, preferring to carry the risk themselves, thus lowering the incentive to report incidents. Also, fires in buses/coaches are a matter of some sensitivity, since recurring fire reports may worry passengers. The true number of bus and coach fires may therefore be significantly greater than reported. In an investigation carried out in 2006, the number of unreported fires was estimated to equal approximately two-thirds of the number of reported incidents[1].

A considerable proportion of the fires originate in the vehicle's engine compartment. The large number of bus/coach fires has several causes [1]:

1. More stringent demands for low noise levels have resulted in more widespread use of engine compartment insulation and encapsulation. Sound proofing may keep the noise in, but it also maintains high engine compartment temperatures.

2. Lowered permissible emission levels have resulted in increased service temperatures in some engine components, in order to increase the combustion efficiency of the engine.

3. Buses and coaches are heavily used and have little maintenance time. The average annual mileage of a Swedish bus or coach is almost three times that of a truck, resulting in high levels of engine wear.

A bus or coach is a public space accommodating a large number of people. A double-decker bus may hold up to 90 passengers, a large portion of which are often children or elderly. Disabled passengers are not uncommon. Walkers, prams and baggage may limit passage on emergency routes. In case of fire, the time available for evacuation is a critical factor, as fires sometimes occur and progress very rapidly [3]. A bus or coach fire in a road tunnel would aggravate the situation considerably. Poisonous gases may spread in the tunnel and chaotic traffic conditions may hinder road users when exiting the tunnel, potentially leading to catastrophic circumstances.

Despite the remarkably high number of bus and coach fires, personal injury is fortunately quite uncommon. On the other hand, the potential risk of a disastrous event is high. There are several international examples of bus/coach fires with fatal outcome in recent years, e.g. Wuxi, China in July 2010 (24 fatalities) [4], Uttar Pradesh in northern India in December 2008 (63 fatalities) [5], Hannover in Germany in November 2008 (20 fatalities) [6], and Wilmer, Texas, in September 2005 (23 fatalities) [7].

Given the fact that most fires start in the engine compartment, adequate active fire protection systems for engine compartment are advantageous both in terms of passenger safety, carrier company economy, and public resource management. Thus, various organisations have identified the installation of automated engine compartments extinguishers as an important fire-safety measure [8-11]. Furthermore, some insurance companies and individual carriers already require extinguishing systems in buses/coaches. In 2004, several Swedish insurance companies jointly made the installation of systems, compliant with the SBF 128 standard [12] mandatory for the insuring all new-build buses and coaches, resulting in a drastic reduction in the number of total losses due to fires in the engine compartment [13, 14]. However, there is still no legislative demand for this course of action, nor an international standard for testing automated bus engine-room extinguishing systems.

Definition of system performance is essential to ensure an acceptable level of safety. Without agreed criteria for system performance it is not possible to ensure that system installation in itself is a guarantee of safety. Indeed, it is possible that an extinguishing system could fail in a real fire incident and its presence may therefore create a false sense of safety. Thus, an international standard for comparative testing and verification of these systems is much needed.

This report is intended as a preliminary study for the design of a test method for bus engine compartment fire protection systems. The aim is also to present an outline of a repeatable and reproducible full-scale testing method. Since there is a distinct lack of literature concerning bus engine compartments and relevant fire extinguishing systems, the data used in this study has largely been provided by vehicle and fire protections system manufacturers, as well as by fire investigators.

This report mainly concerns diesel engines in rear-mounted compartments, since this covers the large majority of buses and coaches currently in use. Finally, the proposed method only tests the *extinguishing capability* of bus/coach fire suppression systems, not their ability to *detect* a fire.

2 Bus and coach engine compartments

Based on the number of passengers, the UN divides buses/coaches into two main categories: vehicles seating up to, and in excess of 22 passengers, respectively [15]. This report is based on the category seating more than 22 passengers. However, further subdivision can be made. The terms *bus* and *coach* reflect the intended range and traffic environment of the vehicles: buses are city vehicles while coaches are used for long-haul services, both scheduled and chartered. So-called intercity buses may be considered a hybrid of the two.

2.1 Engine room geometry

A bus/coach engine may be mounted in one of three positions: (i) the extreme rear of the vehicle, (ii) between the front and rear axles, or (iii) up front. A commonly recognised front-engine vehicle type is the typical yellow US school bus. Front-mounted engine compartments are usually smaller and the airflow through the engine is different. It is also relatively easy for the driver to detect smoke from a fire in a front-mounted engine compartment. The work presented in this report has, therefore, not focussed on front-mounted engines. Rear-mounted engines are by far the most common arrangement, and represent the most difficult situation in terms of driver detection of an incipient fire. Therefore, rear-mounted engines are the focus of this report. Figure 2 shows a rear-mounted engine compartment.

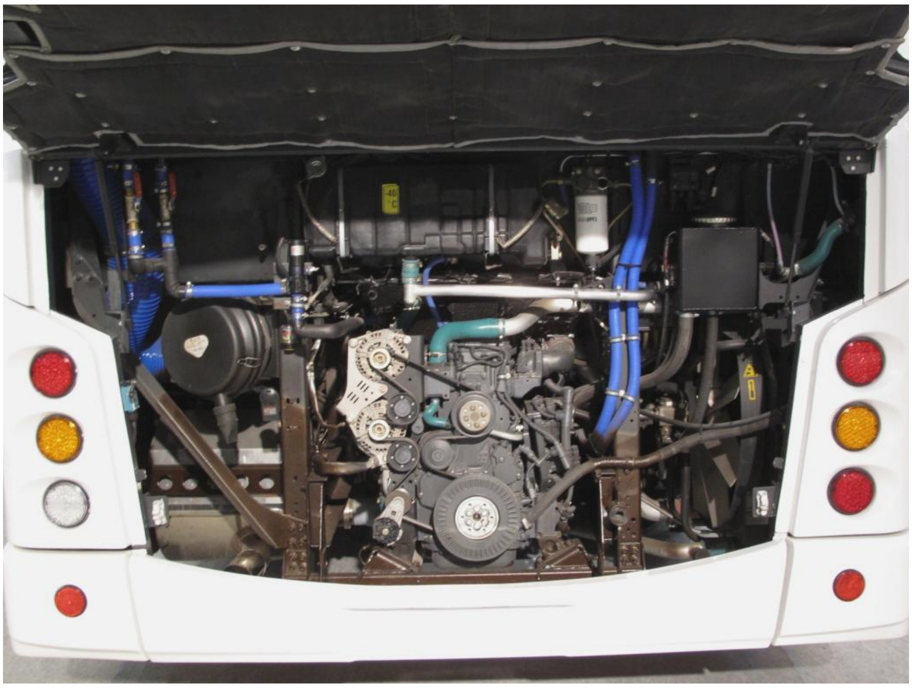

Figure 2 Rear-mounted engine compartment in a city bus.

The size of bus/coach engine compartments is highly variable. A medium-sized rear engine compartment may typically measure 1.20 m × 2.30 m × 1.40 m (height × width × depth, where length is the driving direction of the vehicle). Manufacturers of fire protection systems usually calculate the gross volume of the engine compartment without subtracting the volume of the engine itself and other fittings. Based on the volume calculation the amount of extinguishing agent required to protect the whole engine compartment is estimated. The volume is typically 3 – 4 m^3 [16], but variations from 2 to 6 m^3 are not uncommon. The following definitions may be used when measuring the volume [17]:

Height: the distance from the ceiling of the engine compartment (i.e. its upper partition separating it from the passenger cabin/baggage compartment) to the floor of the engine compartment. If the engine compartment is floorless, the measurement is taken to the lower edge of the vehicle frame girders.

Width: an interior measurement from one side of the bus/coach to the other. If full-height metal-sheet partitions are present between the side of the bus and the engine compartment, the measurement is made up to these.

Depth: the distance from the rear edge of the engine (that is, near the rear hatch) to the front edge of the gearbox.

The difference between city buses and the larger buses and coaches is that the latter have higher and slightly longer engine compartments. The width is usually 2.30 – 2.40 m in all rear-mounted engine compartments since a bus or coach is typically not wider than 2.60 m.

As a rule, engine compartments are not perfectly rectangular. The floor is often slightly inclined and the ceiling may have a stepped profile. The size of the steps varies. The height of the compartment at the rear door might be e.g.1.40 m, decreasing to 1 m above the engine etc. There is often one or two steps in the ceiling profile between these two points, see figure 3.

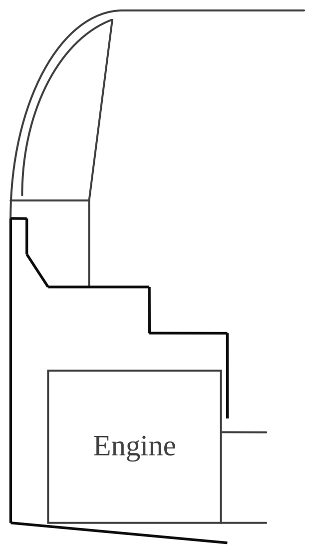

Figure 3 Example of a stepped engine compartment profile.

The proportion of free air varies between engine compartments. Some are roomy and open, while others are very cramped. Coach compartments are, as a rule, roomier than those in buses. In some of the latter, the gap between the engine and the compartment ceiling may be as small as a few centimetres. Installing an efficient extinguishing system in such a small space is a challenge. To a mechanic, the cramped space presents difficulties when repairing or replacing components. For practical reasons, the aprons below the engine are commonly removed, leaving the engine compartment floorless. In some cases, the floor is lost due to road bumps and careless driving [18]. Furthermore, it's not unusual for buses manufactured in countries with less than stringent noise-level regulations to have large apertures in the engine compartment floor as a standard feature.

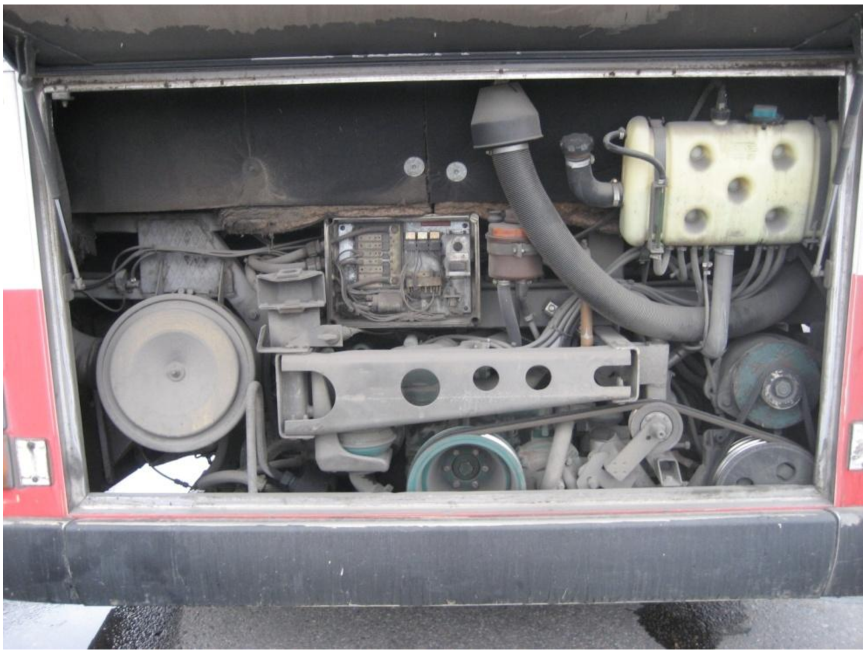

Figure 4 A city bus with a compact engine compartment.

An engine compartment is often compact and packed with various components, see figure 4. In case of a fire, these might prevent the extinguishing agent from reaching the source of the fire. A "shadow effect" may occur, i.e. objects will obscure the fire source from the extinguishing system's ejection field [19] thereby potentially reducing the efficiency of the system.

2.2 Radiation from warm and hot surfaces

Temperatures in bus engine compartments vary due to the type of engine, make and the year of manufacture. The following information is based mainly on data provided by European bus and coach manufacturers.

In a diesel bus or coach engine, the working surface temperature of the main components of the engine block is between 80° and 140° C. A bus/coach engine is usually oblong, and may be upright or horizontal and mounted lengthwise or crosswise in the engine compartment [20]. The engine of a full-size coach or bus weighs roughly one ton, and the external dimensions can e g be 1.0 m × 0.7 m × 1.2 m (height × width × length).

The hottest parts of the engine, manifold and turbocharger, are part of the exhaust system. Their exposed surface within the engine compartment totals roughly 0.3 m^2. The material thickness varies between 5 and 15 mm, and temperatures may reach a maximum of up to

600 – 640° C. These high temperatures are reached when the motor is subjected to high loads. In some cases, the manifold is covered with a baffle plate, in order to minimize heat radiation and prevent any leaking oil from contacting hot components. Normally, bus/coach manufacturers strive to keep hot components away from fuel lines. This is why engines often feature a “hot side” with the manifold and turbocharger, and a “cool side” where the fuel injection system is located.

The dust filter and catalytic converter are also located in or near the engine compartment. These hot components purify the exhaust emissions, and are often located inside the exhaust muffler.

The engine and exhaust dissipate heat, heating the engine compartment to a temperature of approximately 80 – 100° C or even higher (Hammarström et al., 2008). The walls of the compartment are commonly covered with soundproofing panels. These also have efficient thermal insulation properties, thus contributing to high engine compartment temperatures.

2.2.1 Auxiliary heater

An auxiliary heater is a small heating boiler with its own exhaust, completely separated from the main engine of the bus or coach. It’s used to heat the engine, as well as the driver/passenger cabin when the main engine is not running. It may either be located in its own space separate from the main engine, or it may be mounted in a partition within the engine compartment itself. The auxiliary heater may constitute a potential fire hazard.

2.2.2 New emission limits

The pollutant emission regulation Euro 6 will be in force for all new buses and coaches from December 31, 2013, and follows earlier EU regulations in calling for lowered emission levels. This will force bus and coach manufacturers to further raise dust filter and catalytic converter temperatures, in order to improve exhaust purification. This will probably mean that these hot components will more frequently be mounted inside the engine compartment, in order to minimize warm-up time. Thus, the mean surface temperature of exhaust mufflers may be 250 – 300° C, with surface areas totalling from less than 1 m^2 to 2.5 m^2.

