ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

EVALUATION OF FIRE SAFETY ONBOARD PASSENGER SHIPS

Ph.D. THESIS

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Department of Naval Architecture and Marine Engineering

Naval Architecture and Marine Engineering Programme

JANUARY 2025

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YOLCU GEMİLERİNDE YANGIN GÜVENLİĞİNİN DEĞERLENDİRİLMESİ

DOKTORA TEZİ

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OCAK 2025

Tolga AYCI, a Ph.D. student of İTU Graduate School student ID 508152005, successfully defended the thesis/dissertation entitled "EVALUATION OF FIRE SAFETY ONBOARD PASSENGER SHIPS", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my beloved family,

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Tolga AYCI
(Naval Architect and Marine Engineer)

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ABBREVIATIONS

AFFF	: Aqueous Film Forming Foam
AIBN	: Accident Investigation Board Norway
ALARP	: As Low As Reasonably Practicable
ASET	: Available Safe Egress Time
BN	: Bayesian Network
BSI	: British Standards Institution
BSS	: Boat Safety Scheme
CCA	: Cause-Consequence Analysis
CCFM	: Consolidated Compartment Fire Model
CFAST	: Consolidated Fire and Smoke Transport Model
CFD	: Computational Fluid Dynamics
CO	: Carbon monoxide
CO2	: Carbon dioxide
CPS	: Closed Passenger Spaces
DCSs	: Damage Control Systems
DIGIFEMA	: The General Directorate for Railway and Maritime Investigations
DNS	: Direct Numerical Simulation
DNV-GL	: Det Norske Veritas and Germanischer Lloyd
DOM	: Discrete Ordinates Method
EEBDs	: Emergency Escape Breathing Devices
ER	: Engine Room
ETA	: Event Tree Analysis
EV	: Electric Vehicle
EVs	: Electric Vehicles
FAST	: Fire and Smoke Transport Model
FDS	: Fire Dynamics Simulator
FED	: Fractional Effective Dose
FFF	: Fluorine-Free Foams
FMECA	: Failure Mode, Effects, and Criticality Analysis
FP	: Fire Protection

FRP	: Fiber Reinforced Polymer
FSA	: Formal Safety Assessment
FSS	: Fire Safety Systems
FSSIM	: Fire and Smoke Simulator
FTA	: Fault Tree Analysis
FTB	: Fire Test Procedures
FVM	: Finite Volume Method
GISIS	: Global Integrated Shipping Information System
HbCO	: Carboxyhemoglobin
HbO2	: Oxyhemoglobin
HBr	: Hydrobromic Acid
HCI	: Hydrochloric Acid
HCN	: Hydrogen cyanide
HF	: Hydrogen fluoride
HFC	: Hydrofluorocarbon
HRR	: Heat Release Rate
HVAC	: Heating, Ventilation and Air Conditioning
IMO	: International Maritime Organization
INSB	: International Naval Surveys Bureau
ISM	: International Safety Management
ISO	: International Standards Organization
LES	: Large Eddy Simulation
LNG	: Liquefied Natural Gas
LNG	: Liquefied Natural Gas Ship Fire Identification System
MCM	: Monte Carlo Method
MLR	: Mass Loss Rate
MSC	: Maritime Safety Committee
NIST	: National Institute of Standards and Technology
NO	: Nitric oxide
O2	: Oxygen
ODEs	: Ordinary Differential Equations
OPS	: Open Passenger Spaces
PC	: Personal Computer
PCC	: Pure Car Carrier

PCE : Polynomial Chaos Expansion
QRA : Quantitative Risk Analysis
RANS : Reynolds-Averaged Navier-Stokes
ROPAX : Roll-on/Roll-off Passenger Ferry
RSET : Required Safe Egress Time
RTE : Radiation Transport Equation
SAR : Search and Rescue
SF6 : Sulfur hexafluoride
SFIS : Ship Fire Identification System
SFPE : Society of Fire Protection Engineers
SO2 : Sulfur dioxide
SOLAS : Safety of Life at Sea
SOx : Sulfur oxides
SSRC : Ship Stability Research Centre
VLES : Very Large Eddy Simulation

SYMBOLS

μ	: Viscosity
c_p	: Specific heat of air
D^*	: Fire diameter
D_k	: Diffusion coefficient
F_i	: Body forces
g	: Gravitational constant
h	: Enthalpy
h_c	: Heat of combustion
m	: Mass
P	: Pressure
$\dot{Q}$	: Total heat release rate
S_{rad}	: Radiation loss or gain
T	: Temperature
t	: Time
u_i, u_j, u_k	: Velocity
V	: Volume
Y_i	: Mass fraction
ρ	: Density
σ_h	: Prandtl number
τ_{ij}	: Viscous stress tensor

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EVALUATION OF FIRE SAFETY ONBOARD PASSENGER SHIPS

SUMMARY

Fire safety is the whole of the measures and practices related to the prevention of fires, ensuring the safety of life and property in case of fire and carrying out rescue activities after fire. The design of fire safety covers various areas such as fire detection and extinguishing systems, structural passive fire prevention systems, emergency exit routes, fire drills and training. The aim is to create an effective system to prevent the outbreak of fires and to ensure the safety of people in case of fire.

