Effect of Water Mist Suppression System in Engine Room: Case Study of Fire in The Cruise Liner MS Nordlys

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Preface

The present thesis is the finale work of a master degree in Process safety technology at University of Bergen and is credited with 30 ETC points.

The present work has helped me to understand computer simulation of fire in general, simulation reliability and simulation structure. Computer simulation is not a straight forward task, knowledge and ability to be critical to what you read and see is crucial characteristics when you are using a simulation tool. It is very important to have good knowledge of the simulated object, the physics and mathematics that are involved and the simulation tool in use. It is also an advantage to name the simulation files systematically, looking for simulation result back in time could be quite time consuming.

I hope this thesis is a contribution to the discussion about water mist system and Simulation tools and FDS in particular. It is my impression that many user of FDS is not aware of the limitation of the program. I hope that this work will be an eye opener for some one and they could be more critical to CFD program in general. CFD program is helpful tools that can lift science and the society forward but they has to be used properly.

Acknowledgments

I would like to thank my supervisor Dr. Bjarne P. Husted at Stord/Haugesund University College for the encouragement and helpful advices during this project. He also encourage me to me to attend seminar and workshops where I had to present my work. At Interflam 2013 in London, I had a poster and a paper about the earliest work on this thesis. In October 2013 I attended the International Water Mist Conference (IWAC) in Paris, where I had a presentation about water mist system in engine room and how they could be simulated using FDS. At the newly started Nordic FDS user group workshop in Lund 2014, I had a presentation about how FDS could be used to see extinguishing of engine room fire using water mist as extinguishing agent. His glowing commitment to CFD and FDS has been most helpful during the project.

I also want to thank my college at Stord/Haugesund University College PhD student David R. U. Johansen, MSc student Per Fredrik Hemmingson, MSc student Øystein Grøndalh, Dr. Bjarne Hagen and Professor Vidar Frette for their interest, question, discussion and advice during the project. A special thank to Assistant Professor Gisle Kleppe for his knowhow of LaTeXand his willingness to help me out with LaTeX. Lector Lene Lundervold took her time and read through my thesis and corrected my english. And to Ingvild Kvamme one of my student for information about how engine works.

And at the end I would like to thank my wife Eli Kolstad and children Gunhild, Oda and Amalie that have been helpful and supporting through the process.

Abstract

In the 1980s ozone layer depleting was a major concern for the environmentalists. Halon was used as a fire extinguishing agent until it was banned in the early 1990's. The industry was therefore forced to find other solutions to maintain fire protection. Water sprinkle, water mist, carbon dioxide (CO_2) system, foam system and other gas based system was already in use, CO_2 system was widely used in engine room and server rooms. CO_2 system is harmful for human beings. The industry is aware of the situation and a change of mindset is in progress, this may change the industry standard. It is important that a new industry standard is grounded on a system that is safe for the environment and do not harm human beings.

At the morning of the 15. September in 2011 a fire started in the engine room of MS Nordlys. Two people were killed during the fire and 9 was injured. The ship almost capsized after it was towed to quay in Ålesund. MS Nordlys was protected by carbon dioxide extinguishing system, this was not released during the fire. As an additional, or back up, extinguishing system MS Nordlys had a water mist system. The water mist system was in manual mode and it was released several minutes after the fire has started.

The Norwegian Maritime Authority (NMA) wish to examine if water mist is a suitable extinguishing agent for engine rooms. They would also like to know if Fire Dynamic Simulator (FDS) is a useable Computing Fluid Dynamic (CFD) program to predict extinguishing of engine rooms.

FDS is a widely used CFD program among fire safety engineers. FDS is an advanced program with many opportunities. This thesis addresses some of the challenges with FDS.

In this thesis the following question will be answered:

1. How reliable is FDS when it predicts extinguishing in an engine room fire, using water mist as extinguishing agent?

2. How would a full protective water mist system with automatic release have preformed in the MS Nordlys Fire?

3. How could a FDS simulation be executed in a manner that is reliable and verifiable.

4. What benefits have water mist system compared with other extinguishing agent?

Water mist has the potential to contribute to suppression and extinguishing of engine room fires. In order to find the key parameter of extinguishing, when using water mist as

extinguishing agent, several simulation has been conducted. Auto ignition temperature, CO yield, k-factor, particle per second, critical flame temperature and the need for an ignition source was found as key parameter. Adding this in the simulation of MS Nordlys extinguishing was obtained. This project has shown that a well function water mist system, properly installed would most likely extinguish the fire on MS Nordlys within a minute. The following part is answer to the research question of this thesis.

There are uncertainties of using FDS on engine room fire and water mist as extinguishing agent. The main concern is coupled to the extinguishing model that just uses the temperature effect. It is also challenges with the combustion model, but it is possible to use another combustion model. Even there are uncertainties with FDS, it predicted extinguishing when water mist was used as extinguishing agent.

The simulation of MS Nordlys showed that the water mist system was able to suppress the fire, and when the experiment of USCG room is taken in account it is likely to believe that a water mist system would have extinguished the fire with in a minute.

Reliable FDS simulations has a validated test to support them. Several simulation is conducted to see convergence and the sensitivity of parameters. Prior good computer simulation goes hand calculation or experimental result to support it. Analysis of the result is as important as the simulation. This thesis present a list of how a FDS simulation should be conducted.

1. Decide what question the simulation should answer.
2. Find a validation case that are as similar to the simulation object as possible.
3. Find out if FDS is capable to answer the question on the validation case.
4. Sensitivity analysis of input parameters.
5. Use the findings above to simulate the case of concern.

Water mist has a benefit over CO_2 system since it is non-toxic, and it could be released multiple times. But CO_2 system has less residue than water mist system. Water mist uses less water than a traditional water sprinkle, and it has higher surface area that interact with the flame. Water sprinkle has bigger droplet than water mist, therefore sprinkle water penetrate the flame zone better and has a better cooling effect on the surface beneath the fire. Comparing water mist with Inergen and Argonit water mist has the benefit of almost infinite water supply, while Inergen and Argonite has a limiting storage of gas. Water mist produce small amount of residues but gaseous extinguishing agent has no residues.

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Chapter 1

Introduction

1.1 Background

In the 1980s ozone layer depleting was a major concern for the environmentalists. Many news articles and paper was dedicated this issue, and as a result many of the ozone depleting gases were banned. September 16th 1987 the Montreal protocol was signed in Montreal, Canada[1]. In article 2B of the protocol, halon (halon 1211, 1301, 2403) was banned. Halon is a carbon, florid, bromide gas that is an effective fire extinguisher. Halon have no known harmful effect on humans, but halon has a negative influence on the ozone layer. The industry was therefore forced to find other solutions to maintain fire protection. Water sprinkle, water mist, carbon dioxide system, foam system and other gas based system was already in use, and now a competitor was out of the game. The carbon dioxide (CO_2) system was widely used in engine room and server rooms. CO_2 behave much like halon. It has high heat capacity, displace oxygen and leave no residue.

Carbon dioxide systems are less damaging for the environment than halon. But Carbon dioxide system is harmful for human beings. Arne Sagen highlight the hazard of CO_2 systems and concluded that CO_2 based extinguishing systems should be banned due to negative effect on human beings[2]. The industry is aware of the situation and the cruise line company Hurtigruta ASA has already installed water mist systems on their ships. The change of mindset which is in progress may change the industry standard. However, all alternatives should be carefully considered. It is unfortunate that after halon system was banned many companies changed to CO_2 system that may get banned, and if that happens a newer system may also be banned. If there is going to be a change now, it has to be reliable and robust. It is important that a new industry standard or mindset is grounded on a system that is safe for the environment and do not harm human beings.

MS Nordlys is a cruise liner that serve the cruise tour Hurtigruten from Bergen at the west cost of Norway to Kirkenes in the northern parts of Norway. At the morning of the 15th September in 2011 a fire started in the engine room. Two people were killed during the fire and 9 were injured. The ship almost capsized after it was towed to quay in Ålesund. MS Nordlys was protected by a carbon dioxide extinguishing system. This was, however, not released during the fire. As back up MS Nordlys had installed a water mist system. The water mist system was in manual mode and was released several minutes after the fire started.

The Norwegian Maritime Authority(NMA) wish to examine if water mist is a suitable extinguishing agent for engine rooms. They would also like to know if Fire Dynamic Simulator(FDS) is an usable Computing Fluid Dynamic(CFD) program to predict extinguishing of engine rooms fire using water mist as extinguishing agent.

1.2 Purpose

FDS is a widely used CFD program among fire safety engineers. FDS is an advanced program with many opportunities. In FDS it is possible to simulate burnings of both solid and fluid. It is capable to measure a range of properties, e.g pressure , temperature, a variety of heat release rates, concentration of any species and velocity. FDS requires a trained and conscious user. Many fire engineering task is solved using FDS, but it is difficult to find cases covering extinguishing using water mist as an extinguishing agent. FDS is also case sensitive which means that even though a set up will work in one case, it will not necessarily work in another set up. This thesis addresses some of the challenges FDS has with modeling extinguishing when water mist is the extinguishing agent.

1.3 Research Questions

In this thesis the following question will be answered:

1. How reliable is FDS when it predicts extinguishing in an engine room fire, using water mist as extinguishing agent?
2. How would a full protective water mist system with automatic release have preformed in the MS Nordlys Fire?
3. How could a FDS simulation be executed in a manner that is reliable and verifiable?
4. What benefits have water mist system compared with other extinguishing agent?

1.4 Method

In order to answer the research questions FDS will be used. FDS will be validated with a full scale experiment done by United State Coast Guard(USCG) in the late 90's. During the validation the extinguishing time from the simulation will be compared with the experimental, or real, extinguishing time. This is done to ensure that FDS is capable to handle a situation similar to what occurred in MS Nordlys. The validation will determinate the governing parameter in FDS. If FDS is capable to handle this type of scenario, the engine room of MS Nordlys will be simulated with the same set of governing parameters.

Simulating the type of scenarios that occurred in MS Nordlys is challenging. This is because the size of the fire is not known, nor is the ventilation regime. However, a hand calculation to estimate the unknown input variables will be carried out to better simulate what happened in MS Nordlys.

Chapter 2

Theory

2.1 Water Mist

Water is the most common liquid on earth and it has been used to put out fires for milleniums. Water is a good fire extinguish agent due to its heat capacity and phase change, and there is water almost every where. Stefan Särdqvist has written a book about water and other extinguishing agents [3]. Water has high heat capacity and when added as a spray or mist it has a large surface area that lead to fast evaporation. The physical properties of water is seen in tabel 2.1:

Table 2.1: Physical properties of water.

Property		
Heat capacity, liquid at 15°C	4.18	kJ/(kg·K)
Heat capacity, gas gas at 700°C	2.01	kJ/(kg·K)
Heat capacity, ice	2.09	kJ/(kg·K)
Heat of vaporization	2260	kJ/kg
Density(4°C)	1000	kg/m^3
Boiling point	100	°C
Freezing point	0	°C

Water mist is an extinguishing agent that suppresses the fire by the cooling the hot gases in the flames and the burning surfaces. Water mist also displace oxygen [4] and cool all surfaces in the compartment. The main purpose to water mist system is to control the fire. Controlling gives longer evacuation time and facilitates access for firefighter. An additional benefit of water mist and other extinguishing agents is that they often put out the fire.

The American National Fire Protection Association (NFPA) standard for water mist system[5] distinguishes between three type of water mist extinguishing systems

- Low pressure system, pressure below 12 bar.
- Intermediate pressure system, pressure from 12.1 bar to 34.5 bar.

- High pressure system above 34.5 bar.

The low pressure system is often in the range of 5-10 bar Chemetron's nozzles operate at 12 bar, The intermediate pressure system usually operate in the lower part of the range, Grinnell nozzles operate at 13 bar and Fike nozzles at 22 bar. The high pressure system are generally from 70 bar and upwards. Navy nozzle operate at 70 bar, Foctec nozzle operate at 100 bar. All these pressure are taken from USCG test [6].

2.1.1 k-factor

The k-factor is a system constant from the discharge formula shown in eq. (2.1), that gives the flow in liter per minute.

$$Q = k \cdot \sqrt{p} \tag{2.1}$$

Where Q is the flow and p is pressure in bar[7].

2.1.2 Discharge Philosophy

A water mist system could be either wet pipe or dry pipe. Wet pipe system has water filled pipe to the nozzle in standby mode, dry piped system is air or gas filled pipe in standby mode. When dry piped system is released the pipe are filled with water. The discharge philosophy, could be described as: "where and how much water should come out from which nozzle, and when should this occur?".

The water mist system could be activated by heat, smoke or gas. One way to activate by heat is to have a glass bulb at the nozzle filled with liquid alcohol. The alcohol expand when heated and the glass bulb cracks, this allows water to discharge through the nozzle. When glass bulb are used only the heat affected nozzle opens. The liquid alcohol in side the glass bulb has different color for different activation temperature[5].

Another approximation to discharge water mist systems is total flooding. Total flooding is a system that uses all nozzles simultaneously. The discharge could be triggered by a fire detector, such as a smoke, gas or flame detector or it could be manually released. The total flooding system require more water than local discharge, but have the great advantage by the possibility of remote controlling a discharge.

Manually releasing of nozzles with glass bulbs is difficult, if even possible. Deluge system are build up by sections, one valve controls one section. Opening a valve allows discharge of all nozzles in the area controlled by that valve simultaneously.

2.1.3 Spray and Droplet Distribution

The spacing is the diameter to an area in the compartment that one nozzle is capable of covering. It is important to locate the nozzles in a pattern where they fully cover the protected area. The spacing is specified by the spray pattern, and in some cases the ceiling height. The spray pattern is the droplet distribution from a nozzle.

The spray angle is measured by taking a vertical cross section through the center of the nozzle and spray. Outline the cross section of the spray from the nozzle, then measure the angle of the triangle that occur. See figure 2.1:

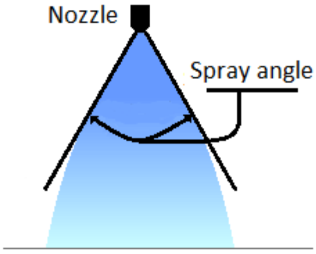

Figure 2.1: Spray angle

Water mist droplets are small, 99 percent of the droplets should have a diameter under 1 mm[5]. In most nozzles this diameter is 50-500μm[8]. Droplets are released from the nozzle with high velocity. When a droplet leaves the nozzle gravity, and drag force slow down the drop velocity. Droplets need momentum, (velocity multiplied by mass), to penetrate the fire. Smaller droplets need higher velocity than larger droplets to achieve the same momentum. The droplets experience a drag force from the surrounding air, which increase when the air is moving towards the particle, such as when hot air is rising from a plume.

Small droplets result in a large surface area for the water see fig. 2.2. A large surface area is important because of droplet evaporation. Stefan Särdqvist [3] describe how a droplet evaporate given in Eq. (2.2). The relation between the change in energy per time(dQ/dt) and convective heat coefficient(h), temperature(ΔT) and surface area(A).

$$\frac{dQ}{dt} = hA\Delta T \tag{2.2}$$

Eq. (2.2) shows that a large area will consume more energy than a small area.

2.2 Extinguishing Agent

There are several extinguishing agents in use. This section is about some of the most common. Water mist is described in section 2.1.

Carbon Dioxide

Carbon dioxide is pure CO_2 gas, compressed and released through nozzles. CO_2 has high heat capacity, 54.3 J/mol·K [9], and it displace oxygen. CO_2 has fatal impact on humans, human that are exposed for CO_2-concentration above 10 volume per cent could die according to Langford[10].

Inergen

Inergen contains 52 percent nitrogen, 40 percent argon and 8 percent CO_2. Inergen displace oxygen. Heat capacity is the mass weighted sum of heat capacity of CO_2,

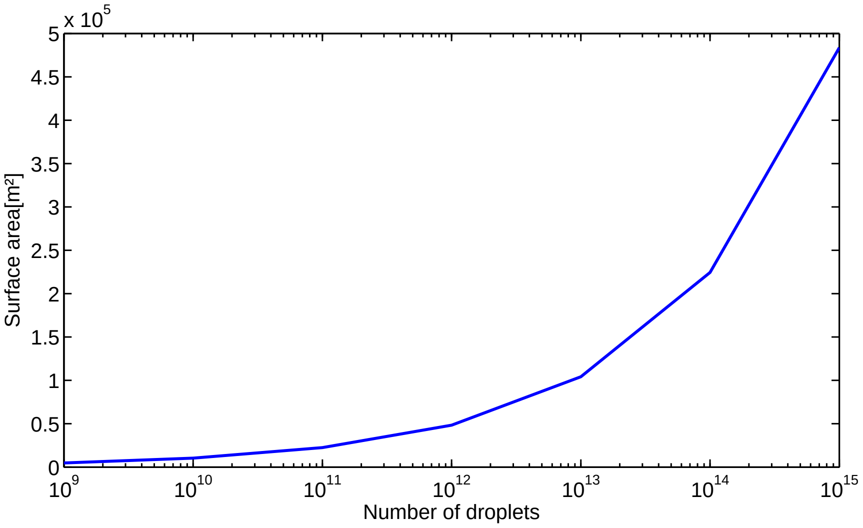

Figure 2.2: Surface area of 1m^3 water as a function of number of droplets.

N_2 and argon. The CO_2 is added in order to trigger the breathing, more CO_2 faster breathing and more oxygen to the exposed person. The CO_2 level in Inergen is to low to be toxic. Argon is a rear gas, which is not toxic. It is less nitrogen in Inergen than in a normal atmosphere. Therefore is Inergen not a toxic gas [11]. Inergen do not produce any residue when released.

Argonite

Argonite is quite similar to Inergen but Argonite does not contain CO_2. It contains 50 percent nitrogen and 50 percent argon. It is supposed that healthy people can be exposed to oxygen levels as low as 12 percent for short periods of time. If the oxygen level becomes any lower it could be dangerous for human[11]. The heat capacity of Argonite is the mass weighted sum of heat capacity of nitrogen and argon. Argonite do not produce any residue after released.

Water Sprinkle

Water sprinkle is quite similar to water mist. Sprinkle system use more water than water mist system. Sprinkle system produce larger droplet than water mist system.

Foam

It is different type of foam. All type of foam produce huge amount of residue when released and is not comparable with water mist.

Dry Chemical

Dry chemical is powder, it is widely used in hand held extinguisher. When released powder is spreed all over the place and cleaning work afterward could be expensive. The residue is the reason that powder extinguisher is not comparable with water mist.

2.3 Fire Theory

A fire is release of heat due to an exothermic chemical reaction between fuel and oxygen initiated and driven by heat. The fire triangle explain the interaction between oxygen, fuel and heat as seen in fig. 2.3.

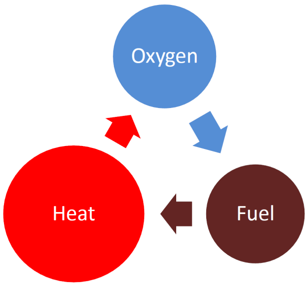

Figure 2.3: Fire triangle

By removing either one of the components, the fire will either not ignite or will be extinguished. As fig 2.3 indicate the heat is more important for the fire than oxygen and fuel. Energy release in a fire $\dot{Q}_c$ is shown in eq. (2.3)[9]

$$\dot{Q}_c = \chi \cdot \dot{m}'' \cdot A_f \cdot \Delta H_c \tag{2.3}$$

A_f is the burning surface(m^2), ΔH_c is heat of combustion, χ is a factor below one which take in account uncompleted combustion, and $\dot{m}''$ is mass rate per unit area($\mathrm{g/m^2s}$).