2.3 Engine compartment airflow

The fan forces air into the engine compartment in order to cool the running engine. Thus, it introduces oxygen, contributing to the progress of any ongoing fire. There are several types of engine-compartment fans, e. g. hydraulic, belt-driven, and electric fans. The fan is usually (but not always) controlled by the engine revolution speed, and will as a rule create an air overpressure in the engine compartment, helping to prevent dirt and dust from entering.

At maximum rotation speed, the fan airflow pressure level may reach approximately 6 kg/s. However, in some bus and coach models, only 30 – 35% of the airflow passes through the engine compartment, most of the balance being forced out through openings immediately below the fan. In bus and coach types where the engine compartment does receive the majority of the airflow from the fan, airspeeds may be considerable.

Simulations have shown that the airspeed in narrow passages above the engine block can be as high as 15 – 25 m/s.

In some vehicles, the fan stops when the engine is idling. However, in many buses and coaches, engine room ventilation continues, though at a lower fan speed, due to low engine speed. Table 1 shows approximate airflow values for buses with the full airflow routed through the engine compartment, and for those with a 1/3 airflow throughput.

Table 1 **Bus/coach engine compartment airflow.**

	Idle	Maximum revs
100 % of fan airflow	0 – 1,5 kg/s	6 kg/s
33 % of fan airflow	0 – 0, 5 kg/s	2 kg/s

The air entering the engine compartment is heated by the cooling system to about 80° C when the cooling system has reached its working temperature. At this temperature, the weight of the air is approximately 1 kg/m^3. This means that in an engine compartment with a net volume of about 2 m^3 (i.e. the free air volume excluding the volume of the engine and fittings) the air is on average replaced 1 – 3 times per second at high airflows.

The configuration of ventilation openings through which air may escape the engine compartment varies between different bus and coach models as well as according to local noise regulations. Stringent noise regulations mean that buses and coaches in western countries have more tightly sealed engine compartments than in some other parts of the world. Air normally enters from the side via the fan, and may exit though apertures above or below the engine hatch, openings in the floor below the radiator unit, or through the floor or side wall on the opposite side of the engine. Air may also escape through openings ahead of the engine, towards the gearbox.

2.4 Fire sources

2.4.1 Fuel

Most buses and coaches are diesel-powered. In Sweden, 89% of the total vehicle fleet have diesel engines. Diesel is also the dominant bus and coach fuel from a global point of view, although there are national differences, e.g. Argentina and Brazil both have large proportions of buses and coaches with natural gas propulsion.

The present trend internationally is increasingly towards the introduction of more eco-friendly vehicle propulsion systems, and there are various types of fuels available. In Sweden, fuels for buses and coaches other than diesel include natural gas (about 8% of vehicles) and ethanol (approx. 3%). There are also a small number of electro-hybrid vehicles.

An increasing number of vehicles, mainly city buses, are gas-driven. When lighter-than-air gases are used (e.g. hydrogen), gas tanks are mounted on the bus roof, since leaks will cause the gas to rise. If a gas leakage occurs, emergency valves automatically cut the gas supply. In order to prevent explosions, the gas tanks are also equipped with failure membranes that melt and release the gas upwards in case of fire.

Ethanol-fuelled buses and coaches are powered by ED95, consisting of 95% ethanol and 5% additives. The flash point of ethanol is low, while the auto-ignition temperature is relatively high. Burning ethanol (in small pool fire scenarios) radiates less heat than diesel, and has a lower energy value per litre.

A hybrid vehicle utilizes two or more propulsion units, usually an internal combustion engine combined with at least one electric motor. An electric motor contains a lot of electronics as well as large generators. It uses several batteries that are often mounted on the roof. The electronics may present several challenges, including high voltages and the risk of short-circuit. If the vehicle utilizes a diesel or ethanol engine, the flammable fluids that power such engines are also present in the engine compartment and present an additional risk.

2.4.2 Flammable liquids in engine compartments

An engine compartment contains several flammable liquids. In a diesel-powered bus or coach, these consist of diesel fuel, engine oil, hydraulic oil and coolant. If the engine is front-mounted, isopropanol (windscreen washer fluid) may also be present. Table 2 shows examples of flash points and auto-ignition temperatures for some flammable liquids typically found in busses. Note that data for ignition temperatures vary widely depending on the fuel composition and the ignition test.

Table 2 Examples of flammable liquids in engine compartments.

Flammable liquid	Flash point (°C)	Auto-ignition temperature (°C)
Diesel	55	225
Ethanol	13	365
Transmission gear oil	200	390
Cooling fluid (50 % glycol)	140	484
Engine oil	205	315

The amounts of flammable fluid present in any given engine compartment varies with the type of engine and the level of filling of each container. A rough estimate would be 35 – 45 litres of engine oil, 15 – 20 litres of power steering/hydraulic oil (which may consist of engine oil) as well as approximately 50 litres of coolant. The amount of diesel fuel present is normally no more than roughly 3 litres, most of it in the fuel filter, but also within the fuel lines. The gearbox, often positioned outside but in close proximity to the engine compartment although it may be inside the engine compartment, may contain an additional 15 – 25 litres of oil[1].

Since the ambient temperature in the engine compartment is high, the margin between this and the auto-ignition temperature of the flammable liquids is smaller than normal, meaning that the ignition and spread of a fire may occur more easily. At room

[1] Information from European bus/coach manufacturers.

temperature, diesel fuel needs to be heated from 20° C to 200° C in order to self-ignite ($\Delta T = 180°C$). In an engine compartment, however, the initial temperature may be as high as 100° C ($\Delta T = 100°$ C). On the other hand, for a liquid to ignite on contact with hot surfaces, the surface temperature has to be significantly higher than the self-ignition point, since the liquid cools the hot surface upon evaporation. High levels of airflow across the surface will also inhibit the fuel's readiness to ignite. Thus, diesel fuel may in some circumstances require a surface temperature in excess of 500° C in order to self-ignite [20]. The coolant may also ignite under certain conditions. The boiling point of glycol is approximately 200° C, whilst water boils at 100 °C. Once the water in the coolant has boiled off, pure ethylene glycol remains, having a auto-ignition temperature of approximate 400° C [21].

A diesel bus or coach engine consumes roughly 2 – 4 litres of fuel per 10 kilometres. However, significantly larger amounts circulate through the fuel system, due to the fact that a substantial amount runs back into the fuel tank. Return fuel line leakage can cause large volumes of diesel to escape into the engine compartment without affecting the fuel supply to the engine. In other words a fuel leakage can occur over a substantial period of time without the driver noticing any malfunction of the engine.

There are several pressurized fuel and oil lines in an engine compartment. A puncture in a high-pressure line causes a hot, dispersed fuel or oil mist to escape. Such sprays are highly flammable and may produce a very quick combustion process. A hydraulic fan drive is pressurized to around 100 bars and might contain several litres of oil. The power-assisted steering system is pressurized to approximately 10 bars. Fuel injection system pressure may reach in excess of 1 500 bars. The diesel pump also features highly pressurized lines.

2.4.3 Flammable solids in engine compartments

Other flammable materials are also present in engine compartments: rubber hoses, casings, cables, plastic containers, acoustic insulation made of textiles or polyurethane foam, plywood ceiling sheets, as well as paper air filters. Plastics in an engine compartment may consist of e.g. polyvinyl chloride (PVC), polyamide (PA) or polypropylene (PP). Road dust entering the engine compartment may absorb leaking oil, forming a thick and porous mixture that may reach a thickness of several centimeters if vehicle maintenance is neglected. Acoustic insulation may wear out and become porous, losing its liquid-repellant properties, thus becoming prone to absorbing leaking oil.

2.5 Ignition sources

Ignition in engine compartments generally occurs due to leaking fuel/oil contacting hot surfaces and overheating, or electrical wiring short-circuits. Often, the cause of the fire can be traced to mistakes made during previous repairs or maintenance. Fire investigators have stated that upwards of 90% of bus and coach engine compartment fires occur due to stress, negligence or incompetence during repairs [22]. The most common ignition sources are generators, starter motors, hot manifolds, turbochargers and unsecured wiring. Amperage may reach 600 – 700 A at 28 V. There are also other ignition sources, e.g. slipping belts may heat up, burn through and be thrown off. If the circumstances are unfortunate, this may cause ignition in other parts of the engine compartment [23]. The “ping tank”, an equalization tank for the pneumatic system, may overheat; igniting nearby wiring in the process and often causing short-circuits.

Once a fire has started, it generally spreads by igniting petroleum products or plastics in the engine compartment [21]. If the fire is allowed to develop unchecked, it may spread to the baggage and passenger compartments. The fire typically enters the passenger cabin by flames exiting the rear of the engine compartment and penetrating the rear window. The fire might also enter through the engine compartment ceiling – often made of plywood – at an early stage. This is, however, less common since burning through a plywood sheet takes a considerable amount of time.

Below are two images of the same engine compartment, with two common ignition sources indicated. The generators are shown in Figure 5 and the manifold in figure 6. Please note that the exact positions of these components vary between manufacturers and vehicle models.


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Figure 5 Bus engine compartment, generators indicated.

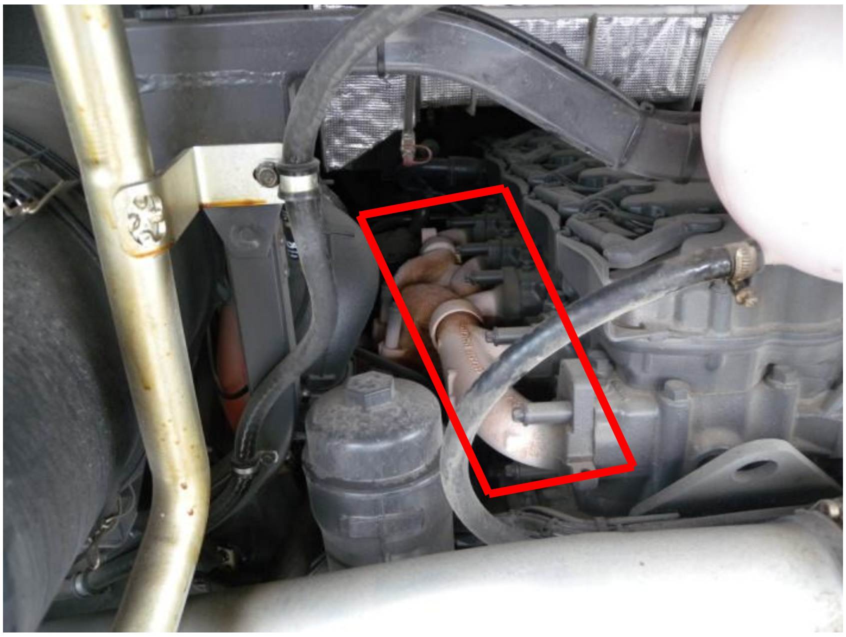


Figure 6 Bus engine compartment, manifold indicated.

If a leakage occurs, causing fluid to come into contact with hot surfaces, ignition often occurs only when the fan revs down, since it effectively airs out any combustible gases when running at normal speed. A realistic scenario would be the driver negotiating a steep incline, putting maximum load on the engine. A leakage occurs, but the fluid does not ignite until the vehicle has reached the top of the hill and the engine revolutions decreases.

2.6 Real-life examples

Below follow some extracts from fire investigations issued by the Swedish Accident Investigation Board and the Swedish Civil Contingencies Agency which illustrate common problems. All investigations concern engine compartment fires in buses and coaches.

2.6.1 Spray fire

"Once the leakages had increased sufficiently, pressure from the power steering pump caused a spray of oil. The oil dispersed and came into contact with the hottest parts of the engine." … "It ignited, functioning as a flame-thrower in the inner left section of the engine compartment, where the generation of heat was massive, causing concentrated fire damage."[10] .

2.6.2 Short-circuit

"Some form of short-circuit has occurred in the wiring." [25].

2.6.3 Oil and fuel leakage

"Through these punctures, the engine oil, roughly 25 litres had leaked. According to the investigation records, the oil was estimated to have had a temperature of at least 100 degrees at the time."[26] .

“The fire was most likely caused by a diesel leakage in the engine compartment, judging by the fast progress of the fire.” [27] .

2.6.4 Ditching followed by fire

“It’s readily apparent that the most severe fire damage is present on the right side of the engine, i.e. the part closest to the ground after the coach turned over. The reason for this is that hot engine oil pouring onto the ground and then ignited [26].

2.6.5 Acoustic insulation soaking up leaked oil

“The situation was exacerbated by the fact that diesel oil was likely to have poured out over the soundproofing mats covering the engine and turbocharger, prior to ignition. Regardless of which measuring method was used [...] it is apparent that the mats will absorb considerable amounts of diesel oil in a reasonably short period of time.” [9] .

2.6.6 Pool fire below bus

“Brandishing the bus’ fire extinguisher, he (the bus driver) *runs towards the rear of the bus, where the flames are now roughly a meter in height, and a large pool of diesel has poured out onto the street” … “which also ignites.” [27].*

3 Extinguishing agents

There are several different types of extinguishing systems available for engine compartments on buses and coaches. They use various types of extinguishing agents or a combination of agents. Some common type of agents are described below.

3.1 Water

Many extinguishing agents are based on water as a main part of the agent. Water, has several properties useful for fire suppression [28]: cooling of hot smoke and flames, cooling of fuel surfaces and finally extinguishment by creating an inert (diluted by steam) atmosphere.

The favourable cooling properties of water are due to the fact that large amounts of energy are required to heat and evaporate water; e. g. to vaporize 1 kg of water more than 2 MJ of energy is needed. The energy used in these processes is drawn from the fire and hot surfaces, which are then cooled. Furthermore, as 1 kg of water evaporates, the volume increases to approximately 1.7 m^3, increasing the likelihood that vapor replaces air in all areas of the enclosure, thereby suppressing the fire. Water therefore works well at high temperatures when a large proportion will evaporate. The size of the water droplets also affect extinguishing efficiency: small water droplets are advantageous since they present larger total contact surface to the fire per unit volume water. On the other hand, small water droplets are sensitive to ventilation and may have problems penetrating and extinguishing glowing fires. Larger water drops are less susceptible to air movement but are more directional and so better suited for local application versus total flooding.[20]. Furthermore, water may become electrically conductive and has to be stored under conditions where the agent don’t freeze. To lower the freezing point additives can be used.