Fire safety measures are of critical importance on ships and marine vessels. The International Convention for Safety of Life at Sea (SOLAS), which was established to ensure the safety of life and property at sea, includes maritime safety criteria and standards, including fire safety. In addition to the SOLAS convention, the International Fire Safety Systems (FSS) code is an important part of the SOLAS convention. It contains detailed details about fire safety systems and equipment on board ships. The FSS code consists of 15 chapters, each dealing with different areas of fire safety.

Although there is detailed legislation, regulations, codes and standards, it is not possible to ensure 100% fire safety on ships. As a result, fire incidents on ships cause loss of life and property. The Global Integrated Shipping Information System (GISIS) by the International Maritime Organization (IMO) contains data in many different areas, including fire incidents. As the first study within the scope of this thesis, statistical data were analyzed according to ship type and severity of fire incident. In the fire incidents that took place between January 2000 and December 2022, fire incidents with serious and very serious consequences were considered. The 323 serious and very serious fire incidents reported between these dates were categorized according to different ship types such as tanker, passenger ship, cargo, fishing vessel, bulk carrier, container and support vessel. When the number of active vessels of each ship type globally is added to this statistic, the fire occurrence rate per 1,000 vessels is calculated. Here, with an average fire occurrence rate of 6.82, passenger ships are the ship type with the highest fire occurrence rate. This statistic is the main reason why passenger ships are selected as the ship type in this study and evaluated in terms of fire safety.

Fire safety, which is an interdisciplinary science, needs to be examined in different fields. Within the scope of this study, which is based on fire safety in ships, fire safety regulations and standards, fire dynamics simulation, fire protection systems used in ships and fire risk management issues have been examined in the literature. As a result of this review, fire dynamics simulation and fire risk modelling applications including passive and active fire protection systems have been applied on selected passenger ship types. Using these fire safety assessment methods aims to establish performance-based fire safety design and execution onboard passenger ships. Fire dynamics simulations monitor temperature and pressure vectors across selected zones. On the other hand, fire risk modelling identifies fire risks and determines the precautions

against fire incidents. In this study, 3 different case studies were selected, and the results are shared.

In the first case, the 600-passenger capacity SH SUTLUCE passenger ship with IMO number 9564009, which is in the ship fleet of the Şehir Hatları subsidiary company operating in the field of maritime passenger transport of Istanbul Metropolitan Municipality, was evaluated for fire safety by applying fire dynamics simulation modelling, which is a computational fluid dynamics (CFD) method. In this case, simulation models were created for 5 different scenarios of fire in the ship's engine room according to the presence and number of fire extinguishing system and fire-resistant bulkheads / decks. These scenarios are categorized as best, medium and worst scenarios in terms of fire severity. Simulation outputs were analyzed at critical locations based on temperature and pressure. Especially in the engine room, the temperature rises to 500 °C from the first seconds, this level reduces the structural strength of the steel elements used in the ships and causes structural collapse. Fire safety on passenger ships is profoundly influenced not only by fire extinguishing systems but also by the presence of structural fire protection systems such as fire-resistant bulkheads and decks. To reduce the risk of fire hazards, structural fire protection systems such as fire-resistant bulkheads and decks can be used in important compartments such as engine rooms. It is of great importance to ensure that fire-resistant bulkheads and decks are properly installed with suitable materials and to pay particular attention to their stability. During the maintenance and operation of passenger ships, regular inspection of fire-resistant bulkheads and decks by both crew and technical teams is mandatory. Findings from fire dynamics simulations underline the critical role that fire-resistant bulkheads play in preventing the spread of fire on passenger ships. In addition, the effect of fire extinguishing systems and the number of nozzles on the temperature was also analyzed by varying the number of fire extinguishing nozzles as 1, 2 and 4 in the so-called best scenario. It was recommended that the number of nozzles should be optimally selected as 2 after 100 seconds of fire outbreak.

In the second case, the fire safety of ROPAX passenger ships, which provide the transportation of electric vehicles, the number and popularity of which have increased rapidly in recent years, by sea, was modelled using computational fluid dynamics and fire safety was evaluated. In this case, the deck with electric vehicles on the 146m long ROPAX ship with a capacity of 800 passengers, 90 vehicles and 60 trucks were selected to be examined. Temperature distributions throughout the control area are important to assess the severity of the fire event. Therefore, to monitor the temperature distribution, the center of the fire sources was aligned, and the temperature distributions were plotted. As a result, it was observed that the temperature increased dramatically to almost 1200 °C. Structural elements, electric vehicles and equipments used on board can organically ignite and lose their function at this temperature level. Due to this temperature level on ferries, areas or compartments where electrical vehicles are transported on ferries need to be designed with structurally fire-resistant materials. In this study, ignition and explosion were ignored due to the reduced complexity of the case study.

In the last case study, the fire safety of a Ro-Ro passenger ship was analyzed with Event Tree Analysis (ETA), one of the fire risk assessment methods. The chain of events starting with the fire outbreak, the type of space where the fire started, whether the detection systems are working or not, user reaction, decision making, extinguishing, compartmentalization and evacuation ends. Event tree analyses for a total of 21 different scenarios constitute the first step in determining the fire risk in Ro-Ro passenger ships. The event tree structure created in this study is planned to be used as an input in the planning of fire safety training of the crew.

As a result, the design, implementation and operation of a performance-based passenger ship that includes fire dynamics simulations and fire risk assessment methods are important in establishing fire safety. In this study, fire safety assessments have been carried out for different types of passenger ships, namely passenger transport ships, ROPAX carrying electric vehicles and Ro-Ro. Thus, performance-based passenger ship design, implementation and operation are carried out by prioritizing the fire safety point of view with fire dynamics simulation and fire risk assessment methods. These performance-based studies will contribute to the updating of regulations, rules and standards published specifically for fire regulations on ships.

