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Durability requirements for fire detectors mounted in engine rooms of heavy vehicles

A theoretical study

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Thesis for the degree of Master of Science in Engineering
Division of Combustion Engines
Department of Energy Sciences
Faculty of Engineering | Lund University

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This degree project for the degree of Master of Science in Engineering has been conducted at the Division of Combustion Engines, Department of Energy Sciences, Faculty of Engineering, Lund University.

Supervisor at the Division of Combustion Engines was Associate Professor Martin Tunér.
Supervisor at SP Fire Research was Ola Willstrand.
Examiner at Lund University was Professor Bengt Johansson.

The project was carried out in cooperation with SP Fire Research, SP Technical Research Institute of Sweden.

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Abstract

This thesis was carried out at the Division of Combustion Engines within the Faculty of Engineering at Lund University in collaboration with SP Technical Research Institute of Sweden. The thesis was part of a project funded by the FFI program of VINNOVA, with the goal of creating a standardized test method when it comes to fire detection systems mounted in engine compartments of heavy vehicles. As of today, there are certifications regarding the fire suppression system but no appropriate test method for fire detection systems has yet been implemented. A stepping stone in the right direction of creating a standard for fire detection systems is by first looking at the durability requirements for fire detectors that are to be mounted in engine rooms of heavy vehicles.

To better understand what can cause fire detectors to malfunction, a deeper knowledge of the operating principles of fire detectors is needed as well as which aspects influence the failure of detectors. The investigation is specified to engine compartments of heavy vehicles and to the physical phenomena arising in that environment. Six physical phenomena that arise in engine rooms due to the operating principles of the vehicle were seen as high priority aspects to be investigated further. These phenomena are: corrosion, ageing, heat and cold, vibrations and mechanical shocks, electromagnetic interference and finally the impacts of the intrusion of water, dust and dirt into the enclosures of electronic devices.

The goal of this thesis was to find appropriate testing methods that are applicable to fire detectors that are to be mounted in the engine compartments of heavy vehicles with respect to their durability requirements. Test methods that are best suited for each of the physical factors mentioned earlier were chosen after consultations with experts at SP. Following this, appropriate test parameters were set by studying already existing standards and having dialogues with representatives of heavy vehicle manufacturers. The test parameters and the resulting durability requirements that have been recommended are based on the feedback from representatives of heavy vehicle manufacturers.

Future work within this area is to conduct experimental tests of the fire detectors based on the test methods that have been suggested in this report. Furthermore, as the time frame of this thesis was limited, only the physical factors mentioned above have been studied. If there is further interest and if time is of no concern, the study of influencing physical phenomena can be expanded and more feasible results may be granted.

Acknowledgements

First of all, I would like to thank my daily supervisor, Ola Willstrand, at SP Fire Research for the continuous support and input during the work of this thesis. I would also like to thank the coworkers in the project at SP Fire Research, Jonas Brandt and Oskar Bialas, for contributing with contact information to representatives of heavy vehicle manufacturers and for pointing me in the right direction when consultation was needed with experts in other departments of SP.

Also, a special thanks goes out to the representatives from different European heavy vehicle manufacturers for providing me with important feedback on the recommended durability requirements. The end result would not have been possible without you.

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Last but not least, I would like to thank my supervisor Martin Tunér and professor Bengt Johansson for examining my report and giving me the opportunity to do this thesis at the Division of Combustion within the Faculty of Engineering at Lund University.

This thesis would not have been possible without the financial support by the FFI program of VINNOVA – Swedish Governmental Agency for Innovation Systems, who finance the project called "Fire detection & fire alarm systems in heavy vehicles – research and development of international standards and guidelines" at SP Technical Research Institute of Sweden.

Nomenclature

Latin letters

A	Frequency factor of the reaction [-]
A	Heat transfer area [m^2]
b	Material thickness [m]
c	Specific heat capacity [J/°C]
c	Damping constant [Ns/m]
E_A	Activation energy [J/mol]
ΔE	Total energy [J]
F	Force [N]
f	Frequency [Hz]
G_{RMS}	Root mean square value of acceleration [m/s^2]
h_c	Convective heat transfer coefficient [W/m^2°C]
K(T)	Reaction rate of the process [s^{-1}]
k	Spring constant [N/m]
ΔKE	Kinetic energy [J]
m	Mass [kg]
P	Pressure [Pa]
ΔPE	Potential energy [J]
Q	Heat [J]
q	Heat flow per unit time [W]
R	Universal gas constant [J/mol°C]
T	Torque [Nm]
T	Temperature [°C unless otherwise stated]
ΔT	Change in temperature [°C unless otherwise stated]
ΔU	Internal energy [J]
t	Time [s]
U_S	Voltage pulse [V]
U_A	Supply voltage [V]
V	Volume [m^3]
ΔV	Velocity change [m/s]
W	Work [J]
x(t)	Body displacement [m]

Greek letters

ε_r	Relative permittivity [-]
ζ	Damping ratio [-]
λ	Thermal conductivity [W/mK]
ρ	Density [kg/m^3]
σ	Stefan-Boltzmann constant [W/m^2K^4]
τ	Pulse duration [s]
ω	Angular velocity [s^{-1}]
ω	Angular frequency [rad/s]
ω_n	Natural frequency [rad/s]

Acronyms & Abbreviations

ASD	Acceleration spectral density
a.c.	Alternating current
d.c.	Direct current
DoF	Degree of freedom
EMF	Electromagnetic field
EMI	Electromagnetic interference
ESA	Electrical/electronic sub-assembly
ESD	Electrostatic discharge
EMR	Electromagnetic radiation
EMC	Electromagnetic compatibility
IP Code	International Protection Code
IR	Infrared
MF	Magnification factor
MGD	Multi Gas Detector
RH	Relative humidity
r.m.s	Root mean square
RoR	Rate-of-Rise
SRS	Shock response spectrum
UV	Ultraviolet

Contents

1. Introduction

Fires in various types of vehicles have always been a reoccurring physical phenomenon due to the nature of how the vehicle is constructed and how it functions. This will continue to be the case as long as flammable materials and fluids, such as polymers and fabrics, are used. The fact that most engines in current vehicles are operated by combustible fuels and liquids is another reason to why fires are likely to arise.

The automotive industry has been subjected to substantial changes during these past decades with regard to limiting the consumption of fossil fuels and lowering the emissions of air pollutants. Several alternative fuels have been employed in modern vehicles as well as new implementations of automobile designs have been made, mainly to lower the weight and increase the safety and comfort of vehicles. Unfortunately, lighter vehicles are often a result of lighter and more flammable parts and materials [1]. It is today believed however, that there are numerous ways of improving the fire safety by simply adopting appropriate fire safety requirements for these materials.

Heavy vehicles in particular are vulnerable to fires that commence in the engine compartment [2]. This fact is not difficult to accept as these vehicles operate during longer periods of time and with shifting loads on the engine. Parameters influencing the probability of fire ignition are the design of the compartment and the placement of different components and systems inside the compartment. Engine compartments of heavy vehicles are often narrow and cramped, resulting in components being mounted tightly to one another and thus causing several physical phenomena to occur, such as heat rise, vibrations, friction and so on.

In order to minimize the risk of large engine compartment fires or the spreading of fires from the compartment to the rest of the vehicle there needs to be a fire detection system installed that can withstand the influences from its environment. There are a number of these on the market, but they vary in how they detect fires, out of which materials they are constructed and how well each handles the environment in the compartment. Like most components in a vehicle, even a fire detector is subjected to improper functioning due to various defects or simply by having its lifespan reduced by the surroundings. Therefore, a proper standard should be implemented with certain durability requirements for fire detection systems installed in engine compartments. These durability requirements are the key to having a fire detector that works, no matter the circumstances inside the compartment.

1.1 Outline

Chapter 2 in this report provides brief insight about the importance of having a fully functioning fire detection system at all times. Various fire ignitions sources will be highlighted and the description of the compartment layout will serve as a hint in how fast fire propagation can happen. How to cope with this challenge due to the nature of the engine compartment layout and the possible causes behind fire development in heavy vehicles will be presented.

Chapters 3 and 4 explain how fires are detected and which detector types that are commercially available today. In order for a detector type to be suited for a certain fire scenario it also needs to be compatible with the environment prior to the fire. Smoke detectors for instance are dependent on clean environments with little dust and dirt in its surroundings. This is not the case for an engine room though. There are some exceptions that will be elaborated in sub-chapter 4.1.3. regarding this statement.

In Chapter 5, the theories behind the most important physical phenomena occurring inside an engine room are explained. It is clarified how they arise and why they are of importance. This theory is the foundation to the study of which durability requirements and test methods that are suitable for a fire detector that will be mounted inside an engine room of a heavy vehicle.

Chapter 6 provides information about which test methods that are suitable to be used for the fire detector with regard to the physical phenomena mentioned in Chapter 5. These test methods should establish the fire detector’s compliance with respect to each physical phenomenon.

Furthermore, Chapter 7 is the key part of this report. The information received from already available durability standards, discussions with representatives from heavy vehicle manufacturers and experts from various departments at SP is interpreted in a way that is suitable for a detector that is to be mounted in any engine room of any heavy vehicle type. Appropriate durability requirements are suggested and showcased with regard to the physical factors mentioned in Chapter 5.

The report is concluded with a discussion section in Chapter 8 regarding the test methods and test parameters that have been suggested and a conclusion and future work section in Chapter 9.

1.2 Objectives

The main purpose of this Master's thesis is to study and identify which of the physical phenomena occurring inside engine rooms of heavy vehicles give rise to critical durability hazards for different components and systems. By performing this study and analyzing the results, suitable test methods and test parameters that should be used for fire detectors which ensure that the detector can withstand those hazards in that type of environment are formulated. Based on the test methods and test parameters that have been brought forth, appropriate durability requirements are presented. The recommended durability requirements for the fire detector are based on the investigation of current durability requirements for other components and systems mounted in the same type of environment, i.e. the engine compartment. Thus assuring that if the already mounted components and systems can outlast the influencing physical factors in this environment, the fire detector should endure the same factors without its functionality or lifespan being reduced.

1.3 Methodology

This thesis is mainly based on theoretical studies. The background information was established by performing literature studies based on other papers about fire detection and having continuous dialogues with both supervisors, along with other relevant sources. In order to solve the problem at hand, current international and European durability requirement standards were studied. In some cases manufacturer specific durability requirements were investigated and then reinterpreted in a way so that no confidential data was revealed. Guidance for appropriate test methods and test parameters was received from representatives from heavy vehicle manufacturers as well as experts from various departments at SP.

No experimental tests were made during the thesis work. However, experimental tests of fire detection systems as a whole were observed during the time at SP Fire Research. These experiments were not relevant for the main problem in this report though, but a general overview of how test are conducted when it comes to fire detection components was obtained. The results from these tests were not used in this report.

This thesis was carried out in collaboration with SP Technical Research Institute of Sweden as part of one of their projects called "Fire detection & fire alarm systems in heavy vehicles – research and development of international standards and guidelines" [3].

1.4 Limitations

The issue that was of utmost importance in this thesis was to inspect the durability requirements for fire detectors mounted in the engine compartment of heavy vehicles. Therefore, it is implicitly understood that only fire detectors subjected to this type of environment will be studied. Fires sometimes commence on other parts of the vehicle, such as at the wheelhouses or due to arson on the inside or outside of the vehicle [4]. The conditions in these environments differ entirely from those in engine compartments. Consequently, the physical phenomena that arise in these locations of the vehicle are different than those inside the engine compartment. Therefore detectors mounted in these places will be subjected to other influencing factors than fire detectors inside engine rooms. To study which durability requirements are needed for detectors mounted in places other than engine rooms is beyond the time frame of this report. These scenarios will therefore not be investigated further.

The physical phenomena listed in Chapter 5 are the most frequent and those of highest impact on components in the engine room. However, there are some phenomena that have not been investigated due to the limited time for this thesis, as it would have been impossible to resolve all minor physical factors that arise in an engine room of a heavy vehicle. Subsequently, different vehicle types will not demonstrate the same physical behavior in the compartment and therefore the factors arising will be dissimilar. As this issue needs experimental testing to be addressed along with many vehicle types and proper testing facilities, it was determined that this was beyond reach in this report.

Lastly, after appropriate test methods and durability requirements had been suggested, the fire detectors should have been physically tested with regard to these test methods and requirements. Due to various reasons, such as the time frame of the thesis and the amount of detectors on the market, these tests were not conducted.

2. Engine compartments

As already mentioned briefly in the introduction, the engine compartments of heavy vehicles can be very cramped and narrow with many different components and systems mounted tightly to one another. The illustration in Figure 2.1 is an attempt to show the reader just how tight the packaging of components can be inside engine compartments of trucks for instance. The engine compartment geometry should be related to the potential generation of fires as well as which physical phenomena that arise. In order to do this, the geometry of the compartment, the radiation from hot surfaces and fire sources inside engine rooms will be outlined. Depending on which type of vehicle that is of interest to study, the engine compartment geometry will of course vary. The layout is rarely the same for a truck, bus and an excavator for instance. An effort will therefore be made in this section of the report to try to generalize an engine compartment layout, regardless of which type of vehicle that is studied. This means that some components and systems that are mentioned may not be mounted in a bus, but in a truck instead and vice versa.

Figure 2.1 – Transparent view of a truck. Courtesy of Scania AB [5].

2.1 Engine room geometry

First of all, a distinction has to be made between where the engine is placed in the vehicle; in the front of or above the front axle, in between front and rear axles or in the extreme back after the rear axle. The most common arrangement for buses is to have their engines mounted in the rear. This placement has both advantages and disadvantages. Front-mounted engine compartments, such as in the classic yellow US school buses, are usually smaller with at different airflow through the compartment compared to those that are rear-mounted. It is also relatively easy for the driver to detect smoke in the case of fire in a front mounted engine compartment. The rear-mounted engine compartments of buses or coaches may vary in dimension but typically measure 1.20 m × 2.30 m × 1.40 m (height × width × depth, where the depth is measured in the driving direction of the bus) [6]. Heavy duty equipment and forestry machines can widely vary in size and as a consequence the placement of the engine compartment and its size differs a lot from vehicle to vehicle. Some have their engine in the front, middle or rear and depending on the size of the vehicle itself, the size of the compartment will vary as well. Most trucks in Europe have their engine compartment on top of the front axle. This is mostly due to the European dimension requirements of the truck as a whole. Since the maximum length of a truck including the trailer is 18 m [7] the engine is not mounted in front of the axle but above it, underneath the cab. As a result, the trailer can be longer which allows for maximum load. Due to this, the engine compartments in trucks are extremely tightly packaged, rarely leaving any room for additional components to be mounted. The design of the compartment layout is therefore a key factor in order for the engine and other vital systems, such as electronics and oil hydraulics for instance, to fit beneath the cab and allow the truck to use its ultimate potential for hauling.

In case of a fire, a compact and cramped engine compartment packed with many components might prevent the extinguishing agent from reaching the source of the fire or even worse, it might lead to the fire never being detected by the installed detection system due to obstruct vision. This is called the “shadow effect”, meaning different objects obscure the fire source from the detection’s field of view and the extinguishing system’s field of ejection which can result in a loss of efficiency for the system [6]. Some illustrations of engine compartment layouts for different vehicles can be seen in Figure 2.2 through Figure 2.4.

Figure 2.2 – Engine compartment layout of a bus. Courtesy of SP.

Figure 2.3 – Engine compartment layout of a small excavator. Courtesy of SP.

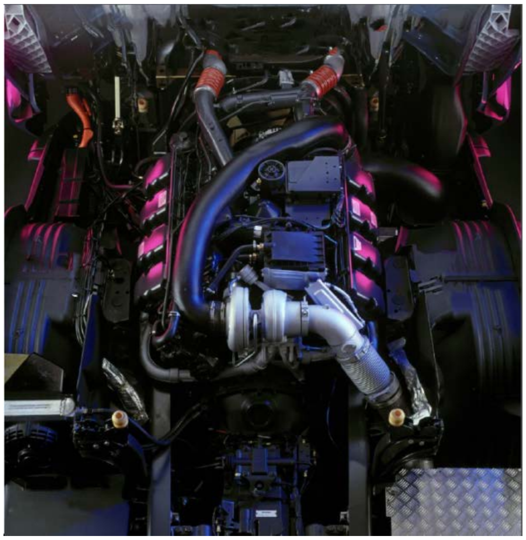


Figure 2.4 – Engine compartment layout of a truck with its cab tilted. Courtesy of Scania AB [7].

2.2 A note on components and systems

The first clarification to be made is that components and systems in an engine compartment need to be differentiated. The term “components” covers all the solids and the “systems” consist of several components and fluids that are interconnected inside an engine room. If the temperature is high enough fluids can evaporate and become gases, yet gases do not count as a component or system on its own. The following systems and components are usually mounted in engine compartments of heavy vehicles; engine block, exhaust system, cooling system, air conditioning system, transmission, generator, starting motor, air compressor, hydraulic pump, batteries and finally electrical system and cables [8].

The solids are all the components consisting of metal alloys, polymers and ceramics which can be found in the engine block, casings, coatings, hoses, insulations, air filters etc [9]. The fluids are the different coolants, fuels, lubricants and oils that in some way flow through the solids or at least come in contact with them. There are some exceptions, such as windshield washer fluid that is mounted inside the engine compartment in front engine vehicles, like trucks for instance, but does not have anything to do with the operation of the vehicle. These fluids are however still flammable.

Table 2.1 holds information regarding the fire hazards of some different fluids [9]. It should be noted that the data for the ignition temperatures in Table 2.1 varies widely depending on the fuel composition and the ignition test type. Distinguishing critical temperatures for the solids is beyond the scope of this report due to the number of different solid materials being present in the compartment.

Table 2.1 – Flammability of different liquids that exist in an engine room.

Flammable liquids	**Flash point [°C]**	**Auto-ignition point [°C]**	**Required surface temperature to ignite the fuel [°C]**
Diesel	55	220	520-550
Motor oil	205	350	350-600
Transmission gear oil	200	390	Unknown
Cooling fluid (50% glycol)	140	484	Unknown
Windshield washer fluid [10]	42	388-470	Unknown
Power steering fluid [10]	174	260-371	Unknown

2.3 Fire sources in short

With temperatures reaching up to 650 °C after the combustion process at operating conditions for heavy vehicles, metals inside the engine compartment will not burn or melt. However, surface ignition is often caused by the contact between evaporated fluid leakages, such as evaporated motor oil or fuel, and with hot metals or electrical wiring short circuits. The hot surface temperature often needs to be higher than the auto-ignition temperature for the fluid, as a considerable amount of energy is required to vaporize the fluid. This energy comes from the hot surface and is delivered to the fluid by heat transfer. At the same time this results in the surface being cooled by the fluid. The typical air temperature in an engine compartment when the engine is running, often called operating temperature, ranges between 80-150 °C**,** depending on the vehicle type and compartment design. Because the flash point for diesel is much lower than the air temperature, as seen in Table 2.1, it can therefore be easily ignited with a flame or spark [9]. The flash point of a volatile material is the lowest temperature at which it can vaporize to form an ignitable mixture in air. The engine coolant in heavy vehicles often consists of 50% water and 50% glycol. The boiling point of glycol is 200 °C while it is 100 °C for water. If the coolant is heated beyond 100 °C by the ambient temperature, the water will evaporate and there will remain 100% glycol which self-ignites at 400°C. Furthermore, there are several pressurized fluids and oils in the engine room. If one of the hoses that is supplying these fluids is punctured it can result in hot and dispersed fuel or oil spray leakage. Such sprays are extremely flammable and can produce a rapid combustion process [6].

The hottest parts of the engine are the manifold and the turbocharger. These are part of the exhaust system. The manifold is sometimes covered with a baffle plate in order to minimize heat radiation and prevent leaking fluids from coming in contact with hot components. The phrases “hot side” and “cold side” are therefore often used when speaking of engines. The hot side refers to the exhaust system and the cold side is where the fuel injection system is located [6].

The most common fire sources are the generator, starter motor, hot manifold, turbocharger and unsecured wiring. There has been other ignition sources reported that have resulted in fires due to unfortunate turn of events. For instance the pneumatic system may overheat, igniting nearby wiring and thereby causing short circuits [6]. After the fire source has been ignited, the fire usually spreads by igniting other petroleum products or polymeric components that are inside the engine compartment. If the fire is left unhindered, it can spread to other parts of the vehicle, such as the luggage or passenger compartment. The fire typically enters the cabin through windows that have been cracked by heat or flames or through the engine compartment ceiling. The latter is more uncommon though since this procedure takes more time.

Furthermore, it is quite common that the fire starts when the fan speed is decreasing because the fan is ventilating out combustible gases at a high rotational speed. Therefore when the fan speed has decreased there are combustible gases remaining inside the engine room which can lead to hot surface ignition because the solid components are still hot. On the other hand, if a fire occurs while the fan is rotating at high speeds it can aid the fire development as it supplies the fire with oxygen [9].

3. Fire development

To minimize the damage that fires cause, the fire needs to be detected at an early stage. This can be achieved by making a detector react on one of the signatures that is generated by the fire. Depending on which type of fire that is occurring, it can vary between which of the signatures is suitable to detect. Therefore, some basic knowledge regarding different fire types as well as typical fire signatures is needed to better understand how detectors work. In this chapter an overview of the two possible fire types is given and is then followed by a brief description of the fire signatures that can be generated by each fire type.

3.1 Flaming fire

All so called flaming fires have one thing in common – the combustion of the fuel occurs in the gaseous phase. Because the combustion of the fuel occurs in the gaseous phase, the fuel powering the fire first needs to be transformed from solid or fluid state to gaseous compounds. This can happen when heat from the surroundings is supplied to the fuel or by the heat transfer process that occurs between the burning surface and the flames. The gaseous fuel travels upwards in the flames. At the same time air pushes in on the sides of the flame. A small zone called the combustion zone forms at the point where air and fuel merge together as illustrated by Figure 3.1.

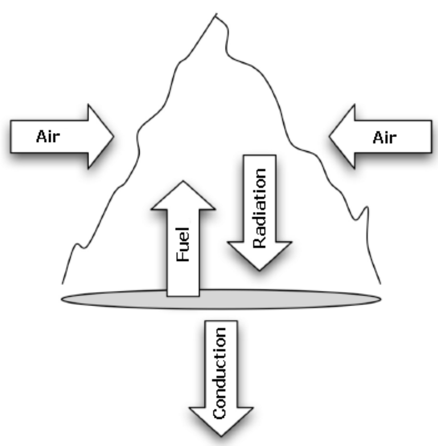


Figure 3.1 – Illustration of a flaming fire process [11].

The concentration of oxygen and fuel are within the limits of combustion inside this zone. Simultaneously as heat is released, oxygen, fuel and other reactants react through a stretched chain of sub-reactions inside the combustion zone. During the sub-reactions, free radicals, such as hydroxides (OH_x), hydrocarbons (CH_x), dicarbon (C_2), are both created and consumed. The radicals radiate with special wavelengths once they have reached a thermodynamic equilibrium. These wavelengths are usually in the UV-spectrum but they can radiate with other characteristic wavelengths as well. Another product which is a result of the combustion is ethyne (C_2H_2). Ethyne creates aromatic hydrocarbon chains by different chemical reactions inside the flame that eventually clump up to form a compound commonly known as soot [11].

The flaming fire described above mostly applies to fires with diffusion flames in organic materials. In cases when flames are premixed, meaning both fuel and air are premixed before ignition, the combustion becomes more effective and incomplete combustion products are reduced, such as soot. Which products that are created after the combustion depends on the fuel and the ventilation aspects inside the compartment. Fuels that do not contain carbon cannot create products such as CO, CO_2 and C_2H_2. If the ventilation is bad, there is not enough oxygen supply which results in more CO being created. If the compartment has good ventilation and therefore is rich in oxygen, the carbon monoxide products are reduced [11].