3.1.1 Foam additives

A surfactant is often added to the water to decrease the surface tension of the extinguishing agent and allow it to produce a foam. This allows it to form a covering film on burning liquids and so block fuel-air contact, and protect the fuel from radiation from flames, thus inhibiting the combustion process. A foam additive also improves the agents ability to penetrate porous materials.

There are different types of foam liquids, e g Film Forming Fluoroprotein Foam (FFFP) and Aqueous Film Forming Foam (AFFF). Most foam liquids are dissolved by polar fuels, e g alcohol, but may be rendered alcohol-resistant using an additive. The foam liquid can be mixed with a gas (e.g. air or nitrogen), producing a light and airy foam.

3.2 Powder extinguisher

Powder extinguishers function by a combination of cooling the flame, i. e. causing the fire to expend energy in heating the powder grains, and chemical inhibition. Certain compounds are released, which then melt and evaporate, expending energy in the process. Some powders release carbon dioxide, causing additional fire suppression. Powders may perform through a chemical effect, i.e. reacting with radicals and forming stable compounds, which arrest the chemical combustion reactions. Some types melt and form a continuous layer, thereby physically preventing heat exchange and transport of pyrolysis gases.

A decrease in powder grain size causes a corresponding increase in total effective fire-suppression surface area, providing a greater extinguishing effect. Additionally, smaller grains heat up faster, causing any chemical suppression effects to occur earlier. Grain size also affects the powder's abibility to penetrate flames. A large grained powder can be thrown further and more forcefully, often drawing small particles into the fire with it. Powders have excellent extinguishing qualities, but often require extensive post-use cleanup. Storage is a limiting factor. It is important that the powder container is stored under good conditions; most powders are e. g. sensitive to high temperatures and moisture.

3.3 Aerosols

An aerosol is a mixture of gas and extremely fine particles. The chemical composition of the particles may be identical to those of powders described above. The most common method of creating and ejecting the aerosol is to activate a solid substance with an aerosol cartridge, causing a vapor to form. Thermal expansion will force the vapor out through a cooling system. The decreased temperature of the vapor causes it to convert into solid or liquid particles suspended in a gas, i.e. an aerosol.

As with powder, aerosols suppress fire when the particles absorb heat from the flame, as well as by interrupting chemical reactions. Additionally, the aerosol gas has an inerting (diluting) effect provided it is non-combustible.

The aerosol particles are airborne, and may easily be ventilated away. This is advantageous from a cleanup point of view, but ventilation will also cause loss of protection against re-ignition [28] and should not be started before the fire scene has cooled sufficiently to prevent re-ignition.

3.4 Gases

Gaseous extinguishing agents are seldom the most cost-efficient choice of agent. However, they work very well at inerting a protected volume and extinguishing fires in highly cluttered areas. Another advantage, is the low detrimental effect of the extinguishing agent itself. Most gaseous agents cause no or negligible ill effects if the extinguishing system is activated accidentally.

Gases cause no direct cooling of the fuel, but work by inerting and reducing the flame temperature. Certain gases, e g halons and HFC-227ea, also have a chemical mechanism. Nowadays the halons are prohibited in most applications. However, as for other extinguishing agents, the suppression effect is dependant on the fuel. Certain fuels, like methanol and ethylene, require significantly higher concentrations of the gaseous agent for extinguishing to occur, than for example heptane and propane. Gas works well in closed spaces where the concentration of extinguishing agent may be kept sufficiently high for an extended period of time. However, re-ignition may occur when the gas is ventilated away [28].

4 State-of-the-art in existing testing methods

A number of existing methods for testing extinguishing system in various types of engine and machinery rooms are described below. Their degree of applicability varies, but they provide some guidance when designing a new testing method for bus and coach engine compartment extinguishing systems.

4.1 Experimental bus engine room test

The report *Bus Fire Safety* (SP Report 2008:41) [20] describes a method of testing fire extinguishing systems in buses and coaches. The method is at a experimental stage, and is primarily designed for water-based agents, but it should be applicable for the testing of other systems as well.

The testing method uses a 1/3 scale simulated engine compartment, featuring a fan, a water-heated engine unit and an LPG-heated exhaust pipe. The test encompasses several different fire sources: a spray fire, three pool fires, a rubber fire and a wood pellet fire. One of the pool fires is located beneath the engine compartment; one is partly hidden inside the dummy engine, whilst the third is located on the side wall of the engine compartment, hidden by a baffle, see Figure 7.

The test simulates engine activity under three different conditions: full load, idling and shut down. These conditions are simulated through various engine and exhaust pipe temperatures as well as through variations in the degree of engine compartment ventilation. Since the engine room is to 1/3 scale, only one third of the tested extinguishing system's nozzles are used. The system's full number of nozzles is installed, but most are not used in the test. The testing method described in the present report represents a further development of this method as described in SP Report 2008:41 [20].

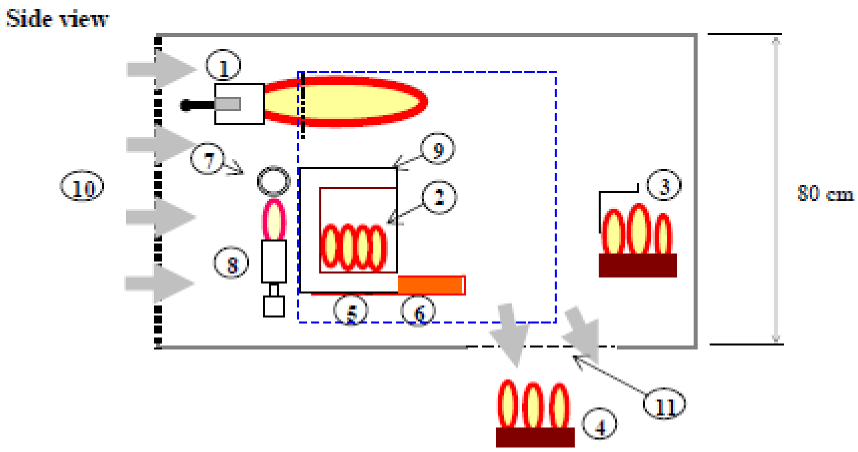


Figure Legend:

1. Spray fire *(diesel)*
2. Engine fire, location in a cavicity in the engine mock-up *(diesel in mineral wool)*
3. Rear wall fire *(diesel in mineral wool)*
4. Pool fire *(diesel in mineral wool)*
5. Smouldering fire *(rubber)*
6. Smouldering fire *(cellulose)*
7. The exhaust pipe mock-up
8. The exhaust pipe heater *(5 propane burners)*
9. The engine mock-up, with a cavity for the engine fire
10. Air inlet
11. Air outlet

Figure 7 Sketch of the engine compartment mock-up used in SP Report 2008:41.

4.2 SBF 128

SBF 128 [12] is a regulatory framework for fixed bus and coach engine compartment extinguishers developed by The Swedish Fire Protection Association (SBF) in collaboration with representatives from the insurance industry. Full-scale tests of fire protection systems are conducted in buses and coaches approved by SBF. The engine must be functional, feature a turbocharger and be mounted in a complete engine compartment no smaller than 2 m^3. In the test, 3 l of sawdust soaked in diesel fuel and oil is dispersed in the engine compartment. Additionally, 200 g of twisted cotton, soaked in lighter fluid, is placed in the compartment. Before the engine compartment is ignited, the engine is idled for 15 minutes and then run for 5 minutes at higher revolutions (1 700 – 1 800 rpm). At this point, 1.5 l of a mixture of diesel, oil and lighter fluid is sprayed into the engine compartment. The cotton is ignited, spreading the fire to the fuel. After 20 s, the extinguishing system is activated manually.

In addition to standards for assessing the extinguishing capability of the system being studied, SBF 128 also features other requirements. The system must fulfill SS/IEC standards for resistance to temperature extremes, moisture and vibration and must also meet standard wiring and ducting requirements. The amount of extinguishing agent in the installed system is calculated based on the size of the engine compartment. SBF 128 requires a liquid-based system to contain a minimum of 3 l/m^3 of extinguishing agent based on engine compartment size. It must also be capable of releasing 85% of the extinguishing agent within 20 s. Powder systems need 5 kg of agent per cubic meter engine compartment volume, with 95% releasable within 20 seconds. In addition, the nozzle that is positioned furthest away from the powder container must have a flow that is not less than 150 g/s. SBF 128 does not require a specific amount of extinguishing agent per cubic meter of engine compartment space for aerosols, but the system must be designed to achieve an extinguishing concentration approved by the SBF.

4.3 SBF 127

SBF 127 [29] is issued by The Swedish Fire Protection Association and regulates extinguishing systems in forestry and earth-moving machinery. The full-scale test specified by the regulation is similar to that required by SBF128, but features larger amounts of flammable material and a spray fire with hydraulic oil. Further, the engine is run at high revolutions for a longer period of time. Finally, the requirements concerning the minimum amount of extinguishing agent are stricter.

4.4 AS 5062-2006

The Australian standard “Fire protection for mobile and transportable equipment” (AS 5062-2006) is a comprehensive document aimed to evaluate and regulate fire safety in various types of vehicles and mobile equipment. It applies to buses, four wheel drives, road haulers, motor homes, forklifts, etc.

The standard is mainly concerned with fixed extinguishing systems and details the required testing method for water-based foam systems. The test is performed essentially at the component level, i.e. not on the system as a whole. The test consists of two stages, focusing on direct and indirect extinguishing capabilities, respectively. Both stages feature re-ignition tests.

Based on the manufacturer’s specifications, the extinguishing agent container is filled to its maximum capacity (i.e. minimum expansion space) at the lowest approved pressure. The system must be installed with the maximum number of nozzles, as well as with the maximum length of tubing of the smallest permissible diameter. The hydraulically least efficient nozzle is selected, and then mounted at a maximum allowable distance from the fire source. The system’s remaining nozzles must also be installed, but are not used in the test. During the test, air speed must not exceed 4 m/s.

4.4.1 Test 1: Direct extinguishing and re-ignition attempt

The test encompasses three objects (see Figure 8):

a) Main fire: A square tray representing a fuel spill, with 50 mm of diesel fuel floating on top of 50 mm of water. The sides of the fire tray must not be less than the diameter of the spray pattern of the extinguisher nozzle.

b) A diesel spray with a 1 mm orifice, connected to a pressure vessel containing 12 litres of diesel fuel, pressurized to 1 500 kPa.

c) A pilot flame: a smaller vessel containing diesel ascertaining continuous ignition of the diesel spray.

The main fire and the pilot fire are ignited and allowed to burn for 1 min 45 sec. The diesel spray is engaged, and 15 seconds later the extinguishing system is triggered manually. The diesel spray is allowed to continue for 30 seconds after the effective discharge time, i.e. the time during which the extinguishing system runs at maximum supply of agent.

The test is considered passed if the system extinguishes the main fire within less than 80% of its effective discharge time. It must also prevent the fire from being reignited by the spray fire. Additionally, all nozzle caps must be ejected without affecting the discharge pattern of the nozzles.

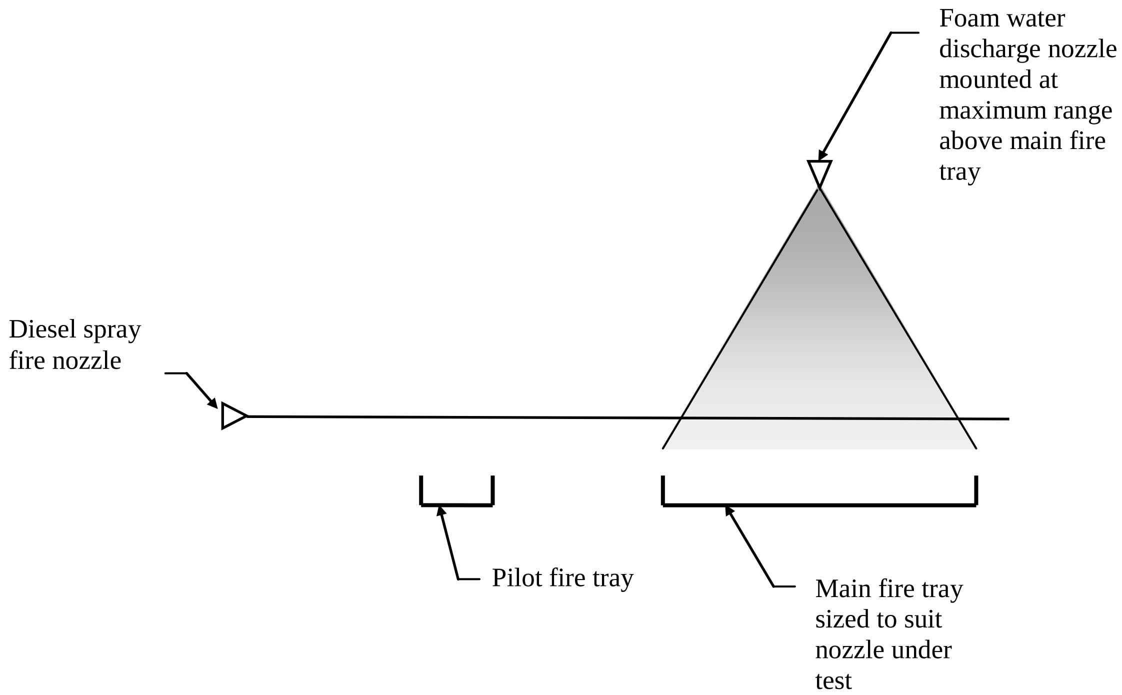


Figure 8 Diagram of a direct fire extinguishing test, based on information from AS 5062.

4.4.2 Test 2: Indirect extinguishing and re-ignition attempt

The second test encompasses three objects (see Figure 9)

a) A main fire tray, as per test 1.

b) A diesel spray, as per test 1.

c) A square steel plate for re-ignition, 3 mm in thickness and with side dimensions equal to the main fire tray.