YOLCU GEMİLERİNDE YANGIN GÜVENLİĞİNİN DEĞERLENDİRİLMESİ

ÖZET

Yangın güvenliği, yangınların önlenmesi, yangın anında can ve mal güvenliğinin sağlanması ve yangın sonrası kurtarma faaliyetlerinin yürütülmesi ile ilgili önlemlerin ve uygulamaların bütünüdür. Yangın güvenliğinin tasarımı ise yangın algılama ve söndürme sistemleri, yapısal pasif yangın önleme sistemleri, acil çıkış yolları, yangın tatbikatları ve eğitim gibi çeşitli alanları kapsar. Amaç, yangınların çıkışını önlemek ve yangın anında insanların güvenliğini sağlamak için etkili bir sistem oluşturmaktır.

Yangın güvenliği önlemleri gemilerde ve deniz araçlarında kritik öneme sahiptir. Denizlerde can ve mal güvenliğinin sağlanması amacıyla oluşturulan Denizde Can Emniyeti Uluslararası Sözleşmesi SOLAS (Safety of Life at Sea) içerisinde yangın güvenliğinin de bulunduğu denizcilikte güvenlik kriterlerini ve standartlarını içermektedir. SOLAS sözleşmesine ek olarak Uluslararası Yangın Güvenliği Sistemleri FSS (The International Fire Safety Systems) kodu SOLAS sözleşmesinin önemli bir parçasıdır. Gemilerdeki yangın güvenlik sistemleri ve ekipmanları için ayrıntılı detayları içermektedir. FSS kodu her biri yangın güvenliğinin farklı alanlarını ele alan 15 bölümden oluşmaktadır.

Detaylı mevzuatlar, yönetmelikler, kodlar ve standartlar olmasına rağmen, gemilerde %100 yangın güveliği sağlanması mümkün olmamaktadır. Bunun sonucu olarak gemilerde çıkan yangın olayları can ve mal kaybına neden olmaktadır. Uluslararası Denizcilik Örgütü IMO (International Maritime Organization) tarafından Küresel Entegre Denizcilik Bilgi Sistemi GISIS (Global Integrated Shipping Information System)'de yangın olayları da dahil olmak üzere birçok farklı alanda veriler bulunmaktadır. Bu tez kapsamındaki ilk çalışma olarak, gemi tipi ve yangın olayının şiddetine göre istatistiksel veriler incelenmiştir. Ocak 2000 ile Aralık 2022 arasında gerçekleşen yangın vakalarında ciddi ve çok ciddi sonuçları içeren yangın olayları ele alınmıştır. Bu tarihler arasında raporlanan 323 ciddi ve çok ciddi yangın olayları tanker, yolcu gemisi, kargo, balıkçı gemisi, dökme yük, konteyner ve destek gemisi gibi farklı gemi tiplerine göre sınıflandırılmıştır. Küresel olarak her gemi tipinin aktif gemi adedi de bu istatistiğe eklendiğinde her 1.000 gemi başına yangın gerçekleştirme oranı hesaplanmıştır. Burada, 6.82 ortalama yangın gerçekleşme oranı ile yolcu gemileri en çok yangın gerçekleşme oranına sahip gemi tipi olarak karşımıza çıkmıştır. Bu çalışmada gemi tipi olarak yolcu gemilerinin seçilerek yangın güvenliği açısından değerlendirilmesinin temel sebebi ise bu istatistiktir.

Disiplinler arası bir bilim dalı olan yangın güvenliğinin farklı alanlarda incelenmesi gerekmektedir. Gemilerde yangın güvenliğinin temel alındığı bu çalışma kapsamında, yangın güvenliği yönetmelik ve standartları, yangın dinamiği simülasyonu, gemi tahliye modellemesi, gemilerde kullanılan yangın korunum sistemleri ve yangın risk yönetimi konuları literatürde incelenmiştir. Bu inceleme sonucunda, yolcu gemileri özelinde pasif ve aktif yangın korunum sistemlerinin de dahil edildiği yangın dinamiği simülasyonu ve yangın risk modellemesi uygulamaları seçilen yolcu gemi tiplerinde

uygulanmıştır. Bu çalışmada 3 farklı vaka çalışması seçilmiştir ve sonuçları paylaşılmıştır.