3.2 Smoldering fire

One of the conditions for a smoldering fire to occur is that there needs to be a porous fuel that creates a compound containing carbon when it is pyrolized. Pyrolysis means that the fuel is heated to temperatures ranging from 200 to 1000 °C, depending on the material, in the absence of oxygen and does not disintegrate during this process. Materials that can burn with a smoldering fire are for instance: paper, sawdust, leather, fabrics and expanded plastics, such as expanded polyurethanes. The combustion of the fuel takes place in the form of surface reactions in solid phase which leads to the fire burning without a flame. However, if there is enough oxygen in the environment, in other words good ventilation, a smoldering fire can become a flaming fire. In a corresponding matter a flaming fire can become a smoldering fire if the ventilation is bad. It should be noted that there often needs to be an ignition source in order for a smoldering fire to start, i.e. a spark or flame [11].

The process of a smoldering fire can be divided into four zones as illustrated in Figure 3.2. The events in each zone can be described as:

- Zone 1 – Untouched material unaffected by the fire.
- Zone 2 – Pyrolysis zone where the fuel is heated to the prescribed temperature and is then pyrolized. The pyrolysis results in solid carbon compounds and gaseous pyrolysis products. The gaseous products mostly consist of tar and fluids with a high boiling point and are very explosive if accumulated in a tight space and then ignited.
- Zone 3 – The solid carbon compounds combust which results in a carbon layer and the temperature reaches its maximum. This temperature makes the fuel radiate as a black body within the visual spectrum which is why zone 3 is smoldering. The heat is led to zone 2 and zone 4 through heat conduction.
- Zone 4 – Cooling zone consisting of residual products from the combustion and a decrease in temperature.

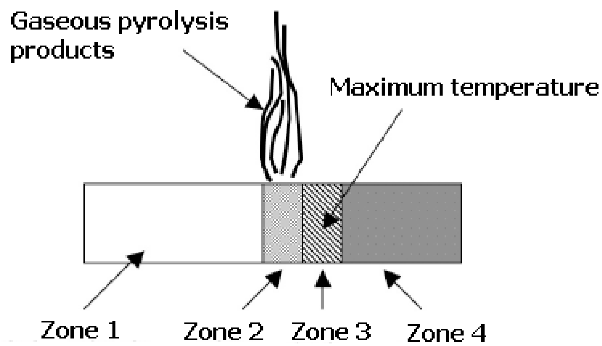


Figure 3.2 – Illustration of a smoledring fire process [11].

Because of the relatively low temperatures of a smoldering fire, the thermic lift force for the gaseous pyrolysis products and combustion products are also small. This is why there is no plume in the case of a smoldering fire. This can cause problems with detectors mounted high above the fire as the combustion gases cannot reach the detector [11].

3.3 Fire signatures

When a fire occurs, the combustion creates new products and releases heat which leads to the fire generating certain signatures that can be used to detect the fire. The term signature refers to measureable changes caused by the fire. These signatures include change in temperature, radiation intensity, gas concentration etc. There are five typical signatures generated by a fire as listed below:

- Radiation, also referred to as flames.
- Gases (both gases that can cause the fire and gases that are products of the combustion).
- Aerosols, also referred to as smoke.
- Thermal, also referred to as heat or temperature.
- Sound and pressure.

Gases, smoke and heat are signatures that are transported with the combustion gases from the fire. The combustion gases most of the time travel upwards because of the thermic lift force generated by the heat released from the combustion. For smoldering fires and small flaming fires the combustion gases are often cool which can lead to their signatures not reaching detectors placed high above them [11]. Figure 3.3 illustrates different signatures.

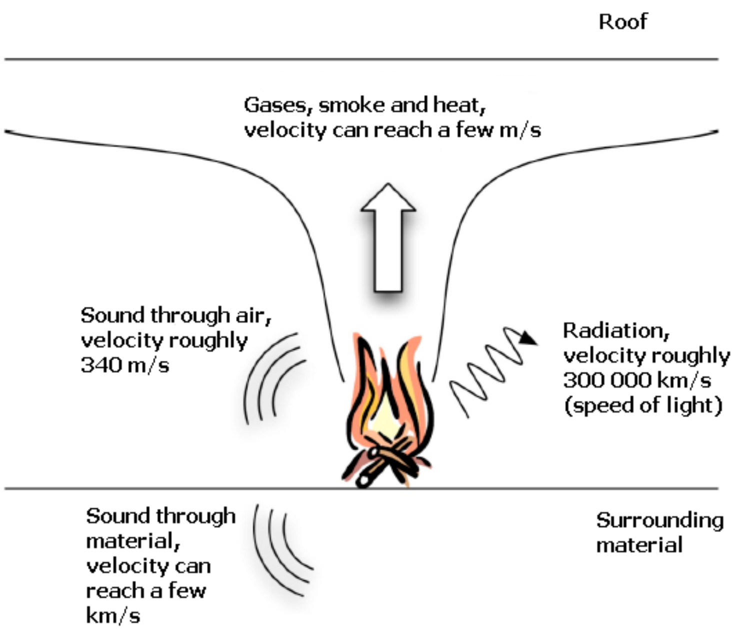


Figure 3.3 – Illustration of how fire signatures are allocated during the combustion process [11].

3.3.1 Radiation

Radiation is by far the fastest fire signature that is generated by a fire. However, smoldering fires are often hidden because the fire is occurring inside of the material which leads to the radiation being blocked and often weak. This radiation therefore resembles the radiation from other nearby hot sources, meaning that there may be many interfering sources. The flames from a flaming fire on the other hand, radiate within a large spectrum of wavelengths consisting of ultraviolet, infrared and visible lights. This radiation is generated thanks to the free radicals, stable compounds and soot that are byproducts of the flaming fire.

Flames do not radiate with a constant intensity. The intensity instead fluctuates somewhere between 0.5 and 15 Hz. A detector that is intended to react on the radiation from a flaming fire is designed to react on the spectral distribution of the flames. In other words, the detector will react on variations in the intensity for specific wavelengths. This spectral distribution is unique for fires, especially flaming fires, and can therefore be used to distinguish a fire from other interfering hot sources [11].

3.3.2 Gases

Products from a fire are different combustion gases whose composition varies depending on the fuel and the access of oxygen. Two typical combustion gases from organic fuels are carbon monoxide (CO) and carbon dioxide (CO_2). The amount of CO_2 in the atmosphere is much greater than the amount of CO. Therefore a small change in the CO concentration is easier to measure than a change in the concentration of CO_2. Other compounds that are a result of incomplete combustion are different hydrocarbons, CH_x. These are the two most common signatures measured if the detector is designed to react on changes in gas concentration [11].

3.3.3 Smoke

A result of all types of fires are particles ranging between 0.01 to 10 μm in diameter. These particles consist of soot, drops of water, tar and carbon compounds with a high boiling point. It is often referred to these particles as smoke. The particles scatter light which means that they themselves become visible resulting in a grey like fog – smoke. The size of the particles varies depending on the fire type. A smoldering fire results in large particles while a flaming fire results in smaller particles, consisting of soot. The most common size of these particles in general is between 0.1 and 2 μm which is why detectors are usually designed to work in this interval. Furthermore, particles are constantly created inside the engine room as a result of mechanical wear of the moving parts inside the engine room, evaporated engine oil, accidental leakage of combustion fumes from the engine, surrounding air, dust, dirt etc. All of these particles accumulate to particles large enough to complicate the usage of smoke as a fire signature. The reason to why this complication occurs will be discussed in the next chapter [11,12].

3.3.4 Heat

The combustion gases that rise upwards when a fire occurs have a higher temperature than their surroundings. A detector designed to react on the temperature rise is therefore the easiest to construct and most common. There can be variations in how it registers the temperature difference. It can for instance register a change rate in the temperature, e.g. 10 °C/min, or react on a maximum static temperature, e.g. 150 °C. However, heat change is the signature that takes the longest to discover. This is because the power or heat generation is small at the early stages at the same time as the cooling of the gases is large. This results in high temperature or large changes in temperature not being developed fast enough. The combustion gases are often cool in the case of smoldering fires, which makes detection of fires with heat signatures almost impossible [11].

3.3.5 Noise and pressure

The sound that is generated by a fire can be caused by the sound of burning flames or the sound of materials being heated. For flaming fires, a low frequency sound is generated by the vortex structure that is formed at the base of the flame. Studies show that detection by sound seems promising if the sound in the background is less than 70 dB [11]. Another signature that is sometimes used is a sudden increase in pressure, such as a shock wave that is caused by the thermal expansion of gases [13].

It should be noted that these two methods are quite uncommon for vehicle applications, especially the noise signature. Due to the engine room being prone to high dB-levels (around 80 dB for trucks and buses traveling around 50 km/h [14]) it would be nearly impossible to register this signature.

4. Current fire detectors on the market

Today there are a number of fire detectors on the market but many of them operate in various ways. To simply say that a heat detector activates when it senses a heat variation is an oversimplification of the operating principles for which it is designed. In order for a fire to be detected, the detector must essentially react on one of the fire signatures discussed in the previous chapter. Additionally, the detector needs to be able to register the signature in the current environment and the correct detector type needs to be chosen with regard to interfering sources in that environment so that no false alarms occur. Each detector type is divided into four detection categories: point detection, line detection, volume detection and sampled detection. The purpose of the categorization is to describe how the detection occurs as illustrated in Figure 4.1.

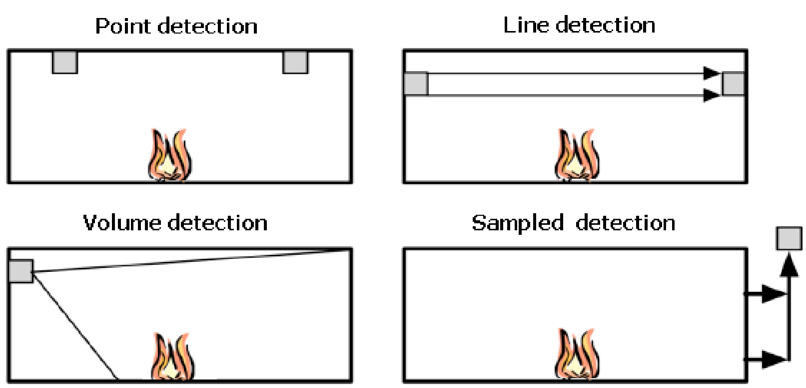


Figure 4.1 – The four detection categories showing how fire signatures are registered [11].

The point detection registers signatures at specific locations in the compartment. The line detection identifies signatures that cross a line created by two detection points facing each other. The volume detector monitors the changes in the compartment volume by a single sensor and finally the sampled detector draws out the air from the compartment to another room where it is analyzed. Four types of detectors that are currently on the market will be discussed in the following sub-chapters and an indication of which is the best suited for certain situations will be made [11].

4.1 The four detector types

Detection systems based on flame and heat recognition are the most common ones in engine compartments today. Smoke and gas detectors are on the rise within vehicle applications and some interesting concepts will be discussed in sub-chapter 4.1.3 and sub-chapter 4.1.4.

There are some special detectors that use different detection categories than those that are frequent but they are in general based on the same detection approach. An interesting detection concept is by making the fire detector react on mechanical effects for instance. This detection type is already commercially available and consists of a pressurized plastic hose somewhere in the engine room that melts when it is heated by the surroundings. Once the hose has melted or cavities have been created in the hose due to the heat from the fire, the pressure is stabilized to atmospheric pressure causing the fire suppression system to be triggered.

It is also typical for two types of fire detectors to be combined, e.g. a cross over between a flame detector and a heat detector which ensure the detection of two types of fire scenarios. The heat detector constantly monitors the temperature inside the engine room while the flame detector serves as a complement if a flaming fire should all of a sudden. These detector types are often termed multi detectors.

4.1.1 Flame detectors

Flame detectors are designed to react on ultraviolet (UV), infrared (IR) or a combination of these two radiations. It was previously mentioned that detecting a fire through flame analysis is one of the fastest methods possible. This type of detection can take less than a second. Because flame detectors register flames they are not suited in environments where smoldering fires may occur. Consequently, they can only be used to detect flaming fires, but there is always an irregularity in how much a flaming fire radiates. It is therefore essential to choose the correct flame detector type, meaning that the detector should react on radiations in the right wavelength interval. Due to this type of detector reacting on the light of the flame it is important for its vision not to be obstructed. Flame detectors are typically used in the presence of flammable liquids that can be easily ignited or when a fast detection of the fire is needed, like at places where explosions are of high risk. Volume detection is usually used for these detectors. However, in engine compartments flame detectors are usually only used as a supplement to other detectors because of their ability to detect rapid fire development, such as spray fires [11,15].

4.1.2 Heat detectors

As mentioned in the previous chapter, if a detector is to react on a heat signature it can do it in two ways, either by registering a gradual change in temperature rise, also called Rate-of-Rise (RoR), or by registering a maximum static temperature. The first one mentioned is called a "RoR-detector" and the latter a "static heat detector". An example of a RoR-detector's functioning principle is that it consists of two thermo elements or two bimetals, where one of them is exposed to the hot combustion gases and the other one is isolated from the gases. The detector is activated once there is a certain temperature difference between the two of them. In the case of a maximum heat detector, the difference is that there is only one thermo element or bimetal that registers a predefined maximum temperature and then activates the detector. A RoR-detector is in general a better solution as it takes less time for a temperature rise to be registered than for a maximum temperature to be reached. However, a combination of them both is by far the best mechanism due to the fact that the maximum static temperature serves as a last resort while the fire can still be detected at a relatively early stage due to the continuous registration of temperature change rate. Heat detectors usually have the slowest activation time since the thermo elements have a certain mass and volumetric heat capacity which results in the elements not instantly reaching the same temperature as its surroundings. It should be noted that heat detectors are mounted as either point or line detectors in the compartment and are by far the most common fire detectors mounted in engine compartments of heavy vehicles today [11,15].

4.1.3 Smoke detectors

Smoke detectors register the particle concentration of air which is why they cannot be mounted in dusty or dirty spaces where the concentration of particles is high. Smoke detectors usually operate on one of the following three principles: ionizing detection, light scattering detection and light transmission detection.

Ionizing smoke detectors work in the way that there are two plates that are electrically charged as negative and positive, respectively, facing each other and a radioactive substance that transmits ionized particles. When these particles come in contact with the gases from the fire they become ionized resulting in negative electrons and positive ions. The negative electrons and positive ions travel between the two electrically charged plates which results in a rate of lost electrical current through the circuit. Once the current reaches a threshold value, called "the fire alarm level", the detector activates [11].

The light scattering detector consists of a transmitter and receiver of light that are angled to one another, see Figure 4.2. When there is no fire, the light is captured by a “light trap” facing the transmitter. In the case of a fire, the smoke from the fire scatters the light coming from the transmitter through smoke particles which then hit the receiver. Once a certain amount of light intensity is registered, the detector activates [11].

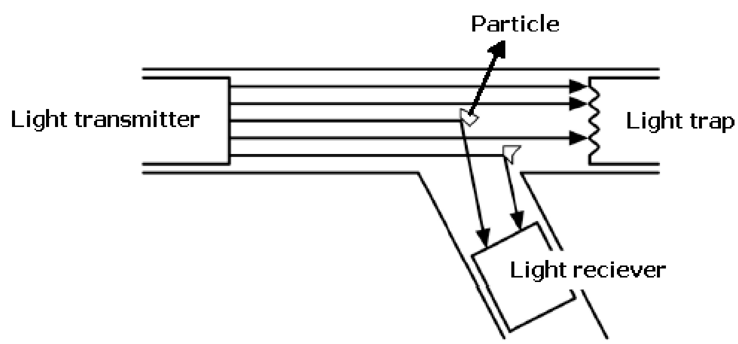


Figure 4.2 – Illustration of the working principles of an optical smoke detector [11].

An alternative version of the light scattering principle is the light transmission detector. The setup is identical to the light scattering detector except for the angled receiver. Instead the receiver is in line and faces the transmitter. The transmitter in this detector usually transmits IR-light with a certain intensity which is registered by the receiver. When gases from the fire fill the space between the transmitter and receiver some of the light is blocked causing a reduction in intensity. Once the intensity reaches a certain threshold the detector activates [11].

Although smoke detectors are vulnerable to dusty and dirty places, such as engine compartments can be, they show promise in the heavy vehicle industry. There is currently an EU-project regarding fire detection in buses called “VULCAN” that aims to develop a vehicle adjusted smoke detection system regardless of the conditions in the engine compartment. Different measures can be initialized based on the cause of the fire by using analog detection. Practical experiments with rough working environments show great results and it is believed that this will change the approach when speaking of smoke detection in engine compartments [16].

4.1.4 Gas detectors

Gas detectors are mostly used to detect high concentrations of gas before a fire or explosion occurs. Most gas detectors are designed to measure gas concentrations of certain combustion products, such as CO or CH_x. There are three types of gas detectors; catalytic, electrochemical and infrared.

The catalytic gas detector is constructed as a Wheatstone bridge, namely consisting of an active catalytic element in an electrical circuit. When gases come in contact with the catalytic element the electrical resistance is changed and a small increase in voltage is created. This increase in voltage causes the detector to activate [11].

An electrochemical detector working principle is that it consists of electrodes that are placed inside an electrolyte. When the smallest of gas concentrations pass the electrodes an electrochemical process follows which creates a small electrical current that is proportional to the gas concentration. The current is registered and the detector activates [11].

The infrared gas detector is mainly used to detect concentrations of CH_x and it is constructed in the same way as the light scattering detector. The transmitter emits IR-light which is absorbed by the gases. The infrared gas detector also works if a fire has already commenced as the IR-light is blocked by the particles created by the combustion [11].

An interesting gas detector concept that can be deployed in several different harsh environments and that is commercialized today is the so called Multi Gas Detector (MGD). It is quite expensive but has the benefit of resembling a human nose electronically. This is done by registering different “smells”, i.e. gas compositions, by using several chemical sensors and then processing the information and storing it. Each smell thereby forms a unique fingerprint which can be used to detect both dangerous gases that are combustible and non-dangerous gases. This results in extremely early fire detection and full system functionality regardless of the environment in the compartment. Furthermore, the MGD detector can distinguish harmless disturbances, such as exhaust fumes from the engine which in turn results in a low frequency of false alarms. The MGD detector can therefore be a viable option for future installations of fire detectors in engine compartments of heavy vehicles. However, exclusive machinery often has a high price which is why it is not implemented in vehicles today [17].

5. Physical phenomena arising inside engine rooms

Due to the nature of many different components and system collaborating inside an engine compartment while the vehicle is in operation, many physical phenomena will occur. Some phenomena are a result of chemical reactions within the environment, such as the oxidation of metals that results in corrosion. Other occurrences can be mechanical, such as temperature rise due to the friction caused between moving parts or by the combustion process in the engine. On cold days, the components and systems inside the engine room should be able to function regardless of the low temperature in the environment. Furthermore, when the vehicle is moving it vibrates or is subjected to shocks due to uneven roads or harsh road bumps for instance. The suspension system can only neutralize this behavior to some degree, thus components inside the engine room will still experience these mechanical influences as well as the vibrating motions caused by the rotating parts inside the engine block itself. Modern vehicles have electronics installed in them and in heavy vehicles there is usually an electric box mounted inside the engine compartment. All electronic devices or installations influence each other when interconnected or close to one another. This is due to the electromagnetic field of different electronics being interfered with in negative ways. In order to minimize this interference they need to be electromagnetically compatible with one another. All these physical factors influence the lifespan of components, i.e. fire detectors, in different ways.

In this chapter, the most frequent physical phenomena occurring inside an engine room and those that are of most importance will be presented. A thorough description about each of them will be made and the corresponding theory of each one will be highlighted.

5.1 Corrosion

Like any other natural process that tends towards its lowest possible energy state due to degradation, different solid materials have a natural tendency to combine with chemical elements, and through chemical reactions, eventually return to their lowest energy state. This process is called corrosion. Solids such as metals, ceramics and polymers can all corrode and they all do so in different ways. When metals come in contact with chemical elements such as water and oxygen they form hydrated iron oxides, also known as rust.

Ceramics are relatively insensitive to corrosion but can become susceptible if the material is subjected to certain acids. Polymers do not corrode in the same way as metals but instead they progressively degrade if they are exposed to inorganic substances or a combination of water, moisture and heat. When polymers are degraded by moisture or heat, the process is often termed "aging". Therefore, corrosion is defined as a chemical or electrochemical reaction between a material and its environment that results in a deterioration of the material and its properties [18].

Corrosion can be classified as "wet" or "dry". Wet corrosion refers to when a liquid, in most cases water, combined with air or other gaseous compounds comes in contact with a material. Dry corrosion is a result of the reaction between materials and high temperature gases. Corrosion can occur through direct chemical reactions, i.e. when water and air physically come in contact with the material, or by electrochemical reactions. Electrochemical reactions refer to a continuous degradation of a material with its surrounding, meaning that oxidation (loss of electrons) for a material occurs constantly due to electrons in the material being transferred from the material's anodes to the surrounding environment's cathodes. It is important to note that corrosion only occurs on the surface of materials [18,19].

Because corrosion has many different forms, some are of more interest than others when the surrounding environment is an engine compartment. Those that deserve special attention can be seen in Figure 5.1 and are explained further in their respective sub-chapter.

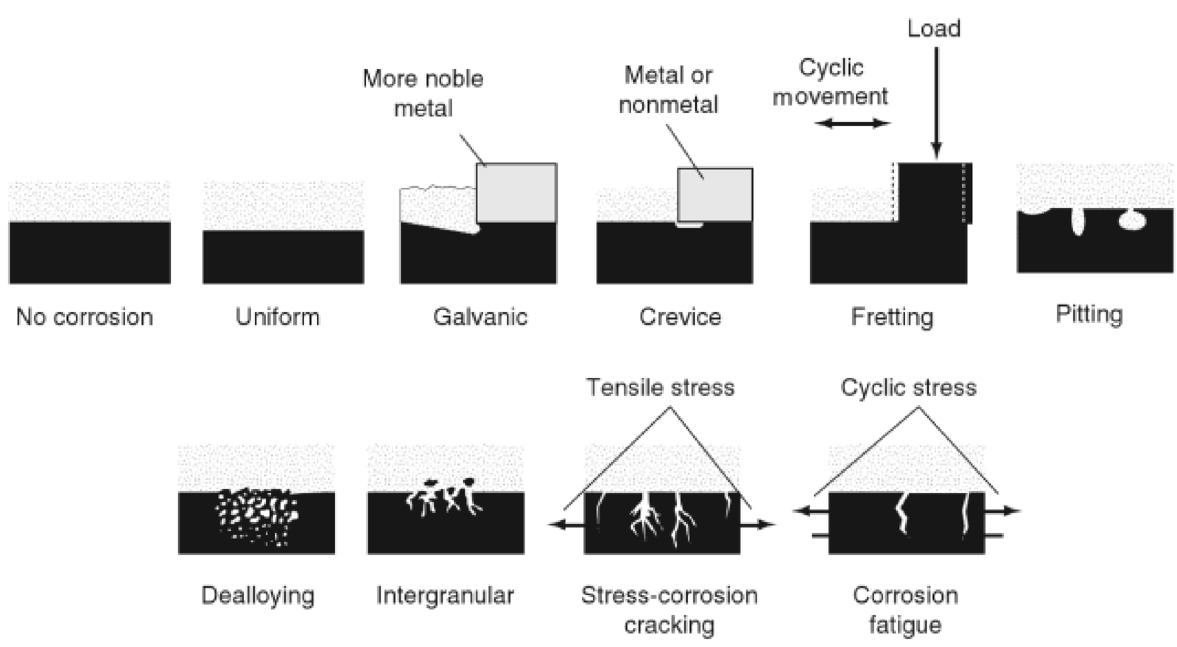


Figure 5.1 – Different forms of corrosion that may occur in engine rooms. Courtesy of ASM International [18].