The steel plate is mounted vertically, 10 cm above the main fire tray. The extinguisher nozzle is directed towards the steel plate, the diesel spray is positioned 120 cm from the steel plate.

The fire sources being ignited and allowed to burn and heat the steel plate for 2 minutes, after which the extinguishing system is discharged manually. Once the effective operational period of the system had passed, i.e. the time during which it operates with maximum extinguishing agent supply, the diesel spray is restarted, remaining active for 15 seconds.

The test is passed if the system is able to extinguish the main fire during its effective discharge time, and prevent re-ignition of both diesel spray and main fire. Additionally, all nozzle protectors must be ejected without affecting the discharge pattern of the nozzles

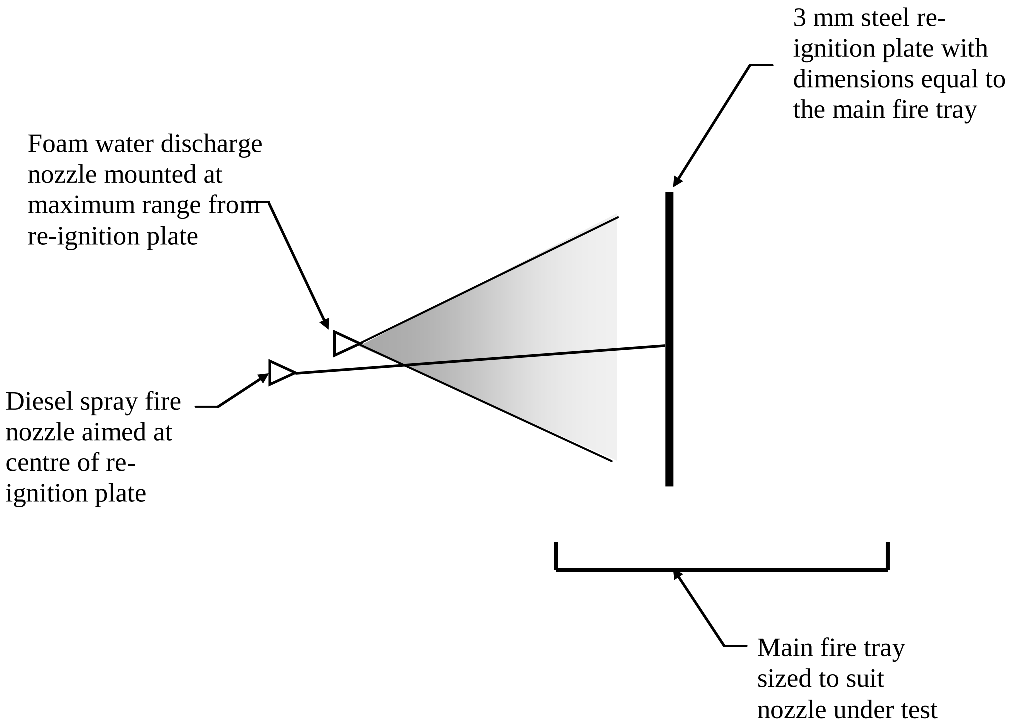


Figure 9 Diagram of a direct fire extinguishing test, based on information from AS 5062.

4.5 MSC/Circ. 1165

The International Maritime Organization (IMO) is a UN agency issuing numerous safety standards. One of these standards, MSC/Circ. 1165 [30] describes a testing method for water-based total flooding extinguishing systems in machinery spaces and cargo pump-rooms. The system is assumed to have unlimited access to water. The testing space must have an area in excess of 100 m^2 and a minimum of 5 m of headroom. Ventilation is through a 2 m × 2 m doorway. A dummy engine measuring 1 m × 3 m × 3 m is installed, featuring two steel tubes simulating exhaust manifolds. The tubes are 3 m in length, with a 0.3 m diameter. The dummy engine is mounted on a floor plate measuring 4 m × 6 m and featuring side walls 0.5 m in height, see figure 10.

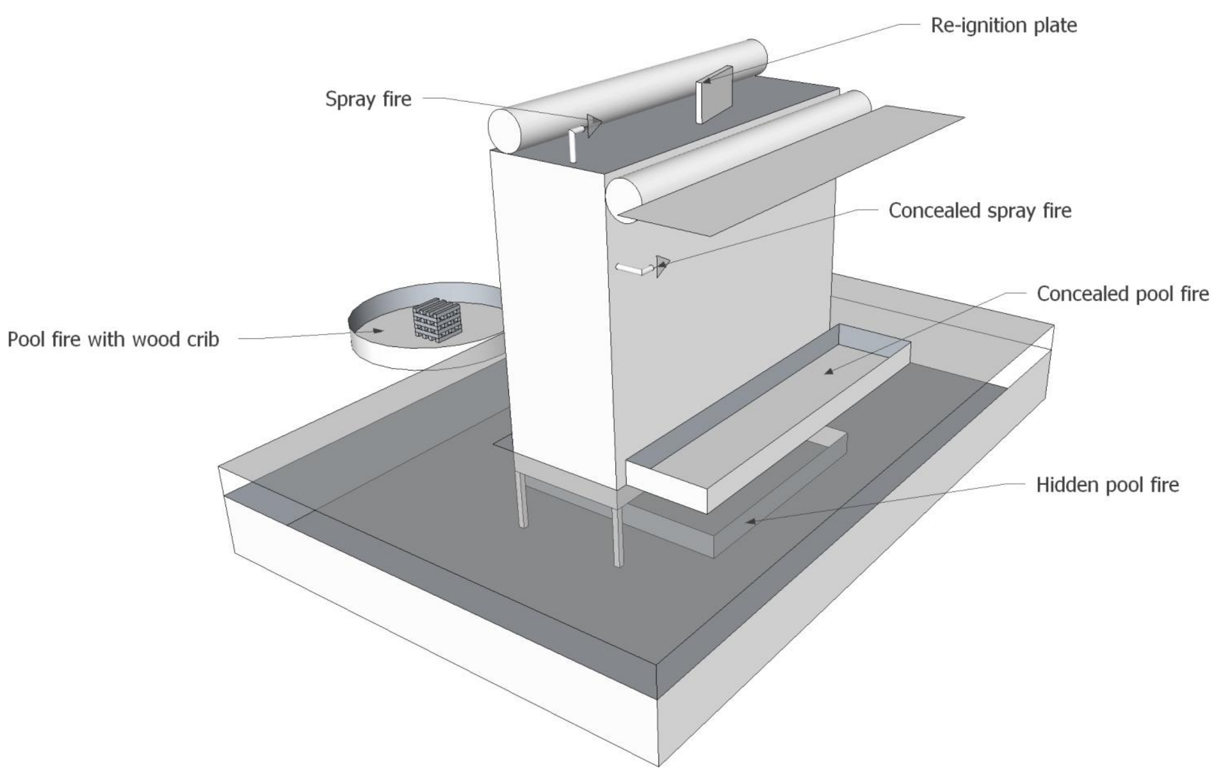


Figure 10 Sketch over dummy engine and test fires, based on information from MSC/Circ. 1165.

The fire sources used are four light diesel or fuel oil sprays, one heptane spray, one heptane pool, a pipe with free-flowing heptane, as well as a wooden pallet in a heptane pool. The combined heat release of all sources is several MW. A horizontal plate prevents the diesel pool from being hit directly by the extinguishing agent. The re-ignition risk is simulated using a hot steel plate being sprayed with heptane. The steel plate is heated with the spray fire to 350 °C prior to the test.

The extinguishing system being tested is installed as per the manufacturer’s instructions. The nozzles must be positioned at a minimum of 5 m above the floor in a uniformly spaced overhead nozzle grid. A separate bilge area protection may also be installed. The test does not allow the use of additional nozzles intended to extinguish the fire sources through direct application. The test is performed with the system at minimum design pressure and water flow.

Prior to the test, all fire sources are ignited. After a pre-burn period, the extinguishing system is activated. If it is capable of extinguishing all fires, as well as preventing re-ignition, the system is considered to have passed the test. Additionally, the method tests the system's capability to lower the temperature within the fire space. A passed result requires the system to lower the mean temperature of the test space to below 100° C within 300 seconds after activation.

In addition to the extinguishing test described above, MSC/Circ. 1165 also features extensive extinguishing system component requirements.

4.6 RINA Doc. 3.13

RINA (Registro Italiano Navale) is an agency for maritime and industrial classification and registration based in Italy. RINA doc. 3.13: ”Rules for Type Approval of Clean Agent Fixed Fire-Extinguishing Systems in Machinery Spaces” [31] describes a testing method for gaseous (clean agent) extinguishing systems in machinery spaces. The object of the method is to determine extinguishing effectiveness at a given agent concentration, as well as whether or not the extinguishing effect is capable of reaching all parts of the test enclosure.

The method only tests suppression systems intended for machinery spaces with a volume less than 70 m^3. Prior to the test, an enclosure equaling the volume of the machinery space for which the system is being tested is constructed.
Figure 11 shows an example of a test enclosure. The manufacturer's extinguishing nozzles must be positioned symmetrically, less than 1 m from the ceiling.

A 0.5 m^2 hidden engine oil pool fire (B) is placed below a steel plate dummy engine. A 0.96 m^2 diesel pool fire (A) is positioned in front of the dummy engine. A hidden diesel spray (C) is placed below an overhanging plate at the top of the dummy engine. Cups containing heptane are positioned in each of the four corners of the space, two at floor level, and two close to the ceiling. A Class A fire, consisting of a square pile of wooden pallets, is also used.

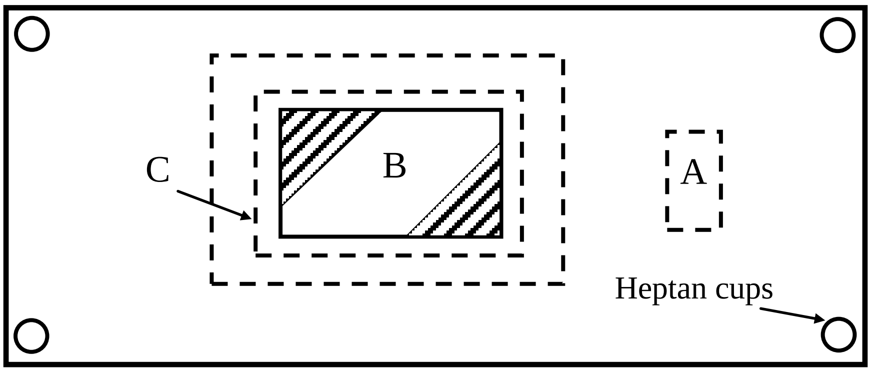


Figure 11 An example of a test enclosure, based on information from RINA Doc 3.13.

All fire sources are not ignited simultaneously, rather the test is divided into five parts:

a) Open pool (A) and cups containing heptane

b) Hidden spray (C)

c) Hidden pool (B), plus hidden spray (C)

d) Open pool (A), hidden pool (B), hidden spray (C), and cups containing heptane

e) Pile of wooden pallets

During the pre-burn time, the test space is well ventilated, but all ventilation openings are closed during the test. After discharge of the extinguishing system, the test enclosure is kept closed for a period of 15 minutes (hold period). During parts (b), (c) and (d) involving the diesel spray, the spray remains active for 15 sec after extinguishing is complete. Towards the end of the 15 minute hold period, the spray is restarted to determine whether re-ignition occurs. In test (a), an electric ignition source attempts to reignite two of the heptane containers on four occasions after extinguishing. If any of the containers ignite and burn for more than 30 seconds, re-ignition is considered to have occurred.

For a passed result, all fires must be extinguished within 30 seconds of the discharge of the extinguishing system, re-ignition may not occur and, after test (e), the wooden pallets may not have lost more than 60% of their original weight. The discharge time of the system is also regulated. A halogen system must be able to achieve 95% of its minimum design concentration within 10 seconds, while systems using other inert gases are required to achieve 85% of its minimum design concentration within 120 seconds.

4.7 UL 1254

UL 1254 [32] is an comprehensive test standard, encompassing several types of methods for the testing of dry chemical extinguishing systems intended for various environments. It contains numerous tests including tests for fire suppression systems used in mining and earth moving equipment. Some parts of this test are described below for full details the reader is referred to the test standard.

For the fire test, a test enclosure is constructed out of plywood boxes. This has the volume, height or area, as well as openings corresponding to the maximum capacity of extinguishing system unit, as stated by the extinguishing system’s manufacturer. The system must be installed according to its specified maximum limits e. g. regarding nozzle placement, number of connections and tubing diameter and length. The extinguishing agent container must be filled and pressurized according to normal operating conditions. Prior to the test, the container is stored at its minimum permitted storage temperature for at least 16 hours, after which it is required to undergo the Class A and/or Class B fire tests. Beyond fire testing, the standard includes a number of other requirements, including several component tests.

4.7.1 Class A fire test

The fire source in this test consists of two wood cribs measuring 0.3 m × 0.3 m × 0.3 m. The cribs are placed in the area within the plywood box space considered to be the most challenging from a firefighting point of view. This is investigated prior to the test by determining which part of the enclosure receives the least amount of extinguishing agent. The two cribs are placed on four bricks, one at each corner of the cribs. Approximately 115 g of shredded newspaper is placed under each crib, after which 236 ml of ethyl alcohol is poured over the crib and the paper and ignited. After ignition, the cribs are left to burn for 2 minutes before the extinguishing system is activated manually.

4.7.2 Class B fire test

The fire source used in this test consists of 10 cm high cups containing heptane or heptane and water. The cups, having diameters of 7 – 10 cm, are placed at the corners of the test enclosure. The number of cups is determined by the requirements of the specific test. The space also contains one larger rectangular heptane tray, the size of which is determined by the testing space openings. If the openings exceed 5% of the space's total wall surface, the area of the heptane tray shall be 0.46 m^2. The tray is then positioned in the area least accessible to the extinguishing system. An additional tray, measuring 0.3 m in width with a length matching that of the testing chamber, is placed along one side (see Figure 12). The extinguishing system is activated manually after 30 seconds pre-burn time.