Birinci vakada, İstanbul Büyükşehir Belediyesi'nin denizcilik yolcu taşımacılığı alanında faaliyet gösteren Şehir Hatları iştirak firmasının gemi filosunda yer alan 9564009 IMO numaralı 600 yolcu kapasiteli SH SUTLUCE yolcu gemisi bir hesaplamalı akışkanlar dinamiği (CFD) yöntemi olan yangın dinamiği simülasyon modellemesi uygulanarak yangın güvenliği değerlendirmesi yapılmıştır. Bu vakada, yangın söndürme sisteminin ve yangına dayanımlı perde / güverte varlığına ve sayısına göre gemi makine dairesinde oluşturulan yangının 5 farklı senaryo özelinde simülasyon modelleri oluşturulmuştur. Bu senaryolar, yangın şiddeti açısından iyi, orta ve kötü senaryo olarak sınıflandırılmıştır. Simülasyon çıktıları sıcaklık ve basınç temel alınarak kritik yerlerde incelenmiştir. Özellikle makine dairesinde sıcaklık ilk saniyelerden itibaren 500 °C seviyelerine çıkmaktadır, bu seviye gemilerde kullanılan çelik elemanların yapısal olarak mukavemetini azaltmakta ve yapısal çökmelere sebebiyet vermektedir. Yolcu gemilerinde yangın güvenliği sadece yangın söndürme sistemlerinden değil, aynı zamanda yangına dayanıklı perdeler ve güverteler gibi yapısal yangından korunma sistemlerinin varlığından da derinden etkilenmektedir. Yangın tehlikesi riskini azaltmak için, makine daireleri gibi önemli bölmelerde yangına dayanıklı perdeler ve güverteler gibi yapısal yangından korunma sistemleri kullanılabilir. Yangına dayanıklı perdelerin ve güvertelerin uygun malzemelerle düzgün bir şekilde monte edilmesini sağlamak ve stabilitelerine özellikle dikkat etmek büyük önem taşımaktadır. Yolcu gemilerinin bakımı ve işletimi sırasında, yangına dayanıklı perdelerin ve güvertelerin hem mürettebat hem de teknik ekipler tarafından düzenli olarak denetlenmesi zorunludur. Yangın dinamiği simülasyonlarından elde edilen bulgular, yangına dayanıklı bölmelerin yolcu gemilerinde yangının yayılmasını engellemede oynadığı kritik rolün altını çizmektedir. Ayrıca, yangın söndürme sistemlerinin ve nozul sayısının sıcaklığa etkisi de "iyi" senaryo olarak adlandırılan senaryoda yangın söndürme nozul sayısı 1, 2 ve 4 olarak çeşitlendirilerek etkisi incelenmiştir. Yangın çıkmasının 100. saniyesi sonrasında nozul sayısının optimumda 2 olarak seçilmesi önerilmiştir.

İkinci vakada ise son yıllarda sayısı ve popülaritesi hızla artan elektrikli araçların, deniz yolu ile taşınmasını sağlayan ROPAX yolcu gemilerindeki yangın güvenliğinin hesaplamalı akışkanlar dinamiği kullanılarak modellemesi ve yangın güvenliği değerlendirilmesi yapılmıştır. Bu vakada, 146m uzunlukta, 800 yolcu, 90 araç ve 60 kamyon kapasiteli ROPAX gemisinde elektrikli araçların olduğu güverte incelenmek üzere seçilmiştir. Kontrol alanı boyunca sıcaklık dağılımları yangın olayının şiddetini değerlendirmek için önemlidir. Bu nedenle, sıcaklık dağılımını izlemek için yangın kaynaklarının merkezi ile hizalanmıştır ve sıcaklık dağılımları çizdirilmiştir. Sonuçta sıcaklığın dramatik bir şekilde neredeyse 1200 °C seviyelerine yükseldiği izlenmiştir. Gemide kullanılan yapısal elemanlar, elektrikli araçlar ve alandaki ekipmanlar bu sıcaklık seviyesinde organik olarak tutuşabilir ve işlevlerini kaybedebilir. Feribotlardaki bu sıcaklık seviyesi nedeniyle, feribotlarda elektrikli araçların taşındığı alanların veya bölmelerin yapısal olarak yangına dayanıklı malzemelerle tasarlanması gerekmektedir. Bu çalışmada, vaka çalışmasının karmaşıklığının azalması nedeniyle tutuşma ve patlama göz ardı edilmiştir.

Son vaka çalışmasında ise, yangın risk değerlendirme yöntemlerinden biri olan Olay Ağacı Analizi (ETA – Event Tree Analysis) ile bir Ro-Ro yolcu gemisinin yangın güvenliği analiz edilmiştir. Yangın çıkışı ile başlayan olaylar zinciri, yangının çıktığı mahalin tipi, algılama sistemlerinin çalışıp çalışmaması, kullanıcı tepkisi, karar verme, söndürme, kompartımanlıma ve tahliye son bulmaktadır. Toplamda 21 farklı senaryo için oluşturulan olay ağacı analizleri, Ro-Ro yolcu gemilerinde yangın riskinin belirlenmesinde ilk adımı oluşturmaktadır. Bu çalışmada oluşturulan olay ağacı yapısının mürettebatın yangın güvenliği eğitimlerinin planlanmasında bir girdi olarak kullanılması planlanmıştır.

Sonuç olarak, yangın dinamiği simülasyonlarının ve yangın risk değerlendirme yöntemlerinin dahil edildiği performans bazlı bir yolcu gemisi tasarımının, uygulamasının ve işletmesinin yapılması yangın güvenliğinin tesis edilmesinde önem arz etmektedir. Bu çalışma ile de farklı tip yolcu gemileri için ki bunlar yolcu taşımacılığı gemisi, elektrik araç taşıyan ROPAX ve Ro-Ro olmak üzere yangın güvenliği değerlendirilmesi yapılmıştır. Böylece, gemilerdeki yangın güvenliği konusuna yangın dinamiği simülasyonu ve yangın risk değerlendirme yöntemleri ile performans bazlı yolcu gemisi tasarımı, uygulaması ve işletmesi yangın güvenliği bakış açısını ön planda tutarak yapılmaktadır. Bu performans bazlı çalışmalar, gemilerdeki yangın yönetmeliği özelinde yayınlanan yönetmelikler, kurallar ve standartların güncellenmesine katkı sağlayacaktır.