The chemical combustion reaction follows the Arrhenius rate according to Drysdale [9] given by:

$$\dot{m} = \frac{dm}{dt} = k' \cdot m \tag{2.4}$$

Here $\dot{m}$ is mass per second, k' is the Arrhenius rate coefficient, m is mass or the concentration, and t is time. Eq. (2.4) indicate that more mass released due to pyrolysis the larger is the fire, as long as the fire is fuel controlled. The Arrhenius equation[9] is given by

$$k' = A \cdot e^{\frac{-E_A}{RT}} \tag{2.5}$$

Here A is a constant [s^{-1}], E_A, the activation energy [J], R, the gas constant and T, the temperature. Inserting eq. (2.4) and eq. (2.5) in eq. (2.3) then the size of the fire is linear coupled to the concentration of oxygen and fuel but it is exponential coupled to the temperature. This means that heat reduction is more effective in therms of extinguishing than removal of fuel or lowering the oxygen concentration. The UK Watermist Coordination Group have a worked out some graphs that illustrate the relationship between oxygen displacement, cooling and extinguishing. Fig. 2.4[12] shows one graph for oxygen concentration and on graph for temperature. A vertical line is drawn where the water mist system is activated. In the "cooling benefit" graph there is an other vertical line, 30 s after the first on, the gap between them is the extinguishing time. Fig2.4 shows that the effect of cooling is significant and it extinguishing the fire. The figure "oxygen displacement benefit" shows that the oxygen level is too high to extinguishing the fire itself[12]. When the fire is extinguished the evaporation of water stops and the oxygen concentration is rising again.

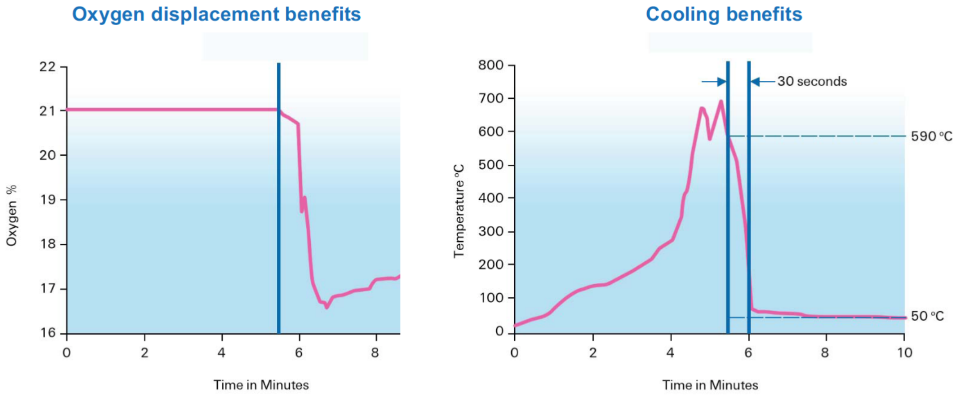

Figure 2.4: The effect of oxygen displacement vs. the cooling effect.

The main reaction for methane in air is shown in eq. (2.6)

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow C0_2 + 2H_2O + 7.52N_2 \tag{2.6}$$

In a fire there are a lot of elementary reaction during combustion. The simplest of all combustion reaction hydrogen and air consist of about 40 elementary reaction [13]. The temperature of the fire determines whether there is production of CO, which also is a combustible gas.

2.3.1 Auto Ignition Temperature

A combustible mixture of air and fuel will ignite when heated. If a combustible mixture is in contact with a surface or flow at a temperature where the mixture instantaneously ignite, then this temperature is called Auto Ignition Temperature(AIT). AIT is not derived from fundamental physics, it is decided with experiment. The AIT for a certain fuel is given in the fuel safety datasheet [9].

2.3.2 Adiabatic Flame Temperature

The adiabatic flame temperature could be calculated by eq. (2.6). Adiabatic means that no heat escape and all energy contribute to heat the products. The correlation between heat of combustion, ΔH_C, and temperature, T, is given by first law of thermodynamic assuming constant pressure and adiabatic condition[13]:

$$\Delta H_c = \int c_p dT \tag{2.7}$$

If c_p is assumed to be constant eq. (2.7) is simplified to eq. (2.8)

$$\Delta H_c = c_p \left(T_{end} - T_{start}\right) \tag{2.8}$$

$c_p = \Sigma c_{p,i}$ when there are more than one product. Heat of combustion for methane is $\Delta H_{c,CH_4}$ the heat capacity at constant pressure to species i from the product is $c_{p,i}^{1000K}$ then the $T_{product}$ according to eq. (2.8) is derived in eq. (2.9).

$$T_{product} = T_{ambient} + \frac{n_{CH_4} \Delta H_{c,CH_4}}{\sum n_i \cdot c_{p,i}^{1000k}} \tag{2.9}$$

n_i is number of mole of species i, $T_{start} = T_{ambient}$ is the ambient temperature. Using eq. (2.9) to calculate the temperature of the product in a methane combustion in air, temperature of the product is then 2096°C. According to Drysdale the measured flame temperature is 1875°C. When using five percent of methane in air, the mixture at Lower Flammability Level (LFL) the adiabatic flame temperature is 1173°C this is the Lower Flame temperature(LFT). If the temperature in a flame drop belowe LFT the fire will extinguish[9]. This temperature is called Critical Flame Temperature (CFT).

2.3.3 Enclosure Fire

Well ventilated fire grows and spread due to the available fuel, it is induced by the fuel. If oxygen level is low, compared to the amount of burning fuel, the fire is under ventilated and the heat release rate is depending on air supply. In an enclosure fire the air is the limiting reactant in the reaction equation. Considering a burning house it is possible to see whether the fire is fuel or oxygen induced. If the flame are burning out of the windows the fire is oxygen induced. Since the flames extends outside the openings it means that some of the reactant has not burned inside the building because of lack of air. Unburned reactant is carried along with the hot smoke, when these reactant reaches the oxygen rich air outside they burn.

2.3.4 Extinguishing vs Suppression

This thesis uses the extinguishing and suppression definitions according to NFPA 750[5]. Here extinguishing is used when activation of an extinguishing system leads to heat release rate from the fire becomes zero. Suppression is when the activation of an extinguishing agent is resulting in a sharp drop of the heat release rate.

2.3.5 Extinguishing Mechanisms

There are three main mechanism to extinguishing; temperature, strain and dilution effect. Temperature is effect is coupled to the AIT as described in section 2.3.1 and CFT which are described in section 2.3.2. The combustible gas has to burn at a temperature higher than CFT or it has to be in contact with something that hold higher temperature than AIT. The temperature effect is often referred as cooling effect. The strain effect is pulling of fire, if the velocity become large it can tear the fire apart and combustion is not permitted. The strain effect is dominating on fire with high velocity. Dilution is the effect of displacement and/or addition particle, water mist displace oxygen and it can add mass to a control volume such as the oxygen concentration is lowered.

Water mist uses both the temperature effect, cooling and dilution, oxygen displacement [4] [14]. The oxygen displacement of water mist is better if the fire is large. And as described in fig. 2.3 the cooling is more important to extinguishing than oxygen displacement. The real benefit is that water mist does not use one of the effects, but both.

In order to have a fire there has to be a combustible material (gas, liquid or solid), oxygen and heat. Oxygen is normally provided by air but in some cases it could be pure oxygen leaking from a tank e.g. in hospital and ambulances. A fire in a pure oxygen environment is violent and it is not described in this thesis. Heat is the ignition source, it could be anything from an arc to a pilot flame and hot surfaces and when the fire has started to burn the heat is produced by the chemical reaction in the fire. This is often presented as the fire triangle, see fig. 2.3

By removing one of the three ingredient of a fire, the fire will extinguish. Oxygen could be displaced by a gas, or steam if water mist is present. This happens when water is in heated by the fire. When water transform from liquid state to steam the volume of water expand approximately 1600 - 1700 times. This lead to displacement of oxygen, although the oxygen displacement occur it has little impact on the extinguishing see fig. 2.4. Other gas extinguishing agent fill the protected volume with so much inert gas that the oxygen level drop below the region of combustion [9]. For CO_2 system the extinguishing occur earlier than the oxygen level indicate. This is because of the cooling effect of the inert gas. The fire has to heat the inert gas therefore the adiabatic flame temperature drop below the LFT (see section 2.3.2) and the fire will extinguish.

If possible the fuel source could be cut. If it is a gas or liquid leak from a pipe it is possible to isolate the section where the leak is, but this must has been taken in account when the system was build. Even this is widely used in the process industry the segment that are isolated is often large, since some of the equipment need large amount of fuel to work or it is processing large amount of flammable fluids.

The heat could be reduced by cooling the flame and the heated structure around. One way of cooling is by water. The more water applied the better is the cooling. Sprinkle system purge more water than water mist system, but water mist has a higher surface area than the sprinkle droplets. More surface area in contact with the fire leads to more evaporation and evaporation demands energy which is extracted from the fire. The phase change consume huge amount of energy.

2.4 Fire Dynamic Simulator

This section is mainly based on Fire Dynamic Simulator(FDS) documentation[15][16][17].

2.4.1 Computation Fluid Dynamic

CFD is a fluid mechanic tool, CDF is uses numerical methods to calculate a wide range of transient problem involving fluid movement, such as water flow in a river, oil in a pipe, smoke spread from a plume, etc.

Fluid dynamic problem are often transient problem, time depending. Some sub-models, such as the pressure solver, require iterative solving of partial differential equation. There are two main orientation of thinking when create a fire simulator, either make a zone model or make a field model. Zone models split the calculation volume in zones, calculation volume is the room or building that should be simulated. Typical zones are an upper zone with hot smoke and a lower zone with cold air[18]. Field models splits the calculation volume in small control volume called cells, the collection of cells is called a mesh or grid[19]. The calculation volume could be separated in several meshes. The CFD program treats every single 'cell' as it is uniform, i.g one temperature in the cell, one density for the cell, one velocity of the gas or particle through the cell, etc. CFD calculate conservation of mass, momentum and energy in each cell and then the interaction with the neighbor cell. The equation is set up as Navier-Stoke equations and the general conservation equation is given in eq. (2.10)[13]

$$\frac{\delta f}{\delta t} + \nabla \Phi_f = q_f + s_f \tag{2.10}$$

Here is $\frac{\delta f}{\delta t}$ the time depending function f. Function f could be mass then f is equal to 1. If f is the entalpi eq. (2.10) is the conservation of energy. Momentum has a conservation equation in three directions using the velocity in u, v and w. $\nabla \Phi_f$ flux density of f. q_f is the production/formation of f and s_f is the generation of f due to long range processes such as radiation and gravity[13]. s_f is also called source or sink.

2.4.2 FDS

FDS is a freeware from NIST(National Institute of Standards and Technology) USA. The main use of the program is to calculate smoke spread and sprinkle and detector activation during a fire. FDS is designed for fire induced flows i.g. it is good at simulating diffusion flame in enclosure. It is also used to predict fire load and detection activation. FDS is also used to study fires. FDS use a deterministic calculation of the fire i.g a simulation will give the same result every time is executed.

FDS is a Large Eddy Simulation(LES) code. LES calculate the large eddies on grid level while sub-grid turbulence is solved with a variation of Deardorff's model[16].

2.4.3 Combustion Model

The default combustion model in FDS is called simple chemistry(one step mixing-controlled reaction) with air, fuel and product treated as lumped species. Background oxygen(air) is lumped species containing oxygen, nitrogen, carbon monoxide and water. The lumped species Air react with the lumped species Fuel and becomes the lumped species Product the general chemistry reaction equation is shown in eq. (2.11).

$$air + fuel \rightarrow product \tag{2.11}$$

The lumped species product contains carbon dioxide, carbon monoxide, water, nitrogen and soot, soot and carbon monoxide is by default zero but they can be specified by the user in the &REAC line by adding SOOT_YIELD and CO_YIELD. The amount of air, fuel and product is calculated by FDS [15] [16]. The Technical Reference Guide to FDS outline the calculation of Heat Release Rate(HRR) pr unit volume[16] using a method outlined from the Eddie Dissipation Concept (EDC). The HRR is calculated by the mean chemical mass production of Fuel, F per unit volume, $\dot{m}_F'''$ shown in eq. (2.12).

$$\dot{m}_F''' = -\rho \frac{\min(Z_F, Z_A/s)}{\tau_{mix}} \tag{2.12}$$

Z_F is the lumped mass fraction to the Fuel and Z_A is the lumped mass fraction of Air. s is the mass stoichiometric coefficient for Air. τ_{mix} is the time scale for mixing. ρ is density. The equation for HRR per unit volume is given in eq. (2.13).

$$\dot{q}''' = -\sum_{\alpha} \dot{m}_{\alpha}''' \Delta h_{f,\alpha} \tag{2.13}$$

in eq. (2.13) $\Delta H_{f,\alpha}$ is heat of formation for species α. Eq. (2.13) is the sum of heat release from all species that has change volume during the combustion. There is an upper limit for the local HRR to prevent unrealistic large HRR, in case of using too coarse grid cells. The τ_{mix} is given in eq. (2.14)

$$\tau_{mix} = \max(\tau_{chem}, \min(\tau_d, \tau_u, \tau_g, \tau_{flame}) \tag{2.14}$$

τ_{chem} is the time scale of the chemical reaction, τ_{flame} is the time scale for the flame height. τ_{chem} and τ_{flame} are user controlled. τ_u is a turbulent time scale, τ_d is the diffusive time scale and τ_g is a time scale coupled to the gravity. Fig. 2.5 shows how eq. (2.14) determinate τ_{mix}

It is possible to defined an other combustion model described in technical reference guide as complex chemistry. And it is also possible to use multiple reactions and “not mixing controlled” reactions.

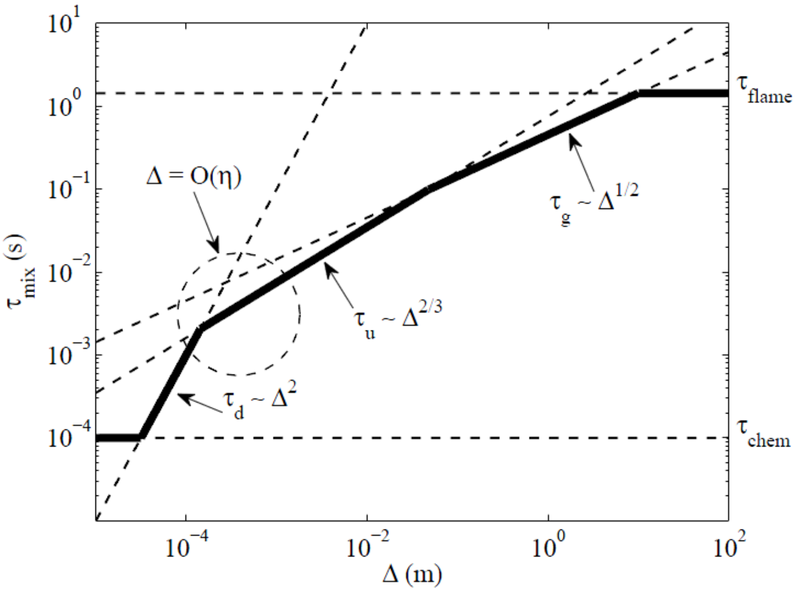

Figure 2.5: Determenate τ_{mix} using correlation of τ_{chem}, τ_{flame}, τ_g, τ_u and τ_d as a function of turbulent length scale.

2.4.4 Extinguishing Criteria in FDS

If oxygen and fuel concentration is below a level that will support combustion of the current fuel the fire will extinguish. FDS uses two temperature criteria:

AIT: The local temperature is below AIT(0K by default) the fire will extinguish or not occur.

CFT: The reaction in the cell has a HRR that do not produce enough heat to rise the local temperature above critical flame temperature.

The technical reference guide[16] present eq. (2.15):

$$\hat{Z}_F\left(h_F\left(T\right)+\Delta h_{c,F}\right)+\hat{Z}_A h_A\left(T\right)+\hat{Z}_P h_P\left(T\right) < \hat{Z}_F h_F\left(T_{CFT}\right)+\hat{Z}_A h_A\left(T_{CFT}\right)+\hat{Z}_P h_P\left(T_{CFT}\right) \tag{2.15}$$

Eq. (2.15) is the criteria to obtain extinguishing. Here is $\hat{Z}$ is the reactant mixture value[16], A, F and P is Air, Fuel and Product. T is the initial temperature in the cell and T_{CFT} is the critical flam temperature of the fuel. Eq. (2.15) is the mathematical expression for CFT criteria in the list above. The eq. 2.15 state that the energy production of the combustion must be larger than the energy produced at CFT.

2.4.5 Some Important Parameter in FDS

Particles Per Second

A liquid spray in FDS has by default 5000 traceable particles, for water mist this is just a fraction of how many particles there actual are, see fig. 2.2. It is not necessary to trace all the particles. But if more particles are traced by the simulation, the spray get a smoother pattern and the evaporation of the droplet is better represented. The droplet in FDS are treated as Lagrangian particles. Lagrangian particles is used by FDS when a particle is too small to be represented in the grid resolution.

Courant, Friedrichs, Lewy Condition

CFL is controlling the time step(DT), if the time step is too long the simulation could loose important information, on the other hand if it is to small it becomes numerical unstable. FDS uses an explicit method of solving partial differential equations. The explicit method uses linear correlation between two time steps, this is acceptable if the time step is small but not if the time step become long. The CLF condition in FDS is given by eq. (2.16):

$$DT = \frac{5 \cdot (\delta_x \delta_y \delta_z)^{1/3}}{\sqrt{Hg}} \tag{2.16}$$

Here δ_x, δ_y and δ_z is the dimension to the smallest grid cell, H is the compartment height and g is gravity. The commando PARTICLE_CFL=.TRUE. and 'PARTICLE_CFL_MAX' is controlling the time step. 'PARTICLE_CFL_MAX=1' is default and it gives that no particle moves more than one grid cell during one time step.

Auto Ignition Temperature

In FDS AIT is by default absolute zero, -273.15°C. AIT could be changed by adding AUTO_IGNITION_TEMPERATURE to the &REAC line in FDS input file. If AIT is set to something else there has to be an ignition source present in order to obtain fire.

Critical Flame Temperature

CFT is by default set to 1600°C, it could be changed by the CRITICAL_FLAME_TEMPERATURE in the &REAC line in FDS input file.

CO Yield

The amount of carbon monoxide is by default zero in FDS it can be changed by adding CO_YIELD to the &REAC line in FDS input file.

Calculation Time

CFD is time consuming, calculation time could be tremendously long. Simulation that takes days is normal and even weeks of simulation is not unusually. When changing parameter it is important to judge how the change will interfere the simulation time. Some parameter are obvious causes to extend the simulation time, such as smaller cells(additional cells), shorter/limiting time steps, additional particles and every parameter that lead to several iterations per time step. All these parameter should help to get a more accurate results. More accurate results mean more time spending on tuning parameters and extended simulation time. In the end it will be a compromise between accuracy and time consumption.

Chapter 3

MS Nordlys

The cruise line MS Nordlys was build in Volkswerft, Germany in 1994. It has 469 beds, place for 45 cars and a passenger capacity of 622. The ship is owned by Kirberg Shipping in Bergen and long term leased by the cruise liner company Hurtigruta ASA. The ship have sister ships called MS Richard With and MS Kong Harald. On the 4th of April 1994 MS Nordlys departed from the port of Bergen on its maiden voyage to Kirkenes.[20]

MS Nordlys has expired several accident during the years. One grounding, a collision and an unspecified accident. The ship also experienced a fire the 11th of March 2011 due to hot work during maintenance.[20]

The following description of the accident is a summary of the investigation report[21].