If the tested system is designed to discharge automatically, an automatic extinguishing test must also be performed. A 0.23 m^2 heptane-filled tray is ignited and the tested system is required to put out the fire automatically within 1 minute.

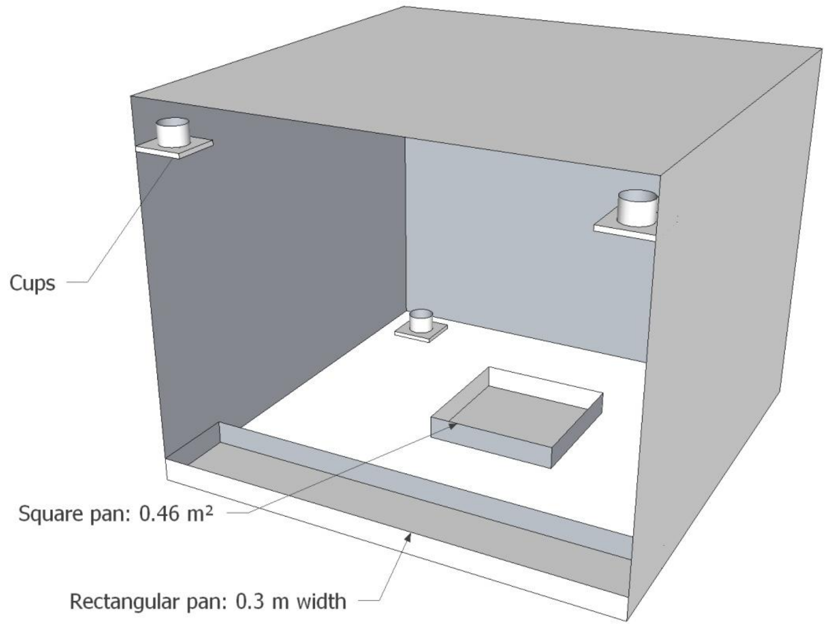


Figure 12 An example of a test chamber for Class B fire test, based on information from UL 1254 .

4.8 SP method 2377

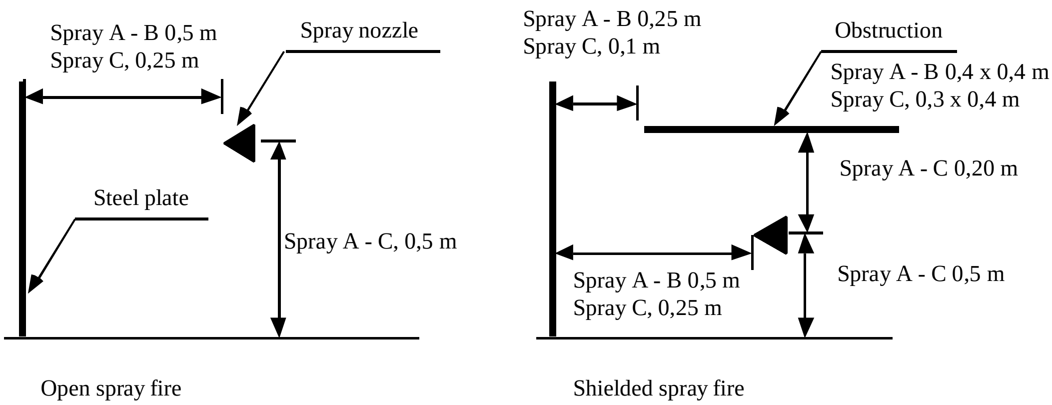
This method evaluates the extinguishing performance of water-spray systems in small machinery spaces [33]. The test is divided into three classes, according to the size of the machinery space for which the system is intended. Class I tests extinguishing systems intended for spaces up to 5 m^3, while classes II and III includes spaces up to 50 m^3 and 250 m^3, respectively.

A full-scale test chamber is constructed, using non-flammable materials. The ventilation system is assumed to be turned off during extinguishment and the enclosure is assumed to have small openings only.

The test evaluates the system's extinguishing properties as applied to Class B fires (spray and pool fires) as well as Class A fires (fires in small wood cribs). The test method states that since small fires are generally more difficult to extinguish than large fires for water spray systems, this test method contains mainly small test fires. Various fire scenarios are used, according to the size of the machinery space, the system is tested depending on whether the system has unlimited water access or not, and whether the system is manually or automatically triggered. Larger fire sources are used for the higher test classes. A total of eight different fire sources are used.

Re-ignition attempts are conducted by placing a 4 mm steel plate in front of the spray fire, allowing it to heat up the plate. Once the fire has been extinguished, the plate is sprayed for an additional 10 seconds to simulate the risk for re-ignition. Both open and shielded (hidden) spray fires are used in the test, see figure 13.

Each fire source is tested separately. A maximum of nine tests are performed to obtain a final result.



Figur 13 Spray fires in SP-method 2377.

5 Design considerations for the test method

5.1 General comments on testing

A method to test extinguishing capacity can be designed according to different principles. One way is to establish a minimum level of required extinguishing capacity and test the system in relation to this level. Another method is to measure the system's maximum capacity and determine its limitations based on the testing results obtained from various scenarios. This approach could be called "test for failure". Different scenarios are studied in which the demands on the system are gradually increased until the system no longer passes the test. Both of these two approaches have been used in designing the test method described here.

5.1.1 Full scale or small scale testing?

An extinguishing system may be tested in full or reduced scale. Both approaches have their advantages and can yield different types of information. In a small-scale test, for example, a nozzle may be tested separately, which makes it cheaper and easier to measure a specific property of the system. A full-scale test, on the other hand, can give information about how well the whole system works in the complex environment in which it is to be installed. Here we suggest a test method based on full scale testing, but with the option to perform complementary small-scale testing to give supplementary data at the component level.

5.1.2 Repeatability and reproducibility

It should be possible to use a test method at different times and places, with different operators and still obtain the same results. To achieve this, the method has to be well defined. This means that all details concerning the method should be clearly described and explained so that no decision-making is left to the testing personnel. A repeatable test implies that the same results can be obtained at the same facility independent of who runs the tests. A reproducible test implies that the same results can be obtained from tests run at different facilities. It is important that test methods are both repeatable and reproducible to ensure objective results.

5.2 Testing extinguishing systems for engine compartments in buses and coaches

This test method will be used to measure fire extinguishing capacity under realistic conditions. It cannot be used to determine how well the extinguishing system is installed or works on a specific bus. Furthermore, specifics such as whether the engine is mounted lengthwise or sidewise in the motor room are not crucial and do not change the basic test set-up. Rather, the test set-up allows the most severe scenarios to be identified and simulated. In order to make the test *appear* realistic, it is important that the test model looks like an engine compartment but in practice the details of the "dummy" engine within the test compartment are not crucial to simulation of relevant extinguishing challenges for the systems being evaluated. The method should point at advantages and disadvantages in different extinguishing systems and identify necessary improvements in sub-standard systems. Therefore, the method needs to contain several different classes of performance and a lowest acceptable class for installation in different situations.

Bus engine compartments may be designed in many different ways, but they have enough commonality to make a general test method useful. Below are some of the factors affecting the fire and extinguishing processes:

- The presence of a fan supplying oxygen
- The presence of apertures
- The presence of hot surfaces (and their temperature)
- The high working temperature in the engine compartment
- The presence of several flammable liquids and other compounds
- The risk of spray fire
- The presence of electrical cabling and the risk of short circuits
- The presence of complex geometries that may conceal fires
- The risk of re-ignition after extinction

Furthermore, the properties of the engine compartment may differ depending on:

- Geometry and compartment size (typically 2 – 5 m^3)
- Size of the apertures (typically varies between less than 1 to 5 m^2)
- Degree of compactness
- Fuel selection
- Degree of fire-preventive geometry*
- Temperature
- Motor fan configuration
- Service level

* More or less fire-preventive geometries can, for example, be achieved by separating hot components from fuel supply tubes.

5.2.1 Engine compartment properties that affect extinguishing capacity

The test has to be applicable to different types of extinguishing systems and not to favor or disadvantage certain extinguishing agents over others. Several properties of the engine compartment affect different agents positively or negatively, e.g.:

(i) hidden fires in a cramped space distinctively disadvantage agents that should hit the fire directly, whereas extinguishing agents that fill the entire compartment (total flooding), such as gaseous agents, are unaffected;

(ii) a high airflow disadvantages agents that are easily aired out, but has a significantly lesser affect on agents consisting of heavier particles;

(iii) a warm compartment with hot surfaces can favor water-based extinguishing systems that work better when evaporated, but may disadvantage agents that are degraded by the heat;

(iv) large fires are challenging for agents consisting of small particles that may not penetrate the fire plume; and

(v) smoldering fires are problematic for agents operating by creating an inert atmosphere in the compartment, since smoldering fires can survive at low concentrations of oxygen.

The main objective when designing the test method is to create a realistic method. The only way to ensure that extinguishing agents are compared in terms of necessary performance is to perform a variety of scenarios which mimic those which might realistically arise in a bus or coach engine compartment. This is discussed in more detail below.

5.2.2 Testing variables

An extinguishing system may work well under certain conditions, while failing to do so under others. Thus, it is important to test the system's performances under various circumstances. Based on fixed nozzle positions, the following variables have been identified as important to change between tests:

- Ventilation level
- Aperture sizes
- Types of flammables
- Heat release rate and size of fire sources
- Fire source placement and degree of obscuring
- Hot surface and test chamber temperature
- Net volume, i.e. free air volume

Importantly, these variables are not independent, but affect each other. Furthermore, it is relevant to vary the condition of the extinguishing system itself, e.g. investigating its functionality under realistic malfunction conditions, e.g. with a blocked nozzle and at reduced pressure or flow of extinguishing agent. The significance of such variations needs to be evaluated through testing before it is possible to determine whether this might be an important part of a future test method.

5.2.3 Test chamber geometry

The test chamber should have a size and shape similar to a real engine compartment. A dummy engine, exhaust manifold and muffler may be placed in the chamber to simulate a "dummy" engine. Installing a fan will ensure a realistic level of ventilation, as will bulky objects that affect ventilation and create blind spots for the extinguisher's ejection nozzles.

5.2.3.1 Simulated exhaust manifold

A simulated exhaust manifold can be manufactured out of steel and heated using an LPG burner or electric heating, prior to the test. A maximum temperature of approximately 640° C should be obtainable. The hot manifold can be subjected to a diesel spray during the test, in order investigate how well the extinguishing system protects against re-ignition.

5.2.3.2 Simulated muffler

A muffler often contains a particle filter as well as a catalytic converter, resulting in high temperatures that affect the overall engine compartment temperature. A simulated muffler should be heated to a temperature of about 300° C.

5.2.3.3 Engine orientation

Utilizing an upright dummy engine results in two spaces being formed, one on each side of the engine, which require protection by the extinguishing system. This type of set-up is probably a greater challenge to an extinguishing system than a horizontally-mounted simulated engine.

5.2.3.4 Test chamber temperature

It is important to ensure that the temperature of the test chamber matches that of a real bus or coach engine compartment, since the behavior of the fire and the capability to extinguish is affected by the ambient temperature. However, the temperature needs to be strictly controlled in order not to become too high. The suppression system needs to function adequately both in hot and cold conditions, since engine compartment temperatures vary considerably. Consequently, testing should simulate both “cold-engine fires”, e. g. fires caused by electrical short-circuits, as well as fires occurring when the engine is running hot at full load.

5.2.3.5 Walls and ceiling

The walls and ceiling of the test chamber can be constructed from thin steel plate, or some other non-flammable material that can be easily rinsed between tests. The chamber should have a large window, allowing the testing process to be observed. The ceiling should be stepped, see Figure 3, as this is a common layout in real engine compartments, and might have an effect on test results.

5.2.4 Test chamber ventilation

5.2.4.1 Fan settings

The various fan power settings should be tested. High fan settings can be challenging for an extinguishing system, as well as low ones. A completely turned-off fan can cause problems for some systems, reducing the dispersion of the extinguishing agent.

5.2.4.2 Apertures

Since aprons normally installed below the engine are commonly missing, leaving the engine compartment in effect without a floor, it is important to investigate how this affects the properties of extinguishing systems. Therefore tests should be conducted both with and without a compartment floor.

5.2.4.3 Hot incoming air

Air entering a real engine compartment is heated in the radiator to a temperature of approximately 80 – 100 ºC . Previous work, performed during the development of the test described in SP report 2008:41 [20], indicates that the temperature of the incoming air does not have a significant impact on the test results, since the air is heated by the fire sources anyway. However, this merits further investigation.

5.2.5 Fire Sources

Different flammable compounds and materials burn in different ways, and different extinguishing agents have varying capacities to extinguish different types of fires. According to the European standard for handheld fire extinguishers, fires can be subdivided into different classes based on the properties of the fuel[34, 35]. The three first classes of fires listed in the standard commonly occur in engine compartments:

- **Class A:** Fires in solid materials, mainly organic materials that usually both smolder and form flames when burning. Wood, textiles, rubber and some plastics belong to this category.
- **Class B:** Fires in liquids and in solid materials that may assume liquid state. Typical examples are oil, diesel, and ethanol. These substances burn with flames but without smoldering, i.e. the surface temperature of the fuel is never higher than its boiling point.
- **Class C:** Fires in gases, such as in natural gas and biogas. As with liquids, these burn with flames without smoldering. However, gaseous fuels obviously do not have to be evaporated prior to combustion.

Although all three types of fires may occur in an engine compartment, Class B Fires are most common. Engine, hydraulic oil, and diesel oil are often moved through pressurized lines and leakage therefore often yields a spray fire. Smoldering fires usually occur in a later phase of the fire process [20]. Sometimes an additional category of fires are added: Electrical fires, e g fires involving electrical cables.

It is important that the testing method covers all significant types of fires. Table 4 lists the different types of fires according to fire class. Note that a high pressure diesel spray burns in a similar manner as a gas fire and is a hybrid between Class B and Class C.

Table 3 Subdivision of fires into fire classes.