1. INTRODUCTION

1.1 Background

No ship can operate 100% safely or be completely error-free. Hazard classification and risk evaluation are primarily targeted on assessing risk levels and identifying the greatest fire hazards on board. Properly conducted analyses can reduce failure risk to an acceptable level and enhance ship reliability in critical conditions. Therefore, risk assessment applications are of great importance to safeguard the system reliability in ships. It is well known that onboard fires are among the main ship accidents, leading to loss of life and property. If fire on board is not extinguished, it can lead to catastrophic consequences, total actual loss, and severe victims.

In this study, historical datasets of fire incidents globally are obtained from the International Maritime Organization (IMO) database called as Global Integrated Shipping Information System (GISIS). In this information system, there is a wide range of details about maritime. One of them is marine casualties and incidents that include fire incidents as well as flooding, collision, grounding etc. In addition to the incident types, this database enables to select severity of marine casualties and incidents. For the serious and very serious fire incidents, Ro-Ro/Ferry/Passenger ships' average incidence rate is 6.82 out of every 1000 such ships reported serious or very serious fire fatalities between 2000 and 2022. This percentage is the highest among the other types of ships such as tankers, general cargos, fishing vessels, bulk/ore carriers, containers, and tug/supply vessels.

Given the high frequency of fire incidents on passenger ships, fire safety onboard ships have to be analyzed from different perspectives such as fire safety regulations, fire protection systems, fire dynamics simulations and fire risk management. This study focuses on fire safety onboard passenger ships, an interdisciplinary field that combines knowledge from various domains such as engineering, physics, and risk management. The main areas explored in the literature include fire safety regulations and standards, fire dynamics simulation, fire protection systems, and fire risk management. The study applies fire dynamics simulation and fire risk modelling to specific passenger ship types to evaluate their fire safety performance. Fire dynamics simulation plays a crucial role in monitoring the temperature and pressure variations within different zones of a ship, offering valuable insights into fire behavior and how it might spread. This simulation helps in understanding the fire’s potential impact on the ship's structural integrity and the safety of its occupants. In contrast, fire risk modelling focuses on identifying potential fire hazards and determining appropriate safety measures to mitigate the risks, ensuring that preventative actions are in place. Both passive and active fire protection systems are considered in the analysis. Passive systems, such as fire-resistant materials and structural elements, work to contain fires and limit their spread. Active systems, including sprinkler systems, fire detection and alarm systems, and firefighting equipment, are essential for actively combating fire incidents once they occur. In this study, three different case studies are chosen to demonstrate the effort of these fire safety assessment methods on passenger ships. The results of these case studies are shared to highlight the effectiveness of performance-based fire safety designs. These case studies show how fire dynamics simulation and fire risk modelling contribute to enhancing fire safety and ensuring the proper execution of fire safety measures onboard ships. Overall, the aim of this study is to establish a comprehensive, performance-based fire safety framework for passenger ships that not only complies with existing regulations but also adapts to the unique needs of each vessel, improving fire safety outcomes across the maritime industry.

The first case is analyzed for a passenger ferry operating public maritime transportation inland sea in Istanbul called SH SUTLUCE (IMO: 9564009) from Sehir Hatlari fleet and second case is analyzed electric vehicle transportation deck of a ROPAX vessel including both passenger and roll-on/roll-off vehicles transportation. Lastly, a Ro-Ro passenger ship is investigated from the perspective of fire risk management in the third case study. In these three cases, fire dynamics simulation and fire risk modelling methods are used to evaluate fire safety onboard passenger ships.

The International Convention for the Safety of Life at Sea (SOLAS) is indeed a pivotal treaty in maritime safety. Its establishment was significantly influenced by the sinking of the RMS Titanic in 1912, which underlined the need for comprehensive safety standards at sea. The first version of SOLAS, adopted in 1914, set minimum safety requirements for ships, including provisions for lifeboats, emergency equipment, and safety drills. Over the years, the convention has been updated several times to address new safety challenges and technological advancements. The current version, adopted in 1974 and known as SOLAS 1974, has been amended numerous times to ensure it remains relevant. SOLAS covers a wide range of safety aspects, including the construction, equipment, and operation of ships, navigation safety, and the safe handling of cargo. SOLAS have 11 chapters relevant to maritime safety. In terms of fire safety, the key chapter of SOLAS is Chapter II-2: Fire Protection, Fire Detection, and Fire Extinction - Focuses on fire safety measures.

- PART A – General
    - Regulation 1: Definitions and applications of fire safety measures.
    - Regulation 2: Requirements for fire safety plans and emergency instructions.
- PART B – Fire Prevention
    - Regulation 3: Requirements related to the construction and arrangement of ships to prevent fire.
    - Regulation 4: Fire-resisting materials used for ship construction.
    - Regulation 5: Measures for preventing fire in spaces containing flammable liquids or gases.
    - Regulation 6: Combustible materials and the need for control in shipboard spaces.
- PART C- Fire Detection and Extinction
    - Regulation 7: Requirements for the installation of fire detection systems, alarms, and manual fire-fighting appliances.
    - Regulation 8: Fire-extinguishing equipment on board, including automatic systems for various types of spaces (machinery spaces, cargo holds, etc.).
    - Regulation 9: Requirements for fire-fighting systems, including foam and CO2-based systems, depending on the type of fire hazard.
- PART D – Fire Safety in Specific Spaces

  - Regulation 10: Fire protection systems for machinery spaces.
  - Regulation 11: Requirements for fire protection in cargo spaces, especially for bulk cargo.
  - Regulation 12: Specific requirements for fire protection in special areas like accommodation spaces, wheelhouses, and others.
- PART E - Emergency Procedures and Fire Drills
  - Regulation 13: Requirements for fire drills, ensuring that ship's crew are adequately trained and prepared for a fire emergency.
  - Regulation 14: Fire precautions for passenger ships, ensuring their safety during an emergency evacuation.