5.1.1 Uniform

This is the most common type of corrosion as it is caused by chemical or electrochemical reactions that result in the entire exposed material surface to deteriorate, eventually to the point of failure. This corrosion type causes the greatest destruction to the material but it is, however, considered to be a safe form of corrosion, as it is predictable, manageable and often preventable. Uniform corrosion is often termed “atmospheric corrosion” [18,19,20].

5.1.2 Localized

Localized corrosion targets a specific area on the material surface, unlike uniform corrosion. It can be classified as one of three types, as seen below [18,19,20].

- Pitting – pitting corrosion leads to small holes or cavities in the material as a result of extreme localized corrosion of a small area on the material surface. This area produces a localized galvanic reaction and becomes anodic, while the rest of the remaining material becomes cathodic. The small holes or cavities function as stress risers which can lead to failures of the material. This type of corrosion can be difficult to detect because the affected areas are very small and may be covered and hidden by corrosion-produced compounds.
- Crevice – this type of corrosion arises at specific locations, such as under gaskets or linings, due to the micro-environment being stagnant at these places. If there are acidic conditions present in combination with a reduction in oxygen, it can accelerate the corrosion process at these locations. Due to where this corrosion arises it can be inflexible to detect and prevention can be difficult because the environment is, as already stated, invariable.
- Filiform – filiform corrosion occurs under painted or plated surfaces when water breaches the coating. The corrosion starts at small defects in the coating but can rapidly spread and cause structural weakness in the material.

5.1.3 Galvanic

This type of corrosion can occur when two different metals are located together in the presence of a corrosive electrolyte, as is often the case in an engine room due to many different materials being mounted close to one another and being repeatedly exposed to salt, water and air during winter time. An electrolyte is a substance which forms ions in an aqueous solution, for instance a combination of air, salt and water. Because of the electrolyte, one metal becomes the cathode and the other the anode. The material which is the anode is the sacrificial metal, since it is the one that oxidizes. The anode corrodes and deteriorates faster than it would alone while the cathode corrodes slower than it would otherwise. For galvanic corrosion to occur the following three conditions must be fulfilled; electrochemically dissimilar metals must be present, the metals must be in electrical contact and they must be exposed to an electrolyte. Heat detectors that consist of two bimetals can be susceptible to galvanic corrosion, as the metals may start acting like anodes and cathodes in the presence of corrosive electrolytes in that environment.

Also, electronics in general can be subjected to galvanic corrosion as two dissimilar metals are often in contact with one another in electrical circuits. This can sometimes be avoided if the bimetals are coated with other non-corrosive materials, such as phenolic, and if noble metals are introduced in the electrical circuits, such as gold [18,19,20].

5.1.4 Environmental cracking

Environmental cracking is a corrosion process that can result from a combination of environmental conditions affecting the metal, such as chemical, temperature, mechanical influences etc. This corrosion type can lead to stress corrosion cracking (SCC) and corrosion fatigue [18,19,20].

- SCC – even if the material has corroded on a microscopic level, cracks can be created on the surface as the material is subjected to tensile stresses and temperature variations. The chemical environment that causes SCC is often one which is mildly corrosive to the material otherwise. Therefore, the material can appear bright and shiny while being filled with microscopic cracks. Hence, it is common for SCC to go undetected prior to failure. Furthermore, SCC can grow rapidly and is hard to control. SCC is difficult to avoid and once it has started, it usually ends in unexpected failure of the material.
- Corrosion fatigue – Corrosion fatigue is, simply put, the mechanical degradation of a corroded material under cyclic loading conditions that induce cracks in the material. Cyclic loading refers to vibrations, temperature fluctuations, impacts, creep, ageing of the material etc. These cyclic processes that can cause fatigue damage on materials will be further investigated in the subsequent chapters.

5.1.5 Intergranular

Intergranular corrosion is a chemical or electrochemical attack on the grain boundaries of a material, in most cases metals or metal alloys. This occurs because of impurities in the metal, which tend to exist in higher numbers near grain boundaries. The boundaries are often more vulnerable to corrosion than the bulk of the metal [20].

5.1.6 De-alloying

In some alloys, a specific element is the selected property to be corroded. This is called de-alloying, as that element acts as the anode and vanishes with time leaving the alloy corroded. The most common type of de-alloying is the de-zincification of brass, where the corrosion in such cases is a deteriorated and porous copper [20].

5.1.7 Fretting

Fretting corrosion is a result of repeated wearing, weight or vibration on an uneven, rough surface. When the surface is subjected to the cyclic variations in these factors it results in pits and grooves on the surface. This corrosion type is found in rotating and impact machinery, bolted assemblies and bearings. It can also be found in surfaces exposed to vibrations during transportation [20].

5.1.8 High-temperature

High-temperature corrosion is a type of corrosion that can take place in machinery coming in contact with hot gases containing certain contaminants. Some fuels contain vanadium compounds or sulfates which have low melting points. During combustion these can form certain mixtures of melted salts in gaseous forms that are highly corrosive. These are especially corrosive for alloys that are normally resilient to corrosion, such as stainless steel. Almost all materials oxidize and corrode at high temperatures. The difference in what separates them in how they corrode is the rate of corrosion and the nature of the corrosion products. Oxidation, which is by far the most common form of high-temperature corrosion, of a material results in scaling, loss of material and changes in its physical properties. High-temperature corrosion is not restricted to the gaseous phase as solid ashes and salt deposits contribute to the corrosive effect. Gaseous corrosion attack is not limited to only oxygen, as sulfur gases, carbon oxides and many other elements all attack materials in different ways. Therefore, materials that will be used in high-temperature environments, such as engine rooms, cannot be selected solely on their corrosion resistance but creep strength and structural stability must be taken into account as well [18,19,20].

5.2 Ageing

Ageing is a natural mechanical phenomenon that takes place in any type of environment. Examples of ageing of a material can be due to corrosion, obsolescence, weathering, heat and so forth. It is defined as a gradual process in which the properties of a material, structure or system, change over time or with use due to interaction with biological, chemical or physical agents in its surroundings. This change can be for better or for worse depending on which type of material that focus lies on. Metals and alloys can be hardened using accelerated heat ageing. This method is however not applicable on polymers, for instance, as they are more susceptible to negative material property changes if subjected to high temperatures. Therefore, it is of interest to set viable requirements for polymers subjected to temperature variations in this report as the operating temperature in engine compartments will not have a noticeable impact on the mechanical properties of metals and alloys during the vehicle's useful lifetime [21].

Natural ageing of polymers is the natural degradation process of the material. Consider an ordinary plastic bag that has been thrown away. Due to weathering conditions and solar radiation in combination with air-borne pollution gases, with time, the bag will feel different compared to a new bag. Almost as if the surface finish of the material is dusty or dirty. This is how polymers degrade as there is rarely a visual flaw in the material but instead the volume is lessened and its physical properties are thereby deteriorated.

It can be hazardous if the degradation process is not managed in a controlled manner, especially in operations where the polymeric components are key components in the machinery itself, as is the case when the fire detector in the engine room is in the form of a pressurized plastic hose. If the ageing process of that plastic is accelerated due to the different operating conditions inside the engine room, the degradation of the material might cause a bad surface finish, leading to lessened mechanical strength in the material and eventually a small penetration in the hose. This will cause the pressure to stabilize, mimicking a fire that has melted the hose, and consequently the result will be a false alarm or a dysfunctional detector. Furthermore, wires in electronics are insulated with plastics which prevent cables from coming in contact with one another and thus preventing short circuits. If these plastic insulation were to age faster than accounted for, short circuits may indeed become a reality which can have critical impacts on vehicle safety. It is therefore important to recognize which physical factors influence the ageing of polymers and connect them to the physical occurrences in engine rooms. These will be established in this chapter as well as an introduction to how the ageing process of polymers can be accelerated and why this can be an issue [15,21].

There are many forms of ageing when it comes to polymers. Not all of these are related to the specific environment that is the engine compartment but some can be induced by others and the process can accelerate even further if that is the case. The four types of ageing processes that are relevant for polymers placed in engine rooms are listed in their respective sub-chapter.

5.2.1 Thermal ageing

Thermal degradation refers to the chemical and physical processes in polymers that occur at elevated temperatures. Higher temperatures accelerate most of the deterioration processes that occur in polymers such as oxidation, chemical attacks and mechanical creep. Oxidation is often considered to be the most serious problem when using polymers at higher temperatures. The influence of temperature on the oxidation processes will depend on the chemical structure of the polymer. Oxidation at elevated temperatures is called thermo-oxidation. Thermo-oxidation is initiated by the reaction of free radicals $P^{\bullet}$ with oxygen to form peroxide radicals

$$P^{\bullet} + O_2 \rightarrow POO^{\bullet} \quad (1)$$

All polymers contain these free radicals due to their polymerization and processing history but the amount of free radicals can be increased by interaction with light, ionizing radiation or the presence of transition elements. Once formed, the peroxide radicals undergo slow reactions that breakdown the polymer chains. The overall degradation process will normally involve a relatively long induction period during which little degradation is noted.

At the end of the induction duration, there is a rapid increase in degradation leading to a major reduction in the mechanical properties of the polymer. This induction period is temperature sensitive and is reduced considerably at elevated temperatures. The induction period of the degradation process is in most cases regarded as the functional lifetime of the polymer [21,22].

In engine compartments, one of the most common situations that polymers are likely to experience is prolonged exposure to elevated temperatures during the operation and lifetime of the vehicle. The Arrhenius equation is one of the most suited methods for estimating the lifetime of polymers mathematically. It is particularly useful for accelerated tests as it allows short-term tests conducted at higher temperatures to simulate long-term exposures at lower temperatures. The Arrhenius equation is

$$\mathrm{K(T)} = A\mathrm{e}^{-\frac{\mathrm{E_A}}{\mathrm{RT}}} \qquad (2)$$

where $\mathrm{K(T)}$ is the reaction rate of the process, $\mathrm{E_A}$ is the activation energy, R is the universal gas constant, T is the absolute temperature in Kelvin and A is a constant called the frequency factor of the reaction. The Arrhenius equation may be used prior to testing in order to approximate how long the ageing duration or the ageing temperature of the experimental test should be to be considered viable, instead of guessing the exposure duration or temperature beforehand.

5.2.2 Weathering

Weathering, also known as photo-oxidation, of polymers denotes the chemical and physical changes that occur when radiation is absorbed by a polymer. Photo-degradation is initiated by solar radiation and results in the absorption of UV radiation by the material. Though, other climatic factors such as heat, moisture and air-borne pollution all influence the mechanisms of degradation and the subsequent results of ageing. The intensity of the UV radiation decreases with increasing depth in the material. Therefore, the reaction tends to be a surface degradation process. Either way, there is an important balance between UV radiation, oxygen diffusion and temperature. During dark periods, i.e. during night time or if the polymer is enclosed in a dark space, some recovery of the oxygen concentration on the material surface can occur [21].

Since engine rooms are not subjected to high concentrations of solar radiation, photo-oxidation will most likely not occur but the slight recovery of the total oxygen concentration in the material can therefore be continuous which can lead to a disoriented ageing projection.

5.2.3 Chemical degradation

Chemical ageing is often a result of hydrolysis, i.e. by cleaving the chemical bonds of the polymer after contact with fluids. Chemical attacks on polymers involve specific chemical reactions between the polymer and water, acids or alkalis. A hydrolysis process between a compound and water is seen in Figure 5.2. By chemical degradation, the material has its molecular weight reduced due to polymer chain scission. This can lead to a reduction in toughness or worse – fracture strains. Furthermore, stress is known to accelerate the chain scission process and to enhance the rate of fluid uptake [21,22].

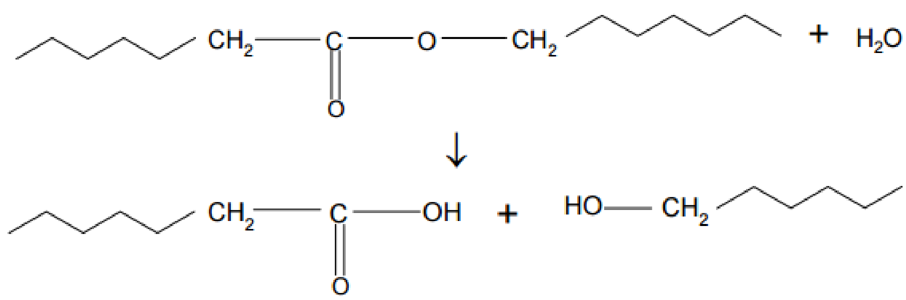


Figure 5.2 – Hydrolysis process of an ester being exposed to water. Courtesy of NPL [21].

Predicting the chemical degradation process requires information about the change in material properties, e.g. strength or stiffness, with time and the rate of change of those properties with the level of degrading agents. However, these test methods assume that only one time-dependent process is occurring when in reality there can be several happening simultaneously. Therefore, it is recommended that these test methods are experimentally performed as mathematical formulations can be complicated to derive.

5.2.4 Biological degradation

Biological degradation is the least common form of degradation for polymers as most thermoplastics are resistant to microbiological attacks. The only instances known were biological attack has influenced the life expectancy of the material has been with certain polyurethanes and some low molecular weight additives in PVC’s. No predictive techniques for the life expectancy of commonly used polymers due to biological degradation have therefore been developed [21].

5.3 Heat

Heat is simply defined as energy in motion from a high temperature object, or closed system, to a low temperature object. A system can therefore not possess heat, as the correct term for microscopic heat for a system is internal energy. Internal energy for a system is the sum of the potential and kinetic energies of all the molecules inside the system. Even if a system is in rest, it will consist of a raging mass of high speed molecules traveling at hundreds of meters per second in different directions within the boundaries of that system. The internal energy may be increased by transferring energy to the system from another system with higher temperature, i.e. a hotter system, resulting in a process commonly known as heating. By heating the system, its molecules will move at a higher pace resulting in them having a higher kinetic energy and indirectly the system's internal energy will rise. Due to the system's boundaries being constant, the rise in internal kinetic energy will result in a temperature rise for the system as a whole, because this energy needs to be released in some way. However, a rise in temperature can also be a result of work done on a system, such as a piston compressing a gas. The compression will lead to the same phenomenon on a microscopic level, as the molecules will start moving rapidly. The outcome of this work will be a rise in temperature indistinguishable from a case where the gas was heated by another system through a heat transfer process [23]. The change in internal energy of a system can be expressed as

$$\Delta \mathrm{U} = \mathrm{Q} - \mathrm{W} \tag{3}$$

where $\Delta \mathrm{U}$ is the change in internal energy of the system, Q is the heat added to or from the system and W is the work done by or on the system.

Heat can be defined as

$$\mathrm{Q} = \mathrm{m}c\Delta \mathrm{T} \tag{4}$$

where m denotes the mass of the system, c is the specific heat capacity of the material and $\Delta \mathrm{T}$ is the change in temperature for the body.

There are many definitions on work in physics and which type of work that is being done by or on components in an engine compartment can vary widely. Therefore the most relevant definitions within this type of environment are listed in Table 5.1.

Table 5.1 – Three definitions of work that are relevant to engine compartments.

Type of work	Equation	Description
Work by movement	$W = \int_{C} Fds$	F is the force applied to the body, ds is the differential displacement of the body and C is the starting and ending points of the displacement.
Work by torque or rotation	$W = \int_{t} T\omega dt$	T is the torque applied to the body, ω is the angular velocity, dt is the differential time span of the rotation and t is the starting and ending points of the time span.
Work by gas	$W = \int_{C} PdV$	P is the pressure applied to the gas, dVis the differential volume displacement and C is the initial and final volumes.

The total change in energy for the system can then be calculated as

$$\Delta E = \Delta U + \Delta KE + \Delta PE \tag{5}$$

where ΔU is the change in internal energy, ΔKE and ΔPE are the changes in kinetic and potential energy, respectively, of the internal molecules of the system.

5.3.1 Heat transfer

It is important not to confuse heat with temperature, as temperature is simply a byproduct of heat. Temperature rise is solely a result of the energy increase in the closed system due to work being done on the system or the system being heated by the surroundings. Once the system has been heated by its surroundings or the work within the system has come to a halt, the closed system's internal energy will be higher than its original state. Energy needs to be released in some way in order for a thermodynamic equilibrium to be reached over time. A system always strives to reach a thermodynamic equilibrium according to the laws of thermodynamics. The way this is established is by continuous heat transfer with the system's surroundings which eventually results in the system having its temperature lowered and indirectly reaching an equilibrium state in energy. Heat transfer can in general occur in three ways: conduction, convection or radiation [24].

Conduction refers to the transfer of internal energy on a microscopic level within a body. This can happen between two components, e.g. a bolt and a nut, which can be seen as a whole body when connected to one another. Conduction can be a result from friction between components or other external heat sources for instance. If the fire detector was to be placed so that it physically comes in contact with the engine block's hot side it would be heated by the conduction process occurring between the materials that are interconnected [24]. The equation for a conduction process is governed by Fourier's Law as

$$q = \frac{\lambda A}{b} dT \quad (6)$$

where q is the heat transferred, λ is the thermal conductivity of the material, A is the heat transfer area, b is the material thickness and dT is the temperature difference across the material.

Convection is the heat transfer process between fluids or gases. However, if these are hot enough and if they flow around solids, the solids will be heated by the fluids or gases. As the internal combustion process takes place in the engine, the combustion gases are extremely hot. They heat the surrounding air inside the engine room which in turn heats the fire detector that is mounted further away from the combustion process, thereby exposing the fire detector to a convective heat transfer process [24]. The equation for a convection process is given by

$$q = h_c A \, dT \quad (7)$$

where q is the heat transferred, A is the heat transfer area of the surface, h_c is the convective heat transfer coefficient of the process and dT is the temperature difference between the fluid and the surface.

Thermal radiation is the electromagnetic radiation that a body emits due to its temperature being above absolute zero (-273,15 °C), i.e. all bodies within the engine room will emit thermal radiation to other components all the time. Radiation is a method of heat transfer that does not rely upon any contact between the heat source and the heated object unlike the case with conduction and convection. Therefore, if the fire detector is placed near a hot surface, this surface will radiate heat and the expectancy of the total temperature within the fire detectors proximity may be misjudged [24]. The Stefan-Boltzmann Law yields the equation for a radiation heat transfer process as

$$q = \sigma A T^4 \quad (8)$$

where q is the heat transferred, A is the area of the emitting body, T is the absolute temperature in Kelvin and $\sigma = 5.6703 \times 10^{-8}$ W/m^2K^4 is the Stefan-Boltzmann constant.

The term “cooling” is a heat transfer process where a cold system, i.e. a system with low temperature, is being heated by a system with high temperature. A cold system can never cool a hot system, but instead it is always the hot system that transfers heat to the cold system, eventually resulting in both systems having the same temperature and being in thermodynamic equilibrium. Therefore the commonly used term “cooling” is a misconception of how heat transfer is conducted in reality. For instance, a cooling fan supplies an engine room with “fresh and cold” air from outside the engine compartment with the single purpose to allow for the hot air inside the engine room to release its higher internal energy by heat transfer [23,25].

5.3.2 Thermal loading and its effects

The term *thermal loading* is used to describe materials that are subjected to variations in temperature under certain loading conditions. Thermal loads can arise from both hot and cold sources, e.g. heat generating equipment such as engines, fires, hot fluids or gases, cold ambient temperatures, low temperature fluids and so forth. Heat issues in engine compartments, which can be seen as closed systems, arise due to internal hot sources, such as the combustion process inside the engine which can reach temperatures up to 650 °C, as stated in Chapter 2.3, and the heat release from rotating or vibrating parts due to friction. The temperature of the ambient air outside of the engine room also has an impact on the heat inside the engine room. Thermal effects on materials are an outcome of thermal loading and they do not only change the mechanical behavior of materials, but also modify all material properties, which can have critical consequences. As metals are heated to higher temperatures they can become more ductile which leads to larger deformations for the component under certain stress levels. The electrical resistivity of metals used in electrical circuits is increased with increased temperature which can cause electrical issues within the circuit. High temperatures can eventually lead to metals corroding that can result in sudden fatigue failure. As metals are heated they tend to expand, which causes volumetric issues inside the engine compartment. If metals are subjected to low temperatures during cold winter days for instance, they will become more brittle, thereby losing a lot of flexibility which can be hazardous in certain situations. The electrical resistivity of metals in electrical circuits will be reduced and metal components will shrink in size, which might have many negative effects in certain constructions inside the engine room. Polymers are degraded if subjected to high temperatures for longer periods of time due to the ageing phenomenon as explained in the previous sub-chapter [26]. They also become softer and can even melt depending on how high the temperature is. If the ambient temperature in the surrounding is low however, polymers tend to be stiff which can lead to unwanted material behavior at certain positions in the compartment.

Consequently, in order to maintain a solid working environment for components in the engine compartment with regard to the possible variations in temperature, precaution must be taken in how to manage different heat scenarios during normal and deviating loading conditions for the vehicle. In order for components to withstand high or low temperatures without having their material characteristics altered with, tests need to be made where the engine room is subjected to temperature variations. The tests ensure that materials inside the engine compartment can survive the different temperature scenarios without having their material properties modified.

5.4 Vibrations and shocks

Vibration, also known as oscillation, is a mechanical phenomenon that is the result from when an object is in motion around an equilibrium point in space that repeats itself in a time interval. Sounds or noises are a byproduct of vibrations as the vibrations cause rapid changes in the density of air molecules when the air is compressed and expanded due to the vibrating motion of the object. The vibrating air molecules move back and forth creating waves, transferring and receiving energy to and from nearby air molecules resulting in sound waves, or commonly referred to as sound only. Vibrations are in some cases desirable in order for a device to function as it should. An example of desirable vibration is the vibrations created by hammering the strings on a guitar and thereby creating the wanted tune. More than often though, vibrations are undesirable as they waste energy and create unwanted noise. Vibrational motions of mechanical devices, such as engines, that are in operation are typically unwanted. These motions can be created by imbalances in the rotating parts, uneven friction, the meshing of gear teeth and so on. Vibrations also generate forces that stretch, compress or twist the object or nearby components. This results in them experiencing alternating stresses and thereby stress-induced fatigue. The component's ability to handle these stresses depends on the magnitude and the number of alternating stress cycles. As a result, sooner or later the component may fail in one way or another [27,28].

Vehicles are frequently subjected to mechanical shocks in the course of its useful lifetime. These shocks can be a result of harsh bumps in the road during transportation, faulty layout design, hard braking etc. Although shocks have an extremely short duration, mostly in the millisecond span, they are often severe and cannot be neglected. Therefore, the study of mechanical shocks is of vital importance as they cause critical damage on components if not managed properly.

Unlike vibration, mechanical shock is a non-periodic force disturbance on an object characterized by suddenness and severity of a large force being reached in fractions of a second. Nevertheless, there are many similarities between the two when it comes to the generation of physical phenomena as well as the behavior in the oscillations that occur. Therefore, the characteristic equations used to describe vibrations are also valid for shocks. Furthermore, while vibrations induce alternating stresses, shocks induce transitory dynamic stresses and if the sustainability of the object is exceeded, it might fail in the end in both cases. While vibrations cause stress-induced fatigue failure, shocks can cause sudden fractures or plastic deformations that can have critical influences on surrounding components and the component itself. If the component does not fail instantly due to the experienced shock, it might fail later on due to accelerated fatigue because of the deformed shape of the component, thereby reducing its operational reliability. The shock induced stresses are a function of the shock's characteristics, such as amplitude, shape and duration, and the dynamic properties of the object exposed to the shock, such as resonant frequencies [29].

5.4.1 Types of vibrations

There are two types of vibrations, namely free vibrations and forced vibrations. Free vibrations can be explained by considering the oscillatory motions of a pendulum, see Figure 5.3. The pendulum travels from one point to the other by the conversion of potential to kinetic energy. As it starts at one end with its velocity at zero, the potential energy will be converted to kinetic energy when it swings around its point of rotation. The velocity will be the highest at the bottom until it comes to a halt at the opposite side from where it started its swing and repeats the process the other way around. A full cycle of potential-kinetic-potential energy conversion has been made. This oscillating motion will, if undisturbed, continue in this matter indefinitely if no losses in energy are acknowledged.