Class	Fire characteristics	Example in diesel fueled engine compartment	In test chamber simulated by:
A	Flaming and smoldering fire	Wood, textiles, paper, rubber, plastics	Wood pellets, fibreboard, wood shavings or rags (maybe damp with diesel), rubber (e g EPDM), plastics
B	Flaming	Diesel, engine oil, hydraulic oil, brake fluid, glycol,	Diesel, heptane, hydraulic oil,
B/C	Intensely flaming	Diesel and oil spray	Diesel and oil spray

The primary objective of this report is to set up a framework for a test method for extinguishing systems in engine compartments in diesel-powered buses and coaches. However, such a method should also be useful for testing the extinguishing efficiency in engine compartments with other fuels, possibly with slight adjustments. Since different types of diesel and engine oil are used in different countries, the specific fuel of interest must be defined in the test method.

5.2.6 Re-ignition attempts

The fire sources can be lit manually using a pilot flame prior to the test. During the test, re-ignition attempts can be made, for example by:

- Spraying fuel on hot surfaces.
- Admitting oxygen to the test chamber to allow hot fire sources to re-ignite.
- A spark or pilot flame attempting to re-ignite the fire source.

5.2.7 Nozzle positioning

The engine compartment is often cramped and filled with different engine components. In a real situation it is not always easy to cover all areas with the extinguishing system or to know exactly where the fire will occur. Therefore, to simulate real fire conditions it is important to design the test method so that it prevents the system manufacturers from optimization of their system classification by placing nozzles right above fixed fire sources. This challenge can be addressed in two ways, i.e. by:

- Using so many fire sources that there are not enough nozzles to aim at all potential ignition sources in every test. Depending on the extinguishing agent, the manufacturers may use about 2-16 nozzles per bus engine compartment [16, 17].
- Placing demands on the positioning of the nozzles. For example, only in the ceiling or on the walls, or not within a given distance from the ignition sources used in the test set-up.

Other, less attractive, ways of solving this problem include, e.g.:

- Placing the fire sources as far away as possible from the pre-positioned nozzles. This can, however, lead to difficult distance calculations.
- Spreading fuel in a random pattern over the engine. This, however, makes the test non-repeatable and is therefore not desirable.

For extinguishing systems with many nozzles (e.g. more than 10), part of the extinguishing strategy is to customize the nozzle positioning based on identified risks associated with that particular engine compartment. In systems with fewer nozzles a standard location is more common, e.g. the upper corner of the compartment.

Furthermore, there are extinguishing systems without nozzles. Instead they contain a tube containing extinguishing agent running through the engine compartment. At high enough temperature the tube breaks up, spraying extinguishing agent over the fire at high pressure in the process. Such a combined detection and extinguishing tube may, however, be difficult to test with a pre-burn time and pre-defined time of agent release.

5.2.8 Extrapolation

The amount of extinguishing agent and the number of nozzles that were used in the test should also be required when the extinguishing system is installed in a real engine compartment in the case when the engine compartment is equivalent in size with the test chamber. For compartments of other sizes these two parameters might need to be changed. The extrapolation might theoretically be done based on one or more of the following considerations:

- The amount of extinguishing agent can be calculated based on the total volume or the net volume (the free air volume not counting the volume of engine and fittings) and the number of nozzles can either remain unchanged or be calculated based on the total volume.
- Tests can be performed at different engine compartment volumes (e.g. 2, 4 and 6 m^3). The amount of extinguishing agent and the number of nozzles required is then interpolated based on the results from these tests.

It should be emphasized that there is no validated scientific theory for how such extrapolations or interpolations should be calculated. More research is required before the results from a test can be used to predict requirements on different, especially larger, engine compartments.

5.2.9 Measurements

Several relevant parameters can be measured during and after the test, e.g. whether a fire source is extinguished, time to extinction, cooling or mixing in the engine compartment. Similarly, re-ignition should be observed. The temperature of hot objects should be measured and controlled to evaluate the extinguishing system's capacity for cooling hot surfaces.

The evacuation time of the extinguishing system should be noted. The difference between the time to extinction and the evacuation time of the extinguishing agent is an important parameter as it defines the potential for the system to extinguish a fire. If the fire is readily extinguished before the system has evacuated all extinguishing agent, the system has a good safety margin.

5.3 Miscellaneous

5.3.1 A bus that overturns

Should the bus or coach be involved in a roll-over incident, there is a risk that a nozzle will be pointing in the wrong direction since a potential pool fire then might occur on the side or ceiling of the engine compartment. The outcome of such a scenario can be tested by turning the entire test chamber upside down or on its side.

5.3.2 Buses with the exhaust system inside the ceiling

It is not uncommon that the exhaust system of American buses runs through the ceiling rather than through the floor as in European buses. A ceiling-mounted exhaust system may in case of fire create problems as it can potentially function as a chimney.

5.4 Other requirements

An extinguishing system needs several features to be able to work in such a challenging environment as a bus engine compartment. The system must: 1) be able to rapidly *detect* a fire, 2) effectively *extinguish* the fire and prevent re-ignition, and 3) have *high quality components*. Should one if these three basic elements fail, the fire extinction efficiency will be severely compromised. This report is concerned with fire extinction efficiency only, but the other two requirements will be commented on below. Furthermore, an authorized firm should inspect the system regularly to ensure that it is intact, has not lost pressure, does not have any broken lines, and that nozzles are not blocked by dust or dirt. In addition, the system must be adequately installed to ensure that it covers significant potential fire hazard in the engine compartment.

5.4.1 Detection requirement

The extinguishing system's ability to detect a fire is absolutely crucial to the outcome of an accident. This ability might give the driver an early warning, thereby allowing him to turn off the engine and evacuate the bus. In some cases, the fire might go out itself if the fan and engine are shut down at an early point. Further, the extinguishing system may be better able to extinguish the fire by getting an early start on fighting it. Then again, the system has to avoid giving false alarms from an over-heated engine or from exhausts from nearby vehicles.

5.5 Component requirements

It is important that relevant tests are also performed at the component level. The extinguishing system's components should be able to handle several years of vibrations, moisture, dirt, and temperature changes from below freezing to the engine compartment running temperatures. Otherwise there is a risk that the system will not work once the fire occurs.

5.6 Development and further research

During development of the test method the test chamber should be adaptable, and a sensitivity analysis conducted to study the difference between alternative positioning of the fire sources, openings and objects in the chamber. Variations due to changes in temperature and ventilation should be examined. The presence of blockages and baffles should also be studied, to determine whether they give a shadow effect similar to that of real objects in a bus engine compartment, as well as whether the test's degree of complexity is relevant or warranted.

Further, one should examine which conditions should be imposed on the extinguishing system, in addition to the requirement for an approved fire extinguishing capability.

6 Test method proposal

6.1 Introductory explanation of the proposed method

Below is a proposal for a test and evaluation method for extinguishing systems in bus and coach engine compartments. The goal is to provide a common test method for any type of engine compartment extinguishing system. In order to finalize the test design, extensive trials must be performed. The method proposed here does not purport to be all-encompassing, and should therefore be considered as a draft.

6.2 Geometry

An illustration of the proposed test chamber is shown in Figure 14. The total volume of the test chamber is approximately 4 m^3, which is typical for a larger engine compartment. The width is 2400 mm and the depth is 1500 mm. In order to recreate a realistic step-like profile, the chamber has a two-level ceiling. At its lower part, the ceiling height is 1000 mm and at the higher part, the rear of the chamber, it is 1300 mm. The chamber's rear (the open part to the right in Figure14) models the rear hatch of the engine compartment. The chamber is raised 300 mm above ground level to mimic the position of a typical engine compartment.

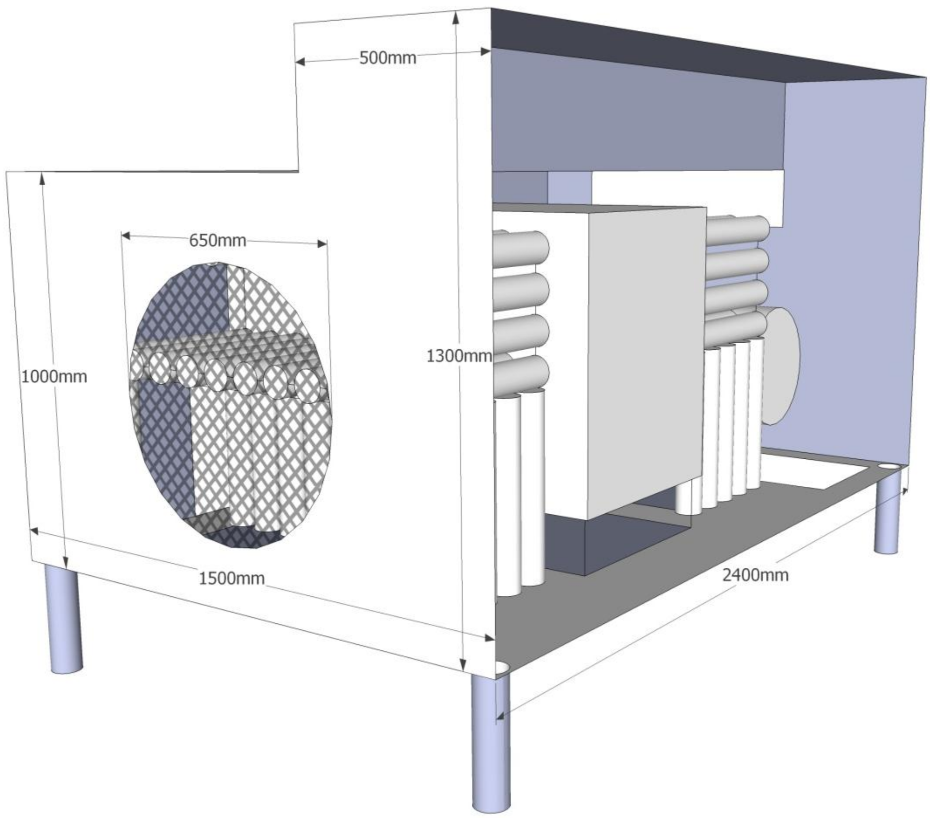


Figure 14 The test chamber in profile.

Apart from fire sources, the test chamber features the following objects (see Figure 15):

- Ventilation fan

- Engine mock-up
- Simulated exhaust manifold
- Simulated muffler
- Tubular obstructions

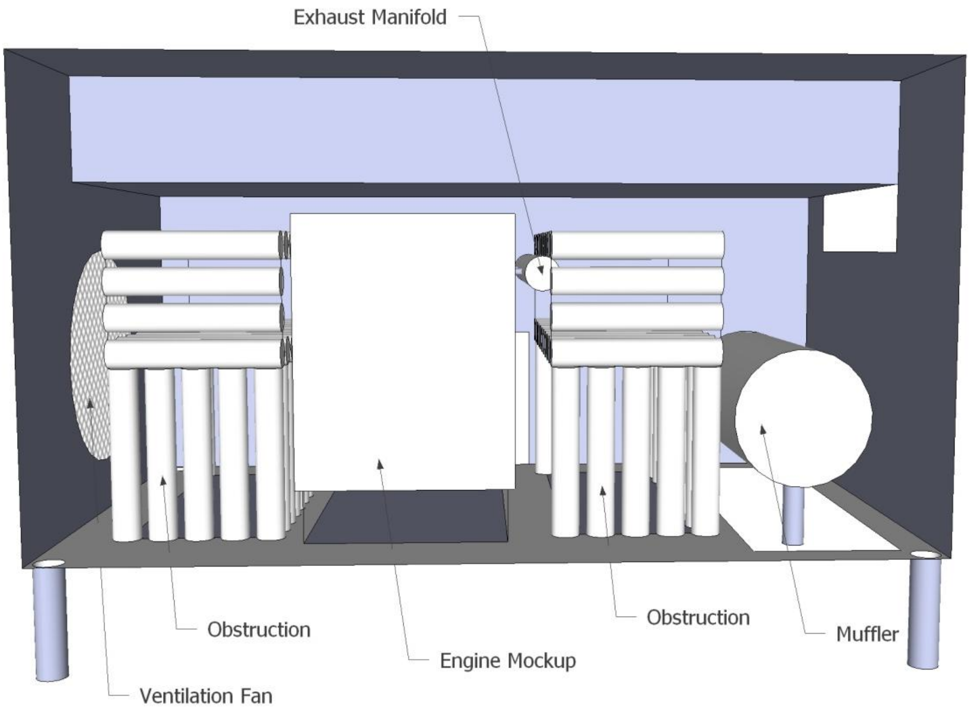


Figure 15 Test chamber geometry as seen from the rear, that is looking into what corresponds to the rear hatchet of the bus.

6.2.1 Fan

A 0.70 m diameter ventilation fan is positioned outside the chamber. There are four air flow settings:

A) No air flow: simulates fan off
B) Low air flow (1 kg/s) simulates idling engine
C) Normal air flow (3 kg/s): simulates engine at normal revs
D) High air flow (6 kg/s): simulates engine at full revs

6.2.2 Engine mock-up

An engine mockup measuring 1200 mm × 600 mm × 750 mm (depth × width × height) is positioned in the chamber. The mockup is constructed from steel plates, and heated to approximately 95 °C.

6.2.3 Manifold

A simulated exhaust manifold measuring 1000 mm × 100 mm (length × diameter), with a material thickness of 9 mm and a total exterior area of approximately 0.33 m^2 is fitted to the engine mockup. It is heated and three heating levels are used during testing:

A) No heating: simulates a cold manifold
B) Warm (approx 400° C): simulates a normal low engine load manifold temperature
C) Hot (approx 640° C): simulates manifold temperature at high engine loads

6.2.4 Muffler

A simulated muffler measuring 800 mm × 400 mm (depth × diameter), is mounted close to the wall opposite to the fan side of the simulated engine compartment. Two heating levels, simulating three conditions, are used during testing:

A) No heating: simulates a bus/coach with the muffler mounted outside the engine compartment or a still-cold muffler, soon after engine start
B) Hot (300° C): simulates maximum working temperature

6.2.5 Heat protection screen

A heat shield is fitted close to the muffler, replicating conditions in real engine compartments.