In addition to SOLAS, The International Fire Safety Systems (FSS) Code is an essential part of the SOLAS Convention, and it provides detailed specifications for fire safety systems and equipment on board ships. The FSS Code consists of 15 chapters, each referring different aspects of fire safety. Here is a brief overview of each chapter:

- Chapter 1: General - Provides general requirements for fire safety systems and includes definitions, documentation, and testing procedures.
- Chapter 2: Fire Main Systems - Details the specifications for fire mains, hydrants, hoses, and nozzles.
- Chapter 3: Fixed Gas Fire-Extinguishing Systems - Covers the requirements for fixed gas fire-extinguishing systems, such as CO2, inert gas, and other gaseous systems.
- Chapter 4: Fixed Foam Fire-Extinguishing Systems - Specifies the standards for fixed foam systems used for fire suppression.
- Chapter 5: Fixed Pressure Water-Spraying and Water-Mist Fire-Extinguishing Systems - Describes the requirements for water-spraying and water-mist systems.
- Chapter 6: Fixed Fire Detection and Fire Alarm Systems - Outlines the requirements for fire detection and alarm systems.
- Chapter 7: Fixed Emergency Fire Pumps - Provides specifications for emergency fire pumps.

- Chapter 8: Automatic Sprinkler, Fire Detection, and Fire Alarm Systems - Details the standards for automatic sprinkler systems, including their fire detection and alarm components.
- Chapter 9: Fixed Fire-Extinguishing Systems for Galley Exhaust Ducts - Specifies the requirements for fire-extinguishing systems in galley exhaust ducts.
- Chapter 10: Sample Extraction Smoke Detection Systems - Covers the standards for sample extraction smoke detection systems.
- Chapter 11: Low-Location Lighting Systems - Describes the requirements for low-location lighting systems to aid evacuation.
- Chapter 12: Fixed Emergency Fire-Fighter's Outfits - Details of the specifications for emergency fire-fighter's outfits, including protective clothing and equipment.
- Chapter 13: Arrangements for Helicopter Facilities - Outlines fire safety arrangements for helicopter facilities on ships.
- Chapter 14: Fixed Fire-Extinguishing Systems for Cargo Spaces - Specifies the requirements for fixed fire-extinguishing systems in cargo spaces.
- Chapter 15: Means of Escape - Provides standards for means of escape, ensuring that safe evacuation routes are available in case of fire.

These chapters collectively ensure that ships are equipped with adequate fire safety measures, significantly reducing the risk of fire-related incidents on board.

In summary, Chapter II-2: Fire Protection, Fire Detection, and Fire Extinction - Focuses on fire safety measures and FSS codes are mainly reviewed from the perspective of fire safety onboard ship codes and regulations.

The evolution of fire computer codes over the past decade has indeed been significant, driven by advancements in computer technology. This progress has facilitated the development of more complex field models, which are essential for accurately assessing fire hazards. These models consider both the thermal and toxic aspects of fires, providing a comprehensive understanding of fire behavior and its potential impacts. Fire modeling can be categorized into three primary types: deterministic, probabilistic and stochastic models. Each of these categories offers unique advantages and limitations.

Deterministic models offer precise predictions based on defined initial conditions and parameters. These models can provide detailed information on fire dynamics, including temperature distribution, smoke movement, and heat flux. They are useful for analyzing specific fire scenarios and understanding the impact of changes in variables like ventilation, material properties, and fire load. In deterministic models, high accuracy requires significant computational resources, which can be time-consuming and expensive. The precision of deterministic models depends heavily on the quality and accuracy of input data.

Probabilistic models are effective for assessing the likelihood of different fire outcomes, which is crucial for risk management and safety planning. They can incorporate uncertainties in input parameters and model predictions, providing a more comprehensive risk profile. The models are suitable for evaluating a wide range of scenarios and conditions, including those with limited or variable data. On the other hand, these models may provide less detailed information on specific fire dynamics compared to deterministic models. Building and validating probabilistic models can be complex and require extensive data and expertise.

Stochastic models incorporate randomness and uncertainty directly into their predictions, making them well-suited for simulating complex systems like fire dynamics where variability and uncertainty are inherent. Here's how they fit into the broader context of fire modeling. Stochastic models explicitly account for uncertainties in input parameters and environmental conditions, leading to more robust risk assessments. They can simulate a wide range of potential outcomes by repeatedly running the model with varying inputs, providing a distribution of possible results rather than a single deterministic outcome. These models can be updated and refined as more data becomes available, improving their accuracy over time. Otherwise, running a large number of simulations to capture variability can be computationally intensive, also developing and validating stochastic models requires a deep understanding of both the physical processes involved and statistical methods. They often require substantial data to accurately characterize the variability and uncertainty in input parameters. Stochastic models are particularly useful in scenarios where there is significant uncertainty or variability in conditions, such as: building design, wildfire prediction and risk management. Assessing fire risks in complex structures where numerous variables (e.g., material properties, ventilation, occupant behavior) can affect outcomes. Modeling the spread of wildfires, which are influenced by numerous unpredictable factors like wind patterns, fuel moisture, and terrain. Evaluating the effectiveness of fire safety measures and emergency response plans under a variety of potential scenarios.