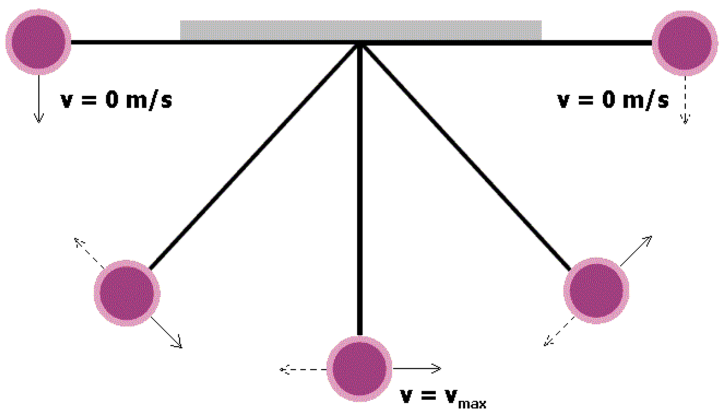


Figure 5.3 – The characteristics of an oscillating pendulum.

Now, consider a vibratory system with a spring and a mass, see Figure 5.4.

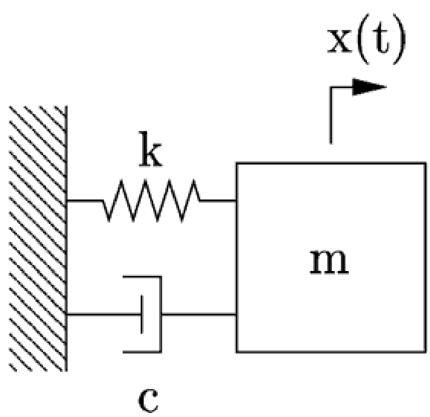


Figure 5.4 - An illustration of a spring-mass system where k is the spring constant, c is the damping constant and x(t) is the displacement of the body with respect to time.

The spring stores the potential energy while the mass, or the inertia, stores the kinetic energy of the oscillatory motion. The spring can be of any kind of elastic element, such as a beam, rotor, blade etc. If the vibrating spring-mass system is now disturbed from its stable position, the oscillations over a certain period of time will diminish. Thus, the system has a damper that absorbs energy from the vibrations and stops the oscillating motion completely. The damper can be a result of friction between components, a dashpot or even the vibrating component itself that undergoes alternating deformations during the vibrating occurrence. Therefore, in order to sustain the vibration, a disturbing force that continuously supplies the system with energy must be applied. If the system has significant damping, the vibration is called damped-forced vibration. If the damping is negligible, the vibration can be seen as undamped-forced vibration or undamped-free vibration, depending on if there is a continuous disturbing force acting on the system or not. When it comes to vehicles and vibrations, as long as the vehicle is in operation there will constantly be damped-forced vibrations acting on it. Regardless of if the vibrations are a result of the engine running while the vehicle is standing still or if they are induced by friction between the tires and the road while driving, there will always be a disturbing force acting on the vehicle. Therefore, only damped-forced vibrations will be considered further on in this sub-chapter [27,30].

5.4.2 Damped-forced vibrations

Consider an object that can be described as the spring-mass system shown in Figure 5.4 above. Assuming linearity and that the system has a single degree-of-freedom, the equation of motion when an oscillating force $F = F_0 \sin \omega t$ is applied on the system is then

$$m\ddot{x} + c\dot{x} + kx = F_0 \sin \omega t \tag{9}$$

where the parameters are explained in Table 5.2 below.

Table 5.2 – Explanation of the parameters for the equation of motion for a spring-mass system.

Parameter	**Force type**
Acceleration of the object, $\ddot{x}$	Inertial force of the object, $m\ddot{x}$
Velocity of the object, $\dot{x}$	Damping force of the object, $c\dot{x}$
Displacement of the object, x	Spring force of the object, kx

The solution to equation (9) is

$$x = Xe^{-\zeta\omega_n t} \sin(\omega_d t - \varphi_1) + \frac{F_0}{\sqrt{(k - m\omega^2)^2 + (c\omega)^2}} \sin(\omega t - \varphi) \tag{10}$$

where the damping ratio is $\zeta = \frac{c}{2\sqrt{km}}$ and the angular frequency of the object is $\omega = 2\pi f$. However, when $\omega = \sqrt{\frac{k}{m}}$ it is often referred to as the natural frequency and is denoted ω_n. At this frequency, the system tends to oscillate in the absence of any driving or damping force.

With time, equation (10) is reduced to

$$x = \frac{F_0}{\sqrt{(k - m\omega^2)^2 + (c\omega)^2}} \sin(\omega t - \varphi) \tag{11}$$

as the first term of the solution becomes negligible because $e^{-\infty} = 0$. The term φ is the phase lag of the displacement relative to the velocity of the object. Thus, the steady state response of the system is given by equation (11).

The ratio of the amplitude of the steady-state response to the static deflection under the action of force F_0 is known as the magnification factor (MF). This is given by

$$MF = \frac{1}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left(2\zeta \frac{\omega}{\omega_n}\right)^2}} \tag{12}$$

When the damping, or the damping ratio ζ, increases, the maximum value of the magnification factor decreases and vice-versa. When there is no damping ($\zeta = 0$), the MF reaches infinity at $\frac{\omega}{\omega_n} = 1$, i.e. when the frequency of the forced vibrations is equal to the frequency of the free vibration. This condition is known as resonance and can be catastrophic to structures or objects, as low frequencies are magnified indefinitely until the system cannot handle the vibrations and the induced stresses which results in total failure or collapse of the system. Note that if the damping ratio is very small and $\frac{\omega}{\omega_n} \approx 1$, the issue of resonance can still arise as the MF will increase and amplify the vibrations in large proportions, thus causing complications to the structure. This is can be of concern for components mounted in vehicles [31].

5.4.3 Degree of freedom

As the tires of a vehicle are exposed to mechanical vibrations and shocks, by hitting a road bump for instance, these are transferred to mounted components inside the engine room through the suspension and frame of the vehicle. A vehicle therefore forms a complicated oscillatory system consisting of several damped multi-degree-of-freedom systems, see Figure 5.5.

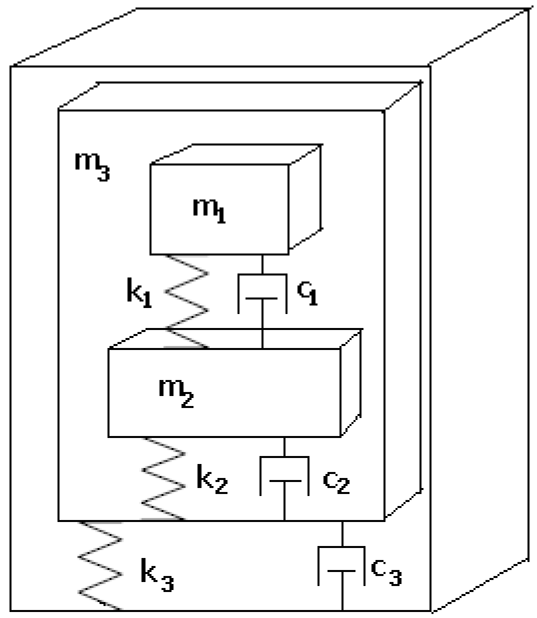
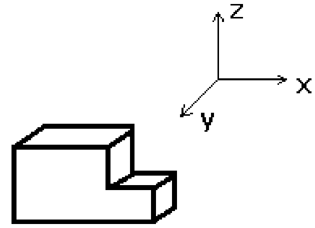


Figure 5.5 – Example of a multi-degree-of-freedom system containing three suspended bodies coupled to each other where m_x denotes the mass of the body, k_x denotes the spring constant and c_x denotes the damping constant.

The term *degree of freedom* (DoF) refers to the number of parameters of the system that may vary independently. For example, the position of an object in the plane has three degrees of freedom: its orientation and the two coordinates of any fixed point of the object. In the case of a multi-DoF system, shock or vibratory excited oscillations in one outer system may cause damage to an inner system by coupled resonance effects. These effects can be described by sets of higher order shock spectra, valid for given combinations of resonance frequencies of the mass-spring subsystems. However, when testing the shock or vibration response of a single component by isolating it from the rest of the oscillatory system, the tests are usually conducted in one direction each time and therefore assumed to be linear one-DoF systems. In reality, the shock or vibration on the component is often generated from six possible directions on a vehicle, either from the sides, the front or back, from down under or from above of the vehicle. Therefore, components are often tested in the following directions as shown in Table 5.3 [30].

Table 5.3 – Shocks and vibrations are applied in the directions as illustrated in the table during oscillatory tests.

Oscillatory motion from the	Direction	Component
Sides	x and -x	
Front or back	y and -y	
Below or above	z and -z	

5.4.4 Mechanical shocks

In reality, a shock does not have a simple pulse shape, as the component will dampen the shock out and the real shape of the incoming shock will have an oscillatory motion. Still, the part of the shock which is harmful for the component is the peak pulse of the whole oscillatory motion and it is this peak pulse that is represented by one of three common shock response pulse shapes. These pulse shapes are used as standards for analysis of components in the automotive industry, namely half-sine pulse, final-peak saw-tooth pulse and trapezoidal pulse. The pulse shapes thereby serve as filters, as they filter out the damping part of the shock and only the peak shock pulse remains. Each pulse filters the shock response differently. The half-sine pulse is the simplest type and diminishes most of the damping response. The trapezoidal pulse has a larger spectrum than the half-sine pulse and therefore yields more information about the damping response, see Figure 5.6 [30,32].

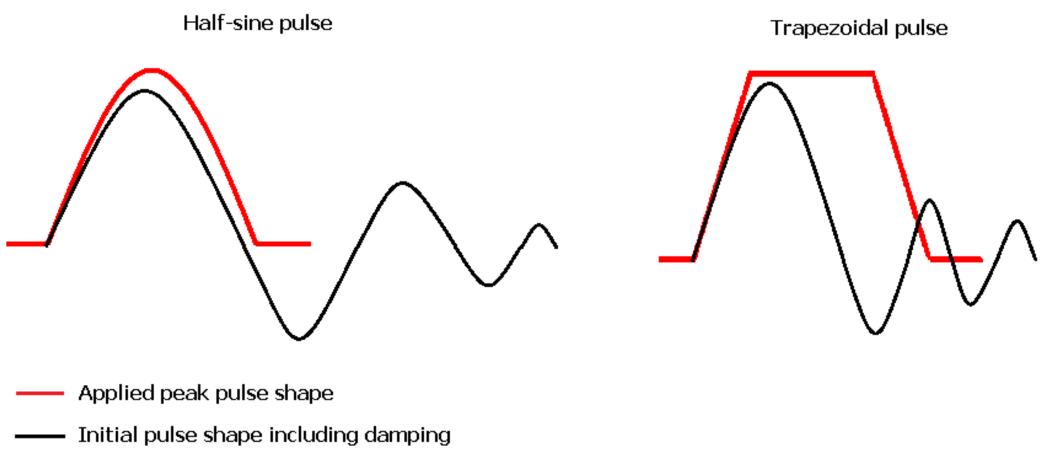


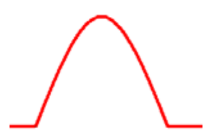
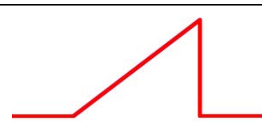
Figure 5.6 – Difference between a half-sine pulse and a trapezoidal pulse in their filtering capabilities of shocks.

When the component is subjected to a shock, the shock duration and peak acceleration of the component, i.e. the duration and the amplitude of the pulse shape, are observed. The peak acceleration is often measured in g-forces. The velocity change of the component can then be expressed as a function of these two parameters. The change in velocity can be calculated from

$$\Delta V = \int_0^\tau \ddot{x}(t)dt \tag{13}$$

where $\ddot{x}(t)$ is the acceleration of the shock, t is time domain and τ is the pulse duration. After integrating each of the pulse shapes in Table 5.4, a corresponding expression for the velocity change is obtained. Depending on which type of pulse shape that is applied, the velocity change of the component will vary. It is the sudden change in velocity of a component that is of interest when studying shock disturbances as only certain velocity changes are within an acceptable durability span. However, since the velocity change is indirectly dependent on the peak acceleration, the durability requirements are often given in terms of allowed g-force. If the change in velocity is extremely high, the component will most likely be susceptible to some degree of mechanical alteration due to the shock-induced stress and later on it might completely fail [29,30,32] .

Table 5.4 – Table containing the main shock waveforms and their corresponding velocity change expression.

Main shock waveforms (Peak acceleration, $\bar{\ddot{x}}$, pulse duration, τ and velocity change, ΔV)		
Waveform		$\mathbf{\Delta V}$
Half-sine		$\frac{2}{\pi}\bar{\ddot{x}}\tau$
Final-peak saw-tooth		$0.5\bar{\ddot{x}}\tau$
Trapezoidal		$0.9\bar{\ddot{x}}\tau$

Due to the irregularity of the number of subsystems in a vehicle and the diversity between individual component characteristics, a standard method known as *Shock Response Spectrum* (SRS) is used to study the severity of the shock for all kinds of DoF systems. This method is based on the assumption that the system is linear and consists of *N* one-DoF resonators. Compromising each resonator is a specific mass, spring and a damping device, chosen so that the fraction of the damping ratio is roughly the same for all resonators. When the system is exposed to a shock, each mass has a specific movement response according to its natural frequency and the chosen damping ratio, while a stress is induced in the elastic element. The purpose of this method setup is to search for the largest stress observed at each frequency in each spring and thereafter draw conclusions to the severity of the shock. In reality, SRS only serves as a reference to the damage potential of the component caused by the shock since SRS can be seen as a database consisting of shock responses for the whole system and not only isolated components. Therefore, the velocity change of a component that has been isolated from its surroundings during the test, e.g. a fire detector that has been removed from the engine room, will be compared to the change in velocity of other isolated components and to the system as a whole under the same shock response. After the comparison, an overview of which durability specifications concerning mechanical shocks that should be set on the detector, with regard to the whole oscillatory system, can be made. SRS also serves as a first impression on how the component is affected by resonance frequencies. If the shock occurs within the resonance frequency range of the component, the impact of the shock may be magnified up to two times its initial size which in turn leads to a larger physical impact on the component than estimated. This of course depends on how stiff the damping of the component is as heavy and stiff objects tolerate higher resonance frequencies before any magnification in the shock response occurs. Small objects are therefore prone to failure at lower shock frequencies which has to be taken into consideration when the durability requirements of shocks are to be set. An example of how SRS shows the magnification potential of a shock with regard to resonance frequencies for a component with a trapezoidal pulse shape applied can be seen in Figure 5.7 [29,30,32].

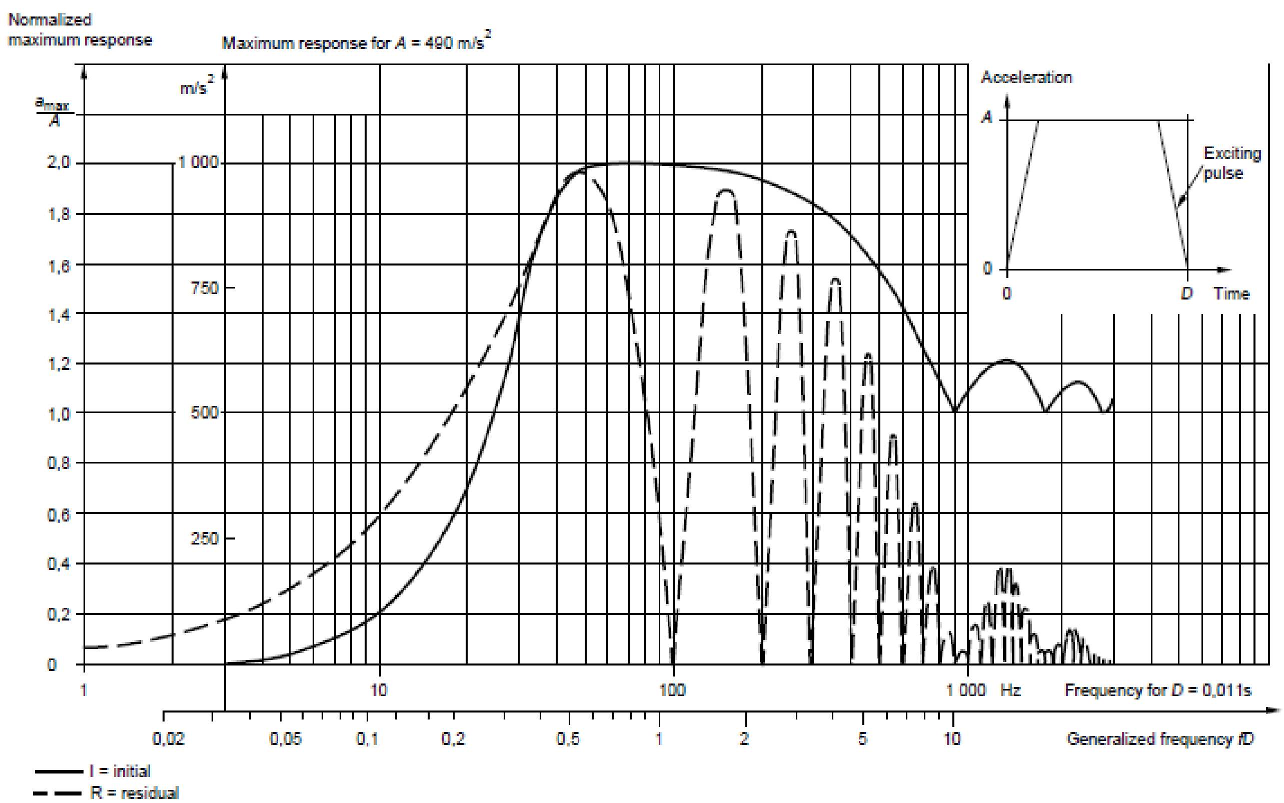


Figure 5.7 – The SRS showing the magnification of a shock with increasing frequency [32].

5.5 Electromagnetic compatibility

Electrical fields are created by the voltage difference between components or circuits and magnetic fields are generated by the current flowing through the electrical circuit when it is powered. Therefore in electronics the term electromagnetic field (EMF) is often used. It consists of electrical and magnetic fields and it can best be described as a physical field generated by electrically charged objects. The electromagnetic field affects the behavior of charged objects in its vicinity in different ways. Most fire detectors are electronically operated and they transmit active feedback to an electrical control center somewhere in the vehicle. Therefore, these types of detectors are classified as electronic devices [33].

In what way EMFs affect different components varies widely from case to case. By placing many electrical systems into a cramped space, as is the case for the electrical box in the engine room and the engine compartment itself, problems with electromagnetic interference (EMI) arise. The EMI between these systems occurs through radiated and conducted electromagnetic emissions, sometimes referred to as *crosstalk*. If the crosstalk is not controlled in a manageable fashion, it can cause many systems and other systems in their proximity to malfunction or fail completely. The electronics inside a vehicle are affected by both internal and external EMI sources. Internal EMI sources are simply the electrical systems that are installed in the vehicle, e.g. ignition system, fuel control system, cruise control, console applications etc. In short, these systems give rise to EMI due to the electrical circuits inside the vehicle emitting EMFs of different strengths. Sometimes EMI problems show themselves as static on the radio, which is not harmful for the functionality of the vehicle but can be of nuisance. In some cases on the other hand, the crosstalk can be dangerous as it can cause loss of control of the vehicle. Therefore, it is essential to design “mission critical” systems that can deal with the safety and control of the vehicle to withstand the impact of certain EMI sources and sizes. External EMI sources include Bluetooth devices, cellphones, third-party navigation, high power transmitters such as radio towers etc. Since the impact of these sources is uncontrollable due to the EMI amount varying irregularly, it is important to design EMI shielding, grounding and filtering properly, often in a way that critical systems can tolerate the worst case scenario. However, EMIs are not the only sources of interference for electronics. Another common interference is voltage deviation within the electrical circuit. This interference is caused by conducted transient disturbances from electrical/electronic sub-assemblies (ESA) to the power supply line or by the power supply line to ESAs. An ESA is an electrical device that is part of an interconnected electrical system consisting of many electrical devices, as is the case for a fire detector. Electrical disturbances can often cause false alarms in different electrical systems or simply lead to certain systems not activating at all, which can lead to critical vehicle failure in the end. Another aspect that is common within the EMC area is a phenomenon called electrostatic discharge (ESD). ESD is caused by a sudden discharge between two objects that come in contact with one another and that have different electrical charges.

The discharge erupts in the form of a microscopic spark which can burn through the electrical circuit in the device. Since ESAs in engine compartments are interacted with physically on a regular basis, either by mechanics' hands or tools during vehicle maintenance or by environmental impacts such as the surrounding air, ESD control is of high importance as it can cause sudden failures to devices [34,35].

Due to the progression in the automotive industry and the advancement of technology in recent years, more and more electrical systems and devices are fitted in vehicles, heavy vehicles in particular. In order for these systems to function correctly even though EMFs and EMIs are continuously present, these influences need to be managed in some way. Electromagnetic compatibility (EMC) is one way to control EMIs from different systems and devices so that unwanted effects are prevented. Since all vehicles differ when it comes to handling EMIs due to irregular amounts or different types of electronic systems fitted, current standards that ensure certain ranges of permissible EMIs are often applied. By incorporating standards into the EMC of electronic systems it ensures that they still function properly in a certain range of EMI or electrical disturbance exposure. In some cases, standards are required by law and sometimes current standards are tweaked with manufacturer specific requirements.

5.6 IP-classification

Engine rooms in vehicles are one of the harshest operating environments for electronics within the vehicle. Electronic equipment is often enclosed in a way that minimal penetration from mechanical impacts, dust, corrosion and corrosive substances, moisture or water, fungus, solar radiation or icing occurs. These factors can often lead to short circuits in electronic devices and therefore risks of electric shocks, fires or explosions can be an issue. Furthermore, devices that have sensors, such as fire detectors, can be sensitive to the factors mentioned earlier and are therefore of operational concern when exposed to these environments. IP-classification, or International Protection Code (IP Code), is a system used for classifying the degrees of protection provided by the enclosures of electrical equipment or electronic devices. This includes the following protection aspects [36,37]:

- Protection of individuals against access to hazardous parts inside the enclosure.
- Protection of the equipment inside the enclosure against ingress of solid foreign objects.
- Protection of the equipment inside the enclosure against harmful effects due to the ingress of water.

6. Test methods used for each of the physical phenomena

In order to investigate how different products are affected by the physical phenomena mentioned in the previous chapter, suitable test methods need to be used. In these test methods, the device should be subjected to each of the resulting physical impacts generated by the physical factors. Yet, the device's functionality should not be affected by these impacts. The fire detector should withstand anything from mechanical stresses and electrical disturbances to visual alterations and mechanical damages without having its predicted lifetime altered with. There are many applicable test methods to be used when investigating the influences from the physical phenomena generated in engine rooms but some are more relevant to this subject than others. In this chapter, certain methods that are deemed appropriate in order to assure that the fire detector can withstand these physical influences in a mechanical way will be suggested. The recommended durability requirements will be based on these test methods and test parameters.

It should be noted that, unless otherwise stated, all test parameters given in the following sub-chapters are based on recommended test conditions that can be found in already existing standard documentations.

6.1 Corrosion tests

Corrosion tests can be done in many ways but the best choice is often to simulate an artificial environment that resembles the environment that the product of interest is exposed to in reality. As natural degradation of metals can take many years, the test is often accelerated in order to make the results feasible. Accelerated tests are designed to quantify how long the test duration should be in weeks if the service duration of the vehicle is in years. Furthermore, corrosion of metallic materials with or without corrosion protection is influenced by many environmental factors, as stated earlier. The importance of these factors may vary with the type of metal and with the type of environment. Laboratory tests are designed to simulate the effects of the most important factors that enhance the corrosion of metallic materials. The accelerated corrosion test methods are designed to simulate and enhance the environmental influences of exposure to an outdoor climate where salt contaminated conditions and corrosive gases from a moderately aggressive traffic environment occur which may promote corrosion [19].