6.2.6 Obstructions

Several tubes, simulating various obstructions affecting the extinguishing system's discharge pattern as well as engine compartment airflow, are placed in the test chamber. Each tube measures 480 mm × 80 mm (length × outside diameter). The tubes are mounted at a distance of 20 mm from each other. The tubes are sealed in order to prevent fuel and extinguishing agent from entering.

6.2.7 Apertures

The test chamber has several apertures, and two different levels of opening size, see Figure 16:

a) One aperture measuring 200 mm × 2300 mm (height × width) at the top of the rear wall (that is, the rear hatched of the bus).
b) A wall aperture, placed in front of the engine mockup, measuring 500 mm × 800 mm (height × width).
c) A floor aperture measuring 1300 mm × 400 mm (depth × width).
d) A wall aperture, on the wall opposite of the fan side, measuring 800 mm × 200 mm (depth × height).

The total aperture area is approximately 1.5 m^2. This is referred to as "normal apertures" in the test protocol. Given the fact that engine compartment floors are commonly absent, a further aperture may be added:

e) Floor removed, creating an aperture measuring 1300 mm × 2200 mm (depth × width), framed with the floor frame girders. This increases the total aperture area to approximately 4 m^2, referred to as "large apertures" in the test protocol.

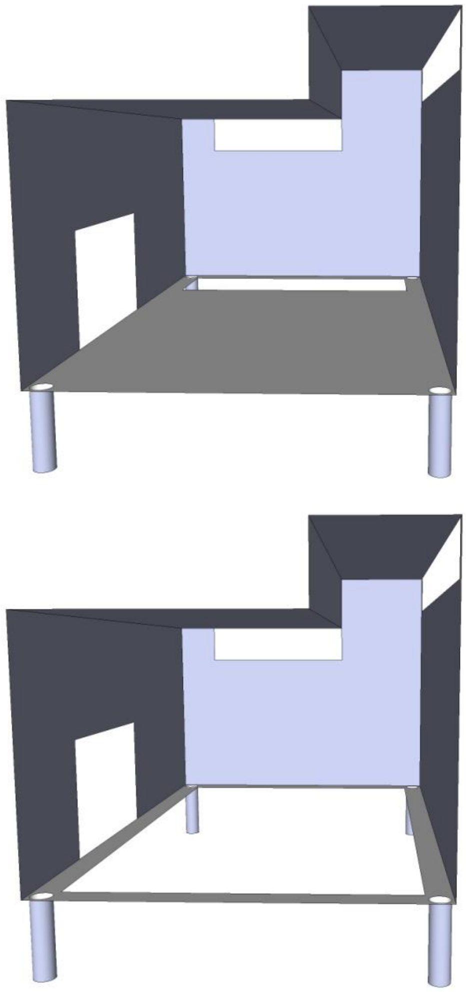


Figure 16 Test chamber with normal and large apertures respectively. The test chamber is seen from the fan side.

6.3 Temperature

Table 4 shows the three temperature scenarios included in the test. The cold scenario simulates a fire occurring before the engine has reached normal operating temperature. The reason for ignition in this case might e g be a short circuit. The warm and hot scenarios simulate fires occurring with the engine running at normal and high loads, respectively. Many engine compartments have separate hot and cool sides, which is simulated by placing the exhaust manifold and muffler on the same side of the test chamber.

Table 4 Temperatures used in the test.

		Cold	Warm	Hot
Simulated component	Engine	Not heated	95° C	95° C
	Manifold	Not heated	400° C	640° C
	Muffler	Not heated	Not heated	300° C

6.4 Test fires

Test fire sources used are pool fires, spray fires, and fires in thermoplastic and fibrous material. Figure 17 to 19 show their positions in the chamber. Which fuels to use, together with the size and placement of the fire sources to be used in the final test method needs to be investigated in future experiments.

6.4.1 Pool fire

The fuels used in pool fire tests are diesel fuel and hydraulic oil. The former is the most common bus and coach fuel, while the latter is used due the fact that it is relatively difficult to extinguish once ignited. In order to create a repeatable heat release, and to prevent the fire vessel from buckling, a 10 mm layer of fuel is used on top of 20 mm of water. The flammable fluid is ignited centrally for 10 seconds, using a 15 kW propane flame, and then serves as the ignition source for the additional fire sources used in the test (Low Density Fibreboard (LDF), polypropylene (PP) and a burning spray).

6.4.2 Spray fire

Diesel fuel is sprayed at various pressures and flow rates. The sprays are started 10 seconds before the extinguishing system is discharged and ignited by the pool fire below them. Spray no. 13, which is directed towards the simulated exhaust manifold, continues to spray throughout the test, in order to investigate whether re-ignition will occur.

6.4.3 Thermoplastic

Polypropylene is a common thermoplastic in engine compartments, and is chosen to represent this class of materials in the test. Polypropylene with fiberglass content is used for increased strength. The PP sheets, which are 300 mm × 150 mm and 5 mm thick, are ignited by the underlying pool fires.

6.4.4 Fibrous material

Low Density Fibreboard, a fibrous cellulosic material, is used to simulate all the fibrous materials used in an engine compartment, e.g. the textile material used for soundproofing, and the plywood commonly used as ceiling liner. The LDF boards, which are 300 mm × 150 mm × 5 cm thick, are ignited by exposing them to by the underlying pool fires.

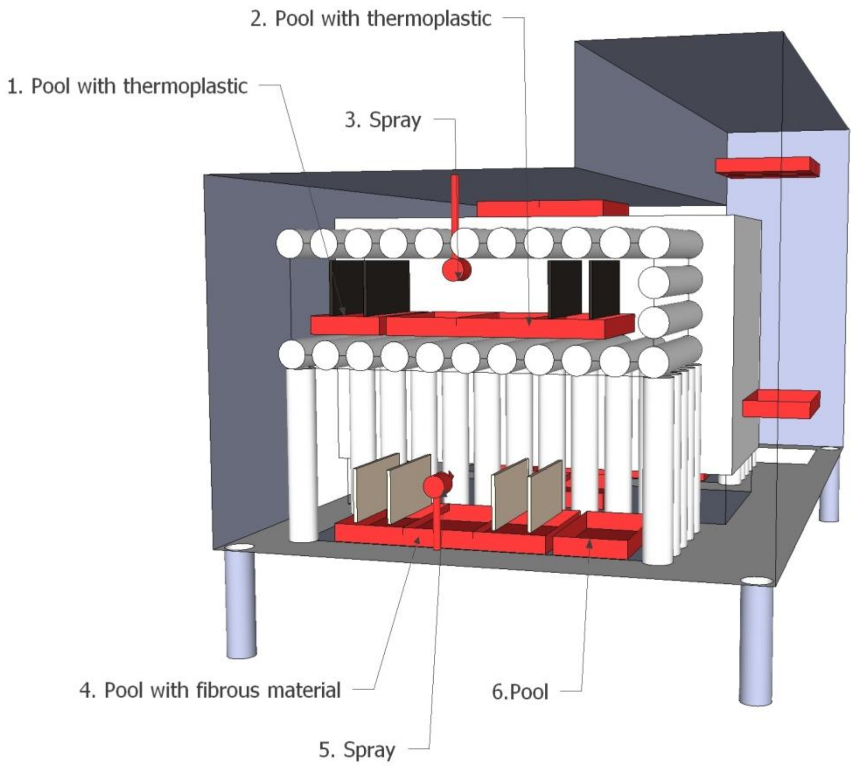


Figure 17 The test chamber, view from the fan side.

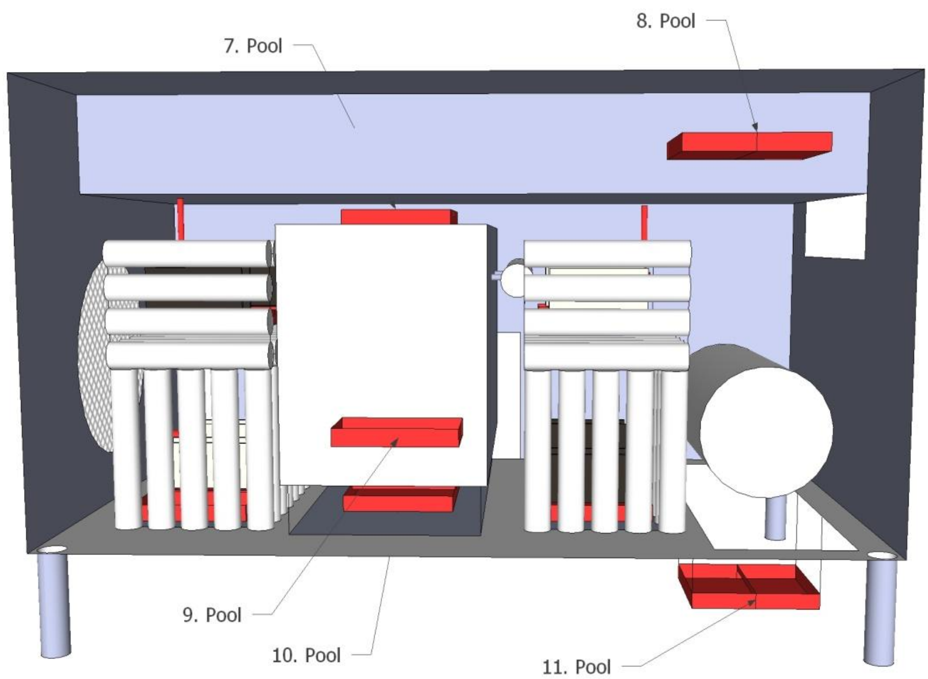


Figure 18 The test chamber, backside view.

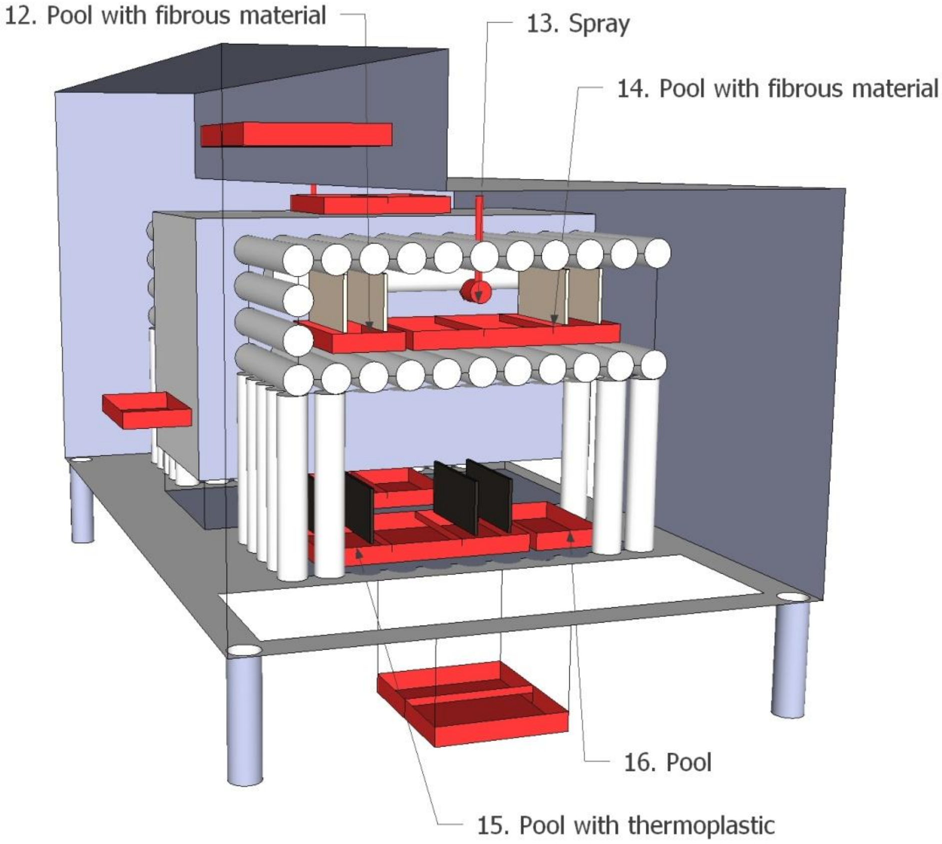


Figure 19 The test chamber, view from the side opposite of the fan.

6.4.5 Test scenario

The tests are conducted according to various set scenarios, testing at two fan power levels within each. In total, eight different tests are performed. For a definition of the temperature scenarios see Table 4. The fire effect calculations are *rough* estimations, providing an approximate value only. These calculations are detailed in Appendix 1.

6.4.5.1 Tests 1 and 2

Tests 1 and 2 simulate an engine compartment with the ventilation fan off. The test fires are presented in Table 5.

Table 5 Test fires in Test 1 and 2

Test	Airflow	Aperture size	Temp scenario	Fire effect	Position	Pre-burn time
1	**0 kg/s**	**Normal**	**Cold**	**73 kW**		
	Diesel pool (0.2 m × 0.35 m)			46 kW	6	30 sec
	Hydraulic fluid pool (0.2 m × 0.35 m)			27 kW	16	30 sec
2	**0 kg/s**	**Large**	**Warm**	**460 kW**		
	4 diesel pools (0.4 m × 0.35 m each)			4 × 115 kW	7, 8, 10, 11	30 sec

6.4.5.2 Tests 3 and 4

Tests 3 and 4 simulate an engine compartment with the engine idling. The test fires are presented in Table 6.

Table 6 Test fires in tests 3 and 4.

Test	Airflow	Aperture size	Temp scenario	Fire effect	Position	Pre-burn time
3	**1 kg/s**	**Large**	**Warm**	**152 kW**		
	Diesel pool (0.2 m × 0.35 m)			46 kW	6	30 sec
	Diesel pool (0.2 m × 0.35 m) + 2 LDF boards			106 kW	12	1 min
4	**1 kg/s**	**Normal**	**Hot**	**809 kW**		
	Diesel spray (0.5 kg/min, 80 bar)			260 kW	13	10sec
	Diesel pool (0.6 m × 0.35 m) + 2 LDF boards			255 kW	14	1 min
	Hydraulic fluid pool (0.6 m × 0.35 m) + 4 LDF			294 kW	15	1 min

6.4.5.3 Tests 5 and 6

Tests 5 and 6 simulate an engine compartment with the engine at normal revs. The test fires are presented in Table 7.