Figure 3.1: The rescue vessel Emmy Dyvi heading for MS Nordlys, photo: Norwegian Coastal Administration

3.1 The Accident

When Ms Nordlys approached Ålesund, on the morning of the 15th September in 2011 an alarm indicated that a fire had started in the engine room of the ship. The clock was 9:13 and the following minutes several alarms were activated. Smoke and flames was observed in the engine room. The officer on the bridge received a call from the control room. A motorman confirmed that there was a fire at the starboard main engine and it was dense smoke in the main engine room. Shortly after this the starboard engine shut down and a moment later the port main engine shuts down. The starboard auxiliary engine started, but shuts down shortly after, the port auxiliary engine kicks in, but this one also stops after a brief time. The emergency generator starts up, run for a while and stops. MS Nordlys becomes a death ship. With no power MS Nordlys drifted. It got on the wrong side of a marker where it almost grounded. The captain managed to maneuver the ship through and away from shallow water. The captain called Florø radio and asked for assistance. The rescue vessel Emmy Dyvi shown in fig. 3.2[22], was in Ålesund and immediate started the work to reach the ship. Fig. 3.1 [23] shows Emmy Dyvi hedding for Ms Nordlys. Emmy Dyvi reached MS Nordlys six minutes later and within five minutes they had manage to fasten a towline to MS Nordlys, and they towed her to quay at the harbor of Ålesund.

Figure 3.2: The rescue vessel Emmy Dyvi, photo: Redningsselskapet

When MS Nordlys was maneuvered to quay in Ålesund the starboard stabilizer fin penetrated the hull and water flowed in to the ship. Water tight door was either left open or the water tightening failed. Anyhow, this leaded to water filling of the ship and the inclination angle was 20°, which is close to what the ship could manage. The rescue team tried to drain the ship but more water was coming in than they manage to pump out. After some search the divers found the leak and manage to seal it. The ship regained its stability, and was towed to Fiskestranda ship yard.

3.2 Evacuation

When the fire was detected there was five persons in the main engine room or in rooms which had escape routes through the main engine room. A motorman was in the separator room and the chief engineer entered the separator room from the incinerator room, just after a minute the chief engineer noticed that something was wrong. He shouted out and ran in to the incinerator room. The motorman went into the main engine room, it was filled with smoke so he ran back to the incinerator room to find the chief engineer. The incinerator was full of smoke. Then the motorman fled through the separator room in to the main engine room down a stairwell and in to the auxiliary engine room. From there he went to the control room and contacted the bridge. During the escape the motorman observed smoke and flame. The smoke was more dense in front of the starboard engine. He also observed flames just above the engine. The chief engineer was later found dead in the incinerator room.

An apprentice engineer, first engineer and a repairman were in a workshop connected to the main engine room. The apprentice engineer saw smoke and fire through a window. They escaped through the only door in the workshop which led them almost through the fire. In that area it was dense smoke and heat. First engineer and the repairman manage to escape through a water tight door on the port side in front of the engine room. Neither of them could remember to have seen the apprentice engineer during the escape. Later fire fighters found him on the kitchen, death due to smoke inhalation. The apprentice engineer and chief engineer were the fatalities during the accident. The first engineer and repairman suffered burn injuries. Seven more people were injured during the accident. There was 207 passengers and a crew of 55 on board MS Nordlys that morning.

3.3 The Fire

The investigation report[21] after the accident suggests that the fire started due to fatigue on a pipe to the fuel pump. On the 3^{rd} of September the fuel pump was exchanged, the investigation discovered that the bolts that hold the fuel pump was not properly tighten. The fuel pump could be be moved 2-3 mm by hand. This movement is enough to cause cyclic stress to the pipe connected to the pump. Calculation done by DNV suggest that the pump has moved up and down 3.6 million times within 12 days.

This leaded to leak of diesel, which ignited when it came in contact with a hot surface. Measurement on the sister ship MS Richard With revealed several hot uninsulated surfaces in the engine room one located only 30 cm from the leaking point. The fire led to leak in the return pipe and this provided more fuel to the fire.

Neither the fire size nor the fire type is mention in the investigation report. It could have been either a spray fire, a pool fire or a combination of these. This project uses spray fire since the USCG test was executed with spray fires.

3.4 Fire Fighting

When the fire started no extinguishing system was activated. MS Nordlys had both a carbon dioxide system and a water mist system. The carbon dioxide system should not have opportunity to automatic release. The water mist system had both an automatic and a manual mode. At the time the fire occured the water mist system was in manual. Therefore it was no automatic fire fighting present during the early phase of the fire. The routines of releasing the carbon dioxide system is quite elaborate, since a release of CO_2 will be lethal to any humans in the enclosed space. The captain need to activate the system by pushing a button on the bridge, but he can only do so if he knows where the crew is. Counting the crew could take some time, and in some cases it is not possible since some of the crew members could have been trapped behind the fire, or even have died.

The further extinguishing work was done by cooling from coast guard ships and fire brigade from land. The fire was extinguished at $13:28$ the 15th September. This is about 4 hours after the fire started.

Chapter 4

USCG Full Scale Tests

In the late 90's United State Coast Guard(USCG) conducted several full scale tests of engine room fires, and fire suppression with water mist. In a report from 1999 [6] they presents their result. The fire tests was preformed according to the requirements of the organization Safety Of Life At Sea(SOLAS), and its standard "international Code for Fire Safety Systems"(FFS Code)[24].

The test method from SOLAS[24] was pushed forward due to the ban of using halon as an extinguishing agent in most areas, not in space shuttle and aircraft.

4.1 USCG Fire Test

The test was done in a room built after SOLAS requirement in the FSS code[24]. The FSS code demands a wide range of fire tests to be executed. There are tests for different ventilation condition, fires and USCG used these tests with different type of water mist nozzles.

The geometry was a 105 m^3 engine room with a floor area of 35 m^2(7m × 5m) and a ceiling height of 3 m. There was two engine mook-ups, one starboard and one port. On the starboard engine it is a plate that protrudes over the port side of the engine. The plate is making a roof, where beneath it it can be a fire. This in order to simulate a fire which are hidden from the water mist nozzle. The first set up is showed in fig. 4.1. This figure shows engine set up in FDS.

The fire test was done with three different ventilation scenario:

1. Closed, no natural ventilation nor forced ventilation.
2. Natural, opening which let air flow through the room in a natural matter.
3. Forced, same as natural but with a fan which blow air in to the room.

The test was preformed with burning wood crib, pool fire and spray fire. In this work it is only the result from test done with spray fire which was with in the scope of this project. It is most similar to the accident on MS Nordlys. There was a heptane spray

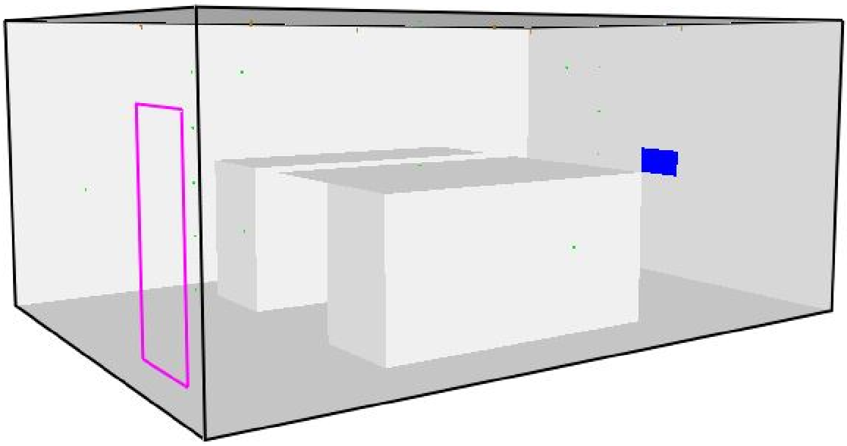

Figure 4.1: First set up of engine room for FDS simulation.

fire used in USCG test. USCG used three different volume flows to make 0.25 MW, 0.5 MW and 1 MW fire. In the future work the 1 MW fire was used since it is closer to what is expected of an engine room fire.

The test facility is presented in fig. 4.1 here the blue solid square in the back of the room is the fan. This is active under forced ventilated scenario. The pink open square in front of the room is a door. This is open under both the ventilated and forced scenario. In the middle of the room the engine mook-up is represented with two gray boxes, one of them with the bench. Below the bench there is a heptane nozzle. The heptane nozzle is hidden behind the closest engine and not shown in the figure. If looking real closely it is possible to spot some small red line in the roof, this is the water mist nozzle. The water mist nozzles are placed according to manufacture requirement for each extinguishing system, such as Navy, Fogtec, etc. see table 4.1. There are also some green dots on fig. 4.1. These are measurement equipment from the simulation.

Table 4.1: Data on water mist system used during the USCG water mist suppression tests[17].

System		Navy	Grinnell	Fogtec	Chemetron	Fike
Number of Nozzles		6	6	6	15	6
Flow Rate	[L/min]	68	75	22	70	48
Assumed Median Drop Size	[μm]	175	225	100		200
Assumed Initial Velocity	[m/s]	75	32	90		41
Assumed Spray Angle	[deg]	120	90	120		90

The result of the fire tests is shown in table 4.2. The majority of fire scenarios was extinguished, "no" indicate that the fire was not extinguished within 5 minutes. When studying the result it is clear that the smaller fire has longer extinguishing time than large fires. This is explained in the report[6]. The report suggest that it is due to evaporation of water that extinguishing the larger fires. This evaporation effect is not as significant in the smaller fire. It is stated in the report that these small fires are possible for trained personal to put out with a hand held extinguisher. Fires at 200-500 kW is according to Leif Staffanson work "Selecting design fires"[25] in the same magnitude as a plastic trash bags, filled with cellulosic trash (1.2-14 kg), 120-350 kW.

Although all fire scenario was not extinguished the result was uplifting. The test showed that water mist extinguishing system was able to control fires and even extinguishing them. The result from this test was used in FDS validation guide[17][26]. This input file is used in this project. The first simulation shown in fig. 4.3 is done with this file without changes.

Table 4.2: Recorded extinguishing times for the USCG water mist suppression tests in a small shipboard machinery space, using various spray fire. "No" means that the fire was not extinguished within 600 s of nozzle activation[17].

System		Navy	Grinnell	Fogtec	Chemetron	Fike
Fire Scenario	Ventilation	Extinguishment Time [s]				
1.0 MW	Closed	15	26	21	27	21
1.0 MW	Natural	15	40	32	43	35
1.0 MW	Forced	17	55	76	357	133
0.5 MW	Closed	34	70	39	53	56
0.5 MW	Natural	41	117	67	158	140
0.5 MW	Forced	124	No	No	No	No
0.25 MW	Closed	157	360	169	314	277
0.25 MW	Natural	206	No	290	525	566
0.25 MW	Forced	No	No	No	No	No

The fire was simulated as a 1 MW heptane spray fire. Default FDS fire, simple chemistry was used.

4.2 The Simulation set Up

In some simulations open doorways or/and windows are present. The pressure profile or velocity is important parameter in FDS. The User Guide[15] recommend that the overall calculation domain is extended in order to move the pressure boundary away from opening. It is desirable that the extra volume is a hydraulic diameter from the edge of the opening to the outline of the mesh. The hydraulic diameter D_h is given by eq. (4.1). The phenomena is covered in a paper by Yaoing He et.al [27]. At openings there could be both an outflow of hot smoke and inflow of cold air, this flow regime is difficult to calculate if just one side of the opening is known.

$$D_h = \frac{4S}{Z} \tag{4.1}$$

Calculation of the hydraulic diameter gave $D_h = 1.2$m and an area of about this size was fitted to the simulation model. The new simulation volume is showed in fig. 4.2.

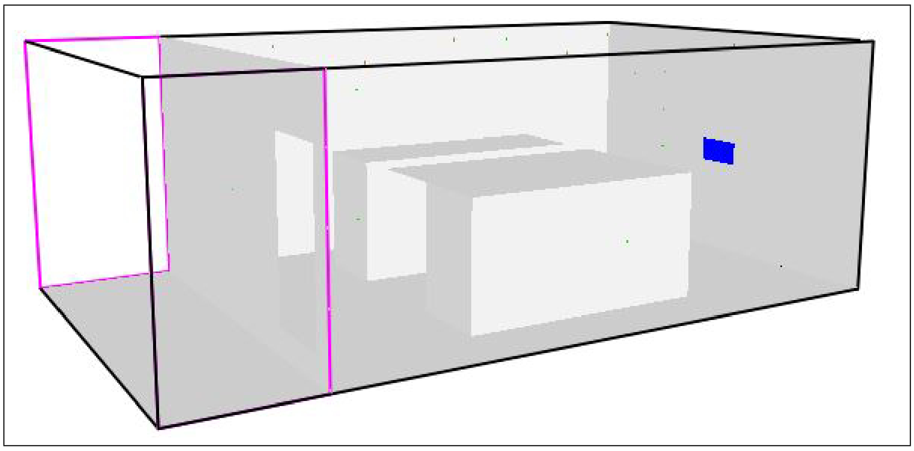

Figure 4.2: Second set up of simulation

4.2.1 Simulation of Water Mist Nozzle

The simulation of water mist spray could be very sophisticated, and the meaning of simulate the very right spray pattern of the nozzle is discussed in the water mist society. Bjarne Husted doctoral thesis[8] and International Water Mist Association(IMWA) conference in Paris September 2013 discussed the spray pattern to water mist nozzles, and how difficult it is to simulate them. A simplified way of simulating the nozzle is to use the water flow, pressure, mean droplet size and spray angel. All this factors but water flow are given from manufacturer. The water flow is calculated by using a k-factor, described in section 2.1.1, and the pressure. The water mist system was activated a minute later than the fire. This is in correlation with the tests conducted by USCG. In the following simulations Navy water mist nozzles were used, except the Particle Per Second simulation which used Fogtec nozzles[26]. The Navy nozzle has almost the same properties as the newly installed water mist system at MS Nordlys. k-factor of 1.35 $\mathrm{l}/\left(\mathrm{min} \cdot \mathrm{bar}^{1/2}\right)$ and a pressure at 70 bar with six nozzle gives a water flow of about 68 [l/min].

4.3 Result of Simulation

These simulations uses a 1 MW heptane spray fire, forced ventilation scenario, Navy water mist system and USCG room according to fig. 4.2. exceptions are the Particle Per

Second simulation which uses Fogtec nozzles and USCG room according to fig. 4.1 and the first simulation that also is a simulation of USCG room according to fig. 4.1.

4.3.1 Moving Average

All graphs are made in MatLab. It was used a moving average algorithm to obtain a smoother curve. The average was taken in every point(time). It was calculated by taking a point and ten point before and ten point after this point, then dividing by 21. The average is taken over 7.5 s. Using this method introduce an error in the beginning and end of the graph. In the beginning the error lead to a slightly slower fire growth. At the end of a simulation this error become visualized by the graph dropping to zero. This vertical line must not be confused with extinguishing. The vertical line indicate that the simulation has stopped of some reason.These errors are neglected.

4.3.2 The Result of The First Simulation

In the first simulation there was used 10 cm grid cells in one mesh. Three scenarios was simulated in order to see how they behaved in the original FDS Validation Guide set up[26]. The room set up is shown in fig. 4.1.

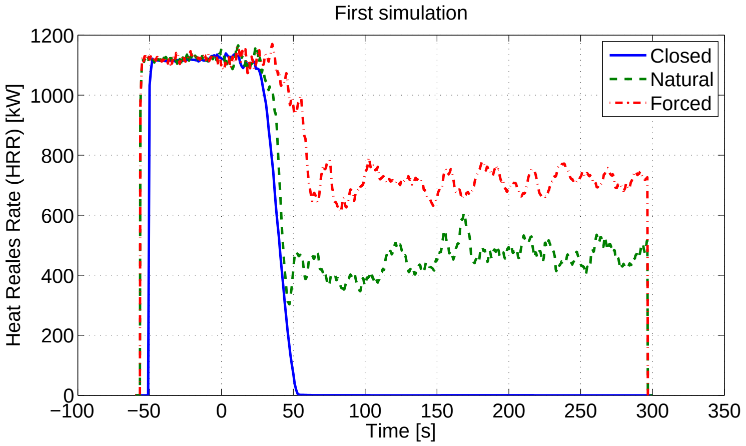

Figure 4.3: First simulation of USCG test in original room.

In fig. 4.3 there is extinction of the closed ventilated scenario, but not for natural nor forced ventilated scenario. According to table 4.2 the extinguishing time for Closed, Natural and Forced ventilated scenario was 15 s, 15 s and 17 s respectively.

Closed Ventilation Scenario

The first simulation was promising because the fire went out after 47 s. The simulation was executed one more time with measurement of pressure. This showed that the room had a 0.9 bar pressure rise during the fire. In another attempt of simulate the fire, water mist nozzles were not activated and still the fire was extinguished after about 150

s. The closed ventilation scenario is not actually interesting.SOLAS regulation of test set up for engine room fire that uses water as extinguishing agent require quite amount of ventilation[24]. The forced ventilated requirement is discussed by Back et.al in their report[6]. The future use of the closed ventilation scenario is to tune parameter. It could be easier to see the effect of a change if there is extinguishing.

Natural and Forced Ventilation Scenario

Neither the natural or the forced ventilation scenario did extinguish. The fire test result shown in table 4.2 showed that the natural ventilated scenario was extinguished with in 15 s and the forced ventilated scenario was extinguished with in 17 s. The smoke view from FDS showed that the fire mowed from its original fire place at the heptane outlet under the bench to the ventilation inlet, see fig. 4.4 After this discovery the following simulations was executed in order to obtain extinguishing for the forced ventilated scenario.

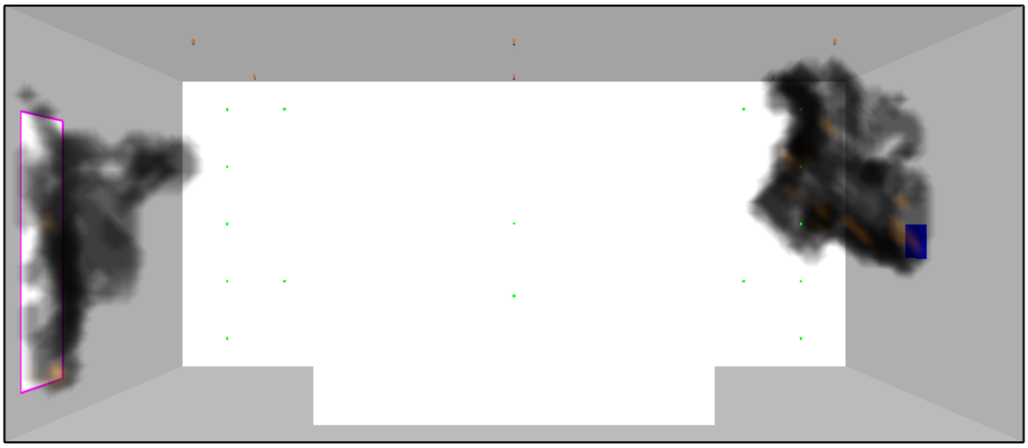

Figure 4.4: Fire has moved from its original place to the ventilation openings.

4.3.3 Grid Cell Size Sensitivity

FDS treats information within one grid cell uniform e.g there is one temperature in one grid cell. This means that grid cell size have significance influence on the simulation result. If the grid cells are to large the information become inaccurate, and if the grid cells are small the simulation time will be extended. Cubic grid cells at 500 mm, 200 mm, 100 mm and 50 mm were used in this simulation. 500 mm and 50 mm grid cells were unstable, and these simulation stopped almost immediately. Therefore shows fig. 4.5 only the simulation done by 100 and 200 mm grid cells and there was one mesh. The result is shown in fig. 4.5.