The following test method is used to assess the corrosion resistance of products in environments where there is a significant influence of chloride ions and of corrosion-promoting gases. It especially applies to metals and their alloys, metallic coatings (anodic and cathodic), conversion coatings, anodic oxide coatings and organic coatings on metallic materials.

The chloride ions that vehicles are exposed to in general are mainly sodium chlorides, NaCl, or simply known as salts, from marine sources, such as driving near the sea during harsh winds, or de-icing salts on the roads during the winter. The corrosive gases are generated by gas emissions from vehicles and can often be found in the traffic air pollution but also as leakage gases from the combustion process inside the engine. Thereby, the engine compartment is exposed to both internal and external corrosive gases. The gases that have the most corrosive effect are those with a low pH value, such as nitrogen oxides, NO_x, and sulfur oxides, SO_x. Lastly, this test method is especially suitable for assessing the corrosion resistance of sensitive products with metals, e.g. electronic devices, used in traffic environments [38,39].

Unless otherwise stated, all tests should be conducted with the following standard atmospheric conditions: 25 ± 5 °C, 101,3 ± 10 % kPa and 20-50 % relative humidity (RH). For further reference beyond the content in this chapter, it is recommended to see ISO21207.

6.1.1 Chosen test method and test setup

The test specimen is subjected to a test cycle containing two parts. The first part of the test cycle is neutral salt spray testing for 2 hours in a mist of water containing a 5 % mass fraction sodium chloride solution at 35 °C, followed by drying for 22 hours in standard atmospheric conditions. The second part of the test cycle is exposure of the specimen for 120 hours in a test atmosphere containing a mixture of corrosive gases. The volume fractions of the gases are $1{,}5 \times 10^{-6}$ NO_2 and $0{,}5 \times 10^{-6}$ SO_2 at a relative humidity of 95 % and temperature of 25 °C. This is followed by drying the specimen for 24 hours at standard atmospheric conditions. One test cycle thereby corresponds to one week’s exposure. The test should be conducted for a period of 4 to 6 weeks, i.e. 4 to 6 test cycles should be made. The test setup where this artificial environment is simulated can be seen in Figure 6.1 [39].

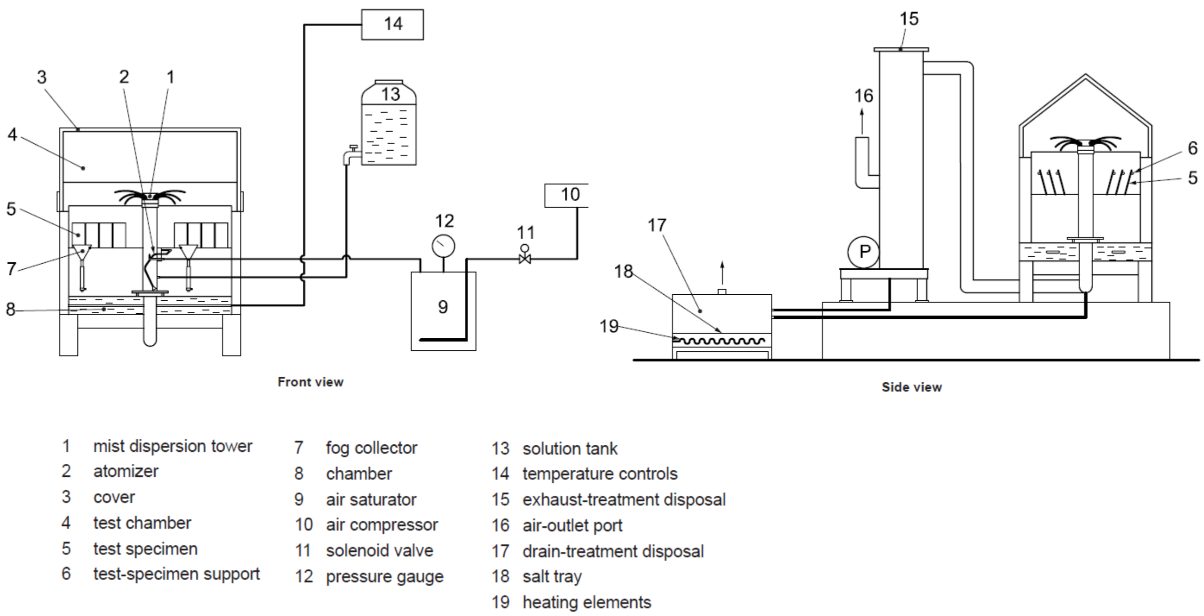


Figure 6.1 - Illustration of the test chamber where corrosion tests are made [39].

The salt spray and the corrosive gases are distributed homogenously over the test specimen inside the test chamber. The upper parts of the chamber are designed in a way that no drops formed by the sprayed solution fall on the specimens being tested. The device for spraying the test solution includes a supply of clean air with controlled pressure and humidity, a reservoir to contain the solution to be sprayed and one or more atomizers. The compressed air supplied to the atomizers passes through a filter to remove all traces of oil or solid matter and the atomizing pressure is at an overpressure of 70 kPa to 170 kPa. The pressure inside the test chamber should be at standard atmospheric conditions. In order to prevent the evaporation of water from the sprayed droplets, the air is humidified before entering the atomizer. Finally, at the bottom of the test chamber there should be a minimum of two collecting devices that are placed in the zone of the cabinet where the test specimen is placed, one close to an inlet of spray and one distant from an inlet. The placement of these should be so that only mist and gases, and not condensed water drops falling from the specimen or from other parts of the test chamber, is collected [40].

In order for this method to be proved a satisfactory corrosion test method and for valid measurement of the corrosivity of the tests in accordance with this method, four reference panels of copper are used with minimum 99,85 % mass fraction of Cu. The reference panels should have dimensions of 50 mm × 50 mm × 1 mm. During testing, the reference panels are handled in the same way as the test specimen and are placed in four different positions of the test chamber, as denoted by number 5 in Figure 6.1. The test is deemed satisfactory if the loss in mass of each reference panel is within the intervals of 14,5 ± 1,5 g/m^2 if the test duration is 4 weeks and 20,0 ± 4,0 g/m^2 if the test duration is 6 weeks [39].

6.1.2 Salt spray test in detail

The fire detector and the reference panels shall be placed in the test chamber and then be exposed to a salt mist of 5 % NaCl solution at 35 °C, as stated above. After 1 hour of testing, the orientation of the reference panels is changed so that the surface facing upwards becomes the surface facing downwards. After 2 hours of testing, the fire detector and the reference panels are removed from the chamber and brought to a constant climate room at standard atmospheric conditions without being cleaned or washed off in order for detector and panels to dry. The fire detector and panels should be stored in this room for 22 hours before being exposed to the second part of the cycle, i.e. the corrosive gas exposure [39].

6.1.3 Exposure to corrosive gases test in detail

The test chamber should be prepared for testing by first adjusting the temperature to 25 °C, the air humidity to 95 % RH and the air flow rate to somewhere between 0,5 mm/s and 5 mm/s. After the desired conditions have been established, the corrosive gas flows are adjusted so that the SO_2 and the NO_2 concentrations in the inlet airflow to the working space are at a level of $0{,}5 \times 10^{-6}$ and $1{,}5 \times 10^{-6}$ volume fraction, respectively, as stated above. Once these conditions have been set the fire detector and reference panels are placed in the working space. After a test time of maximum 6 hours, the concentration of SO_2 and NO_2 in the outlet airflow from the working space should be at minimum of 80 % of that in the inlet airflow. If the concentration of the corrosive gases in the outlet airflow is lower than that, it is most likely that the total area of the detector in the chamber is too large. During the test, the exposure conditions shall be checked regularly and adjustments should be made to meet the specified levels accordingly. After 120 hours of testing, the detector and the reference panels are removed from the test chamber without any rinsing and then placed in a constant climate room at standard atmospheric conditions in order for them to dry [39].

6.1.4 Evaluation of results

Many different criteria for the evaluation of the test results may be applied to meet particular requirements. Some are:

- Appearance after the test – does the fire detector look different due to the corrosion layers, are the paint coatings and labels still visible etc.
- Number and distribution of corrosion defects – do the vital parts of the detector have pits, cracks, blisters etc.
- The time elapsed before the appearance of the first signs of corrosion – are there certain terms regarding elapsed time before corrosion occurs in the product specification?
- Alteration revealed by microscopic examination – does fire detector show alteration in the mechanical structure, such as the change in the HCP-structure of the material?
- Change in mechanical or electrical properties – if the mechanical properties of the material have been lessened, e.g. less strength or elasticity eventually leading to rapid fatigue failures. Has the corrosive effect influenced the electrical conductivity of the material?

6.2 Ageing tests

When speaking of the testing procedure of material ageing, as already mentioned, the most common methods are accelerated tests. As it takes many years for polymers to degrade naturally while not knowing exactly how and at which rate polymers degrade during continuous use in different atmospheres, accelerated tests are the most practical. These tests simulate a certain timespan that will reflect the actual usage time of the product. Bearing in mind that the polymeric products are mounted in an engine compartment, which is subjected to large variations in temperature during the vehicle's operational use, accelerated thermal tests of polymers are the best suited and will be further considered in this report. However, not all polymers can be tested in the same manner. Some materials, such as polyamide, are quite resistant to high temperatures and weathering but can be very susceptible to chemical exposure. When polyamide comes in contact with water or other chemicals it is prone to having its molecular bonds cleaved, resulting in polymeric chain scissions. This effect will only be seen if subjecting the polymer to a test involving them being placed in baths that contain different fluids with variations in temperature. These tests are similar to the *Hot air and cold water shock test* as well as the *Cold and boiling water shock test* as described in Chapter 6.3.5 and Chapter 6.3.6, respectively. Therefore, if the product specification for the fire detector states which type of polymer that is the main polymer in the material composition of the product, consideration to this alternative when choosing the test method for ageing should be taken into account [22].

In this chapter, the thermal ageing test method of polymeric products will be highlighted. Unless otherwise stated, all tests should be conducted with the following standard atmospheric conditions: 25 ± 5 °C, 101,3 ± 10 % kPa and 20-50 % relative humidity (RH). For further reference beyond the content in this chapter, it is recommended to see ISO6722-1.

6.2.1 Accelerated thermal ageing of polymers

This test method applies mostly to plastic insulations on electrical wires in electronic devices, as is the case for fire detectors. It ensures that a long exposure to high temperatures and variations in pressure will not cause any deviation in the electrical performance of the device, such as short circuits due to flaws in the plastic insulation of the wires. However, this test method and test verification can also be applied to the case where the fire detector is a pressurized plastic hose that melts when a fire erupts, as similar test conditions are valid. Exposure to low and high temperature are used in this test method, as polymers are susceptible to both of these in different ways. Typical failure modes of accelerated thermal ageing tests are mechanical fracture, melting, deformation, embrittlement, oxidation, loss of optical properties due to overheating, non-functional device due to degradation and short circuits and so forth [22,41].

The tests are conducted in a test chamber that resembles an oven. The air exchange in the oven should either be natural or by pressure and should enter the chamber in such a way that it flows over the surface of the test specimen and exits at the top of the oven. There should be a minimum of 8 and a maximum of 20 complete air changes per hour at the specified ageing temperature in the test chamber. The fire detector should be tested in powered off mode.

6.2.2 Verification procedure

If the polymer is a cable insulator that protects the electrical wires inside the fire detector, the following verification test is used to verify that the cable insulation is capable of withstanding the required rated voltage.

A test specimen, both cable and insulation, of a minimum length of 350 mm with 25 mm of insulation from each end of the specimen stripped off, should have its ends twisted together to form a loop. Thereafter, a non-conductive container is partially filled with salt water containing 3% mass fraction sodium chloride, NaCl, with the twisted ends of the test specimen emerging above the bath. The test specimen is immersed in the fluid as shown in Figure 6.2 for a minimum of 10 minutes after which a test voltage of 1 kV a.c. should be applied using a 50 or 60 Hz a.c. voltage source. The test voltage should be applied for one minute [41].

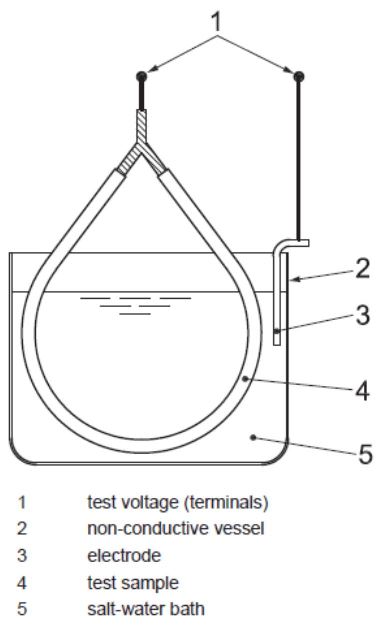


Figure 6.2 - Test setup of the wire and insulation in the verification procedure [41].

If the fire detector is in the form of a plastic hose, the verification procedure stated above does not apply. Instead several other test verifications may be of interest. As the most important factor for a fire detector that consists of a pressurized plastic hose is that no pressure equalization may occur, simple visual inspections are the most appropriate. If there are cracks or holes in the hose post testing, the device should be deemed as have failed the test as cavities in the hose result in instant pressure equalization and, indirectly, false alarm feedback from the fire detector. This is due to no fire occurring in reality and the hose not being able to withstand the temperature inside the compartment which has slowly degraded the material during its useful lifetime. However, if no visual alteration is noticeable, the material might still have been worsened by the ageing procedure which can lead to fatigue failure later on. A way of testing the mechanical characteristics of the polymer in this case may be in form of solid mechanics tests, such as stress and strain tests [22].

6.2.3 Long term heat ageing test

This test is intended to verify the upper value of the temperature endurance for the fire detector. The test is conducted by preparing two test specimens, either cable insulation or a plastic hose, each of a minimum length of 350 mm. The oven should be at the temperature specified by the operating temperature of the engine room in reality. An appropriate ageing temperature to be used is often mathematically estimated by using the Arrhenius equation (2) as specified in sub-chapter 5.2.1. As the average operating temperature, T_{OP}, in engine rooms of heavy vehicles is somewhere between 80 to 150 °C in reality, as stated in sub-chapter 2.3, a reasonable ageing temperature, T_{AGE}, may be T_{OP+30} in order for the test to simulate the vehicle's service life. This is an estimation based the results from the Arrhenius approximation and personal experience from experts at SP [22]. Thereby, the ageing temperature may be chosen from Table 6.1.

Table 6.1 – Appropriate ageing temperatures with regard to the operating temperature of the vehicle.

T_{OP} [°C]	$T_{AGE} = T_{OP+30}$ [°C]
80	110
90	120
100	130
110	140
120	150
130	160
140	170
150	180

The test specimens are then wrapped around a mandrel as seen in Figure 6.3 and then placed in the oven for 1000 to 3000 hours. The test samples shall be separated by at least 20 mm from each other and from the inner surface of the oven. Specimens made of different materials should not be tested simultaneously. After the ageing process, the test specimens should be withdrawn from the oven and maintained at standard atmospheric conditions for at least 16 h. After temperature stability has been reached, the specimen should be subjected to the *Low temperature winding test* followed by the verification procedure as stated in Chapter 6.2.2 [41].

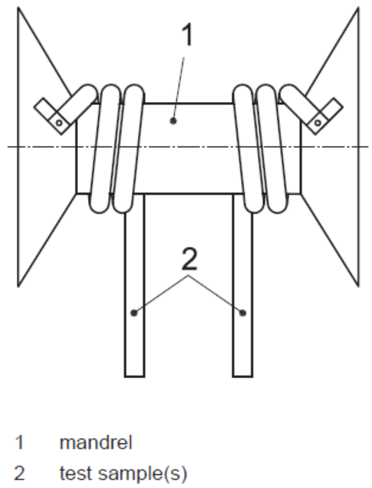


Figure 6.3 – An illustration of the winding of the specimen around the mandrel [41].

6.2.4 Low temperature winding test

This test intends to examine if the cable insulation or plastic hose can withstand bending at low temperature without cracking and still maintain intact, i.e. a cable should still have its insulation properties and the plastic hose should not have any leakage cracks that can stabilize the pressure inside. The test is therefore also used to detect defects caused by environmental stresses.

Two test specimens, either cable insulation or a plastic hose, of minimum length of 600 mm are wrapped around a mandrel for 0,5 to 3 turns, depending on its thickness, as seen in Figure 6.3. The mandrel and specimens should be placed in the test chamber at a temperature of -40 ± 2 °C where they must lie for a minimum of 4 hours. After the duration, the specimens are allowed to return to room temperature followed by a visual inspection for cracks and hollows. The verification procedure as stated in Chapter 6.2.2 should follow [41].

6.3 Temperature tests

Unless otherwise stated, all tests should be conducted with the following standard atmospheric conditions: 25 ± 5 °C, 101,3 ± 10 % kPa and 20-50 % relative humidity (RH). For further reference beyond the content in this chapter, it is recommended to see ISO16750-4.

6.3.1 Dry heat test

This test simulates the exposure of the fire detector to high temperatures while being under electrical operation and control in typical operating mode, e.g. the use of the device at very high ambient temperature. The test is relevant in order to simulate the working environment in the engine room as temperatures can be very high. It is recommended that the relative humidity should not exceed 50% during the test.

The test is conducted by placing the fire detector inside the test chamber. Thereafter, the temperature inside the chamber is gradually increased so as to cause no harmful effects on the detector due to the temperature change. The gradual increase depends on the type of device that is being tested. The temperature is increased until the desired maximum temperature has been reached. Once done, the fire detector is powered on, the test commences and the detector is subjected to this maximum temperature for a duration of time. Normal maximum test temperatures are 30 to 1000 °C and durations range from 2 to 1000 hours, depending on the device's operational environment in reality. After the duration has surpassed, the temperature is gradually lowered again in the same manner as it was increased until the temperature is the same as the ambient temperature outside the test chamber [38,42].

The fire detector should be visually, electrically and mechanically inspected post testing. Failure modes caused by the high ambient temperature inside the test chamber can be mechanical fracture, melting or deformation of materials (polymers in particular), loss of surface finish and optical properties due to overheating, internal short circuit due to the breakdown of electrical insulation materials and finally a non-functional device after the test.

6.3.2 Damp heat test

This test simulates the use of the fire detector under high ambient humidity while being switched on during normal operation. This test was created to resemble certain environments with high humidity, such as sudden rain during hot summer days or the working environment in rain forests where forestry machines operate.

The test starts by placing the fire detector inside the test chamber, both of which are at standard atmospheric conditions. The temperature should then be adjusted to the prescribed test condition and the detector should be allowed to reach temperature stability. This is accomplished by changing the temperature 1 °C/min every five minutes. During this period, and during the whole test, condensation on the fire detector must not occur. Typical testing parameters are seen in Table 6.2. Once the temperature has been reached, the RH should be adjusted to the corresponding test condition for the humidity. This should be reached within two hours. Now the test is ready to commence for the chosen test duration [43].

Table 6.2 - Table illustrating possible test parameters to be chosen for the damp heat test.

Temperature [°C]	RH [%]	Duration	
		Hours [h]	Days
30 ± 2	93 ± 3	12, 16 or 24	2, 4, 10, 21 or 54
30 ± 2	85 ± 3		
40 ± 2	93 ± 3		
40 ± 2	85 ± 3		

After the test duration, the equipment is shut off and the ambient conditions inside the test chamber are allowed to return to their normal values naturally. The specimen should be visually, electrically and mechanically inspected post testing. Typical failure modes are swelling of material, corrosion, discoloration, electrical malfunction caused by moisture, e.g. leakage current caused by a printed circuit board which is soaked with moisture.

6.3.3 Cold test

This test simulates the exposure of the fire detector to low temperatures while being powered on, e.g. the use of the detector at very low ambient temperature. This is the case for extremely cold operating environments for vehicles, such as for trucks being driven in Alaska for instance.

The fire detector is introduced into the test chamber which is at the same temperature as the surroundings. The temperature is then adjusted to the temperature appropriate to the degree of severity, usually somewhere in between +5 to -65 °C for a duration of 2 to 96 hours. The change in temperature should be 1 °C/min every five minutes. After temperature stability of the fire detector has been reached, it is powered on and then exposed to these conditions for the whole test duration. When the duration has elapsed, the temperature inside the chamber is then gradually heated at the same temperature change rate as it was cooled with until it has reached standard atmospheric conditions [44].

The specimen should be visually, electrically and mechanically inspected post testing. Failure modes are mechanical fractures of materials, seal leakage due to loss of elasticity at low temperatures and electrical malfunction caused by low temperature.

6.3.4 Rapid change of temperature test

This is an accelerated test which simulates a very high number of slow temperature cycles in the engine compartment. The acceleration is possible due to a much higher temperature change rate and a bigger temperature change in one cycle in comparison to real vehicle stress. Because this test creates mechanical defects, such as cracks in the material, it is not required to have the fire detector powered on. The testing procedure can be seen in Figure 6.4.

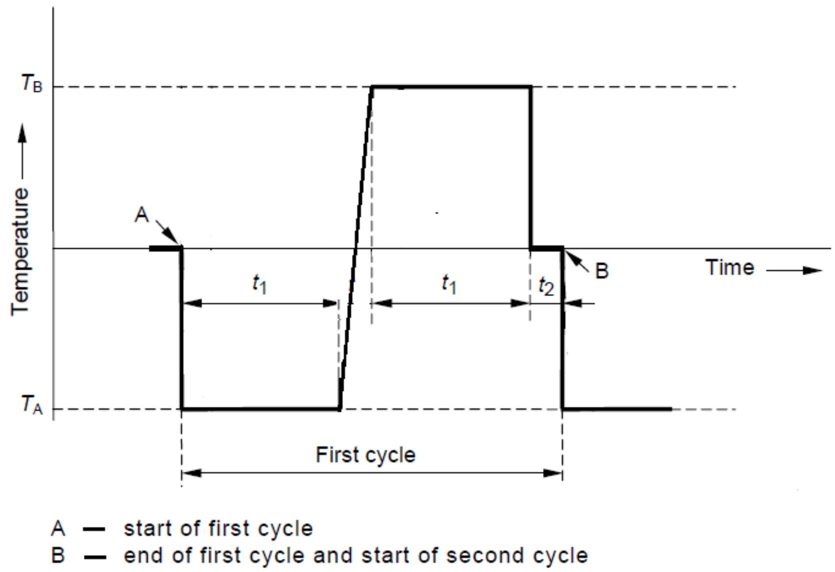


Figure 6.4 – Illustration showcasing the temperature cycles.

The test cycle starts by placing the detector inside the test chamber, starting at standard atmospheric conditions. The temperature inside the chamber should then be lowered to a cold temperature, T_A, as chosen in the *Cold test* within 15 seconds or less. This temperature should then be held for a specified period of time, t_1. The time period, t_1, is chosen from 10 to 180 minutes. If no exposure period is stated in the product specification, the exposure period for the specimen should be 180 minutes. After this duration, the specimen is exposed to a rise in temperature as to reach the hot temperature, T_B, as chosen in the *Dry heat test*. This temperature should be reached within 30 seconds or less. This temperature is once again held for the same duration, t_1. The temperature is finally decreased to the ambient temperature within 15 seconds, thereby concluding one rapid temperature change cycle. The recommended number of cycles for this test is 5 to 1000 depending on where the fire detector is placed in the compartment. After the final test cycle, the detector should remain in standard atmospheric conditions until temperature stabilization has been reached, denoted by t_2 in the figure above [45].

The fire detector should be visually, electrically and mechanically inspected post testing. Failure modes for this test are cracking of materials, seal failures due ageing (polymers in particular) and different temperature expansion coefficients.