Table 7 Test fires in tests 5 and 6.

Test	Airflow	Aperture size	Temp scenario	Fire effect	Position	Pre-burn time
5	**3 kg/s**	**Normal**	**Cold**	**160 kW**		
	Hydraulic fluid pool (0.2 m × 0.35 m) + 2 PP boards			114 kW	1	1 min
	Diesel pool (0.2 m × 0.35 m)			46 kW	9	30 sec
6	**3 kg/s**	**Large**	**Hot**	**1297 kW**		
	Hydraulic oil pool (0.6 m × 0.5 m) +2 PP boards			207 kW	2	1 min
	Diesel spray (8 bar, 1.0 kg/min)			520 kW	3	10 sec
	Diesel pool (0.6 m × 0.35 m) + 4 LDF boards			315 kW	4	1 min
	Diesel pool (0.6 m × 0.35 m) + 2 LDF boards			255 kW	14	1 min

6.4.5.4 Tests 7 and 8

Tests 7 and 8 simulate an engine compartment with the engine at high revs. The test fires are displayed in Table 8.

Table 8 Test fires in tests 7 and 8.

Test	Airflow	Aperture size	Temp scenario	Fire effect	Position	Pre-burn time
7	**6 kg/s**	**Large**	**Warm**	**321 kW**		
	Hydraulic fluid pool (0.6 m × 0.35 m) + 4 PP boards			294 kW	15	1 min
	Hydraulic fluid pool (0.2 m × 0.35 m)			27 kW	16	30 sec
8	**6 kg/s**	**Normal**	**Hot**	**2075 kW**		
	Diesel pool (0.6 m × 0.35 m) + 4 LDF boards			315 kW	4	1 min
	Diesel spray (8 bar, 2.5 kg/min)			1300 kW	5	10 sec
	4 × diesel pools (0.4 m × 0.35 m)			4 × 115 kW	7, 8, 10,	30 sec

6.4.6 Nozzle placement

The nozzles may be positioned freely within 100 mm of the lower ceiling level, and no closer to the side walls than 150 mm. Nozzles may also be placed on the rear wall, 50 –

550 mm from the lower ceiling level and within 100 mm from the rear wall and a at least 150 mm from the side walls, see Figure 20 . Nozzles may only be directed to an angle of 0° - 90°, i.e. somewhere between straight down and straight ahead. The extinguishing system must, as far as possible, be installed according the manufacturer’s instructions, and yet comply with the above limitations.

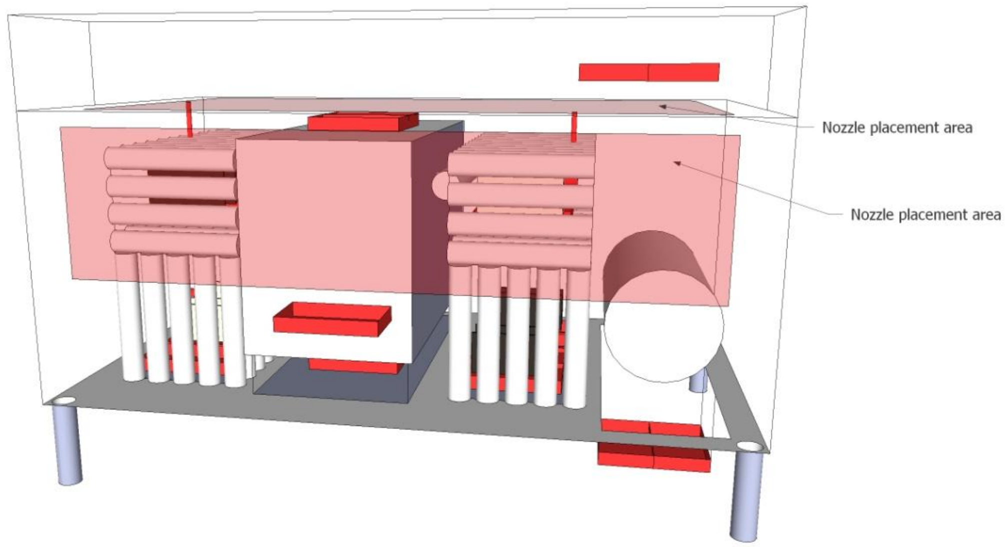


Figure 20 Permitted areas for nozzle placement.

6.4.7 Measurements

Measurements are taken of the temperature above the test fires to determine whether the test fires are extinguished. A thermocouple is positioned 0.05 m above the center of each pool fire. Four evenly spaced thermocouples are positioned on the exhaust manifold, muffler and engine mockup. To ensure a consistent temperature throughout each test scenario, thermocouples are also placed in various other positions in the test chamber, i.e. on the walls and ceiling. The flow and emptying time of the extinguishing system is also measured during the test.

6.4.8 Test procedure

The test chamber is heated to the temperature relevant to the test scenario at hand. The fire sources are ignited, and then allowed a pre-burn time according to Table 5 – Table 8. After this period, the extinguishing system is released manually. From the time the system is activated, each test lasts 2 minutes. During this time period, measurements are made, and any fire source re-ignition is observed. In scenarios requiring the fan to be active, this continues to ventilate the test chamber for the duration of the test. If the scenario calls for a diesel spray, this is deactivated after extinguishing, except for spray nr 13, which will create repetitive diesel sprays against the exhaust manifold throughout the test.

6.4.9 Results

Whether the fire has been extinguished is determined by the temperature above the test fires. The final test results depend on the number of fires extinguished, as well as whether any of them re-ignited. Scoring is made according to a graded scale. Relevant score and requirement levels need to be investigated in future experiments.

6.5 Security aspects

The utilization of spray and pool fires is inherently hazardous. There is a risk that the progress of the fire becomes explosive. This may occur as the extinguishing agent is ventilated out of the test chamber, being replaced by fresh oxygen, re-igniting the fire sources. As a security measure, the roof and walls of the test chamber could be featured with pressure-release hatches.

7 Conclusions

The risk of fire in buses and coaches is significant enough motivate the establishment of an international requirement for extinguishing systems in engine compartments and auxiliary heaters. In order to introduce such a regulation, relevant performance standards for such systems must be defined. Further, such standards must include a method for the testing of the extinguishing capabilities of such systems. Designing such a test method presents several challenges:

- Developing a realistic test method with a relevant level of difficulty assuring that an extinguishing system that passes the test will also have sufficient power to suppress a fire in a real engine compartment
- Constructing an easily reproducible geometry that is still complex enough to accurately model a real engine compartment.
- Creating realistic airflows, temperature profiles, and fire processes
- Creating a test that does not favor or disqualify any specific manufacturer of extinguishing systems, featuring fair requirements concerning, e.g. nozzle placement.

A successful extinguishing system needs to be able to both detect that a fire has started, and to suppress it, since both factors are instrumental to the outcome of the fire process. Delayed detection may cause the fire to increase beyond the extinguishing capacity of the system. Inadequate suppression capacity may cause the fire to re-ignite. Therefore, qualified methods for the testing of both fire suppression and re-ignition protection are of the utmost importance.

In the continued work on the proposed test method, it would be advantageous if the number of test variables included could be reduced, in order to simplify the test without making it less accurate. Future experiments will demonstrate whether or not this is possible.

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35. EN 3, Portable fire extinguishers. Comité Européen de Normalisation, CEN, 2007.

Appendix 1: Calculations based on Swedish bus statistics

On page 10 in this report statistics, for Sweden, is given on average life spans of buses and estimated fraction of all buses that are involved in a reported fire. In this appendix the background for these figures are presented.

Table shows the total number of buses and the number of new entries of buses in Sweden for the period 2000 – 2009 [2].

Table 1　Total number of buses and new entries into the registry per year in Sweden [2].

Year	No. of buses	No. of new entries
2000	14417	1385
2001	14246	1187
2002	14013	1230
2003	13742	1187
2004	13363	1172
2005	13477	1252
2006	13643	1465
2007	13315	1051
2008	13474	1262
2009	13407	1225
Average	**13 710**	**1 242**

The average life span for the entire period is estimated as the ratio between the average total number of buses and the average number of new entries for the period:

Estimated average lifespan 2000-2009 = 13710/1242 = 11.04 years.

Table shows the number of reported bus fires [1, 2], in Sweden, and the percentage of all buses that these fires constitute for the period 2000-2009.

Table 2 **Number of reported fires in buses per year in Sweden [1, 2], and the percentage of all buses that these fires constitute.**

Year	No. of fires	% per year
1999	83	0.55
2000	105	0.73
2001	121	0.85
2002	123	0.88
2003	139	1.01
2004	125	0.94
2005	131	0.97
2006	162	1.19
2007	137	1.03
2008	139	1.03
2009	153	1.14
Average	**129**	**0.93**

The fraction of all buses that will undergo a reported fire in their lifespan is calculated as the risk for a fire, each year, multiplied by the life span.

$$\text{Estimated fraction of buses undergoing a reported fire 2000-2009} = 0.93 \cdot 11.04 = 10.3\%$$

This calculation assumes that no bus catch fire more than once.

Appendix 2: Calculations of estimated fire effect

Table 3 Nomenclature (units in brackets).

A	Pool fire area (m^2)
D	Pool fire diameter (m)
$k\beta$	Material constant (m^{-1})
m''	Burn rate (kg/s m^2)
m''_{∞}	Burn rate for a pool fire with large diameter (kg/s m^2)
$\dot{Q}$	Heat release rate (kW/s)
x	Degree of efficiency (-)
ΔH_c	Total combustion energy (kJ/kg)

Table 4 Material data for diesel fuel and hydraulic oil.

	Diesel	Hydraulic oil
Total combustion energy (ΔH_c)	$44400\ kJ/kg$	$39500\ kJ/kg$
Mass burn rate (m''_{∞})	$0.045\ kg/s * m^2$	$0.035\ kg/s * m^2$
Constant ($k\beta$)	2.1 m^{-1}	1.7 m^{-1}
Estimated degree of efficiency (x)	0.7	0.7

Equations from Karlsson & Quintere (2000):

$$\dot{Q} = A * m'' * \Delta H_c * x \qquad (1)$$

$$m'' = m''_{\infty} * e^{(1-kB*D)} \qquad (2)$$

$$D = 2\sqrt{A * \pi} \qquad (3)$$

$$\dot{Q} = m'' * \Delta H_c * x \qquad (4)$$

Calculation of heat release rate

The estimated fire effect on pool fires has been calculated using the formulas (1), (2) & (3) and the material data presented in Table 4.

Explanatory example: The area of a rectangular diesel pool with dimensions 0.4 m x 0.35 m is 0.14 m^2. Since formula (1) and (2) are based on circular pool fires, the diameter of a circle with the same area as the rectangle is calculated with equation (3). This diameter is determined to be 0.42 m. The diesel in the pool burn with a maximum mass loss rate of 0.027 kg/s*m^2, according to equation (2). The material data used in the equation can be find in Table 4. Diesel has a total energy value of about 44 MJ/kg. Since combustion in a fire usually not is complete and some residue remains, the degree of combustion efficiency is estimated to be 70% The maximum heat release rate in the pool fire is therefore estimated to be about 115 kW, according to equation (1). Note that these equations only gives a rough estimation of the heat release rate.

For a spray fire, the mass burn rate (m'') is estimated to be the same value as the stated fuel flow (e.g. 1 kg/min, which is 0.016 kg/s) and the efficiency is estimated to be 70%. The heat release rate has been calculated with equation (4).

Two polypropylene plates, described in section 7.5.3 has an estimated maximum heat release rate of 68 kW. Two low-density fiberboard, described in section 7.5.4 has an estimated maximum heat release rate of 60 kW.

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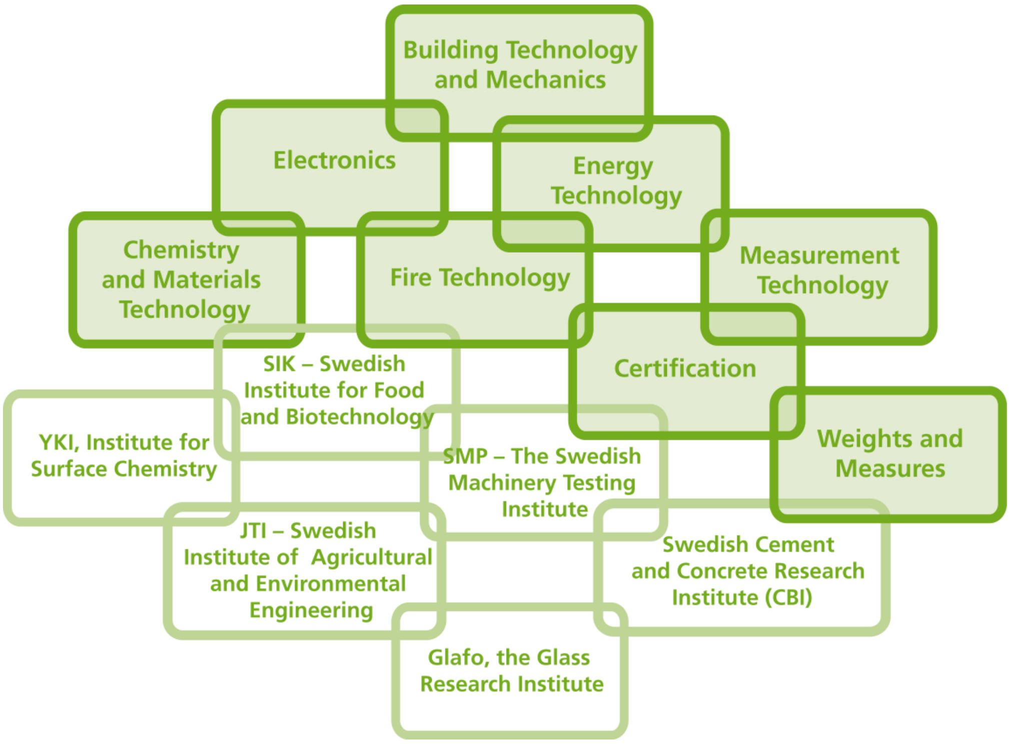

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