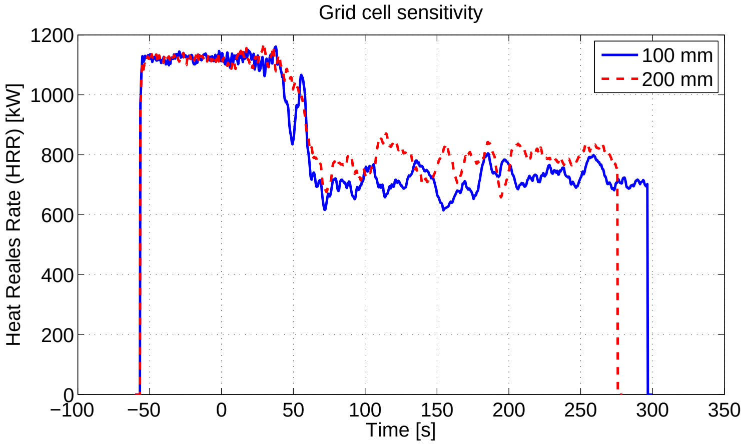

Figure 4.5: Grid cell sensitivity used 100 mm and 200 mm cubic grid cells.

Two simulation is not enough in order to see convergence of in HRR. The result from the 100 and 200 mm simulations are although quite similar. In fig.4.5 the 100 mm cell simulation was successful finished after 300 s. The 200 mm simulation was ended by a mistake of the operator. The simulation was distinct and there where no reason to run a new simulation.

Since the 100 and 200 mm grid cells showed similar result, 200 mm cells should have been preferred due to simulation time. Using half the length of a grid cell there will be eight times as many grid cells in the simulation. This will extend the simulation time by a factor of 16 since the time step must be halved. 100 mm grid cell was chosen due to an impression of smaller grid cells gives more accurate simulation result.

4.3.4 Particle Per Second

As described in section 2.4.5 the PPS parameter could be helpful in order to obtain extinguishing. A better distribution of the water in the compartment should lead to better cooling of the fire and other surfaces.

This simulation uses Fogtec nozzles, information about Fogtec is found in table 4.1. The set up of the room is shown in fig. 4.1. Closed ventilation scenario and 10 cm cubic grid cells were used. Particle per second(PPS) was set to default(5k=5000 PPS), 15k, 30k, 50k 100k and 150k. Result of the simulation is shown in fig. 4.6. And according to table 4.2 the extinguishing time in the USCG test was 21 s.

The vital information from this simulation is that all lines but 5k is almost similar. The calculation time of PPS is shown in table 4.3

There are uncertainties in the closed scenario, the fire will extinguish without applying water mist and the simulation shows that the fire produce a very high pressure in the compartment. This simulation should be seen as a comparative study, preconditions are the same, and by changing just one variable it is possible to see the effect of this variable, even if comparing is done with an unrealistic scenario.

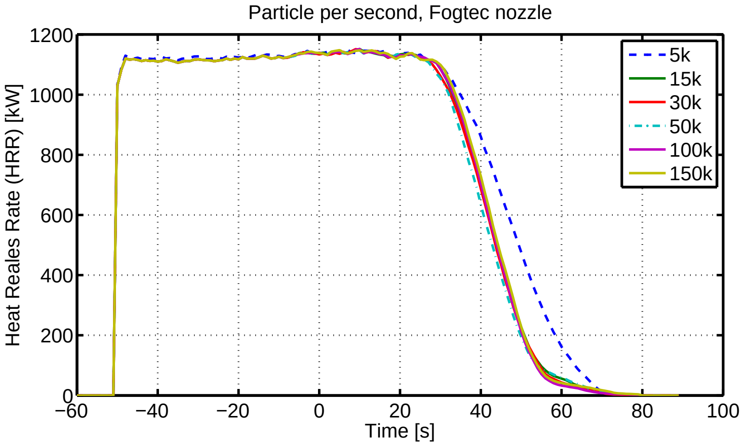

Figure 4.6: PPS simulated on the closed ventilated scenario with Fogtec nozzle, k is 1000

Table 4.3: Calculation time increase with number of particles in the simulation.

PPS	Simulation time	Fraction of 5k droplets time
5k	4 h 56 min 8 s	1.0
15k	21 h 59 min 15 s	4.5
30k	85 h 35 min 53 s	17.3
50k	295 h 37 min 4 s	59.9
100k	599 h 14 min 30 s	121.4
150k	785 h 21 min 10 s	159.1

Number of particles has a drastic influence on the simulation time as seen in table 4.3. In fig. 4.6 the lines for 15k to 150k are almost identical. When calculation time is taken in consideration the 15k particle simulation is the best option.

4.3.5 Courant, Friedrichs, Lewy Condition

FDS uses an explicit method when solving partial differential equations. In an explicit solver the time step is important, section 2.4.5 describe this further. This simulation was executed in order to see the effect of time steps. Simulation was conducted with cubic grid cells at 10 cm in one mesh and 15 k PPS. The time step was set to the time a droplet used to cover the distance of 100, 75, 50 and 25 percent, of the smallest, grid cell.

The CFL calculation was enormously time consuming and it was aborted after simulated in 52 days. The result from the simulation is shown in fig. 4.7. Although the simulation was stopped it gives an impression of the effect of changing the time step. The graph shows that the effect was rather small. Conclusion is that the effect obtained was to small, and not worth the extra simulation time.

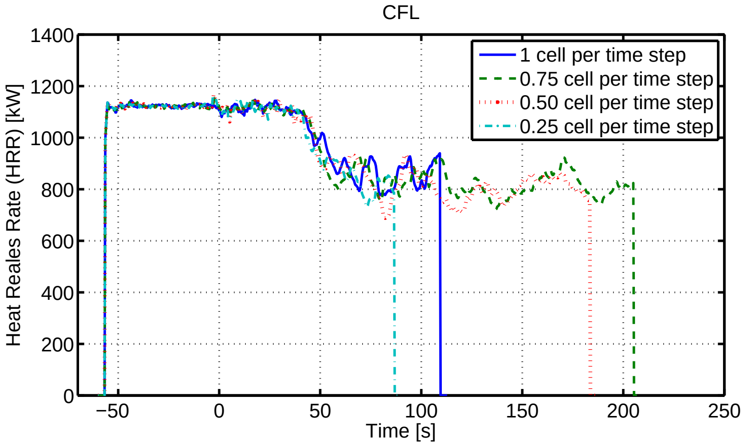

Figure 4.7: CFL time step controlling.

4.3.6 Critical Flame Temperature

The extinguishing criteria in FDS is described in section 2.4.4 here it is shown that the CFL is one of the governing parameter for extinguishing in FDS. This simulation used 10 cm cubic grid cells in one mesh and 15000 PPS. CFT was set to 1400°C, 1500°C, 1600°C, 1700°C, 1800°C and 2000°C. The result of the simulation is presented in fig. 4.8. The simulation shows that high value of CFT gave a unrealistic drop in the HRR even before the water mist system was activated. CFT between 1600°C and 1700°C is default in FDS and correspond with CFT of heptane. This simulation did not lead to any change of CFT in later simulation.

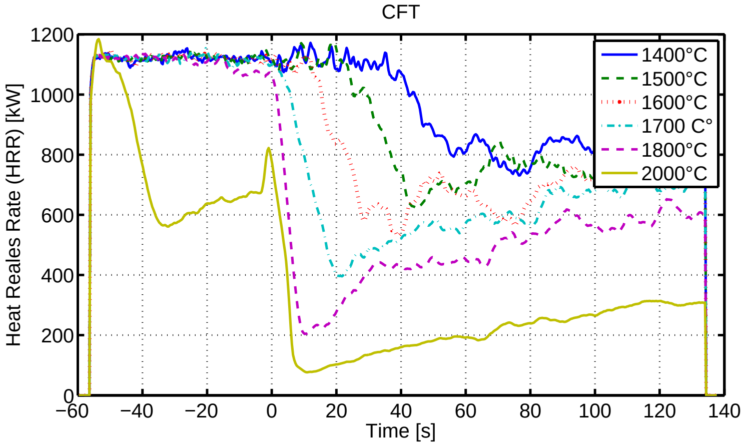

Figure 4.8: CFT, simulated at USCG-room, forced ventilation scenario.

If CFT is increased it is harder to maintain the combustion. The graph shows that CFT has a impact on the fire both in order to get a stable fire with in 60 s and when the water mist is activated. Although the fire almost extinguished boot for CFT at 2000°C and 1800°C, it recovers and burning where there is oxygen available.

The HRR becomes smaller with higher CFT. It was questioned if the CFT should have been changed to 1700°C or if more simulation was to be conducted to see how high the CFL could have been and still have a similar free burn phase. The default CFT of heptane correspond with the real CFT for heptane. Fig 4.4 showed that the flame moved from the original burning place and to the air inlet. This indicate that the original fire was extinguished, and new fires was started at air inlets. Therefore the CFT was not changed in the MS Nordlys simulation and future USCG simulation.

4.3.7 CO Yield

Fire that start at the inlet, starts due to the FDS combustion model, that allows air and fuel to burn if they are at a combustible level in one grid cell. Now AIT was introduced and one simulation showed that even if the AIT was set to 1000°C it still burned at the air inlet. In FDS it is possible to set AIT for only one species when simple chemistry combustion model is used. It was then clear that it was the CO that burned and therefore the CO yield was studied.

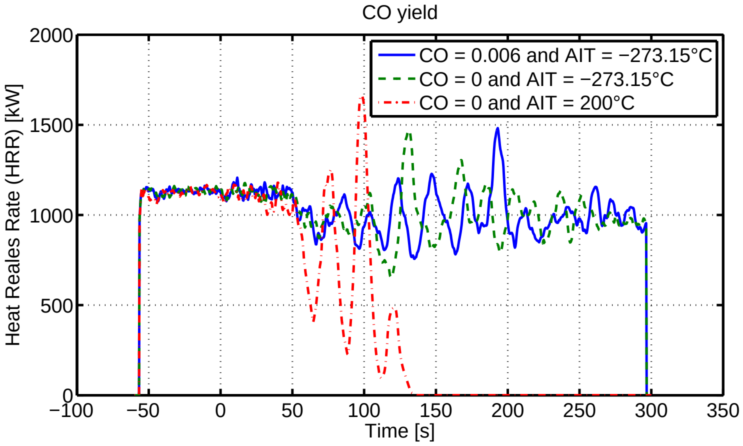

Figure 4.9: CO yield, forced ventilation scenario

It is possible to set a Carbon monoxide(CO) yield in the in put file. In a real fire CO is produced and it contribute to the combustion. In order to obtain extinguishing CO production is set to zero, and AIT is set to 200°C. In fig. 4.9 this is compared with CO production fraction of 0.006, and with no CO production and AIT at -273.15°C. 10 cm cubic grid cells and 15000 PPS is used. Result is shown in fig. 4.9.

This simulation and the following was done iterative, first AIT simulation was conducted with depressing result. Then CO yield was set to zero, and simulated. This simulation was up lifting since extinguishing was obtained. The contribution from CO burning seems to be rather small. The HRR of the fire is about the same with and without CO. Extinguishing is obtained when AIT is set to 200°C.

4.3.8 Auto Ignition Temperature

AIT is the other criteria for FDS to obtain extinguishing. and with CO out of the equation, AIT could be studied more specific.

If the AIT is set higher than 0 K an ignition source has to be added. In this simulation a hot air flow is added, just under the heptane outlet. The air in the air flow is given a temperature which is above the AIT to the fluid, in this simulation 500°C. AIT was set to -273.15°C(0K), 150°C, 200°C, 210°C, 220°C, 225°C, 230°C. There was used 10 cm cubic grid cells over eight meshes, and 15 k PPS. The result of this simulation is shown in fig. 4.10 The graphs in fig. 4.10 is untidy, therefore fig. 4.11 is showing just for 210°C and 220°C.

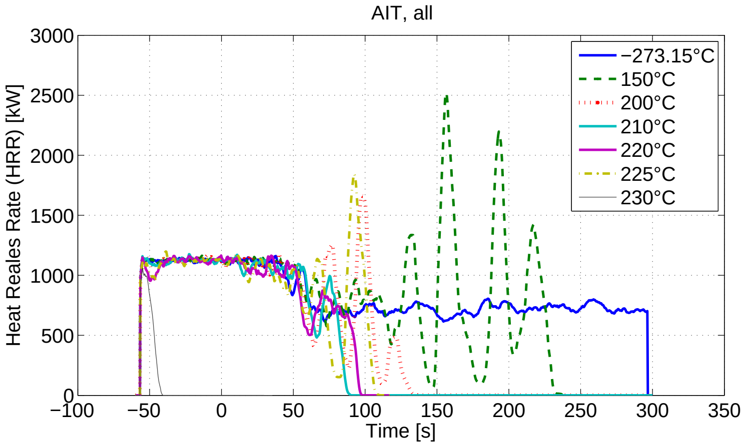

Figure 4.10: AIT, simulated at USCG-room, forced ventilation scenario.

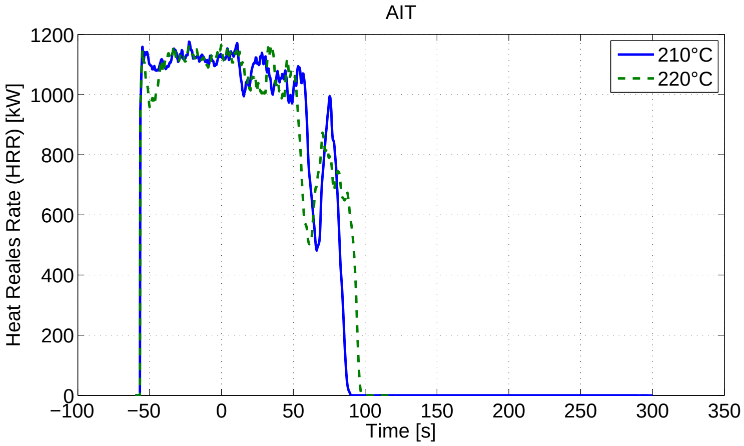

Figure 4.11: The difference between AIT at 210°C and AIT at 220°C.

The result shows that AIT at 210°C and 220°C is quite similar. Extinguishing was obtained and there was fluctuation in the graph.

AIT is by default -273.15°C, this lead to combustion as long as the oxygen and fuel mixture in a grid cell is at a combustible level. By applying a AIT the combustion is only allowed if the temperature in the cell is above AIT. A ignition source was added, an air flow with a temperature of 500°C was used. This air flow would lead to mixing of the air and fuel in the compartment. The hot air flow would also introduce a different flow pattern in the compartment. This effect of the ignition source is neglected in this project. It is assumed that during the free burning phase the buoyancy force of hot air from the fire and the forced ventilation would have canceled this effect. The graph in fig 4.10 shows that the HRR is similar for all AIT prior the water mist release.

Fig.4.10 shows a lot fluctuation in the HRR from the fire in these simulations. The fluctuation is lowest at AIT around 220°C. For AIT at 225°C the fluctuation is increasing and when AIT of 230°C is present the fire is not stable, and it died out after the hot air flow was turned off. The graph in fig. 4.10 is chaotic in terms of many lines. The difference between AIT at 210°C and AIT at 220°C is shown in fig. 4.11. This figure shows that it is little difference between the two AIT temperatures.

When AIT was set to 220°C extinguishing was obtained. Although it took nearly 90 s before the fire was extinguished. This is over four times as long as it took in the USCG test. Although the fire was extinguished, even for the forced ventilated scenario.

4.3.9 Multi-Mesh Simulation

During this project many simulation has been conducted, some with one mesh and other with multiple meshes. There was noticed inconsistent in the results and therefore was this mesh study conducted. Simulation was done using 10 cm cubic grid cells, 15000 PPS, CO yield at zero and AIT at 210°C. There was simulated in 1, 4, 8 and 12 meshes. Fig. 4.12 shows the result of those simulations.The calculation time is shown in table 4.4. An example of the FDS input file is shown in appendix A.1.

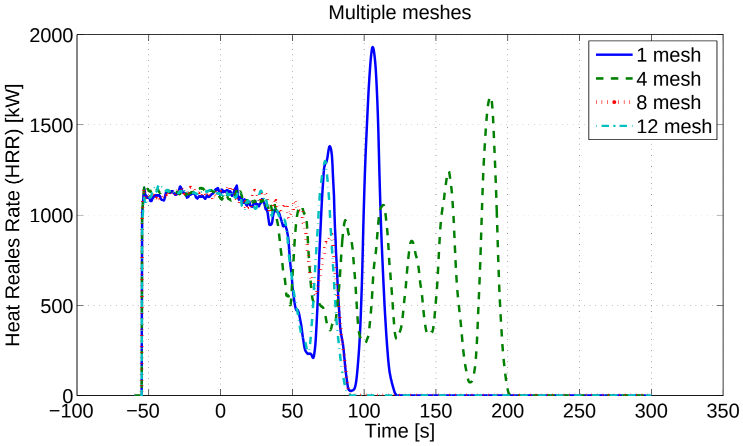

Figure 4.12: Multiple meshes.

This simulation reveals that multiple meshes simulation are different from each other.

Table 4.4: Calculation time of multiple meshes simulation

Number of meshes	Simulation time	% of 1 mesh
1	14 h 16 min 1 s	100%
4	3 h 57 min 59 s	27.8%
8	1 h 58 min 9 s	13.8%
12	7 h 21 min 39 s	51.6%

The expectation is that all multiple meshes simulation should give approximately the same results as the single mesh simulation, as fig. 4.12 shows they do not. The graph was expected to be one line representing all meshes. This is because FDS is deterministic and if number of meshes do not interfere with the physics of the simulation only the simulation time. The result should be represented with one single line for all simulations. Fig. 4.12 show clearly that this is not true. Use of multiple meshes could result in drastic chance in the results. In this simulation it is shown that the 4 meshes simulation predicts extinguishing within 200 s, 1 mesh within 120 s and 8 and 12 meshes within 80 s. One mesh calculation should be closest to the experiment, but the 8 and 12 mesh simulation are closest to the real extinguishing time. Fig. 4.12 show that few meshes is not necessarily more accurate than many meshes.

4.3.10 k-factor

By using AIT at 220°C, 10 cm cubic grid cells, 15000 PPS and no CO production. Two k-factors was tested first the original at 1.35 $\mathrm{l}/\left(\mathrm{min} \cdot \mathrm{bar}^{1/2}\right)$ and second 2.70 $\mathrm{l}/\left(\mathrm{min} \cdot \mathrm{bar}^{1/2}\right)$ which is twice the original k-factor. The difference between them are shown in fig. 4.13

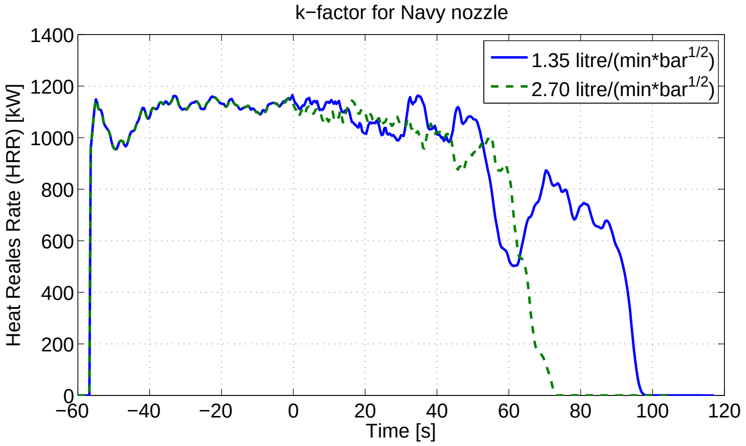

Figure 4.13: Simulation with original k-factor and double k-factor.

Fig. 4.13 shows that a double water flow predicts an extinguishing time closer to the one obtained in the USCG test, than the simulation with the correct water flow.

4.4 Summary of the USCG simulation

The question is; could FDS be used to confirm extinguishing of a fire in an engine room when water mist is the extinguishing agent? In order to determinate this the USCG test of small engine room fires were used and several parameters were tested and tuned in FDS.

The first simulation showed in fig.4.3 made it clear that this simulation case was not straight forward. Many attempts were done in order to obtain extinguishing.