6.3.5 Hot air and cold water shock test

This test simulates the effects of thermal loading due to thermal shocks that are induced by cold water while the fire detector is in operation. The test applies to products in the splash areas of the vehicle. The purpose of this test is to simulate cold water splashing over a hot device. This happens when driving on wet roads during the winter or if the engine compartment is exposed to cold water whilst the temperature in the compartment is still high, e.g. if the engine room were to be cleaned with a high-pressure water jet right after the vehicle is powered off. The testing procedure is as follows:

- Place the fire detector, while in full operational mode, in a hot air oven at temperature between 65 to 160 °C for at least 60 minutes or until temperature stabilization has been reached.
- With the device still operating, submerge it for 5 min in an ice water tank, in a depth of more than or equal to 10 mm. The test fluid in the water tank should be de-ionized water between 0 to 4 °C.
- The time it takes for the detector to be transferred from the hot oven to the water tank should be less than 20 seconds.
- Minimum number of test cycles to be performed is 10.

The fire detector should be visually, electrically and mechanically inspected post testing. Failure modes in this test are mechanical cracking of materials, seal failures caused by different temperature expansion coefficients and loss of tightness [38].

6.3.6 Cold and boiling water shock test

This test is similar to the *Hot air and cold water shock test* as it also simulates the effects of thermal loading due to thermal shocks. However, the difference is that in this test, the effects induced by boiling water are studied instead, rather than the effects of cold water. This is the case when the engine compartment is first exposed to cold water splashes or cold water jets during cleaning and then straight after fluid leakage from hot fluids inside the engine room when the vehicle is powered.

In this test there are two baths, one containing cold water at 2 ± 2 °C and the other containing hot or boiling water at 95 ± 5 °C. Under no circumstances may the water deviate from the temperature interval stated in either of the two baths. First off, the fire detector is placed in the cold bath and should be completely immersed by the fluid. It should be exposed to this condition for a duration between 10 to 180 minutes. If no exposure period is stated in the product description, the exposure period for the specimen should be 180 minutes. When the exposure period has elapsed, the detector is transferred to the hot bath within 20 seconds. Here it should lie for the same duration as in the cold bath. This is one test cycle and it should be repeated for a minimum of 10 times. At the end of the final cycle, the fire detector should be allowed to reach temperature stabilization through standard atmospheric conditions [38].

The fire detector should be visually, electrically and mechanically inspected post testing. Failure modes in this test are similar to those in the *Hot air and cold water shock test*, i.e. mechanical cracking of materials, seal failures caused by different temperature expansion coefficients and loss of tightness.

6.4 Random vibration and mechanical shock tests

The most reasonable vibration scenario in engine rooms and vehicles is random vibrations, as the vehicle is subjected to continuous irregular oscillatory motions due to uneven roads and from the rotating machinery inside the engine room in reality. Random vibrations may be used to identify accumulated stress effects and the resulting mechanical weakness and degradation in the specified performance of the fire detector. The test setup when testing vibrations and shocks can be seen in Figure 6.5. The detector is mechanically connected to the mounting surface of the test apparatus either directly or through a rigid test fixture. The test apparatus is an electrodynamic or a servo-hydraulic vibration generator that generates random vibrations but it can also be stimulated to cause singular motions with low frequencies to simulate shock behavior. Any connections to the specimen such as cables, pipes, bolts etc. should be arranged in a way that they impose similar restraint and mass as when the device is installed in its operational position. In order to achieve this, it may be necessary to fasten the additional connections to the fixture. The fundamental purpose of the test fixture is to transmit the mechanical influences from the test apparatus to the device [46].

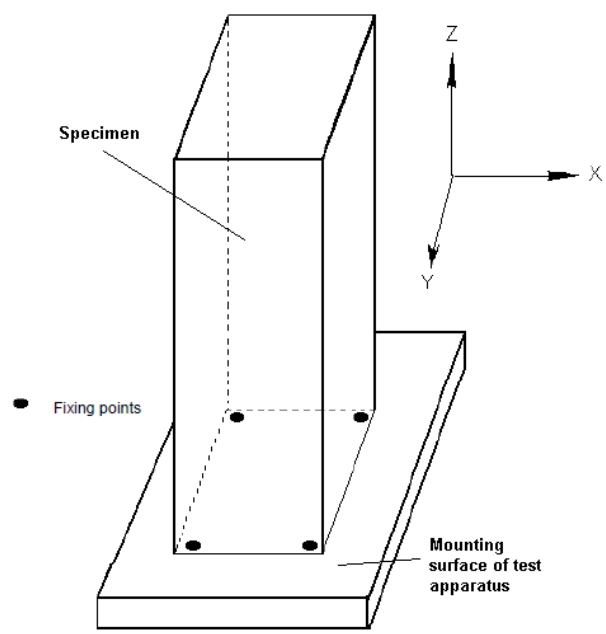
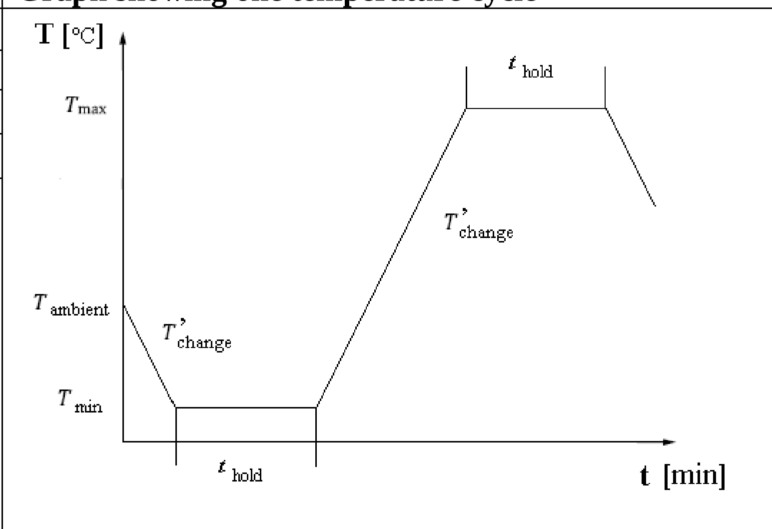


Figure 6.5 – A vibration generator with the test sample mounted on its mounting surface [46].

Most vibration and shock tests are performed under temperature influences. This is done in order to make the test resemble reality as much as possible. As components that are mounted in engine compartments of vehicles are subjected to both vibrations and temperature variations simultaneously while in operation, it is common for vibration tests to be performed under thermal cycling conditions as well. By doing so, both thermal and mechanical stresses will act on the device and the repercussions of these influences can be studied after the test. An example of a common failure is that a plastic part of a system mellows due to the high temperature and cannot withstand the vibration under this condition. The rapid temperature changes can occur due to sudden weather changes or if the engine load is increased more than usual. Therefore, it is practical to have the vibration apparatus inside a chamber that can change the temperature, a sauna-like test chamber for instance. The temperature intervals should be agreed upon between manufacturer and supplier but recommended values are seen in Table 6.3. The temperature cycle is represented by the graph in Table 6.3. The cycle starts at the ambient temperature and is gradually cooled to the lowest permissible temperature where it is held for a period of time. It is then heated with the same change in temperature as it was cooled with until the highest temperature has been reached. The maximum temperature is held for a duration as long as when the temperature was the lowest. Following this, the temperature is naturally cooled by heat transfer with the surroundings to the ambient temperature and a full temperature cycle has been completed. The temperature cycling is active continuously until the full vibration test has been concluded. It should be noted though that temperature cycling during vibratory tests is completely optional and should be agreed upon between manufacturer and supplier [38,46,47].

Table 6.3 – The vibrational temperature cycle and recommended values on the parameters.

Parameter	Unit	Graph showing one temperature cycle
$T_{ambient}$	25 ± 5 °C	
T_{low}	-40 ± 5 °C	
T_{high}	130 ± 20 °C	
T'_{change}	4 ± 1 °C/ min	
t_{hold}	80 ± 20 min	

Unless otherwise stated, all tests should be conducted with the following standard atmospheric conditions: 25 ± 5 °C, 101,3 ± 10 % kPa and 20-50 % relative humidity (RH).

6.4.1 Testing vibrations

The random vibration tests are carried out in order to investigate how rough driving influences the sprung mass of the vehicle. As the engine compartment is part of the sprung mass, i.e. the vehicle body, this is the most appropriate test to be made. The main failure to be identified by this test is breakage due to fatigue. The vibration and shocks are applied in each of the directions as mentioned in Table 5.3. The tests is conducted by selecting the appropriate test frequency range f_{range}, the overall r.m.s. value of acceleration, G_{RMS}, the shape of the acceleration spectral density curve (ASD) and the test duration. Usually, the test is carried out with a varying frequency range from 10 to 2000 Hz for a minimum of 8 hours in each direction. The recommended maximum test duration for practical reasons is 100 hours per axis. For most vibration environments, equivalent fatigue damage is easily accomplished within this duration. The ASD is the usual way to specify random vibration. The spectrum decomposes the content of the random signal generated by the vibration into the different frequencies present in that process and helps identify periodicities. ASD is expressed in g^2/Hz and is the relation between the acceleration of the test fixture at a specific frequency. The r.m.s. acceleration, G_{RMS}, is the square root of the area under the ASD curve in the frequency domain and is calculated by

$$G_{RMS} = \sqrt{\text{ASD}(f_2 - f_1)} \tag{14}$$

The r.m.s. acceleration should be held constant during the test, meaning that the relation between frequency and ASD should change, e.g. a higher frequency should yield a lower ASD and vice versa. Typical values for ASD and frequency span can be seen in Table 6.4 with regard to differences in the testing axis and frequency. Using the intervals of the ASD and frequency given in Table 6.4, corresponding G_{RMS} values may be calculated by using equation (14).The specimen should be in full operational mode during the test and should be submitted to visual, dimensional and functional checks post testing [46,47].

Table 6.4 – Typical values for G_{RMS} and ASD with regard to the frequency span

Frequency, f_{range} [Hz]	ASD [g^2/Hz]	G_{RMS} [m/s^2]
10 – 2000	0,1 – 0,5	140 – 315

For further information regarding random vibration tests beyond the content in this sub-chapter, see ISO16750-3 and IEC60068-2-64.

6.4.2 Testing shocks

Testing mechanical shocks is pretty straight forward and similar to how random vibrations are tested. The same test equipment is used in both cases and the test is conducted in the same directions as for vibrations. The only difference is that the fire detector is not subjected to the shock during long periods of time but instead to a number of shocks that last a certain amount of time and are in a certain g-force range. This test checks the specimen for malfunctions and breakage caused by shocks to the body and frame of the vehicle. As stated in the previous sub-chapter, the engine compartment is part of the vehicle body and therefore any shocks absorbed by the body will influence the detector mounted in the engine room. The test simulates a load on the vehicle that occurs when driving over a curb stone at high speed for instance.

Failure mode is mechanical damage, e.g. a detached capacitor inside the housing of the electronic device due to the occurring high accelerations or other critical failure. The specimen should be in full operational mode during the test and should be submitted to visual, dimensional and functional checks post testing. Typical values on the testing parameters can be seen in Table 6.5 [32,47].

Table 6.5 – Values for testing parameters of mechanical shocks.

<table>
<tr><th>Applied pulse shape</th><th>Peak acceleration, $\bar{\ddot{x}}$ [m/s^2]</th><th>Shock duration, τ [ms]</th><th>Number of shocks in each direction, N</th><th>Change in velocity, ΔV [m/s]</th></tr>
<tr><td>Half-sine</td><td rowspan="3">150 – 15000</td><td rowspan="3">0,5 – 18</td><td rowspan="3">3-10</td><td>0,118 – 424</td></tr>
<tr><td>Final-peak saw-tooth</td><td>0,0375 – 135</td></tr>
<tr><td>Trapezoidal</td><td>0,0675 – 243</td></tr>
</table>

For further information regarding mechanical shock tests beyond the content in this sub-chapter, see ISO16750-3 and IEC60068-2-27.

6.5 EMC tests

EMC tests on certain electrical devices can be conducted in two ways. One of them is by testing their electromagnetic compatibility whilst mounted in the vehicle. By doing so, the test assures that the device, i.e. the fire detector, is compatible with the electromagnetic environment for that specific engine compartment. By changing the environment, meaning installing the same detector in the engine room of another vehicle type, it can result in improper functioning due to the composition of installed electronic devices being different and therefore indirectly affecting the detector negatively. Consequently, the detector will need different manufacturer specific EMC requirements in this environment than in the previous one. The alternative way of testing the fire detector is by conducting “isolated” tests. The detector is then removed from the engine compartment and tested in a facility where it should withstand certain EMC requirements. If it passes the test, it should be suited for any engine compartment in any vehicle type. However, some detectors are well integrated with other electrical equipment and custom fitted into the engine room. This results in the removal of the detector being impossible and in turn “isolated” tests cannot be performed. Therefore, it is often recommended that electronic devices are subjected to “isolated” tests prior to mounting in the vehicle according to the United Nations regulation: *UNECE – Add. 9 – No. 10 – Rev. 5*, as it assures that it will tolerate the harshest EMC requirements regardless of the environment it is mounted in. If a fire detector has been tested this way and is to be mounted in the engine room of a vehicle, it is most likely that if further requirements are determined, they are manufacturer specific and serve only as a complement to the requirements made by the UN regulation. This is usually the case if the manufacturer wants to be certain that the detector will not disturb other important electrical equipment mounted in that specific engine compartment, and vice versa. Studying manufacturer specific EMC requirements for a fire detector is therefore difficult in this regard as they will differ depending on which engine room and vehicle type they are fitted in as well as what type of electronics it is interconnected with. It would for this reason be impossible to generalize manufacturer specific EMC requirements to match all vehicle types. Therefore only standard regulations are studied when it comes to EMC requirements for fire detectors mounted in engine compartments of heavy vehicles [35,48].

In order to pass standard regulations for “isolated” tests the aspects listed in the following sub-chapters need to be addressed in general. For further reference beyond the content in this chapter, it is recommended to see *UNECE – Add. 9 – No. 10 – Rev. 5*. Unless otherwise stated, all tests should be conducted with the following standard atmospheric conditions: 25 ± 5 °C, 101,3 ± 10 % kPa and 20-50 % relative humidity (RH).

6.5.1 Narrow– and broadband EMI generated by ESAs

This test is intended to measure narrow- and broadband electromagnetic interferences generated by ESAs, i.e. investigate the EMI strength (dB µV/m) that the fire detector will emit while powered on. The fire detector shall be in normal operation mode during the test, preferably on maximum load. The limits apply throughout the frequency range 30 to 1000 MHz for measurements performed in a semi anechoic chamber with a spectrum analyzer or a scanning receiver. The approval limits are as seen in Table 6.6. The measured values shall be below these limits [48].

Table 6.6 – Permissible EMI strength values with respect to the frequency interval.

Frequency, F (MHz)	**Limit, E (dB µV/m)**		
	Broadband	**Narrowband**	
30 – 75	62 – 52 $E = 62 - 25.13\log\frac{F}{30}$	52 – 42 $E = 52 - 25.13\log\frac{F}{30}$	Decreasing logarithmically
75 – 400	52 – 63 $E = 52 + 15.13\log\frac{F}{75}$	42 – 53 $E = 42 + 15.13\log\frac{F}{30}$	Increasing logarithmically
400 – 1000	63 $E = 63$	53 $E = 53$	Constant

The test setup can be seen in Figure 6.6 and the fire detector should be placed accordingly. It is recommended that the test device is placed on a non-conductive plate with a relative permittivity, $\varepsilon_{r,}$ lower than 1.4. The specimen should also be at 50 mm ±5 mm above the ground plane during the test.

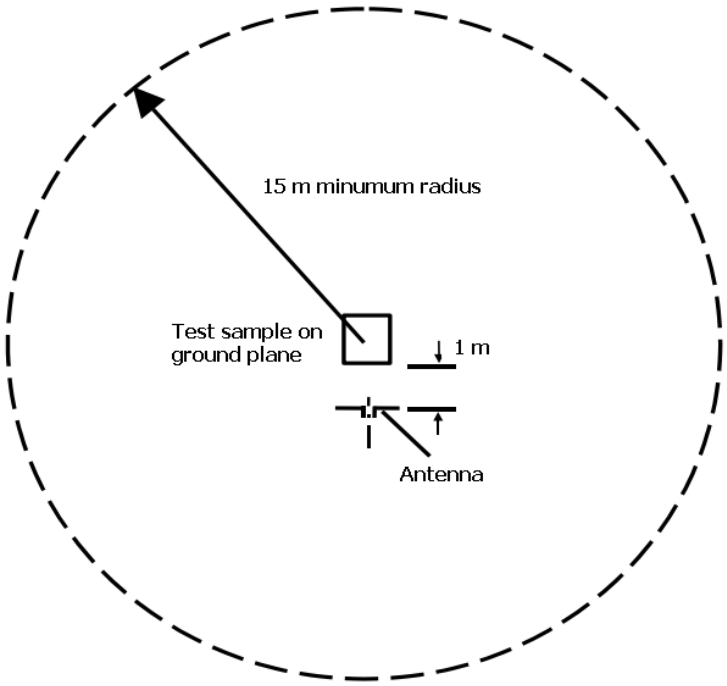


Figure 6.6 – Test setup of the semi anechoic chamber with the test sample placed in the middle [48].

6.5.2 Immunity of ESAs to electromagnetic radiation (EMR)

When testing the immunity of ESAs to EMR there are many possible test methods to be used. A common method is by using an 800 mm stripline as seen in Figure 6.7. This method can test complete electronic systems including sensors and actuators as well as the controller and wiring loom. It is suitable for ESAs whose largest dimension is less than one-third of the plate separation, which is often the case with fire detectors as they are relatively small. The fire detector is positioned centrally between two parallel metallic plates separated by 800 mm and at a height of 0.4 m. It is then subjected to an electromagnetic field. The detector shall be switched on and stimulated to be in normal operation condition during the whole test. To ensure that reproducible measurement results are obtained when tests and measurements are repeated, the test signal generating equipment and its layout shall be the same each time the test is performed. The test will be performed with frequencies ranging between 20 to 2000 MHz. At each desired test frequency, a level of power is fed into the stripline to produce the required EMR field strength. The immunity test levels should be to a minimum of 30 V/m over the whole 20 to 2000 MHz frequency band. If the fire detector fails the test it should be verified as having failed under the relevant test conditions and not as a result of the generation of uncontrolled fields [48].

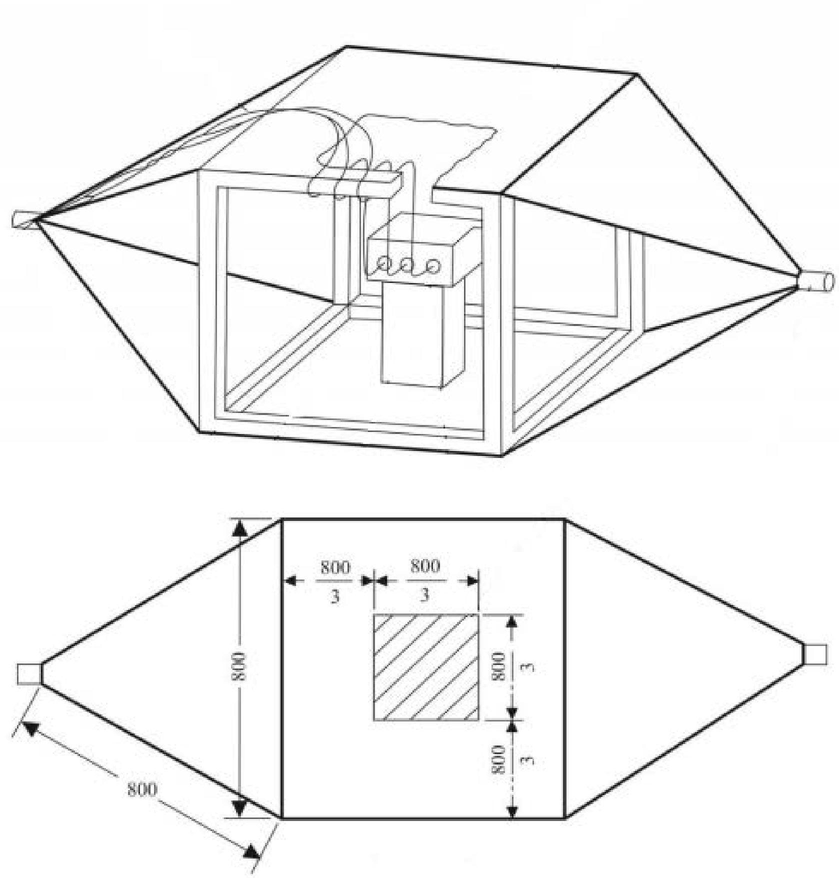


Figure 6.7 – Test setup when investigating ESAs' immunity to EMR using an 800 mm stripline [48].

6.5.3 ESAs' immunity to transients disturbances and the emission of transients disturbances from ESAs

These test methods should ensure the immunity of ESAs to conducted transient disturbances on the vehicle power supply and limit conducted transient disturbances from ESAs to the vehicle power supply. The methods are only applicable if the vehicle power supply line is 12 or 24 V.

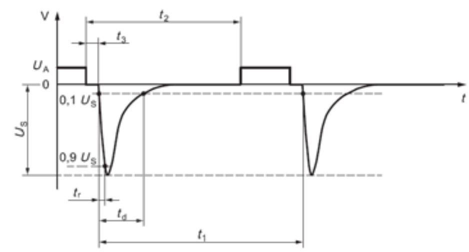
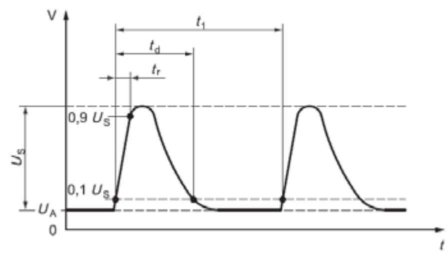
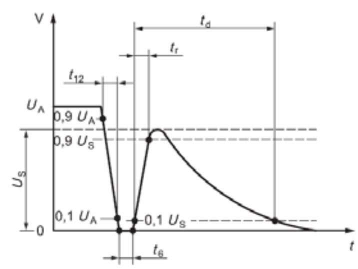
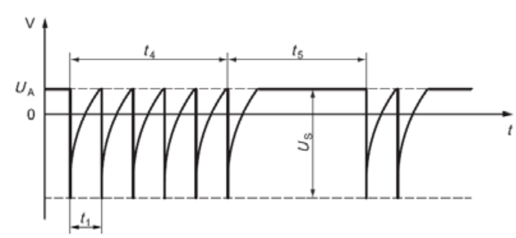
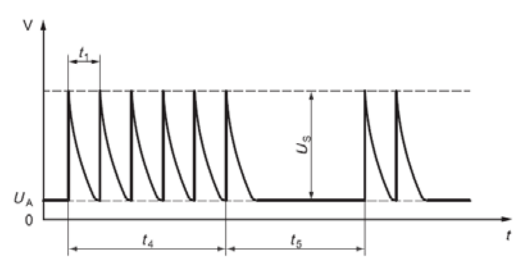
When testing the immunity of ESAs to transients, five different test pulses are applied to the supply line. These voltage pulses are generated by an external pulse generator coupled to the supply line. Each pulse simulates a different scenario and the test pulse generator should be capable of producing an open circuit test pulse for each situation. The voltage pulse sent by the external generator is denoted U_S and the supply voltage is denoted $U_{A.}$ The test pulses are categorized as 1, 2a, 2b, 3a and 3b and are defined in Table 6.7 [49].

Table 6.7 – Description of the five voltage pulses that are supplied by the voltage generator.