Overall, the integration of more advanced computational methods and increased computational power has allowed for significant improvements in the accuracy and applicability of fire modeling. The choice between deterministic, probabilistic and stochastic models depends on the specific requirements of the hazard assessment, the available data, and the desired balance between detail and computational efficiency. In this study, deterministic models are selected for two case studies depending on the requirements. Among deterministic models, zone and field models are applied to the fire dynamics simulation models.

Zone models are a simplified approach to fire modeling that divides a compartment into a few large regions (zones) to predict the behavior of fire and smoke. They typically use a two-zone approach: an upper hot gas layer and a lower cool gas layer. The compartment is divided into an upper hot gas layer and a lower cool gas layer, representing the primary regions affected by the fire. They rely on simplified mass and energy balance equations for each zone to predict variables like temperature, smoke concentration, and gas composition. Zone models are computationally efficient, requiring less processing power and time compared to more detailed models. However, zone models have some limitations such as limited ability to capture detailed spatial variations within a compartment, not well-suited for large or complex spaces where fire behavior is more intricate, and simplified models may not accurately capture detailed interactions between fire, smoke, and ventilation systems.

Field models, or CFD models, use detailed numerical methods to simulate the physical and chemical processes involved in fire dynamics on a fine spatial scale. They divide the compartment into a large number of small cells (control volumes) and solve the fundamental equations of fluid dynamics and thermodynamics for each cell. The compartment is divided into thousands or even millions of small cells, providing detailed spatial resolution of fire behavior. They solve the Navier-Stokes equations, which govern fluid flow, along with equations for heat transfer, combustion, and species transport. Also, this model can capture intricate details of fire spread, smoke movement, and interactions with the environment. Field models are used for in-depth analysis of fire scenarios, especially in complex geometries or large spaces and help in optimizing the design of fire protection systems, smoke control systems, and ventilation systems. However, this model requires significant computational power and time due to the complexity and fine resolution of the calculations and detailed input data and expertise in CFD modeling.

Both models have their place in fire safety engineering, with the choice depending on the specific requirements of the scenario being analyzed. Zone models are suitable for many practical applications where efficiency and simplicity are important, while CFD models are used when detailed analysis and high accuracy are required.

In summary, due to the complexity of geometry and the need of accuracy on the results field model inside the deterministic models is selected to simulate fire dynamics in the selected compartments of the case studies.

Fire protection systems on board ships are crucial for safety and include several types of equipment and procedures designed to detect, contain, and extinguish fires. Here are the primary systems and measures:

- Fire Detection Systems:
    - Smoke Detectors: Detect smoke particles and trigger alarms.
    - Heat Detectors: Detect changes in temperature and activate alarms.
    - Flame Detectors: Identify the presence of flames and initiate alarms.
- Fire Suppression Systems:
    - Water-Based Systems:
        - Sprinkler Systems: Automatically release water when a fire is detected.
        - Hydrants and Hoses: Allow crew to manually fight fires using water.
        - Water Mist Systems: Use fine water sprays to control and suppress fires.
    - Gas-Based Systems:

        - CO2 Systems: Flood the area with carbon dioxide to displace oxygen and extinguish the fire.
        - Inert Gas Systems: Use gases like nitrogen or argon to reduce oxygen levels and put out fires.
    - Foam Systems: Apply foam to smother fires, particularly effective for flammable liquids.
    - Dry Chemical Systems: Disperse chemical powders to interrupt the chemical reactions in a fire.
- Fire Extinguishers:
    - Portable Fire Extinguishers: Different types for various fire classes (A, B, C, D, K).
    - Fixed Fire Extinguishers: Installed in specific locations, like engine rooms or galleys.
- Fire Containment:
    - Fire-Resistant Bulkheads and Doors: Compartmentalize the ship to prevent the spread of fire.
    - Ventilation Control: Shutting down ventilation systems to prevent the spread of smoke and fire.
- Emergency Systems and Procedures:
    - Fire Alarms and Public Address Systems: Alert crew and passengers about a fire.
    - Emergency Lighting and Exit Signs: Guide people to safety during an evacuation.
    - Fire Drills and Training: Regular drills to ensure crew members are prepared to handle fire emergencies.
- Specialized Systems:
    - Galley Protection Systems: Automatic suppression systems for kitchens.

    - Engine Room Protection: High-capacity suppression systems due to the high risk of fire in engine rooms.
- Safety Management Systems:
    - Safety Plans and Manuals: Detailed procedures for fire prevention and emergency response.
    - Regular Maintenance and Inspections: Ensuring all fire protection systems are operational and compliant with regulations.

These systems work together to provide comprehensive fire protection on ships, safeguarding lives, property, and the environment.