From the USCG report the extinguishing time and a 1 MW fire is used. This means that there is a known start point, the HRR of the fire, and a known end point Extinguishing. It would have been preferable to have several check point in the compartment such as temperature at one point, air flow through the door, oxygen concentration etc. If only one target value is known, it is possible for a simulation to reach this value in a variate of paths, e.g following linear expression, quadratic expression or cubic expression. It is not necessarily the correct path that is represented in FDS, even if the target value is achieved. This make the validation and simulation challenging.

The result from the simulation showed that CO yield and AIT was the most important parameter in order to obtain extinguishing. CFT is also important but this value has FDS got correct and it should not bee tuned.

Calculation Time

Calculation time can span from minutes to months just by changing some parameter. When changing parameter it is important to judge how the change will interfere with the simulation time. Simulation of PPS and mesh sensitivity showed the extended simulation time in table 4.3. Some parameter are obviously extending the simulation time, such as smaller cells(additional cells), shorter/limiting time steps, additional particles and every parameter how lead to several iterations per time step. All these parameters should help to get a more accurate simulation. More accurate simulation means more time spending on tuning parameter and extended simulation time. The key is to find a compromise that gives the best match between accuracy and time consume.

From the multiple mesh simulation shown in fig. 4.12 the simulation time is studied. The time is supposed to be a little longer than the respective fraction of a single mesh simulation. This is correct for 4 meshes using just over 1/4 of the single mesh simulation time and 8 meshes which uses just over 1/8 of the single mesh simulation time. This is not correct for 12 meshes according table 4.4. 12 meshes simulation uses just over 1/2 of the single mesh simulation time. It was expected that it should use just over 1/12 of the single mesh simulation time.

USCG to MS Nordlys

The finale set up of the USCG test in FDS did predict extinguishing of a 1 MW heptane fire under forced ventilation. The setup used 15 k PPS, AIT at 220°C, CO yield at zero, the double k-factor and 10 cm grid cells over 8 meshes. CFT was not changed since it behaved as expected. The fire was extinguished within 50 s this is not in the same time range as for the USCG-test, which obtained extinguishing within 17 s. Although the result was implemented in the MS Nordlys simulation.

Chapter 5

Simulation of MS Nordlys

5.1 The Set Up

The engine room with the auxiliary engine room is drawn in FDS. In fig.5.1 the set up is shown from the main engine room side, and in fig.5.2 it is shown from the auxiliary engine room side. Details in the geometry which not influence the fire scenario were neglected. At the first floor there is drawn engine mook-up which reach some inches in to the next floor, a stairway room and a structure just beside the fire. On the second floor there is drawn the work shop, the incinerator room, a hole for the stairway, a stairway room and an opening around both engine mook-ups.

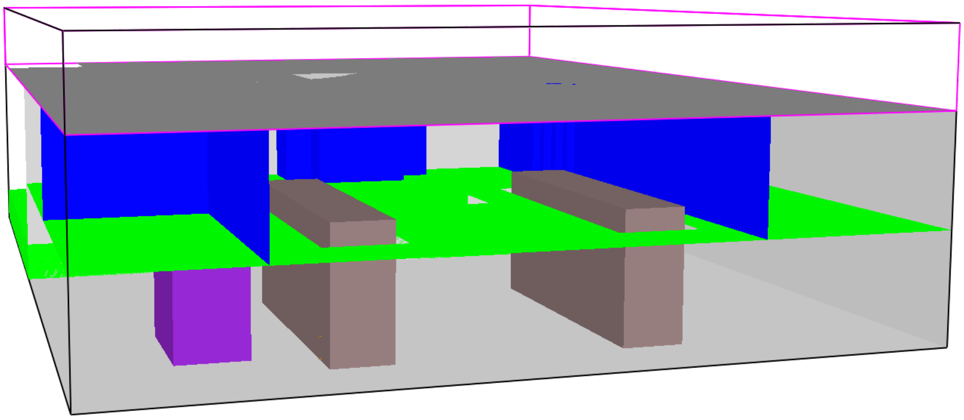

Figure 5.1: The main engine room,

The size of the room is 21 m x 16 m x 5 m which gives a volume of approximately 1700 m^3. This gives the main engine room a volume of 920 m^3(11.5 m x 16.0 m x 5 m). The main purpose with the simulation is to decide whether the fire will extinguish or not when the water mist system is activated. The simplification of the engine room is conservative in the term of more open space. This result in more air to the fire and

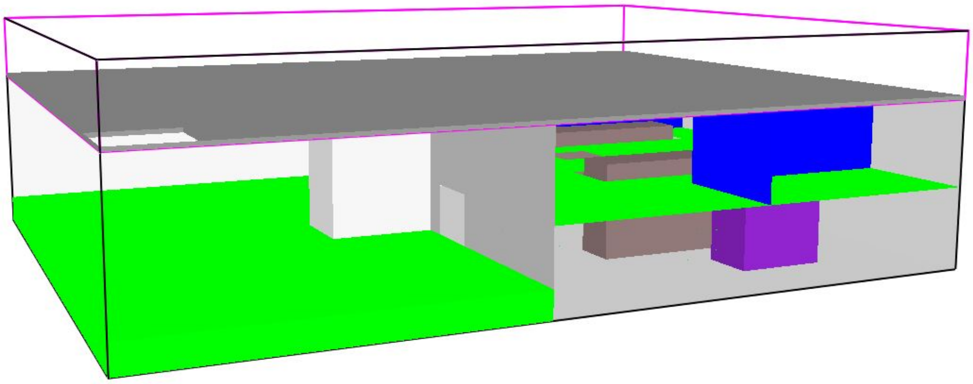

Figure 5.2: Auxiliary engine room, simulated empty.

more difficult to suppress the fire by displacement of oxygen with water steam. There is a large opening in the corner of the auxiliary engine room. This represent the funnel which goes from the engine room and all the way to the top of the ship, this gives a huge amount of air to the fire.

5.1.1 Ventilation

According to USCG report[6] the air change in an engine room is 15 x volume per hour. This was in the high end of the scale and therefore it is considered conservative. This is applied to the simulation of MS Nordlys. A change from the USCG test is that MS Nordlys has nine times more engine room volume than the USCG test and instead of one forced ventilation fan this simulation uses 12, six on the first floor and six on the second floor. Two of the ventilation fans at the second floor are in the iniciator room, and one in the work shop. Fans in the iniciator room could give a wrong impression of the smoke filling in this room. Smoke filling is not an issue in this thesis and the possible effect is therefore acceptable.

To calculate the input value for FDS the simple correlation between the volume flux and areal of the fan opening is used. This gives a volume flux at 0.32 m^3/s and the information VOLUME_FLUX=0.32 is added to the surface id 'Blower'. During the accident there was a power failure more than five minute after the fire started. This is not considered for in this set up as only calculate the early phase of the fire.

5.2 Calculation of The Fire Size

The fire is simulated as a heptane spray. Heptane is very similar to diesel. It is known that the fire in the engine room was large. In order to determinate how large it was the knowledge about the fuel system is used. According to the investigation report[21] the booster pump circulate $3m^3/h$ diesel in the register, the cylinder pick up fuel from the register and pressurize it to 350 bar with an injection pump, each engine has eight cylinders with their own injection pump. The pipe from the fuel register to cylinder five's pump was broken just at the inlet to the injection pump. Here the investigation report assume the fire is most likely to have started[21]. This gave a leak from the 5 bar register system. Circulation of 50 l/min fuel in the register is twice the amount of fuel required by the engine. Assuming this 50 l/min is equal distributed on the cylinders, the volume flow of fuel is then 6.25 l/min to each cylinder. The cross section of the ruptured pipe is not given in the report, but measuring of pictures in the investigation report indicate an inner diameter of the pipe to be 12 mm. This gives the fuel a velocity inside the pipe at 0.92 m/s, Using Bernoulli's eq. (5.1)[28] for energy conservation per unit mass:

$$\frac{p}{\rho} + gz + \frac{V^2}{2} = constant \tag{5.1}$$

Where p is the pressure, ρ is the density of the fluid, g is gravity, z is elevation from a reference level and V is the velocity. In eq. (5.1) it is calculated from one point to another point along the same streamline, and the part with gz is canceled. Then assuming steady state flow, incompressible fluid, friction is negligible and no energy is added or removed from the system. Energy conservation according to eq. (5.1) gives a velocity at the outlet of 17.2 m/s.

Another way to address the problem is to say that the booster pump circulate twice the amount of fuel that is required. If all of this fuel is allowed to leak out from cylinder 5 together with the fuel used by cylinder 5 then the flow rate will change to 28.125 l/min. Using Bernoulli's equation 17.6 m/s. Then the result showed that the outlet velocity is weakly dependent on the velocity inside the pipe, if the velocity inside the pipe is relatively low.

There is an other opportunity of calculating the outlet velocity. in the "Handbook for Fire Calculations and Fire Risk Assessment in the Process Industry"[29] published by SINTEF the following equation for the mass flow per unit volume is given:

$$\dot{m} = C_D \cdot A \cdot \rho_r \cdot \sqrt{2 \cdot \frac{p_1 - p_r}{\rho_r}} \left[\frac{kg}{s}\right] \tag{5.2}$$

Modifying eq. (5.2) by taking away the $A \cdot \rho_r$ the mass flow becomes a velocity.

$$V = C_D \cdot \sqrt{2 \cdot \frac{p_1 - p_r}{\rho_r}} \left[\frac{m}{s}\right] \tag{5.3}$$

C_D is a discharge coefficient with a value of 0.62 after recommendation from SINTEF [29]. ρ is still density and p is the pressure. subscript r is condition at the release point while subscript 1 is condition inside the pipe. Density of diesel is about $\rho_r = 850\mathrm{kg/m^3}$, the pressure in side the pipe is $p_1 = 5 \cdot 10^5\mathrm{kg/(m \cdot s^2)}$ and using $p_r = 0.55p_1$ according to long pipe in SINTEF handbook[29]. Using these value in eq. (5.3) the velocity is 14.3 m/s.

This calculation gives outlet velocity in the same magnitude. The outlet velocity calculated by using SINTEF handbook is preferred used in this calculation and PARTICLE_VELOCITY=14.3 is added to the simulation of MS Nordlys.

The flow rate determinate the effect, the flow rate is somewhere between 6.3 l/min and 28.1 l/min, using eq. (5.3 gives a volume flux within this range. The flow rate is calculated by an equation in FDS user guide[15].

$$P = q \cdot \rho \cdot \Delta H_T \tag{5.4}$$

In eq. (5.4) the q is fuel flow in m^3/s, ρ is the fuel density[kg/m^3], ΔH_T is the net heat of combustion in MJ/kg, and the product of these gives the effect, P in MW. The density of diesel is about 850 kg/m^3, and the net heat of combustion is about 42 MJ/kg. There is uncertainty about the number since diesel often is mixed with kerosene in order to higher the ignition point. This is manly used in arctic climate. The amount of propane added to the diesel is unknown. In appendix B is the safety datasheet of SDM diesel attached.

The flow rate is 6.25 l/min, low, and 28.1 l/min, high. The density of diesel is about $\rho = 850$ kg/m^3 and ΔH_T of diesel is 42 MJ/kg. Adding this value to eq. (5.4) the effect P is 3.6 MW for the low flow and 16.8 MW for high flow. It is likely that the real effect of the fire on MS Nordlys is someting between these two values. It is not easy to choose a value that are conservative in means of extinguishing. USCG full scale test[6] showed that it was easier for water mist system to extinguishing large fire than small. This due to the water evaporation effect according to USCG test[6]. If the fire is large more water evaporate to steam and more steam displace more oxygen and contribute to the extinguishing of the fire. This indicating that the smaller fire is more conservative. A larger fire produce more smoke and it make it harder to escape. This indicate that a large fire is more conservative than a small. An engineering solution of this problem is to choose a fire in the middle. Then the volume flow becomes 14.8 l/min. Adding this to eq. (5.4) the effect of the fire becomes 10.2 MW. An earlier calculation gave the result 8.8 MW, this value is also around the middle of the effect range and is used instead of a 10 MW fire.

Rewriting eq. (5.4) and setting the value of ρ and to heptane, such as ρ is 689 kg/m^3, then solving the equation with respect to the volume flux of heptane, q_h, that will generate a 8.8 MW fire. q_h is 18.25 l/min and then FLOW_RATE is set to 18.25. ΔH_T is almost similar for heptane and diesel and it is 42 MJ/kg

Soot yield to mineral oil 0.097 according to SFPE-handbook [30], the value is high and even if some rubber will burn during the fire. The soot production of rubber is fairly high but the SOOT_YIELD is set to 0.05, half of mineral oil.

5.3 Water Mist Nozzle Simulation

The water mist nozzle is simulated the same way in the MS Nordlys simulation as for the USCG simulation. A brief presentation of the new water mist system installed on MS Nordlys after the fire, indicated that the two system correlated on the most important parameters, such as k-factor and operation pressure. The nozzles were placed with 2.5 m spacing which is under 3 m that is recommended according to the USCG test report[6].

5.4 Result of The MS Nordlys Simulation

From the USCG test in section 4 some parameter was found to be important and these parameter is implemented in the MS Nordlys simulation. Table 5.1 shows the parameter with the respective value. Notice that CO yield and CFT is not in the table, this is because they should be at default FDS value.

Table 5.1: Parameter from USCG simulation that is used in MS Nordlys simulation

Parameter	Value
AIT	220°C
Particle Per Second	15000
Ignition source	Yes

5.4.1 Grid Cell Size Convergence

The engine room was simulated with 100 mm and 200 mm cubic grid cells in order to see convergence of the grid. There was used 1 mesh in the simulation. It has also been conducted with 50 mm and 400 mm cubic grid cells but these simulations were unstable and did not produce any graph to present. The graph in fig. 5.3 shows the result of the 100 and 200 mm cells simulation.

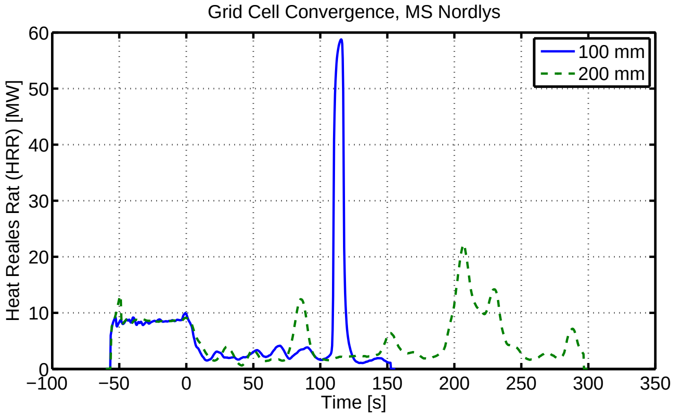

Figure 5.3: Simulation of the engine room in MS Nordlys, with different k-factores.

In this simulation 100 and 200 mm showed similar behavior but it is not clear which is closest to real life. In the 100 mm cells simulation there was a HRR peak after about 100 s. Looking at the smoke view at this time both the engine room and auxiliary engine room was engulfed in fires. The same effect is seen in the 200 mm grid cells simulation but not as large as in the 100 mm grid cell simulation. The 100 mm grid cell simulation was stopped just after 150 s. The reason why it stopped is unclear. But these simulations show that more work need to be done with the MS Nordlys simulation in order to have reliable results.

5.4.2 k-factor

The k-factor simulation of the USCG test showed that introducing twice as much water helped on the extinguishing time, but it was still considerable longer than in the test. In this light a simulation with twice as much water is conducted on the MS Nordlys case. This simulation of Nordlys was done with Navy nozzle, a 8.8 MW fire and 10 cm grid cells distributed over 20 meshes. The k-factor of the nozzle was set to both 1.35 $\mathrm{l}/\left(\mathrm{min}\cdot\mathrm{bar}^{1/2}\right)$ and 2.70 $\mathrm{l}/\left(\mathrm{min}\cdot\mathrm{bar}^{1/2}\right)$ the result of simulation is shown in fig.5.4. An example of a FDS input file is shown in appendix A.2.

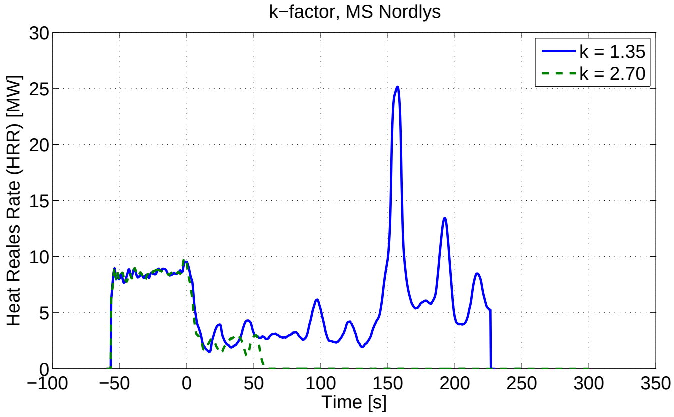

Figure 5.4: Simulation of the engine room in MS Nordlys, with different k-factores.

In fig. 5.4 the same peak as in fig. 5.3 occur about 50 s later in fig. 5.4. This is because the cell size simulation uses one mesh while the k-factor simulation uses 20 meshes.

The double k-factor simulation predicts extinguishing within 55 s. The uncertainty regarding to numbers of mesh is not taken into account. The aborted 10 cm simulation in single meshes is not valid for a 20 meshes simulation. The result of this simulation showed that the fire was extinguished within 55 s when using twice as much water than a Navy nozzle.

5.5 Summary of MS Nordlys simulation

The result from full scale test by USCG indicate that the fire would have been put out by a water mist system. Simulation is not so conclusive. FDS overestimate the extinguishing time by a factor of three for the forced ventilated scenario, compared to the USCG test in small engine room.

To obtain extinguishing in the simulation of MS Nordlys engine room, it was necessary to set an AIT. The USCG simulation showed a small region of AIT, where it was possible to obtain a stable fire. This fire burned after the ignition source was turned off. Then the fire extinguished after the water mist system was turned on. This tuning with parameter to obtain a certain result is not the best approach. But the tuning of parameter was done to get FDS behave more realistically. The parameter was also in consistent with the physics, a fuel has an AIT therefore should the simulated fuel also have an AIT.

In a real fire CO is produced and it burns. A simulation without CO seems strange, but so do a simulation with no AIT for CO. The lack of CO was not studied in particular in this thesis. But the HRR was at the same level before extinguishing started in both the simulation with and without CO present, see fig 4.9. This means that the contribution of CO combustion to the HRR in the compartment is small. The error introduced with removing CO could therefore be neglected.

The learning from these simulation is that it is not straight forward to simulate. Simulations takes time, both running them on a computer and writing the code. Effort in how to write a good code can save time both when simulating and rewriting the code.

MS Nordlys was simulated and extinguishing obtained. There was not shown any convergence on the grids and the extinguishing was obtained with much more water present than the nozzle produce. Although the equivalent USCG simulation also obtained extinguishing but it used three times the time of the test. Therefore it is likely that a functioning water mist system based on Navy nozzles would have extinguished the MS Nordlys fire in a earlier state.

Chapter 6

Discussion

6.1 The Accident vs Simulation

According the investigation report[21], the fire at MS Nordlys most likely started due to fatigue on the fuel pipe to cylinder five. Therefore it was acceptable to use a scenario with spray fire when dimensioning the fire. A pressure at 5 bar and an outlet of 1.2 cm is not likely to produce a spray it self. If the fuel beam hits an obstacle it could be broken up in small droplets. The idea of this simulation was to simulate the same fire as in the accident, but the report do not state anything about the fire other than it was large. It could have been a pool fire, a spray fire or both.

The soot production in the calculation seem to be high. The investigation report claim that the engine room was rapidly filled with smoke. The smoke view from the simulation showed that the engine room was filled with smoke after 30 to 40 second. In the investigation report it was described that a man saw the fire from the opposite side of the room, exactly when in the fire development he saw it is unknown, but it is likely within the first minutes of the fire. The reason of too rapid smoke filling could be that the soot yield is high or the fire it self is too large. The investigation report[21] and the material damage in the engine room indicate a large fire, but it is difficult to estimate the exact fire size.