Test pulse	Description
1	Simulates transients due to supply disconnection from inductive loads. It applies to an ESA if it remains connected directly in parallel with an inductive load.
2a	Simulates transients due to sudden interruption of currents in a device connected in parallel with the ESA due to the inductance of the wiring harness.
2b	Simulates transients from DC motors acting as generators after the ignition is switched off.
3a	Simulates transients that occur as a result of the switching processes. The characteristics of these transients are influenced by distributed capacitance and inductance of the wiring harness.
3b	

The test pulses and their corresponding test parameters are shown in Table 6.8. The actual pulse shapes may not deviate more than 10% of the theoretical pulse shapes in Table 6.8. If that is the case, the fire detector is deemed not to have passed the test. Recommended test values for each pulse will be given in the next chapter. If the detector functions properly after the recommended test pulse for each pulse test, the recommended value will be applicable as a passing requirement.

Table 6.8 – Test parameters for each of the test pulses and their applied voltage pulses visualized in a graph.

Test	Parameters	12 V supply line	24 V supply line	Pulse shape
1	U_S R_i t_d t_r t_1 t_2 t_3	−75 to 150 V 10 Ω 2 ms $1^{0}_{-0,5}$ µs ≥ 0,5 s 200 ms <100 µs	−300 to −600 V 50 Ω 1 ms $3^{0}_{-1,5}$ µs ≥ 0,5 s 200 ms <100 µs	
2a	U_S R_i t_d t_r t_1	+37 to +112 V 2 Ω 0,05 ms $1^{0}_{-0,5}$ µs 0,2 s to 5 s		
2b	U_S R_i t_d t_r t_{12} t_6	10 V 0 Ω to 0,05 Ω 0,2 s to 2 s 1 ms ± 0,5 ms 1 ms ± 0,5 ms 1 ms ± 0,5 ms	20 V 0 Ω to 0,05 Ω 0,2 s to 2 s 1 ms ± 0,5 ms 1 ms ± 0,5 ms 1 ms ± 0,5 ms	
3a	U_S R_i t_d t_r t_1 t_4 t_5	−112 to −220 V 50 Ω 150 ns ± 45 ns 5 ns ± 1,5 ns 100 µs 10 ms 90 ms	−150 to −300 V 50 Ω 150 ns ± 45 ns 5 ns ± 1,5 ns 100 µs 10 ms 90 ms	
3b	U_S R_i t_d t_r t_1 t_4 t_5	+75 to +150 V 50 Ω 150 ns ± 45 ns 5 ns ± 1,5 ns 100 µs 10 ms 90 ms	+150 to +300 V 50 Ω 150 ns ± 45 ns 5 ns ± 1,5 ns 100 µs 10 ms 90 ms	

The test procedure to evaluate ESAs for conducted emissions of transients along supply lines of a device under test are performed as follows. The supply voltage and the disturbance voltage generated by the ESA shall be measured using a voltage probe and an oscilloscope. The test applies to an inductive load with a large inductance or a high load current, which connects to the vehicle power supply or an ESA which switches such an inductive load. If an inductive load has a small inductance or a low load current and is driven by an internal regulated voltage, e.g. 5 V, which is isolated from the vehicle power supply, the test is not applicable unless specified in the test. Two types of conducted emission transients are tested, namely slow and fast pulses. The test setup is seen in Figure 6.8 [49].

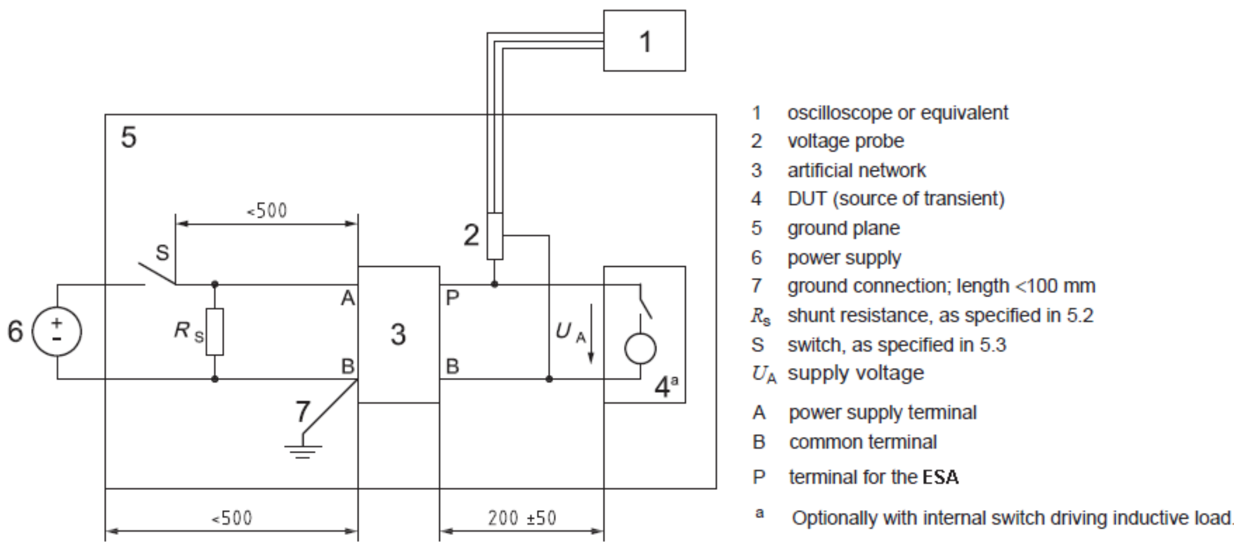


Figure 6.8 – Test setup for establishing the generation of transient disturbances by the fire detector [49].

The sampling rates and trigger levels for the different test pulses should capture a waveform displaying the complete duration of the transient disturbance. By utilizing the proper sampling rate and trigger level, the voltage amplitude should be recorded by powering on the fire detector according to the test plan. Other transient parameters, such as rise time, fall time, transient duration etc. may also be recorded but are not necessary. Unless otherwise specified, ten waveform acquisitions are necessary. It is obligatory to report only the waveforms with the highest positive and negative voltage amplitude. Typical waveforms for slow and fast pulses can be seen in Figure 6.9.

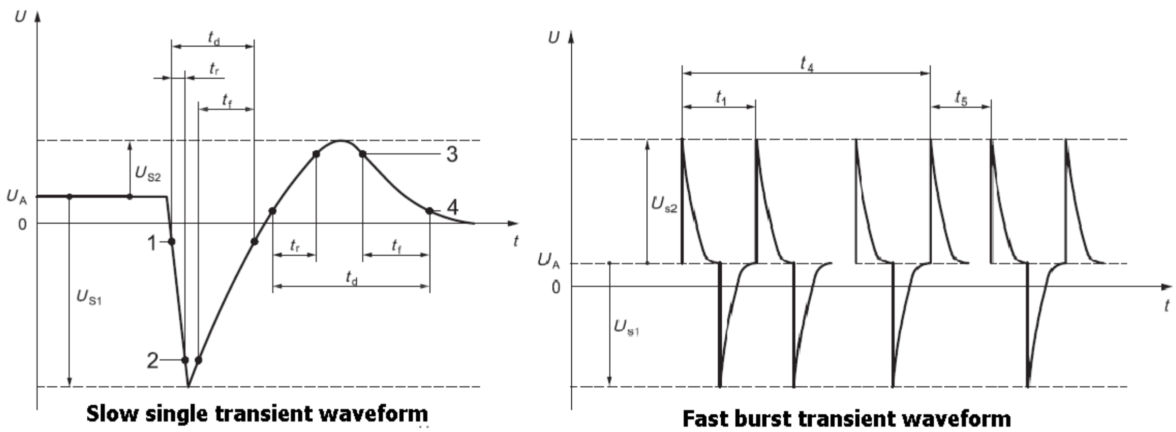


Figure 6.9 – Common waveforms representing slow and fast voltage pulses [49].

6.5.4 ESD

There are two forms of ESD and they occur either by physical contact with the ESA or when the ESA is discharged due to the surrounding air. Therefore, simulated discharges can be applied by two discharge modes: contact and air. In contact discharge mode, the tip of the ESD generator's discharge electrode is brought in contact with the fire detector before the discharge switch is triggered to apply the discharge. An ESD generator is an instrument that simulates the human ESD model, i.e. a human charged with a higher level of static electricity than the fire detector. When air is the cause of the discharge, the discharge electrode is charged to the test voltage and then brought with the demanded speed of approach to the fire detector, applying the discharge through an arc that ensues when the tip approaches close enough to the ESA to break down the dielectric material between the tip and test point. The speed of approach of the discharge electrode is a critical factor in the rise time and amplitude of the injected current during an air discharge. The ESD generator should therefore in practice approach the fire detector as fast as possible until the discharge occurs or the discharge tip touches the discharge point without causing damage to the detector or the generator. However, in reality ESD can be caused by both direct and indirect discharges. The direct type discharges, either by contact or air, are applied directly to the detector and to the remote parts that are accessible by the vehicle user, e.g. switches and buttons. This also applies on physical contact between persons and the fire detector or external objects and the detector. The indirect type discharges happens due to contact. These occur to other conductive objects in the proximity of the fire detector and are applied through an intervening metal, an HCP for instance. The tests are done while the detector is powered on in normal operating mode and when it is delivered from supplier prior to mounting in the vehicle, the latter being termed “powered off”. During the tests, the parameters seen in Table 6.9 should be valid [50].

Table 6.9 – Test parameters showcasing the fire detector's ability to withstand ESD.

	Powered on				**Powered off**		
	***Direct* discharge**		***Indirect* discharge**		***Direct* discharge**		***Indirect* discharge**
	By contact	By air	By contact	By air	By contact	By air	
Number of charges	≥ 3		50	–	≥ 3		No test to be performed as there are no components in the ESAs vicinity to be affected during the test.
Time interval between charges	≥ 1 s		≥ 50 ms	–	≥ 1 s		
Test voltage (± denotes the polarity)	±2 to ±15 kV	±2 to ±25 kV	±2 to ±20 kV	–	±2 to ±15 kV	±2 to ±25 kV	

Once the testing has been completed, the fire detector should pass complete function testing successfully. There shall be no permanent damage. In addition, the effectiveness of the EMC protective circuits e.g. input capacitors ensuring electromagnetic interference immunity and emission, respectively, should be tested after ESD exposure.

6.6 IP Code testing

The degree of protection provided by an enclosure is indicated by the IP Code and is written in the form of: IPXxYy, the last two indices being optional. The indices are explained below:

- X – protection of *equipment* against ingress of solid foreign objects and protection of *persons* against access to hazardous parts, seen as a numeral between 0-6 or letter X.
- x – protection of *equipment* against ingress of water with harmful effects, seen as a numeral between 0-9 or letter X .
- Y – protection of *persons* against access to hazardous parts, i.e. a part that is hazardous to approach or touch, seen as letter A, B, C or D. This index is optional.
- y – supplementary information regarding the type of condition that is applied during the test, seen as letter H, M, S or W. This index is optional.

Table 6.10 below showcases a brief description of the IP Code indices. If the product does not have a specification for protection of equipment against ingress of water or solid objects, the numeral is replaced by the letter X and the IP Code is then written as e.g. IP3X with respect to ingress of solid objects and IPX3 with respect to ingress of water [37].

Unless otherwise stated, all tests should be conducted with the following standard atmospheric conditions: 25 ± 5 °C, 101,3 ± 10 % kPa and 20-50 % relative humidity (RH). For further reference beyond the content in this chapter, it is recommended to see *IEC 60529*.

Table 6.10 – IP Code indices and descriptions.

Index	**Numeral or letter**	**Protection of *equipment***	**Protection of *persons***
		Against ingress of solid foreign objects	**Against access to hazardous parts with:**
First numeral	0 1 2 3 4 5K 6K	Non-protected Object ≥ 50 mm diameter Object ≥ 12,5 mm diameter Object ≥ 2,5 mm diameter Object ≥ 1,0 mm diameter Dust-protected Dust-tight	Non-protected Back of hand Finger Tool Wire Wire Wire
		Against ingress of water with harmful effects	
Second numeral	0 1 2 3 4 4K 5 6 6K 7 8 9K	Non-protected Vertically dripping Dripping (15° tilted) Spraying Splashing Splashing with increased pressure Jetting Powerful jetting Jetting with further increased pressure Temporary immersion Continuous immersion High pressure and temperature water jet	–
			Against access to hazardous parts with:
Additional letter	A B C D	–	Back of hand Finger Tool Wire
		Supplementary information specific to:	
Supplementary letter	H M S W	High voltage apparatus Motion during water test Stationary during water test Weather conditions	–

6.6.1 The first numeral in the IP Code

The first numeral indicates that the enclosure provides protection of people against access to hazardous parts by preventing or limiting the admittance of a part of the human body or an object held by a person. The enclosure must simultaneously provide protection of equipment against the ingress of solid foreign objects. Therefore, both conditions for a given first numeral in the IP Code with regard to equipment and individuals needs to be met as seen in Table 6.11.

Table 6.11 - Explanation of the requirements that need to be met for the first IP numeral.

First numeral	Degree of protection against access to hazardous parts		Degrees of protection against solid foreign objects	
	Description	**Definition**	**Description**	**Definition**
0	Non-protected	No test required	Non-protected	No test required
1	Protected against access to hazardous parts with the back of a hand.	A sphere of 50 mm Ø, simulating a human body part, shall have sufficient clearance from hazardous parts.	Protected against solid foreign objects of 50 mm Ø and greater.	A sphere of 50 mm Ø, applied with a force of 50 ± 5 N shall not fully penetrate.
2	Protected against access to hazardous parts with a finger.	A modeled test finger of 12 mm Ø, 80 mm length, shall have sufficient clearance form hazardous parts.	Protected against solid foreign objects of 12,5 mm Ø and greater.	A sphere of 12,5 mm Ø, applied with a force of 30 ± 5 N shall not fully penetrate.
3	Protected against access to hazardous parts with a tool.	A test rod of 2,5 mm Ø, simulating a tool held by a person, shall not penetrate.	Protected against solid foreign objects of 2,5 mm Ø and greater.	A test rod of 2,5 mm Ø, applied with a force of 3 ± 0,3 N shall not penetrate at all.
4	Protected against access to hazardous parts with a wire.	A wire of 1,0 mm Ø, simulating a tool held by a person, shall not penetrate.	Protected against solid foreign objects of 1,0 mm Ø and greater.	A wire of 1,0 mm Ø, applied with a force of 1 ± 0,1 N shall not penetrate at all.
5K	Protected against access to hazardous parts with a wire.	A wire of 1,0 mm Ø, simulating a tool held by a person, shall not penetrate.	Dust-protected	Ingress of dust is not fully prevented, but dust shall not penetrate enough to interfere with satisfactory operation of the apparatus.
6K	Protected against access to hazardous parts with a wire.	A wire of 1,0 mm Ø, simulating a tool held by a person, shall not penetrate.	Dust-tight	No admittance of dust.

In the case where there is no full penetration, the sphere with a diameter (∅) of 50 mm shall not completely pass through openings, if there are any. The modeled test finger may penetrate up to its full length, but should successively be bent through an angle between 0-90° in all directions during the test. In the case where sufficient clearance should be met for low voltage equipment (rated voltages lower than 1000 V a.c. or 1500 V d.c), as is the situation for fire detectors in vehicles, the test probe must not touch hazardous live parts, i.e. a part that can give an electric shock. Talcum powder is used to estimate the dust penetration. The powder should pass through a square-meshed filter with the nominal wire diameter of 50 μm and the nominal width of 75 μm between wires. The amount of talcum powder to be used is 2 kg/m^3. The purpose of the test is to draw a volume of air 80 times the volume of the sample into the enclosure being tested without exceeding the extraction rate of 60 volumes per hour while continuously depriving the pressure in the enclosure. The pressure depression rate shall never exceed 2 kPa. If an extraction rate of 40-60 volumes per hour is obtained, the duration of the test is 2 hours. If the extraction rate is less than 40 volumes per hour, the test is continued until 80 volumes have been drawn through, or a period of 8 hours has passed [37].

6.6.2 The second numeral in the IP Code

The second numeral in the IP Code specifies the degree of protection provided by enclosures regarding harmful effects on the equipment due to the ingress of water. These tests are carried out with fresh water. The actual protection may not be satisfactory if other solvents are used or by exceeding the requirements regarding pressure and temperature for numeral 9. The degrees of protection against ingress of water are described in Table 6.12.

Table 6.12 – Explanation of the requirements that need to be met for the second IP numeral.

Second numeral	Degrees of protection against ingress of water	
	Description	**Definition**
0	Non-protected	No test required
1	Protected against vertically falling water drops.	Vertically falling drops with 1 mm/min for 10 min shall have no harmful effects.
2	Protected against vertically falling water drops when enclosure is tilted up to 15° in 4 fixed positions.	Vertically falling drops with 3 mm/min for 2,5 min at each position shall have no harmful effects when the enclosure is tilted at any angle up to 15° on either side of the vertical.
3	Protected against spraying water from a distance of maximum 200 mm.	Water sprayed at an angle up to 60° on either side of the vertical shall have no harmful effects. The water is sprayed with either a nozzle at 10 ± 0,5 l/min for 5 min or by an oscillating tube at 0,07 l/min for 10 min.
4	Protected against splashing water.	Water splashed against the enclosure from any direction shall have no harmful effects. The test is conducted in the same manner as for numeral 3.
4K	Protected against splashing water with increased pressure.	Water splashed against the enclosure from any direction with increased pressure shall have no harmful effects. The test is conducted in the same manner as for numeral 3.
5	Protected against water jets from a distance of 2,5-3 m with nozzle diameter of 6,3 mm.	Water projected in jets against the enclosure from any direction at 12,5 ± 0,625 l/min for 3 min shall have no harmful effects.
6	Protected against powerful water jets from a distance of 2,5-3 m with nozzle diameter of 12,5 mm.	Water projected in powerful jets against the enclosure from any direction at 100 ± 5 l/min for 3 min shall have no harmful effects.
6K	Protected against powerful water jets with increased pressure.	Water projected in powerful jets with further increased pressure against the enclosure from any direction for 3 min shall have no harmful effects.
7	Protected against the effects of temporary immersion in water. Water-level on enclosure is 0,15 m above top and 1 m above bottom.	Ingress of water in quantities causing harmful effects shall not be possible when the enclosure is temporarily immersed in water under standardized conditions of pressure and time of 30 min.
8	Protected against the effects of continuous immersion in water. Water-level on enclosure is determined by agreement between manufacturer and user.	Ingress of water in quantities causing harmful effects shall not be possible when the enclosure is continuously immersed in water under conditions which shall be agreed between manufacturer and user but which are more severe than for numeral 7.
9K	Protected against high pressure and temperature water jets.	Water projected at high pressure and high temperature (less than 80 °C) with 15 ± 1 l/min at 30 s at each position against the enclosure from any direction shall not have harmful effects.

During the tests for IPX1 to IPX6K the water temperature should not differ by more than 5 °C from the temperature of the specimen under test. If the water temperature is more than 5 °C below the temperature of the specimen a pressure balance should be provided for the enclosure. Necessary safety precautions should be taken when testing the equipment in the energized condition. In this case the manufacturer should have relevant product specifications. During the test, the moisture contained inside the enclosure may partly condense. The dew which may thus occur shall not be mistaken for ingress of water. Up to and including IPX6K, compliance with the requirements for all lower numerals is implied. The tests establishing compliance with any one of the lower degrees of protection than IPX6K therefore does not necessarily need to be carried out, provided that these tests obviously would be met if applied. Requirements that are met by IPX7-IPX9K do not need to comply with the requirements for IPX6K and lower. If compliance is a necessity, the IP Code must be multiple coded, e.g. IPX6K/IPX9K, which then indicates that all requirements are met regarding exposure to all types of water jets. If any water has entered during the inspection after the test, acceptance conditions are [37]:

- The amount of water should not be sufficient enough to interfere with the correct operation of the equipment or impair the safety of people.
- The water shall not remain on insulation parts where it could lead to tracking along the creepage distances.
- The water must not reach live parts or windings not designed to operate when wet.
- The water may not accumulate near the cable ends or enter the cables, if there are any.
- The inspection should prove that any water that has entered does not accumulate at drain holes on the enclosure, if there are any, and that it drains away the water without harming the equipment.

6.6.3 The letter indices in the IP Code

The letter indices are only used if the actual protection against access to hazardous parts is higher than that indicated by the first numeral or if the first numeral is represented by an X. For example, such higher protection may be provided by barriers, suitable shape of openings or distances inside the enclosure. This is represented by the letters A-D. Supplementary information, represented by the letters H, M, S or W, conform with specific conditions that apply during the test, if there are any. The absence of the letters S and M implies that the degree of protection does not depend on whether parts of the equipment are in motion or not. This may necessitate tests being done under both conditions. However, the test establishing compliance with one of these conditions is generally sufficient, provided that the test in the other condition obviously would be met if applied. A brief explanation of the letter indices is seen in Table 6.13 [37].

Table 6.13 - Explanation of the requirements that need to be met for the first and second IP letter.

Letter	Degree of protection	
	Description	**Definition**
A	Protected against access with the back of the hand.	A sphere of 50 mm Ø, simulating a human body part, shall have sufficient clearance from hazardous parts.
B	Protected against access with a finger.	A modeled test finger of 12 mm Ø, 80 mm length, shall have sufficient clearance form hazardous parts.
C	Protected against access with a tool.	A rod of 2,5 mm Ø, 100 mm length, shall have adequate clearance from hazardous parts.
D	Protected against access with a wire.	A wire of 1,0 mm Ø, 100 mm length, shall have adequate clearance from hazardous parts.
	Significance	
H	High-voltage apparatus	
M	Tested for harmful effects due to the ingress of water when the movable parts of the equipment (for example, the rotor of a rotating machine) are in motion.	
S	Tested for harmful effects due to the ingress of water when the movable parts of the equipment (for example, the rotor of a rotating machine) are stationary.	
W	Suitable for use under specified weather conditions and provided with additional protective features or processes.	

7. Recommendation of appropriate durability requirements

After numerous discussions and consultations with representatives from different heavy vehicle manufacturers as well as experts from various departments at SP, appropriate durability requirements for fire detectors mounted in engine compartments of heavy vehicles have been established with regard to the environmental phenomena mentioned in Chapter 5. It should be noted that these requirements are valid for detectors in general, i.e. they do not apply to one more than another but are instead what any type of detector should endure if mounted in an engine room in any type of heavy vehicle. Hence, it is impossible to set perfect test conditions for each physical factor with regard to a specific detector type or heavy vehicle. That is why most of the test parameters have been set in relevant intervals as prescribed by representatives from heavy vehicle manufacturers and experts at SP. The durability requirement for each physical phenomenon based on the recommended test parameters are listed in its respective sub-chapter.

7.1 Corrosion requirements

After input was received from certain experts within the corrosion field at SP, suitable test conditions were deemed to have been found. In the test method recommended to be used in order to identify the effects of corrosion, 6 weeks of exposure time corresponds to 8 years in reality. It is safe to say that a heavy vehicle’s service life is most definitely not lower than that in general. Therefore, an accelerated corrosion exposure corresponding to 6 weeks was deemed suitable for a fire detector that is to be tested. The recommended corrosion requirements and test conditions are listed in Table 7.1.

Table 7.1 – Corrosion resistance requirements

Accelerated corrosion resistance	
Type of test	Salt spray and exposure to corrosive gases test
Component	Fire detector
Test method	As described in Chapter 6.1.
Test conditions	Exposure for 6 weeks.
Acceptance criteria	All functions of the component perform as designed during and after the test. No electrical, mechanical or functional failure may occur. Insignificant visual deviation may be present, but markings and labels must remain visible after exposure.

7.2 Thermal ageing requirements

Several propositions for the requirements and test conditions regarding accelerated thermal ageing for polymers were made by both heavy vehicle manufacturers and experts at SP. Some of the suggested test conditions are set in intervals since not all temperatures and exposure times are suited for all vehicles types, depending on their operational purpose as well as the environment they operate in. After some consideration and brief consultations with the parties involved, the parameters listed in Table 7.2 and Table 7.3 are believed to be appropriate. It should be noted that the fire detector should be subjected to both these tests and comply with the requirements for each one.

Table 7.2 - Thermal ageing resistance requirements - long term heat exposure.

Accelerated thermal ageing resistance – Test 1	
Type of test	Long term heat ageing test
Component	Cable insulation in fire detectors or the fire detector directly (if it is in the form of a plastic hose).
Test method	As described in Chapter 6.2.3.
Test conditions	Exposure for 1250 ± 250 hours at T_{AGE} = 125 ± 25 °C.
Acceptance criteria	There should be no cracks in the material after winding. During the verification procedure as described in Chapter 6.2.2, breakdown shall not occur and all functions of the component should perform as designed after the test. No electrical, mechanical or functional failure may occur.

Table 7.3 – Thermal ageing resistance requirements - low temperature winding of material

Accelerated thermal ageing resistance – Test 2	
Type of test	Low temperature winding test
Component	Cable insulation in fire detectors or the fire detector directly (if it is in the form of a plastic hose).
Test method	As described in Chapter 6.2.4.
Test conditions	Exposure for 5 hours at -40 °C.
Acceptance criteria	There should be no cracks in the material after winding. During the verification procedure as described in Chapter 6.2.2, breakdown shall not occur and all functions of the component should perform as designed after the test. No electrical, mechanical or functional failure may occur.

7.3 Temperature requirements

The durability requirements and test conditions were set after discussions with representatives from heavy vehicle manufacturers combined with the recommended requirements that can be found in the standards that have been reviewed. Many of the test conditions are set in intervals as not all temperatures and exposure durations are suited for all vehicles types, depending on their operational purpose as well as the environment they operate in. The heat requirements that are seen as fitting can be viewed in Table 7.4 through Table 7.9.

Table 7.4 – High temperature exposure requirements.

Accelerated thermal resistance – Test 1	
Type of test	Dry heat test
Component	Fire detector
Test method	As described in Chapter 6.3.1.
Test conditions	Exposure for 100 hours at T = 130 ±20 °C.
Acceptance criteria	All functions of the component perform as designed during and after the test. No electrical, mechanical or functional failure may occur

Table 7.5 – Damp heat at steady state exposure requirements.

Accelerated thermal resistance – Test 2	
Type of test	Damp heat test
Component	Fire detector
Test method	As described in Chapter 6.3.2.
Test conditions	Exposure for 21 days at T = 40 ± 2 °C and 93 ± 3 % RH.
Acceptance criteria	All functions of the component perform as designed during and after the test. No electrical, mechanical or functional failure may occur. Insignificant visual deviation may be present due to high humidity, but markings and labels must remain visible after exposure.

Table 7.6 – Low temperature exposure requirements.

Accelerated thermal resistance – Test 3	
Type of test	Cold test
Component	Fire detector
Test method	As described in Chapter 6.3.3.
Test conditions	Exposure for 24 hours at T = -40 ± 5 °C.
Acceptance criteria	All functions of the component perform as designed during and after the test. No electrical, mechanical or functional failure may occur.

Table 7.7 – Requirements for temperature fluctuation exposure.

Accelerated thermal resistance – Test 4	
Type of test	Rapid change of temperature test
Component	Fire detector
Test method	As described in Chapter 6.3.4.
Test conditions	T_A = -40 ± 5 °C, T_B = 130 ± 20 °C, t_1 = 180 min, number of cycles, N = 1000 ± 100.
Acceptance criteria	All functions of the component perform as designed after the test. No electrical, mechanical or functional failure may occur. In addition, no mechanical damage may occur.

Table 7.8 – Requirements for cold thermal shock exposure.

Accelerated thermal resistance – Test 5	
Type of test	Hot air and cold water shock test
Component	Fire detector
Test method	As described in Chapter 6.3.5.
Test conditions	T_{WATER} = 2 ± 2 °C, T_{AIR} = 150 ± 10 °C, t_{HEAT} = 60 min, $t_{SUBMERGE}$ = 5 min, number of cycles, N = 10.
Acceptance criteria	All functions of the component perform as designed during and after the test. No electrical, mechanical or functional failure may occur. In addition, no mechanical damage may occur.

Table 7.9 – Requirements for hot thermal shock exposure.

Accelerated thermal resistance – Test 6	
Type of test	Cold and boiling water shock test
Component	Fire detector
Test method	As described in Chapter 6.3.6.
Test conditions	T_{COLD} = 3 ± 3 °C, T_{HOT} = 97 ± 3 °C, t_{COLD} = t_{HOT} = 180 min, number of cycles, *N* = 10.
Acceptance criteria	All functions of the component perform as designed during and after the test. No electrical, mechanical or functional failure may occur. In addition, no mechanical damage may occur.

7.4 Random vibration and mechanical shock requirements

The durability requirements and test conditions were agreed upon after conversations with representatives from heavy vehicle manufacturers and expertise input from representatives at SP's Mechanical Institute. These contributions combined with the recommended requirements that can be found in the standards that have been reviewed have resulted in the vibration and shock requirements as listed in Table 7.10 and Table 7.11. Many of the test conditions are set in intervals as not all parameters are suited for all vehicles types, depending on their operational purpose as well as the environment they operate in. The temperature cycle conditions for the random vibrations were selected by choosing the highest temperature of the cycle to be the same as in the *Dry heat test* and the lowest temperature of the cycle to be the same as in the *Cold test*. The temperature change rate and hold-duration were chosen according to recommended values in the existing standards.

Table 7.10 – Requirements for exposure to random vibration.

Accelerated stress resistance – Test 1	
Type of test	Random vibrations
Component	Fire detector
Test method	As described in Chapter 6.4.1.
Test conditions – temperature cycle (optional)	T_{low} = -40 ± 5 °C, T_{high} = 130 ± 20 °C, T'_{change} = 4 °C/min, T_{hold} = 80 min
Test conditions – vibration cycle	Random vibrational frequency range, f_{range} = 10 – 2000 Hz, G_{RMS} = 265 ± 10 m/s^2, ASD = 0,35 ± 0,05 g^2/Hz, duration in each axis = 60 ± 15 hours
Acceptance criteria	All functions of the component perform as designed during and after the test. No electrical, mechanical or functional failure may occur. In addition, no mechanical damage may occur.

Table 7.11 – Requirements for exposure to mechanical shocks.

Accelerated stress resistance – Test 2	
Type of test	Mechanical shocks
Component	Fire detector
Test method	As described in Chapter 0.
Test conditions	Applied pulse shape: half-sine, $\bar{\ddot{x}}$ = 150 ± 50 m/s^2, τ = 6 ms, number of shocks in each direction, N = 10. In addition one shock of $\bar{\ddot{x}}$ = 500 m/s should be applied in each direction with the same shock duration.
Acceptance criteria	All functions of the component perform as designed during and after the test. No electrical, mechanical or functional failure may occur. In addition, no mechanical damage may occur.

7.5 EMC requirements

It has already been established that vehicle specific EMC requirements are very impractical and complicated to set due to the fact that it differs depending on which engine room and vehicle type they are fitted in as well as what type of electronics it is interconnected with. Unless all electronic devices that are mounted in the vehicle and configurations of these devices are available, it is impossible to set specific requirements. Therefore, after consulting professionals at SP's EMC Vehicle group it was determined that the most appropriate requirements to be chosen are those that are regulated by law. If further requirements need to be incorporated it should be discussed between vehicle manufacturer and fire detector supplier. The durability requirements and test conditions were determined by studying already existing EMC regulations for road going and off-road vehicles. The requirements can be seen in Table 7.12 through Table 7.17.

Table 7.12 – Requirements for broadband electromagnetic interference generated by the fire detector.

EMC – Test 1		
Type of test	Broadband EMI generated by the component	
Component	Fire detector	
Test method	As described in Chapter 6.5.1.	
Test conditions	Frequency range [Hz]	Limit of approval [dB µV/m]
	30 – 75	62 – 52
	75 – 400	52 – 63
	400 – 1000	63
Acceptance criteria	EMI levels generated by the fire detector shall not exceed the limits stated above.	

Table 7.13 – Requirements for narrowband electromagnetic interference generated by the fire detector.

EMC – Test 2		
Type of test	Narrowband EMI generated by the component	
Component	Fire detector	
Test method	As described in Chapter 6.5.1.	
Test conditions	Frequency range [Hz]	Limit of approval [dB μV/m]
	30 – 75	52 – 42
	75 – 400	42 – 53
	400 – 1000	53
Acceptance criteria	EMI levels generated by the fire detector shall not exceed the limits stated above.	

Table 7.14 – Immunity related requirements for the fire detector to electromagnetic radiation.

EMC – Test 3	
Type of test	Immunity of the component to EMR
Component	Fire detector
Test method	As described in Chapter 6.5.2.
Test conditions	EMR frequency band = 20 – 2000 MHz, immunity approval = 30 V/m
Acceptance criteria	All functions of the component perform as designed during and after the test. No electrical functional failure may occur.

Table 7.15 - Requirements regarding emissions of transient disturbances generated by the fire detector.

EMC – Test 4		
Type of test	Emission of transient conducted disturbances generated by the component.	
Component	Fire detector	
Test method	As described in 6.5.3.	
Test conditions	Maximum allowed pulse amplitude for (± denotes the polarity)	
	12 V supply line	24 V supply line
	+75 V, -100 V	+150 V, -400 V
Acceptance criteria	Transient disturbance levels generated by the fire detector shall not exceed the limits stated above.	

Table 7.16 – Requirements regarding immunity to transient disturbances for the fire detector.

EMC – Test 5			
Type of test	Immunity of the component to transient conducted disturbances.		
Component	Fire detector		
Test method	As described Chapter 6.5.3.		
Test conditions	Test pulse	12 V supply line	24 V supply line
	1	U_S = -112 V, t_1 = 0,5 s, test time = 500 pulses	U_S = -450 V, t_1 = 0,5 s, test time = 500 pulses
	2a	U_S = +55, t_1 = 0,2 – 5 s, test time = 500 pulses	U_S = +55, t_1 = 0,2 – 5 s, test time = 500 pulses
	2b	U_S = +10, t_1 = 0,5 – 5 s, test time = 10 pulses	U_S = +20, t_1 = 0,5 – 5 s, test time = 10 pulses
	3a	U_S = -65, t_1 = 90 – 100 ms, test time = 1 hour	U_S = -220, t_1 = 90 – 100 ms, test time = 1 hour
	3b	U_S = +112, t_1 = 90 – 100 ms, test time = 1 hour	U_S = +220, t_1 = 90 – 100 ms, test time = 1 hour
Acceptance criteria	All functions of the component perform as designed during and after the test. No electrical functional failure may occur.		

Table 7.17 - Electrostatic discharge requirements.

EMC – Test 6		
Type of test	ESD	
Component	Fire detector	
Test method	As described in Chapter 6.5.4.	
Test conditions	Maximum allowed voltage disturbance causing ESD (± denotes the polarity)	
	Powered on mode	Powered off mode
	±25 kV	
Acceptance criteria	All functions of the component perform as designed during and after the test. No electrical functional failure may occur.	

7.6 IP Code

After meetings and dialogues with engineers at SP and representatives from vehicle manufacturers, it was learned that there should be high safety requirements for the fire detector's enclosure when exposed to water, dust and dirt in different ways and that optional indices are not relevant to this type of device as there are not hazardous parts to persons that are accessible. Consequently, the IP Code requirement as seen in Table 7.18 is the one recommended for fire detectors that will be mounted in the engine compartments of heavy vehicles.

Table 7.18 – Protection provided by the fire detector's enclosure against ingress of water and solid foreign objects.

Ingress protection				
Type of test	IP Code			
Component	Fire detector’s enclosure			
Test method	As described Chapter 6.6			
Test conditions	First numeral index	Second numeral index	First letter index	Second letter index
	6K	6K and 9K	Optional	Optional
	IP6K6K/IP6K9K			
Acceptance criteria	All functions of the component perform as designed during and after the test. No electrical, mechanical or functional failure may occur. No ingress of water and no admittance of dust or dirt is permitted. The component must not have any mechanical damages post testing.			

8. Reasoning behind the chosen test methods and test parameters

Determining general durability requirements for multiple products that may or may not be fitted in different environments is a complicated task. There are many uncertainties when making the recommendations for suitable requirements as it is not for certain that a specific fire detector will comply with them all. Not all fire detectors operate in the same way or are constructed out of the same material. Therefore, it can be of a nuisance generalizing and assuming which test parameter intervals that are deemed appropriate for all detector types in all types of operating environments as it can be hard interpreting the result. An example of this confusion is that the recommended requirements for the *Dry heat test* may imply that a certain fire detector must withstand a temperature of 150 °C regardless of the circumstances. This may not be the case in reality, as the operating temperature in the engine room where this detector will be mounted may have a much, much lower operating temperature. Therefore, the requirement of 150 °C would be pointless because this temperature is never reached. Nevertheless, it is necessary to set the requirement this way because of the lack of information, such as what type of detector it actually is and in which type of environment the detector actually will be mounted in.

It is also troublesome to determine exactly which test methods that are best suited for which applications. Yet, an effort has been made in doing so in this report. There are numerous well-established test methods for each of the physical factors that have been brought up in Chapter 5. Some have more applicability and validity in certain areas than others. The test methods that have been suggested for each physical factor in this report were chosen based on recommendations from experts at SP and representatives from different heavy vehicle manufacturers. The basis behind these choices was that the test methods are standardized, more or less, for vehicle applications and are well regulated. However, there are many other test methods that could have been applied to reach similar results but it was beyond the scope of this report to analyze and compare all of them in order to find out which was the best suited for a certain application. Instead the guidance received from experts and people with great experience was followed.

8.1 Corrosion

As it was stated in the corresponding chapter about corrosion, there are many forms of corrosion and therefore many test methods. The test method featured in this report was determined as the most appropriate as this simulates the type of environment that the fire detector most likely will be exposed to if mounted in an engine compartment. This method does not specify which type of corrosion that will occur however, as anything from uniform to galvanic corrosion may be developed in this type of environment. Therefore, key focus lies on which physical influences the detector will be exposed to and how these influences affect the degradation of metallic materials found in fire detectors. The test method assumes a moderately aggressive traffic environment which may be a faulty assumption in some cases. Depending on where the vehicle operates, the amount of pollution in the air will certainly vary. There is a big difference in the exposure to corrosive gases if the vehicle's operational environment is a coal mine or a highly polluted city compared to that of truck driving on an open road in Sweden. Therefore, an adjustment to the test method may be necessary if this is considered.

8.2 Ageing

It has been clarified that testing the ageing of polymers can be problematic since not all polymers can be tested in the same way. This was pointed out by polymer experts at SP. Knowing that polyamide cannot be tested in the same manner as e.g. polyethylene means that extra recognition is needed when looking over the materials involved in the product specification for the fire detector. If there is an uncertainty to if the polymer type will have reliable results after using the test method prescribed in this report, it is recommended to use this method for the ageing process nevertheless. If the product passes the ageing requirements in this test method, it should be subjected to the *Accelerated thermal resistance – Test 5 and Test 6* but with minor alterations in the exposure time. The correction in exposure time needs to be adapted to an exposure time that will reflect the corresponding ageing time of the polymer due to chemical degradation when exposed to water or another suitable fluid. Thereby, the polymer will still have been subjected to correct testing procedures with regard to the ageing of polymers. However, this may be costly as ageing tests are time consuming which is why it is highly recommended to be certain as to if the polymer is compatible with this test method prior to testing or not.

Furthermore, because it is difficult to quantify which tests are suitable for polymeric materials in general, it was proposed by the experts at SP's Polymer and Fiber Institute that standards regarding cable insulations in vehicles should be considered when determining appropriate thermal ageing tests for polymers. As most cable insulations in vehicles are made up from polymers, often different types, this was determined to be a justifiable approach method. Moreover, the fire detector can be seen as an electronic device with electrical wires that need insulation. Thus, these test methods apply directly to the functionality of the fire detector in general. Additionally, when the fire detector is in the form of a pressurized plastic hose that melts when a fire arises, it was considered viable to use similar testing methods for this case because the plastic hose used for fire detection resembles that of cable insulation, only larger.

8.3 Temperature

It is well-known what type of impact high or low temperatures can have on different materials. Everything from mechanical property alteration to sudden failure is some of the effects of variations in temperature. The recommended heat tests for testing the fire detector to different temperature scenarios were reached after several discussions with representative from heavy vehicle manufacturers as well as already existing and well-established documentations regarding heat standards. Although adopted for electronic devices, these standards may be used in other fields, such as testing the ability of metals, ceramics or polymers to withstand sudden temperature rises, drops or fluctuations as they are very flexible in the way that the tests are conducted. Either way, the conditions stated in these recommended tests are circumstances that all components will be subjected to if mounted in the engine compartment of a vehicle. Therefore, these tests are a general way of establishing fitting durability requirements when it comes to heat tolerances for fire detectors that will be exposed to similar environments.

8.4 Vibration and shocks

When studying which vibration tests that are the most relevant, it was mainly after a conversation with a representative at SP’s Mechanical Institute that it was pointed out that random vibration tests are those of most interest. If the purpose is to simulate how a vehicle is exposed to vibrations in reality, then indeed random vibrations are the way to go. The reason to this is that there is rarely any consistency while driving because the road is inconsistent. Vibrations induced by the road cannot have a sinusoidal motion because the road at which a vehicle travels on is not smooth, flat and predictable but the opposite – bumpy, rough and random. Besides, it needs to be remembered that the requirements in this report are based on the consideration of heavy vehicles in general, that is the requirements should be valid for both a forestry machine that operates off-road as well as a coach bus that travels longer distances on the highway for instance. This distinction, between off-road driving and continuous driving along a motorway, is enough to motivate why random vibration was chosen as the test method for the requirements to be based on. Mechanical shocks on the other hand have standardized testing methods that are well-established in the form of documented standards. Shock testing is pretty straight forward, as the information that is of interest is simply how many g-forces a device can withstand without malfunctioning post exposure. Therefore, for the purpose of maintaining an effective approach when it comes to shock testing, already available shock testing standards were studied.

The temperature cycling during the random vibration test is optional as not all test apparatus’ have this installation available. The temperature cycling is also performed separately in the accelerated thermal resistance tests. However, this test method is believed to yield the most viable results if vibration tests are performed during the influence of temperature changes since it illustrates authentic scenarios for engine compartments. The detector might pass the thermal stress tests and then the vibration tests separately, but a combination of the two may result in accumulated stresses from them both that could be the deciding factor between if the detector fails the test or not.

The reasoning behind the test parameters in the mechanical shock test is as follows. In the case where the peak acceleration is lower with a repetitive number of test cycles, it is an attempt to simulate a car driving over a harsh bump or hole in the road multiple times. The shock value in the range of 10 to 20g seems feasible for this type of scenario. However, in a high speed crash with a wall or tree, the impact will be much higher. A vehicle traveling at 100 km/h that crashes into a solid wall has an impact force corresponding to a deceleration value of roughly 90g. Therefore, it is recommended that the fire detector is exposed to one shock, in each direction of the vehicle, with a magnitude of minimum 50g. This criterion is important to pass because if a fire arises post crashing, it is vital that the fire detector is intact and can register the hazard followed by deploying the fire suppression system.

8.5 IP Code

After meetings and dialogues with engineers at SP and representatives from vehicle manufacturers, it was learned that most engine rooms of heavy vehicles are cleaned by high pressure water jets. High pressure water jets may cause internal electrical components or other vital parts of the detector to be knocked off due to the shear force arising from the jet. With this in mind and the fact that the fire detector can be seen as a critical safety device in the vehicle, unless truly water proof, it has been determined that no ingress of water may be permitted in order to be assured that the detector will sustain functional integrity. In a similar way, there may be no admittance of dust or dirt. Water and dust may eventually cause other negative environmental influences to arise if they reach sensitive parts of the fire detector, such as corrosion, reduction in the electrical conductivity, structural weaknesses in the material etc. Furthermore, if the detector is a smoke detector, the ingress of dust may cause false alarms as the detector might register the dust as smoke. Similarly, dust may impose a dusty film on sensors in flame detectors which may cause the detector to not activate at all.

An alternative IP Code than the one recommended may be just IP6K5, IP6K6 or IP6K6K as this also provides protection of the fire detector enclosure to ingress of water when it is exposed to water jets. However, as the flow rate of water and temperature varies in IPX5, IP6K6, IPX6K and IPX9, and the distance between the nozzle and enclosure is restricted in each of the cases, it has been deemed appropriate to set a requirement that complies with all kinds of exposures to water jets. This is mostly due to the fact that when an engine room is cleaned by a water pressure jet, a constant distance of minimum 2,5 m, as is required for IPX5, IP6K6 and IPX6K, between the engine compartment and the nozzle of the water pressure cleaner is rarely held in reality. Therefore, high pressure water jets from close distances need to be considered in order for the test to have feasible results. Also, the IP Code that has been recommended in the previous chapter implies that the fire detector’s enclosure complies with all the requirements for all lower second numeral indices than 6, i.e. IPX1 to IPX6K, including high pressure and temperature water jets, as indicated by IPX9K. Although, a problem that will most likely occur is that the air inside the enclosure may condensate due to variations in the ambient temperature. This can be an issue if there are no drain holes for the enclosure as condensed water can cause harmful effects on the device in the long run. It is therefore recommended that the enclosure has some sort of drain hole that allows the condensed water to vacate the enclosure. But if there are drain holes the ingress of water is a high probability. Therefore, an IP Code that allows for ingress of water may be considerable, as long as the water that enters the enclosure does not interfere with the operation of the fire detector.

The reason to why no temporary immersion in water was considered is because this scenario does not seem to be applicable in vehicles. The engine compartment is rarely soaked in water during the vehicle's use. This may be the case in extreme working environments for the vehicle, such as excavators digging river canals where its engine room might be subjected to temporary water immersion if the water level rises high enough. This is highly improbable and is why this condition was not seen as needed.

9. Conclusions and future work

Safety requirements are of high priority in modern vehicles. It is therefore vital for fire detectors that are to be mounted in engine compartments of heavy vehicles to have sufficient durability requirements with regard to their functionality and lifetime. The research in this report has resulted in a holistic methodology when it comes to setting appropriate durability requirements for fire detectors that are to be mounted in engine rooms of heavy vehicles, with respect to the environment and environmental factors arising in these compartments. These requirements are not complete however, as they only serve as a stepping stone in the right direction. Because of the lack of information about each fire detector available on the market, its material properties and functional procedure, it is impossible to set complete requirements. Especially when there is no information regarding as to where the detector will be mounted, i.e. in which type of heavy vehicle. Therefore, the requirements that have been recommended in this report mainly serve as a future work reference.

Naturally, the next step would be to actually conduct the test methods that have been mentioned in this report, with respect to the recommended test parameters and conditions, for all fire detectors that are suited to be mounted in the engine compartments of heavy vehicles and that are commercially available today. The tests may yield information about the applicability of the test methods and the test conditions. If one fire detector does not pass a certain test with the test conditions as specified in the report, these may have to be altered or completely redefined. However, if the test method is changed entirely, it should not be forgotten that the test conditions are still valid, as this reflects the operational terms inside the engine compartment of any heavy vehicle type and cannot be altered with. All things considered, the test methods and test conditions should be viewed as a guideline to establishing proper standardized test methods for testing the sustainability of fire detectors to the physical factors mentioned.

Another aspect that needs to be brought up is that only six physical phenomena arising inside engine compartments have been studied in this report. The reason for this is that identifying all environmental influences is too time consuming and only those of most importance have been investigated. There are other factors that should be studied further, for instance the effects of chemical influences on the fire detector. What happens if the fire detector is exposed to battery fluid or motor oil leakage? This may not be a frequent occurrence but safety precautions must be highlighted that investigate these influences further in order for the fire detector's sustainability to be intact. Environmental influences such as these and many more may need addressing if there is enough interest and time given.

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