Holding the simulation of MS Nordlys beside the simulation and test on the USCG room it is not unlikely that a functioning water mist system in the engine room would have suppressed the fire and even extinguish it. This is stated on the evidence from the test and simulation not only the simulation.

6.2 FDS

FDS has over the years proven it self as a reliable simulation tool. Many experiments and validation project has been conducted. In the validation guide[17] there are many examples of experiment that has been conducted. Furthermore, it is stated that it cannot predict extinguishing when water mist or CO_2 are extinguishing agents. The result from this thesis confirms the statement.

According to Susanne Kilian [31] the multiple mesh solver in FDS is inadequate. In particular the multiple meshes pressure solver is a problem. Multiple meshes calculation do not give the same result as single mesh. They are not even comparable with other number of meshes. The pressure solver it self is out of the scope of this thesis. Problem with multiple meshes is worth to take in consideration. Kilian address the multiple meshes problem to the numerical method in the multiple meshes algorithm, not the physics. Therefore the problem is not present in single mesh simulations[31]. Kilian and Münch has made a new alternative pressure solver, ScaRC. In the second part of their work they have done some validation and verification on the ScaRC code[32]. The ScaRC is under development and has not been used in this thesis, but their work has triggered a mesh sensitive analysis.

FDS divided the compartment into a grid of grid cells, it is possible to use several grids or meshes in one simulation. Multiple mesh calculation is preformed such as all meshes is calculated simultaneously. The problem with multiple mesh is when information is transferred between the meshes. Each mesh is solved implicit, information is exchanged between the meshes and for every iteration there will be a slightly delay. In many situation this delay is no problem, but for pressure and high velocity movement it gives an error.[31].

Meshes and problem with multiple meshes is described. In order to see this difference, simulation was done on the USCG-room fig. 4.12 shows the result of those simulations. And as described above the result of this simulation seems to support Kilian's statement.

6.3 A Good Approach to FDS Simulation

When using CFD it is important that the user know the code's opportunities and limitations. It is difficult to come up with a recipe for FDS simulation. The list of concerns grow with the user's knowledge. FDS is used in a various range and almost every type of problem has it own way of simulation. Although, here is a list which can be useful when planing a simulation. The main step is something that fits for most simulations. The bullet point are examples and a short description of how they was used in this thesis.

1. Decide what question the simulation should answer.
2. Find a validation case that are as similar to the simulated object as possible.
3. Find out if FDS is capable to answer the question on the validation case.
4. Sensitivity analysis of input parameters, in the validation case.
5. Use the findings above to simulate the case of concern.

Examples of what answer a simulation could give is: Extinguishing time, heat release, visibility, smoke detection, oxygen level etc. It is possible to take out a lot of information from FDS. The User Guide[15] is a good place to look after possible out data. In this project the main concern was extinguishing of engine room fire. Heat release rate was used to see whether the fire was extinguished or not. By using the heat release instead of extinguishing it is possible to see if the fire is suppressed, if it is not extinguished.

There has been conducted many validation cases and they are available at NIST[17]. Report on the case could be found other places. In the validation files there was a case on engine room fire. A Google scholar search provide the report written by USCG.

The set up and convergence of the set up is important. It is necessary to consider how many meshes the simulation has to use, remember the possibility of errors with multiple meshes calculation described in section 6.2. After deciding how many meshes to use, then start searching for convergence with respect to grid cells size. There has to be conducted several simulation with different grid cell sizes in order to see convergence. When the mesh an cell size is decided other parameters could be tuned, one at the time.

In this thesis number of meshes was not considered. Simulation in order to see convergence on grid cell size was conducted for 5 cm, 10 cm, 20 cm and 50 cm grid cells, that should have been plenty but since the simulation for 5 cm and 50 cm cells was inconclusive the convergence also was poor. Although several parameters were tested. Before simulation on the USCG room was conducted the FDS User Guide was studied in order to understand how the different parameters interact. AIT, PPS and CO_YIELD was found as critical parameters.

Sensitivity analysis of the input parameters are fruitful in order to see the strength of the parameter. If there are small change in the output when it is large difference in the input it is a weak parameter. On the other hand if the output value changes a lot with small variation of the input value it is a crucial parameter. This is worth a lot effort to get a correct value or to present the sensitivity analysis. In this thesis there has been conducted several sensitivity analysis e.g. CFT, AIT. The uncertainties around these parameters have been discussed and a conclusion has been drawn.

When the validation is finish use the same parameter at the case of concern. In this project the case of concern was the MS Nordlys fire. Simulation was conducted to see convergence on grid cell size in the MS Nordlys fire. Cell size is not necessary the same as in the validation case. After this MS Nordlys was simulated with the same value for AIT, PPS and CO_YIELD, as found in the USCG test.

6.4 Water Mist vs. Other Extinguishing Agent

Water mist has a benefit over CO_2 system since it is non-toxic, and it could be released multiple times. But CO_2 has less residue than water mist.

Water mist uses less water than a traditional water sprinkle, and it has higher surface area that interact with the flame. Water sprinkle has bigger droplet than water mist, therefore sprinkle water penetrate the flame zone better and has a better cooling effect on the surface beneath the fire. Sprinkler tolerate more debris in the water and can use sea water with minimal filtration.

Comparing water mist and gaseous extinguisher like Inergen and Argonit, water mist has a benefit of almost infinite water supply. It could use sea water, while gaseous extinguisher has a limiting storage of gas. A drawback with water mist is that it need a booster pump in order to operate. Gaseous extinguisher drive the extinguishing agent to the fire area by pressure relief. Water mist system could use pressure difference as well but then it need a booster pump if it should be able to multiple release.

Chapter 7

Conclusion

Water mist has the potential to contribute to suppression and extinguishing of engine room fires. This contribution could be simulated by FDS but some key parameter has to be set. In order to find the key parameter several simulation has been conducted. Auto ignition temperature, CO yield, k-factor, particle per second, critical flame temperature and the need of an ignition source is was found. Adding this to the simulation of MS Nordlys, extinguishing was obtained. This project has shown that a well function water mist system, properly installed would most likely extinguish the fire on MS Nordlys within a minute. The following part are answers to the research question of this thesis.

How reliable is FDS when it predicts extinguishing in an engine room fire, using water mist as extinguishing agent?

There are uncertainties of using FDS on engine room fire and water mist as extinguishing agent. The main concern is coupled to the extinguishing model that just uses the temperature effect. It is also challenges with the combustion model, but here it is possible to use another model. But even there are uncertainties with FDS, it predicted extinguishing when water mist was used as extinguishing agent.

How would a full protective water mist system with automatic release have preformed in the MS Nordlys Fire?

The simulation of MS Nordlys showed that the water mist system was able to extinguish the fire, and when the experiment of USCG room is taken in account it is likely to believe that a water mist system would have extinguished the fire with in a minute.

How could a FDS simulation be executed in a manner that is reliable and verifiable?

Reliable FDS simulation has a validated test to support it. Several simulation is conducted to see convergence and the sensitivity of parameters. Prior good computer simulation goes hand calculation or experimental result to support the simulation. Analysis of the result is as important as the simulation. This thesis present a list of how a FDS simulation should be conducted.

1. Decide what question the simulation should answer.
2. Find a validation case that are as similar to the simulatied object as possible.
3. Find out if FDS is capable to answer the question on the validation case.
4. Sensitivity analysis of input parameters, in the validation case.
5. Use the findings above to simulate the case of concern.

What benefits have water mist system compared with other extinguishing agent?

Water mist has a benefit over CO_2 system since it is non-toxic, and it could be released multiple times. But CO_2 system has less residue than water mist system. Water mist uses less water than a traditional water sprinkle, and it has higher surface area that interact with the flame. Water sprinkle has bigger droplet than water mist, therefore sprinkle water penetrate the flame zone better and has a better cooling effect on the surface beneath the fire. Comparing water mist with Inergen and Argonit water mist has the benefit of almost infinite water supply, while Inergen and Argonite has a limiting storage of gas. Water mist produce small amount of residues but gaseous extinguishing agent has no residues.

7.1 Suggestions for Future Research

In light of the work done for this thesis, it is possible to look closer at:

a) The possibility to enhance the extinguishing module in FDS in a manner that it can handle water mist as extinguishing agent.

b) Simulate the case of this thesis again with attention on sensitivity e.g The fire size, amount of water and other variables with unsure values.

c) The droplet distribution in the room, with a fire present. Paying attention to the spray pattern from a nozzle with and without a fire present.

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Appendix A

FDS input files

A.1 USCG Simulation

```
[U+FFFD]&HEAD CHID='8_mesh', TITLE='med utgangs punkt i CO\_YIELD
    settes til 0, AIT=210 degree' /

/&MESH IJK=88,50,30, XB=-1.8,7.0,0.0,5.0,0.0,3.0 / set inn flere
     grid

&MESH ID='mesh1' , IJK=22,25,30, XB=-1.8,0.40 , 0.0,2.5 ,
    0.0,3.0 /
&MESH ID='mesh5' , IJK=22,25,30, XB=-1.8,0.40 , 2.5,5.0 ,
    0.0,3.0 /

&MESH ID='mesh2' , IJK=22,25,30, XB=0.40,2.60 , 0.0,2.5 ,
    0.0,3.0 /
&MESH ID='mesh6' , IJK=22,25,30, XB=0.40,2.60 , 2.5,5.0 ,
    0.0,3.0 /

&MESH ID='mesh3' , IJK=22,25,30, XB=2.60,4.80 , 0.0,2.5 ,
    0.0,3.0 /
&MESH ID='mesh7' , IJK=22,25,30, XB=2.60,4.80 , 2.5,5.0 ,
    0.0,3.0 /

&MESH ID='mesh4' , IJK=22,25,30, XB=4.80,7.00 , 0.0,2.5 ,
    0.0,3.0 /
&MESH ID='mesh8' , IJK=22,25,30, XB=4.80,7.00 , 2.5,5.0 ,
    0.0,3.0 /


&TIME T_BEGIN=-60.0, T_END=300.0 /
```

```
&DT_DEVC=1., DT_HRR=1. /



&OBST XB= 0.00, 0.00, 0.00, 5.00, 0.0, 3.00, / Roomwall with
    door


&SURF ID='Blower', VOLUME_FLUX=-0.42, COLOR='BLUE' /
&VENT XB=7.00,7.00,2.20,2.80,1.20,1.50, SURF_ID='Blower' /

&VENT XB= -1.80,0.00,0.0,0.00,0.00,3.00, SURF_ID='OPEN' /
&VENT XB= -1.80,0.00,5.00,5.00,0.00,3.00, SURF_ID='OPEN' /


&HOLE XB=-0.10,0.10 , 0.30,1.15 , 0.30,2.30, /

&SPEC ID='WATER VAPOR' /



&REAC FUEL        = 'N-HEPTANE'
      FYI         = 'Heptane, C_7 H_16'
      C           = 7.
      H           = 16.
      CO_YIELD    = 0.00
      SOOT_YIELD  = 0.015
      AUTO_IGNITION_TEMPERATURE = 210.0 /

/tennkilde varm flate

&SURF ID='HOT'
      COLOR='RED'
      VEL=-1.0
      TMP_FRONT=500.0
      RAMP_V='wind'
      RAMP_T='heat'/


&VENT XB=3.00,4.00,2.60,3.00,0.00,0.00,  SURF_ID='HOT' /
&RAMP ID='wind', T= -60.0, F=1.0 /
```

```
&RAMP ID='wind', T= -50.0, F=0.0 /
&RAMP ID='heat', T= -60.0, F=1.0 /
&RAMP ID='heat', T= -50.0, F=0.0 /

&OBST XB=2.00,5.00,0.75,1.75,0.00,1.50 /  Port Engine
&OBST XB=2.00,5.00,3.25,4.25,0.00,1.50 /  Starboard Engine
&OBST XB=2.00,5.00,1.75,2.75,1.50,1.50 /  Horizontal Obstruction
     Plate

&PART ID='heptane droplets', SPEC_ID='N-HEPTANE', DIAMETER=200.,
     HEAT_OF_COMBUSTION=45000. /
&PART ID='water droplets', SAMPLING_FACTOR=100, SPEC_ID='WATER
    VAPOR', DIAMETER=175. /

&PROP ID='Bete P54', PART_ID='heptane droplets', FLOW_RATE
    =2.190, PARTICLE_VELOCITY=8., SPRAY_ANGLE=0.,15.,  /
&PROP ID='Navy', PART_ID='water droplets', K_FACTOR=1.35,
    OPERATING_PRESSURE=70., PARTICLE_VELOCITY=75., SPRAY_ANGLE
    =0.,60., PARTICLES_PER_SECOND=15000. /

&SLCF PBY=2.5,QUANTITY='TEMPERATURE',VECTOR=.TRUE. /
&SLCF PBZ=0.1,QUANTITY='TEMPERATURE',VECTOR=.TRUE. /
&SLCF PBY=2.5,QUANTITY='HRRPUV' /
&SLCF PBY=2.5,QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN' /
&SLCF PBY=2.5,QUANTITY='VOLUME FRACTION', SPEC_ID='WATER VAPOR'
    /

&ISOF QUANTITY='TEMPERATURE', VALUE(1)=300, VALUE(2)=500, VALUE
    (3)=1000/ 3D filer visende hvor temperaturen er henholdsvis
    80 degree C og 400 degree C

&BNDF QUANTITY='WALL TEMPERATURE' /
&BNDF QUANTITY='GAUGE HEAT FLUX' /

&MATL ID               = 'STEEL'
      FYI              = 'Quintiere, Fire Behavior'
      SPECIFIC_HEAT    = 0.46
      CONDUCTIVITY     = 45.8
      DENSITY          = 7850. /

&SURF ID          = 'STEEL SHEET', DEFAULT=.TRUE.
      MATL_ID     = 'STEEL'
      COLOR       = 'GRAY 80'
```

```
      THICKNESS = 0.005 /

TC Trees

&PROP ID='Sheathed Type K', BEAD_DIAMETER=0.0032 /

&DEVC XYZ=1.00,2.50,0.50, QUANTITY='THERMOCOUPLE', PROP_ID='
    Sheathed Type K', ID='TC 1-1' /
&DEVC XYZ=1.00,2.50,1.00, QUANTITY='THERMOCOUPLE', PROP_ID='
    Sheathed Type K', ID='TC 1-2' /
&DEVC XYZ=1.00,2.50,1.50, QUANTITY='THERMOCOUPLE', PROP_ID='
    Sheathed Type K', ID='TC 1-3' /
&DEVC XYZ=1.00,2.50,2.00, QUANTITY='THERMOCOUPLE', PROP_ID='
    Sheathed Type K', ID='TC 1-4' /
&DEVC XYZ=1.00,2.50,2.50, QUANTITY='THERMOCOUPLE', PROP_ID='
    Sheathed Type K', ID='TC 1-5' /

&DEVC XYZ=6.00,2.50,0.50, QUANTITY='THERMOCOUPLE', PROP_ID='
    Sheathed Type K', ID='TC 2-1' /
&DEVC XYZ=6.00,2.50,1.00, QUANTITY='THERMOCOUPLE', PROP_ID='
    Sheathed Type K', ID='TC 2-2' /
&DEVC XYZ=6.00,2.50,1.50, QUANTITY='THERMOCOUPLE', PROP_ID='
    Sheathed Type K', ID='TC 2-3' /
&DEVC XYZ=6.00,2.50,2.00, QUANTITY='THERMOCOUPLE', PROP_ID='
    Sheathed Type K', ID='TC 2-4' /
&DEVC XYZ=6.00,2.50,2.50, QUANTITY='THERMOCOUPLE', PROP_ID='
    Sheathed Type K', ID='TC 2-5' /

Heat Flux Gauges

&DEVC XYZ=0.00,2.50,1.50, QUANTITY='GAUGE HEAT FLUX',     IOR=
    1, ID='Total Flux Wall'/
&DEVC XYZ=0.00,2.50,1.50, QUANTITY='RADIATIVE HEAT FLUX', IOR=
    1, ID='Rad Flux Wall'/
&DEVC XYZ=3.50,2.50,3.00, QUANTITY='GAUGE HEAT FLUX',     IOR
    =-3, ID='Total Flux Ceiling'/
&DEVC XYZ=3.50,2.50,3.00, QUANTITY='RADIATIVE HEAT FLUX', IOR
    =-3, ID='Rad Flux Ceiling'/

Gaseous Sampling

&DEVC XYZ=1.50,2.50,1.00, QUANTITY='VOLUME FRACTION', SPEC_ID='
    OXYGEN', ID='O2 1'/
```

```
&DEVC XYZ=5.50,2.50,1.00, QUANTITY='VOLUME FRACTION', SPEC_ID='
    OXYGEN', ID='O2 2'/
&DEVC XYZ=1.50,2.50,2.50, QUANTITY='VOLUME FRACTION', SPEC_ID='
    OXYGEN', ID='O2 3'/
&DEVC XYZ=5.50,2.50,2.50, QUANTITY='VOLUME FRACTION', SPEC_ID='
    OXYGEN', ID='O2 4'/

&DEVC XYZ=1.50,2.50,1.00, QUANTITY='VOLUME FRACTION', SPEC_ID='
    CARBON DIOXIDE', ID='CO2 1'/
&DEVC XYZ=5.50,2.50,1.00, QUANTITY='VOLUME FRACTION', SPEC_ID='
    CARBON DIOXIDE', ID='CO2 2'/
&DEVC XYZ=1.50,2.50,2.50, QUANTITY='VOLUME FRACTION', SPEC_ID='
    CARBON DIOXIDE', ID='CO2 3'/
&DEVC XYZ=5.50,2.50,2.50, QUANTITY='VOLUME FRACTION', SPEC_ID='
    CARBON DIOXIDE', ID='CO2 4'/

&DEVC XYZ=1.50,2.50,1.00, QUANTITY='VOLUME FRACTION', SPEC_ID='
    CARBON MONOXIDE', ID='CO 1'/
&DEVC XYZ=5.50,2.50,1.00, QUANTITY='VOLUME FRACTION', SPEC_ID='
    CARBON MONOXIDE', ID='CO 2'/
&DEVC XYZ=1.50,2.50,2.50, QUANTITY='VOLUME FRACTION', SPEC_ID='
    CARBON MONOXIDE', ID='CO 3'/
&DEVC XYZ=5.50,2.50,2.50, QUANTITY='VOLUME FRACTION', SPEC_ID='
    CARBON MONOXIDE', ID='CO 4'/

Compartment Pressure

&DEVC XYZ=3.50,0.10,1.00, QUANTITY='PRESSURE', ID='Pressure' /

Compartment HRR

&DEVC XB=1.00,6.00,1.00,4.00,0.00,3.00, QUANTITY='HRRPUV',
    STATISTICS='VOLUME INTEGRAL', ID='HRR' /

Spray Nozzles

&DEVC XYZ=3.50,1.80,1.00, PROP_ID='Bete P54', QUANTITY='TIME',
    SETPOINT=-60., ORIENTATION=0.,1.,0., ID='fuel_nozzle' /

&DEVC XYZ=1.00,1.25,2.90, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=3.50,1.25,2.90, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
```

```
&DEVC XYZ=6.00,1.25,2.90, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=1.00,3.75,2.90, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=3.50,3.75,2.90, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=6.00,3.75,2.90, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /

&TAIL /
```

A.2 Nordlys Simulation

```
[U+FFFD]&HEAD CHID='k_double', TITLE='setup MS Nordlys' /

  /Single mesh
  /&MESH IJK=105,80,30, XB=-9.50,11.5 , 0.0,16 , 0.0,6.0 /

  /Multi mesh
  &MESH ID='mesh1' , IJK=25,20,30, XB=-9.50,-4.50 , 0.0, 4.0 ,
      0.0,6.0 / Auxiliary room with
  &MESH ID='mesh2' , IJK=25,20,30, XB=-9.50,-4.50 , 4.0,8.0 ,
      0.0,6.0 /Auxiliary room with
  &MESH ID='mesh3' , IJK=25,20,30, XB=-9.50,-4.50 , 8.0, 12.0 ,
      0.0,6.0 / Auxiliary room with
  &MESH ID='mesh4' , IJK=25,20,30, XB=-9.50,-4.50 , 12.0,16.0 ,
      0.0,6.0 /Auxiliary room with

  &MESH ID='mesh5' , IJK=45,40,60, XB=-4.50,0.0 , 0.0, 4.0 ,
      0.0,6.0 / Auxiliary room with
  &MESH ID='mesh6' , IJK=45,40,60, XB=-4.50,0.0 , 4.0,8.0 ,
      0.0,6.0 /Auxiliary room with
  &MESH ID='mesh7' , IJK=45,40,60, XB=-4.50,0.0 , 8.0, 12.0 ,
      0.0,6.0 / Auxiliary room
  &MESH ID='mesh8' , IJK=45,40,60, XB=-4.50,0.0 , 12.0,16.0 ,
      0.0,6.0 /Auxiliary room

  &MESH ID='mesh9' , IJK=40,40,60, XB=0.0,4.0 , 0.0, 4.0 , 0.0,6.0
       /
  &MESH ID='mesh10' , IJK=40,40,60, XB=0.0,4.0 , 4.0, 8.0 ,
      0.0,6.0 /
  &MESH ID='mesh11' , IJK=40,40,60, XB=0.0,4.0 , 8.0, 12.0 ,
      0.0,6.0 /
  &MESH ID='mesh12' , IJK=40,40,60, XB=0.0,4.0 , 12.0, 16.0 ,
      0.0,6.0 /

  &MESH ID='mesh13' , IJK=40,40,60, XB=4.0,8.0 , 0.0, 4.0 ,
      0.0,6.0 /
  &MESH ID='mesh14' , IJK=40,40,60, XB=4.0,8.0 , 4.0, 8.0 ,
      0.0,6.0 /
  &MESH ID='mesh15' , IJK=40,40,60, XB=4.0,8.0 , 8.0, 12.0 ,
      0.0,6.0 /
  &MESH ID='mesh16' , IJK=40,40,60, XB=4.0,8.0 , 12.0, 16.0 ,
      0.0,6.0 /
```

```
&MESH ID='mesh17' , IJK=35,40,60, XB=8.0,11.5 , 0.0, 4.0 , 0.0,6.0 /
&MESH ID='mesh18' , IJK=35,40,60, XB=8.0,11.5 , 4.0, 8.0 , 0.0,6.0 /
&MESH ID='mesh19' , IJK=35,40,60, XB=8.0,11.5 , 8.0, 12.0 , 0.0,6.0 /
&MESH ID='mesh20' , IJK=35,40,60, XB=8.0,11.5 , 12.0, 16.0 , 0.0,6.0 /



/Time start and end, note that the set point of water mist is 0.0s
&TIME T_BEGIN=-60.0      T_END=300.0/
&DT_DEVC=1., DT_HRR=1. /Dumping to excel files




/Buliding the engine room, the wall between main and auxiliary room is set at 0.0 x-dir,
/means that main engine room is positive and auxiliary room is negative
/open area
&VENT XB=-9.5,11.5 , 0.0,16.0 , 6.0,6.0 ,SURF_ID='OPEN'/Roof vent
&VENT XB=-9.5,11.5 , 0.0,0.0 , 4.3,6.0 ,SURF_ID='OPEN'/Port wall vent
&VENT XB=-9.5,11.5 , 16.0,16.0 , 4.3,6.0 ,SURF_ID='OPEN'/Starbord wall vent
&VENT XB=-9.5,-9.5 , 0.0,16.0 , 4.3,6.0 ,SURF_ID='OPEN'/Aft wall vent
&VENT XB=11.5,11.5 , 0.0,16.0 , 4.3,6.0 ,SURF_ID='OPEN'/Bow wall vent
&HOLE XB=-9.5,-7.5 , 0.0,2.0 , 4.2,4.5 /Opening representating the funnel

&SURF ID='Blower', VOLUME_FLUX=-0.32, COLOR='BLUE' /
&VENT XB=11.50,11.50 ,  7.60, 8.60 , 1.40,1.90, SURF_ID='Blower'/0.5m^2 giving an air velocity of 0.64m/s
&VENT XB=11.50,11.50 ,  2.40, 3.40 , 1.40,1.90, SURF_ID='Blower'/0.5m^2 giving an air velocity of 0.64m/s
```

```
&VENT XB= 2.50, 3.50 ,  0.00, 0.00 , 1.40,1.90, SURF_ID='Blower
    '/0.5m^2 giving an air velocity of 0.64m/s
&VENT XB= 7.50, 8.50 ,  0.00, 0.00 , 1.40,1.90, SURF_ID='Blower
    '/0.5m^2 giving an air velocity of 0.64m/s
&VENT XB= 2.50, 3.50 , 16.00,16.00 , 1.40,1.90, SURF_ID='Blower
    '/0.5m^2 giving an air velocity of 0.64m/s
&VENT XB= 7.50, 8.50 , 16.00,16.00 , 1.40,1.90, SURF_ID='Blower
    '/0.5m^2 giving an air velocity of 0.64m/s

&VENT XB=11.50,11.50 ,  7.60, 8.60 , 3.40,3.90, SURF_ID='Blower
    '/0.5m^2 giving an air velocity of 0.64m/s
&VENT XB=11.50,11.50 ,  2.40, 3.40 , 3.40,3.90, SURF_ID='Blower
    '/0.5m^2 giving an air velocity of 0.64m/s
&VENT XB= 2.50, 3.50 ,  0.00, 0.00 , 3.40,3.90, SURF_ID='Blower
    '/0.5m^2 giving an air velocity of 0.64m/s
&VENT XB= 7.50, 8.50 ,  0.00, 0.00 , 3.40,3.90, SURF_ID='Blower
    '/0.5m^2 giving an air velocity of 0.64m/s
&VENT XB= 2.50, 3.50 , 16.00,16.00 , 3.40,3.90, SURF_ID='Blower
    '/0.5m^2 giving an air velocity of 0.64m/s
&VENT XB= 7.50, 8.50 , 16.00,16.00 , 3.40,3.90, SURF_ID='Blower
    '/0.5m^2 giving an air velocity of 0.64m/s

&SPEC ID='WATER VAPOR' /

&MATL ID             = 'STEEL'
      FYI            = 'Quintiere, Fire Behavior'
      SPECIFIC_HEAT  = 0.46
      CONDUCTIVITY   = 45.8
      DENSITY        = 7850. /

&SURF ID        = 'STEEL SHEET', DEFAULT=.TRUE.
      MATL_ID   = 'STEEL'
      COLOR     = 'GRAY 80'
      THICKNESS = 0.005 /

&REAC FUEL        = 'N-HEPTANE'
      FYI         = 'Heptane, C_7 H_16'
      C           = 7.
      H           = 16.
      CO_YIELD    = 0.00
      SOOT_YIELD  = 0.05
      AUTO_IGNITION_TEMPERATURE = 220.0
      HEAT_OF_COMBUSTION=42000.0 /
```

```
/tennkilde varm flate

&SURF ID='HOT'
      COLOR='RED'
      VEL=-2.0
      TMP_FRONT=500.0
      RAMP_V='wind'
      RAMP_T='heat'/


&VENT XB=9.00,10.0 , 4.4,4.0 , 0.0,0.00, SURF_ID='HOT' /XYZ
    =9.5,4.5,0.5,
&RAMP ID='wind', T= -60.0, F=1.0 /
&RAMP ID='wind', T= -50.0, F=0.0 /
&RAMP ID='heat', T= -60.0, F=1.0 /
&RAMP ID='heat', T= -50.0, F=0.0 /

/water mist nozzle and heptane nozzle

&PART ID='heptane droplets', SPEC_ID='N-HEPTANE', DIAMETER=200.,
     HEAT_OF_COMBUSTION=42000.0 /Heat of Combustion
&PART ID='water droplets', SAMPLING_FACTOR=100, SPEC_ID='WATER
    VAPOR', DIAMETER=175. /

&PROP ID='Bete P54', PART_ID='heptane droplets', FLOW_RATE
    =18.25, PARTICLE_VELOCITY=14.3, SPRAY_ANGLE=0.,15.,
    PARTICLES_PER_SECOND=15000. /
&PROP ID='Navy', PART_ID='water droplets', K_FACTOR=2.70,
    OPERATING_PRESSURE=70., PARTICLE_VELOCITY=75., SPRAY_ANGLE
    =0.,60., PARTICLES_PER_SECOND=15000. /


/Main engine room ground floor
&OBST XB= 0.0,0.0 , 0.0,16.0 , 0.0,4.3, RGB=170,170,170/wall
    between auxiliary and main engine room
&OBST XB= 0.0,11.5 , 0.0,16.0 , 2.1,2.1, COLOR='GREEN'/Floor
    between levels in main engine room
&OBST XB=-9.5,11.5 , 0.0,16.0 , 4.3,4.4, COLOR='GRAY'/the roof

/Engine
&OBST XB= 4.0,9.8 , 4.5, 5.7 , 0.0,2.5, RGB=120,100,100 /Port
    engine
```

```
&OBST XB= 4.0,9.8 , 10.2,11.4 , 0.0,2.5, RGB=120,100,100 /
   starbord engine

/some equipment

&OBST XB= 6.5,8.8 , 2.0,3.4 , 0.0,1.7, RGB=120,30,170 /starbord
   engine


/stairway
&HOLE XB= 4.6,5.9  , 7.8,9.0   , 2.0,2.2 /stairway opening

/Openings around port engine
&HOLE XB= 3.8,10.0 , 4.3,4.5 , 2.0,2.2 /opening for engine
&HOLE XB= 3.8,10.0 , 5.7,5.9 , 2.0,2.2 /opening for engine
&HOLE XB= 3.8,4.0 , 4.5, 5.7 , 2.0,2.2, /opening for engine
&HOLE XB= 9.8,10.0 , 4.5, 5.7 , 2.0,2.2, /opening for engine

/starbord
&HOLE XB= 3.8,10.0 , 11.4,11.6 , 2.0,2.2 /opening for engine
&HOLE XB= 3.8,10.0 , 10.0,10.2 , 2.0,2.2 /opening for engine
&HOLE XB= 3.8,4.0 , 10.0,11.6 , 2.0,2.2 /opening for engine
&HOLE XB= 9.8,10.0 , 10.0,11.6 , 2.0,2.2 /opening for engine

/interiore second floor main
/Workshop
&OBST XB=5.7,5.7 , 0.0,3.2 , 2.1,4.3  ,COLOR='BLUE'/workshop
&OBST XB=5.7,11.5 , 3.2,3.2 , 2.1,4.3 ,COLOR='BLUE'/workshop
/&HOLE XB=/door

/Iniciator room
&OBST XB= 2.9,11.5 , 12.2,12.2 , 2.1,4.3 ,COLOR='BLUE'/Iniciator
&OBST XB= 2.8,2.9 , 12.1,12.2 , 2.1,4.3 ,COLOR='BLUE'/Iniciator
&OBST XB= 2.7,2.8 , 12.0,12.1 , 2.1,4.3 ,COLOR='BLUE'/Iniciator
&OBST XB= 2.6,2.7 , 11.9,12.0 , 2.1,4.3 ,COLOR='BLUE'/Iniciator
&OBST XB= 2.5,2.6 , 11.8,11.9 , 2.1,4.3 ,COLOR='BLUE'/Iniciator
&OBST XB= 2.4,2.5 , 11.7,11.8 , 2.1,4.3 ,COLOR='BLUE'/Iniciator
&OBST XB= 2.3,2.4 , 11.6,11.7 , 2.1,4.3 ,COLOR='BLUE'/Iniciator
&OBST XB= 2.2,2.3 , 11.4,11.6 , 2.1,4.3 ,COLOR='BLUE'/Iniciator
&OBST XB= 0.0,2.2 , 11.4,11.4 , 2.1,4.3 ,COLOR='BLUE'/Iniciator
&HOLE XB= 8.4,9.6 , 12.1,12.3 , 2.2,4.2 /door
```

```
/Starirway room
&OBST XB= 0.0,1.0 , 5.8,5.8 , 2.1,4.3 ,COLOR='BLUE'/Iniciator
&OBST XB= 1.0,1.0 , 5.8,6.4 , 2.1,4.3 ,COLOR='BLUE'/Iniciator
&OBST XB= 1.0,1.8 , 6.4,6.4 , 2.1,4.3 ,COLOR='BLUE'/Iniciator
&OBST XB= 1.8,1.8 , 6.4,8.4 , 2.1,4.3 ,COLOR='BLUE'/Iniciator
&OBST XB= 1.0,1.8 , 8.4,8.4 , 2.1,4.3 ,COLOR='BLUE'/Iniciator
&OBST XB= 1.0,1.0 , 8.4,9.2 , 2.1,4.3 ,COLOR='BLUE'/Iniciator
&OBST XB= 0.0,1.0 , 9.2,9.2 , 2.1,4.3 ,COLOR='BLUE'/Iniciator


/Auxiliary engine room
&OBST XB=-9.5,0.0 , 0.0,16.0 , 0.0,0.7 , COLOR='GREEN'/floor in
     auxiliary engine room
&OBST XB=-2.7,0.0 , 6.7, 8.6 , 0.7,4.3 /Stairway from aux eng
   room

&HOLE XB= -0.1,0.1 , 4.6,6.1 , 0.7,2.0 /one door
&HOLE XB= -0.1,0.1 , 9.0,10.5 , 0.7,2.0 /one door

/messurrement
&BNDF QUANTITY='WALL TEMPERATURE'/
&ISOF QUANTITY='TEMPERATURE', VALUE(1)=100, VALUE(2)=220, VALUE
   (3)=1000/ 3D filer visende hvor temperaturen er henholdsvis
   80 degree C og 400 degree C
&SLCF PBX=10.0, QUANTITY='VISIBILITY'/
&SLCF PBX=5.0, QUANTITY='VISIBILITY'/

&SLCF PBY=3.6, QUANTITY='VISIBILITY'/
&SLCF PBY=11.7, QUANTITY='VISIBILITY'/

&SLCF PBX=10.0, QUANTITY='PRESSURE'/
&SLCF PBX=5.0, QUANTITY='PRESSURE'/

&SLCF PBY=3.6, QUANTITY='PRESSURE'/
&SLCF PBY=11.7, QUANTITY='PRESSURE'/
&SLCF PBX=-2.5, QUANTITY='PRESSURE'/
&SLCF PBX=-7.5, QUANTITY='PRESSURE'/

&SLCF PBY=3.6 , QUANTITY='VELOCITY' ,VECTOR=.TRUE./
&SLCF PBY=11.7, QUANTITY='VELOCITY',VECTOR=.TRUE./
&SLCF PBX=-2.5, QUANTITY='VELOCITY',VECTOR=.TRUE./
&SLCF PBX=-7.5, QUANTITY='VELOCITY',VECTOR=.TRUE./
```

```
TC Trees

&PROP ID='Sheathed Type K', BEAD_DIAMETER=0.0032 /

&DEVC XYZ=1.00,2.50,0.50, QUANTITY='THERMOCOUPLE', PROP_ID='
    Sheathed Type K', ID='TC 1-1' /
&DEVC XYZ=1.00,2.50,1.00, QUANTITY='THERMOCOUPLE', PROP_ID='
    Sheathed Type K', ID='TC 1-2' /
&DEVC XYZ=1.00,2.50,1.50, QUANTITY='THERMOCOUPLE', PROP_ID='
    Sheathed Type K', ID='TC 1-3' /
&DEVC XYZ=1.00,2.50,2.00, QUANTITY='THERMOCOUPLE', PROP_ID='
    Sheathed Type K', ID='TC 1-4' /

&DEVC XYZ=6.00,2.50,0.50, QUANTITY='THERMOCOUPLE', PROP_ID='
    Sheathed Type K', ID='TC 2-1' /
&DEVC XYZ=6.00,2.50,1.00, QUANTITY='THERMOCOUPLE', PROP_ID='
    Sheathed Type K', ID='TC 2-2' /
&DEVC XYZ=6.00,2.50,1.50, QUANTITY='THERMOCOUPLE', PROP_ID='
    Sheathed Type K', ID='TC 2-3' /
&DEVC XYZ=6.00,2.50,2.00, QUANTITY='THERMOCOUPLE', PROP_ID='
    Sheathed Type K', ID='TC 2-4' /


/Heat Flux Gauges

&DEVC XYZ=0.01,2.50,1.50, QUANTITY='GAUGE HEAT FLUX',     IOR=
    1, ID='Total Flux Wall'/
&DEVC XYZ=0.01,2.50,1.50, QUANTITY='RADIATIVE HEAT FLUX', IOR=
    1, ID='Rad Flux Wall'/
&DEVC XYZ=3.50,2.50,2.09, QUANTITY='GAUGE HEAT FLUX',     IOR
    =-3, ID='Total Flux Ceiling'/
&DEVC XYZ=3.50,2.50,2.09, QUANTITY='RADIATIVE HEAT FLUX', IOR
    =-3, ID='Rad Flux Ceiling'/

/Gaseous Sampling

&DEVC XYZ=1.50,2.50,1.00, QUANTITY='VOLUME FRACTION', SPEC_ID='
    OXYGEN', ID='O2 1'/
&DEVC XYZ=5.50,2.50,1.00, QUANTITY='VOLUME FRACTION', SPEC_ID='
    OXYGEN', ID='O2 2'/
&DEVC XYZ=1.50,2.50,2.00, QUANTITY='VOLUME FRACTION', SPEC_ID='
    OXYGEN', ID='O2 3'/
```

```
&DEVC XYZ=5.50,2.50,2.00, QUANTITY='VOLUME FRACTION', SPEC_ID='
    OXYGEN', ID='O2 4'/

&DEVC XYZ=1.50,2.50,1.00, QUANTITY='VOLUME FRACTION', SPEC_ID='
    CARBON DIOXIDE', ID='CO2 1'/
&DEVC XYZ=5.50,2.50,1.00, QUANTITY='VOLUME FRACTION', SPEC_ID='
    CARBON DIOXIDE', ID='CO2 2'/
&DEVC XYZ=1.50,2.50,2.00, QUANTITY='VOLUME FRACTION', SPEC_ID='
    CARBON DIOXIDE', ID='CO2 3'/
&DEVC XYZ=5.50,2.50,2.00, QUANTITY='VOLUME FRACTION', SPEC_ID='
    CARBON DIOXIDE', ID='CO2 4'/

&DEVC XYZ=1.50,2.50,1.00, QUANTITY='VOLUME FRACTION', SPEC_ID='
    CARBON MONOXIDE', ID='CO 1'/
&DEVC XYZ=5.50,2.50,1.00, QUANTITY='VOLUME FRACTION', SPEC_ID='
    CARBON MONOXIDE', ID='CO 2'/
&DEVC XYZ=1.50,2.50,2.00, QUANTITY='VOLUME FRACTION', SPEC_ID='
    CARBON MONOXIDE', ID='CO 3'/
&DEVC XYZ=5.50,2.50,2.00, QUANTITY='VOLUME FRACTION', SPEC_ID='
    CARBON MONOXIDE', ID='CO 4'/

/Compartment Pressure

&DEVC XYZ=3.50,1.00,1.00, QUANTITY='PRESSURE', ID='Pressure' /

/Compartment HRR

&DEVC XB=1.00,6.00,1.00,4.00,0.00,3.00, QUANTITY='HRRPUV',
    STATISTICS='VOLUME INTEGRAL', ID='HRR' /

/Heptane nozzle
&DEVC XYZ=9.5,4.5,1.5, PROP_ID='Bete P54', QUANTITY='TIME',
    SETPOINT=-60.0, ORIENTATION=0.0,-1.0,0.0, ID='fuel_nozzle' /
/&DEVC XYZ=9.5,4.5,0.5, PROP_ID='Bete P54', QUANTITY='TIME',
    SETPOINT=   0.0, ORIENTATION=0.0,-1.0,0.0, ID='fuel_nozzle_2'
     /

/water mist nozzle(spacing ?)
/first floor
&DEVC XYZ=1.00,1.00,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=1.00,3.40,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
```

```
&DEVC XYZ=1.00,6.00,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=1.00,8.20,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=1.00,9.90,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=1.00,12.4,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=1.00,14.9,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /

&DEVC XYZ=3.40,1.00,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=3.40,3.40,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=3.40,6.00,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=3.40,8.20,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=3.40,9.90,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=3.40,12.4,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=3.40,14.9,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /

&DEVC XYZ=5.80,1.00,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=5.80,3.40,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=5.80,6.00,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=5.80,8.20,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=5.80,9.90,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=5.80,12.4,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=5.80,14.9,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /

&DEVC XYZ=8.20,1.00,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
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```
&DEVC XYZ=8.20,3.80,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=8.20,6.00,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=8.20,8.20,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=8.20,9.90,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=8.20,12.4,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=8.20,14.9,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /

&DEVC XYZ=10.5,1.00,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=10.5,3.80,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=10.5,6.00,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=10.5,8.20,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=10.5,9.90,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=10.5,12.4,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=10.5,14.9,2.0, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /

/second floor
&DEVC XYZ=1.00,1.00,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=1.00,3.40,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=1.00,6.00,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=1.00,8.20,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=1.00,9.90,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /

&DEVC XYZ=3.40,1.00,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
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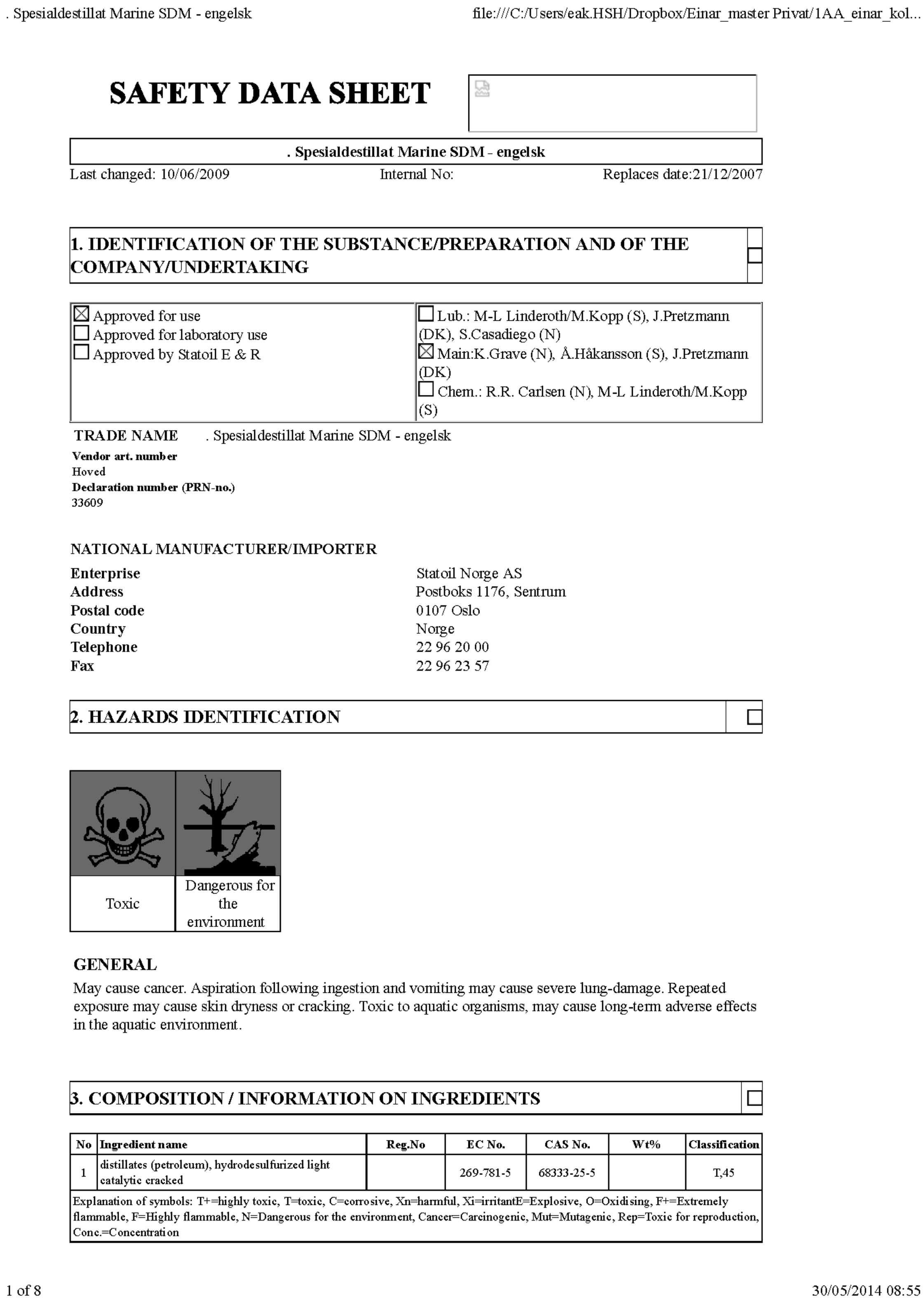
```
&DEVC XYZ=3.40,3.40,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=3.40,6.00,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=3.40,8.20,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=3.40,9.90,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /

&DEVC XYZ=5.00,1.00,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=5.80,3.40,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=5.80,6.00,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=5.80,8.20,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=5.80,9.90,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /

&DEVC XYZ=8.20,4.50,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=8.20,6.00,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=8.20,8.20,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=8.20,9.90,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /

&DEVC XYZ=10.5,4.50,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=10.5,6.00,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=10.5,8.20,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /
&DEVC XYZ=10.5,9.90,4.20, PROP_ID='Navy', QUANTITY='TIME',
    SETPOINT=0., ID='mist_nozzle' /

end
```

Appendix B

Diesel Datasheat



SAFETY DATA SHEET

. Spesialdestillat Marine SDM - engelsk

Last changed: 10/06/2009 Internal No: Replaces date:21/12/2007

1. IDENTIFICATION OF THE SUBSTANCE/PREPARATION AND OF THE COMPANY/UNDERTAKING ☐

☒ Approved for use ☐ Approved for laboratory use ☐ Approved by Statoil E & R	☐ Lub.: M-L Linderoth/M.Kopp (S), J.Pretzmann (DK), S.Casadiego (N) ☒ Main:K.Grave (N), Å.Håkansson (S), J.Pretzmann (DK) ☐ Chem.: R.R. Carlsen (N), M-L Linderoth/M.Kopp (S)

TRADE NAME . Spesialdestillat Marine SDM - engelsk

Vendor art. number

Hoved

Declaration number (PRN-no.)

33609

NATIONAL MANUFACTURER/IMPORTER

Enterprise	Statoil Norge AS
Address	Postboks 1176, Sentrum
Postal code	0107 Oslo
Country	Norge
Telephone	22 96 20 00
Fax	22 96 23 57

2. HAZARDS IDENTIFICATION ☐

Toxic	Dangerous for the environment

GENERAL

May cause cancer. Aspiration following ingestion and vomiting may cause severe lung-damage. Repeated exposure may cause skin dryness or cracking. Toxic to aquatic organisms, may cause long-term adverse effects in the aquatic environment.

3. COMPOSITION / INFORMATION ON INGREDIENTS ☐

No	Ingredient name	Reg.No	EC No.	CAS No.	Wt%	Classification
1	distillates (petroleum), hydrodesulfurized light catalytic cracked		269-781-5	68333-25-5		T,45
Explanation of symbols: T+=highly toxic, T=toxic, C=corrosive, Xn=harmful, Xi=irritantE=Explosive, O=Oxidising, F+=Extremely flammable, F=Highly flammable, N=Dangerous for the environment, Cancer=Carcinogenic, Mut=Mutagenic, Rep=Toxic for reproduction, Conc.=Concentration						

INGREDIENT COMMENTS

Section 16 contains the full text of the abovementioned R-sentences.

4. FIRST AID MEASURES ☐

GENERAL

Immediately remove the patient from further exposure. General first aid. Fresh air, rest and keep warm. If unconscious: Loosen tight clothing, place in stable position on one side. If breathing stops, provide artificial respiration. If heart stops, provide cardiac massage. If breathing stops, provide oxygen if necessary. Get medical advice.

INHALATION

Fresh air. Administer oxygen if breathing is difficult. First aid personnel should have special training in the administration of oxygen.

SKIN CONTACT

Wash the skin with soap and water. Remove contaminated clothing immediately. Avoid using white spirit or similar products to remove oil from the skin. Get medical advice if irritation persists. Use moisturizing skin cream to replace lost skin moisture.

EYE CONTACT

Flush immediately with plenty of water, also under the eyelids. Get medical advice if discomfort continues.

INGESTION

Do not give anything by mouth. Do not induce vomiting but obtain medical attention immediately.

5. FIRE-FIGHTING MEASURES ☐

EXTINGUISHING MEDIA

Water, foam, CO2, dry material, sand. Powder, foam, carbondiokside (CO2) or water-fog / spray. sand Water fog.

IMPROPER EXTINGUISHING MEDIA

Do not use strong water jet for extinguishing - may cause spattering of burning material.

FIRE AND EXPLOSION HAZARDS

May ignite if heated above flash point. Vapours are heavier than air and may travel to distant ignition sources via drains etc. Carbon monoxide (CO) may be formed in the event of incomplete combustion. The product may accumulate static electricity and cause ignition upon discharge.

PROTECTIVE EQUIPMENT FOR FIRE FIGHTERS

For big fires in areas where product is stored: Self-contained breathing apparatus and eye protection must be used by rescue personnel exposed to gas or fumes. If possible, fight fire from protected position. If not: withdraw.

OTHER INFORMATION

Keep run-off water out of sewers and water sources. Dike for water control. Move containers from fire area if it can be done without risk. Withdraw immediately in case of rising sound from venting safety devices or any discoloration of tanks due to fire. If risk of water pollution occurs, notify appropriate authorities.

6. ACCIDENTAL RELEASE MEASURES ☐

PERSONAL PRECAUTIONS

Warn persons in the vicinity and keep unauthorized personnel away. Use personal protection as stated in section 8.

SAFETY ACTIONS TO PROTECT EXTERNAL ENVIRONMENT

Waste must be removed promptly. EFFLUENT TO WATER: The product floats on water, and will not dissolve. Be aware of possible water-intakes, and alert implicated users. Remove all sources of ignition. WASTE ON ROADS, FIELDS etc.: Restrain spreading of waste with for ex. sand. Pump up larger amounts with suitable equipment.

METHODS FOR CLEANING UP

Spillage may be pumped up or absorbed with dry, inert material such as sand, earth etc.

OTHER INFORMATION

Keep away from narrow rooms owing to danger of explosion. Remove all sources of ignition. By greater incidents: call fire department, police or local authority.

7. HANDLING AND STORAGE ☐

HANDLING PRECAUTIONS

May attack some plastics, rubber and paint.

HANDLING ADVICE

Avoid heat, sparks and open flames. Avoid spillage, skin and eye contact. Avoid inhalation of vapours.

STORAGE

Inflammable: keep away from oxidizing material, heat and open fire. Must not be exposed to heat and sunlight. Earth (ground) container and transfer equipment to eliminate sparks caused by static electric discharge. Outside or detached storage preferred. Store as a flammable material.

OTHER INFORMATION

Smoking and open fire are forbidden. Explosion and fire-hazard.

8. EXPOSURE CONTROLS/PERSONAL PROTECTION ☐

EXPOSURE CONTROL

Wear eye protection. Eyewash facilities. Shower near the workplace. Wash promptly if skin becomes contaminated. Wash skin at the end of each work shift and before eating, smoking and using the toilet.

RESPIRATORY PROTECTION

Normally not required. Use respiratory protection for operations which generate gas, fumes, vapour or mist, e.g. gas mask with combination cartridge A2/P2.

EYE PROTECTION

Wear approved goggles if there is a possibility of splashes. Contact lenses should not be used when handling this product.

HAND PROTECTION

Use protective gloves of: neoprene, nitrile rubber, polyethylene, polyvinyl alcohol or polyvinyl chloride. Viton.

PROTECTIVE CLOTHING

Wear appropriate protective clothing to protect against possible skin contact.

OTHER INFORMATION

Promptly remove any clothing that becomes wet or contaminated.

9. PHYSICAL AND CHEMICAL PROPERTIES ☐

PHYSICAL STATE

Liquid

COLOUR

Yellow

ODOUR

Characteristic Mild, characteristic.

SOLUBILITY

Soluble in organic solvent (most).

PHYSICAL AND CHEMICAL PARAMETERS

Density:	875 kg/m^3 V/15°C	**Expl. limit LEL-UEL%:**	0,5 vol-% - 7 vol-%
Boiling point/range:	310-375°C/760 mmHg	**Flash point:**	65°C. (Min55°C)
Viscosity:	5.0 mm^2/s v/50°C	**Ignition temp.:**	220 - 300°C
Brennverdi MJ/kg nedre	42.5	**Densitet**	875 kg/m3 v/15 °C
Brennverdi MJ/kg øvre:	45.2	**Svovel, masse-%:**	maks 0.25

10. STABILITY AND REACTIVITY ☐

STABILITY

Keep away from ignition sources. Avoid storing for very long periods.

MATERIALS TO AVOID

Strong oxidizing agent such as liquid chlorine and concentrated oxygen.

HAZARDOUS DECOMPOSITION PRODUCTS

Do not decompose at standard temperatures. Incomplete combustion generates toxic and highly flammable carbon monoxide. Complete combustion generates carbon dioxide, which displaces air and oxygen.

OTHER INFORMATION

The product may damage gaskets, painted surfaces, protective grease and oil, and rubber-objects.

11. TOXICOLOGICAL INFORMATION ☐

Acute oral tox.:	LD 50 - rotte	>5000 mg/kg

Acute derm. tox.:	LD 50 - kanin	>2000 mg/kg
Inh. toxicity:	LC 50 - rotte	>2500 mg/m3

GENERAL

The product is low acute poisonous. Risk of chemical pneumonia by aspiration to the lungs.

INHALATION

Be aware of poisonous combustion-products. Oil mist may irritate respiratory system.

SKIN CONTACT

The product acts defattening, and may cause soreness, rash and eczema .

EYE CONTACT

Irritating to the eyes.

INGESTION

Low order of acute toxicity, but aspiration following ingestion and vomiting may cause severe and potentially fatal chemical pneumonitis.

SENSITIZATION

Sensitizing properties are not known.

CARCINOGENICITY

Available data indicates that prolonged or repeated exposure may cause skin-cancer.

MUTAGENICITY

Most data indicates no mutagenicity.

TERATOGENIC EFFECTS

Data do not lead to classification.

ACUTE AND CHRONIC TOXICITY

Low order of acute toxicity, but aspiration following ingestion and vomiting may cause severe and potentially fatal chemical pneumonitis.

OTHER TOXICOLOGICAL INFORMATION

The information is derived from data from similar products.

12. ECOLOGICAL INFORMATION ☐

ECOTOXICITY

Contaminated (fouled) fur and feathers lose their insulating properties. Animals and birds may die of the cold as a result. Moderately poisonous to organisms in water and soil. Polluted fur and feathers loose their insulating power . Animals and birds may as a consequence of this freeze to death . The product is moderately poisonous for organisms living in water and soil.
Diesel
Data for akutt toksisitet (Concawe rapport 01/54)

				Resultat [mg/l]
Fisk				
-	Oncorhynchus mykiss	WAF	LL50, 96 h	21-230
-	Jordanella floridae, Pimephales promelas	OWD	LL50, 96 h	31, 54
-	Cyprinodon variegatus, Menidia beryllina og			

	Fundulis similis	OWD	TLm, 96 h	33-125
Virvelløse dyr				
-	Daphnia magna	WAF	EL50, 48 h	6,2-210
-	Mysidopsis almyra	OWD	TLm, 48 h	1,6
-	Palaemonetes pugio	OWD	TLm, 48 h	3,4
-	Penaeus aztecus	OWD	TLm, 48 h	9,4
Alger				
-	Raphidocelis subcapitata	WAF	IrL50, 72 h	>10-78

MOBILITY

The product floats on water. It penetrates the soil, and may pollute the ground-water. The product evaporates partly from soil and water-surfaces.

DEGRADABILITY

The product is expected partly to have a moderate biodegradation rate and partly to resist biodegradation, and will partly persist in the environment.

ACCUMULATION

The product is supposed to bioaccumulate on basis of high log Pow-value. Experimental data however have shown that the components may be metabolised in som test -

OTHER EFFECTS

The combustion-products may contribute to photochemical ozone-formation.

OTHER INFORMATION

Petroleum products destoy the insulating properties of fur and feathers. Sea birds and mammals may freeze to death as a result.

13. DISPOSAL CONSIDERATIONS ☐

GENERAL REGULATIONS

Collect minor residues and dispose of at hazardous waste treatment facility if the amount is more than 1 kg anhually.

CATEGORY OF WASTE

16 09 01 contaminated fuels and fuel oils

14. TRANSPORT INFORMATION ☐

Classified as Dangerous Goods: **Not assessed**

UN No.: 1268

ADR/RID

Class:	3.31(c)	**Packing group:**	
Hazard Id:	30		

IMDG

Class:	3.3	**Packing group:**	

IATA

Class:	3	**Packing group:**	III

OTHER INFORMATION

15. REGULATORY INFORMATION ☐

	
Toxic	Dangerous for the environment

EC-Label Not assessed

COMPOSITION

R-PHRASES

R-45 May cause cancer.
R-65 Harmful: may cause lung damage if swallowed.
R-51/53 Toxic to aquatic organisms, may cause long-term adverse effects in the aquatic environment.
R-66 Repeated exposure may cause skin dryness or cracking.

S-PHRASES

S-45 In case of accident or if you feel unwell, seek medical advice immediately (show the label where possible).
S-53 Avoid exposure - Obtain special instructions before use.
S-24 Avoid contact with skin.
S-36/37 Wear suitable protective clothing and gloves.
S-61 Avoid release to the environment. Refer to special instructions/safety data sheet.
S-62 If swallowed, do not induce vomiting: seek medical advice immediately and show this container or label.
S-2 Keep out of the reach of children.

REFERENCES

Edited as laid down by regulations "classification and labelling of dangerous chemicals, and list of subsatnces (SFT, Occupational Safety and Health Administration, DBE) last issue.

16. OTHER INFORMATION ☐

INFORMATION SOURCES

Produsenter
Forskrifter om klassifisering, merking m.v. av farlige kjemikalier
Forskrifter om liste over farlige stoffer
Administrative normer for forurensning av arbeidsatmosfære
Arbeidstilsynet: Åndedrettsvern
Arbeidstilsynet: Øyevern
Foreningen for arbetsskydd: Guide for val av kemskyddsmaterial
SFT-rapport 91:04-Petroleumsprodukter - Hovedtyper, sammensetning og helsevurdering
ADR
IMDG CODE
IATA DGR

VENDOR NOTES

The safety data sheet has been prepared on the basis of information given by our suppliers and our present knowledge.

LIST OF RELEVANT R-PHRASES

Nr.	R-Phrase text
R45	May cause cancer.

SDS IS PREPARED BY

Enterprise PKS-MS

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