In the first case, among the fire protection systems fire containment and fire suppression systems are implemented to the fire dynamics simulations. From the fire containment fire-rated bulkheads and decks are designed to model and from the fire suppression systems, water-based sprinkler systems are established in the control room derived from one nozzle, two nozzles and four nozzles in different scenarios. In the second case, only fire containment systems called fire-rated hull are designed to the model in the fire dynamics simulations. Due to the literature gap of the suppression of battery fires, any fire extinguishing systems cannot be implemented in the scenarios. Lastly, the third case study is structured depending on fire risk modelling with event tree analysis method to evaluate fire risk onboard Ro-Ro passenger ships.

1.2 Aims and Objectives

The aims of the study are as follows:

- Outline strategies for mitigating fire risk, particularly on passenger ships, with three different types of passenger ships these are a domestic public transportation passenger ship, a ROPAX including electric vehicle transportation space and a Ro-Ro passenger ship.
- Simulate fire dynamics including fire protection active and structural systems in the part of passenger ship and analyze engine room fires due to the fatality and risk of these fires,
- Observe outcomes of fire protection systems for instance extinguishing and structural systems on the fire dynamics simulation,

- Develop a risk framework for onboard fire casualties, especially on passenger ships, to minimize their occurrence,
- Determine which variables contribute to onboard fire casualties, particularly on passenger ships, thereby expanding our understanding of these phenomena and supporting new approaches to preventing onboard fires.

1.3 Thesis Layout

The brief thesis layout is as follows:

- Chapter 2 provides literature review in the field of fire safety onboard ships and includes the sub-sections such as fire safety regulations, fire modelling, fire risk assessment, evacuation modelling and fire protection systems.
- Chapter 3 contains detailed information about fire principles, objectives, qualitative and quantitative fire safety analysis methods, fire dynamics modelling and fire risk modelling methods in the subject of materials and methods.
- Chapter 4 provides general insight of fire protection systems divided into two main sub-topics, active and passive fire protection systems and implementations of these systems to this study.
- Chapter 5 gives historical data sets of fire incidents depending on types of ships and brief details about past fire fatal incidents onboard ships globally.
- Chapter 6 provides the methodologies used in this study. Data collection and analysis, fire modelling and fire risk assessment methods are analyzed in the methodology section.
- Chapter 7 contains the results of fire dynamics simulations and fire risk modelling onboard passenger ships. Firstly, background of fire dynamics simulations and the details of case study in terms of fire dynamics simulations. This chapter includes model validation, mesh dependency, boundary and initial conditions of model, details of the case studies and fire dynamics simulation results. In this chapter, three case studies explain in detail. First one is a public transportation passenger ship called as SH-SUTLUCE from Sehir Hatları fleet and second one is a ROPAX ship that is transporting electric vehicles in the

selected compartments. Fire modelling of these two cases is driven by a Computational Fluid Dynamics method called field modelling and simulations are designed depending on the exact models including active and passive fire protection systems such as fire-rated bulkheads, sprinklers etc. In these simulations, critical fire simulation parameters such as Heat Release Rate (HRR), Pressure (P) and Temperature (T) are monitored along the time and these two cases have fatal consequences depending on fire safety. Lastly, the details of fire risk modelling from the perspective of event tree analysis (ETA) method and gives a case study of fire safety event tree analysis for a Ro-Ro passenger ship.

- Chapter 8 gives conclusions from the study and recommendations for future research.

1.4 Hypothesis

Depending on the high fire incidents rate onboard passenger ships, this study focuses on fire safety analysis of three different passenger ship types: public transportation passenger vessel from Istanbul Municipality, ROPAX including electric vehicle space and Ro-Ro passenger ship. These are analyzed depending on fire modelling and fire risk management performances.

Main outcome from this case studies are that performance-based design including both active and passive fire protection systems have to be adapted to passenger ships by using a fire modelling method and a risk assessment method. In this study, a computational fluid dynamics-based field model is used for field modelling and event tree analysis is used for fire risk assessment. Performance based fire safety design is not implemented to the codes and regulations in maritime industry. This gap can be fulfilled with the contribution of this study, initially for passenger ships.

2. LITERATURE REVIEW

The literature review section covers the main aspects of fire safety onboard passenger ships. Firstly, the codes and regulations that control and impose fire safety in the maritime industry are analyzed including the developments and improvements over time. Afterwards, studies that focus on marine fields are reviewed with the subjects of fire modelling, evacuation modelling, fire protection systems onboard ships specifically passenger ships and fire risk management.

2.1 Fire Safety Codes and Regulations

The International Convention for the Safety of Life at Sea (SOLAS) is indeed a crucial treaty governing maritime safety, with its origins dating back to the tragic sinking of the Titanic in 1912. The initial version of the convention, established in 1914, aimed to establish minimum safety requirements for ships. Over the years, subsequent versions of the convention have been continuously amended in response to major accidents, reflecting evolving safety concerns and technological advancements (SOLAS, 2020). When modifications to SOLAS regulations are deemed necessary, typically after accidents or in response to emerging safety concerns, proposals are submitted to the International Maritime Organization's (IMO) Maritime Safety Committee (MSC). If many delegates agree on the proposal, it is then discussed within the Fire Protection (FP) sub-committee. This sub-committee calls for papers on the subject and carefully considers the submitted materials. Proposed changes, in the form of draft amendments, are then reported back to the MSC for further review. After this extensive review process, the proposed amendments are circulated to all participating countries for consideration. A minimum period of six months is typically allowed for countries to review and provide feedback on the amendments. Following adoption by the MSC, contracting governments have a two-year window to raise any objections before the amendments enter into force. This process ensures that all stakeholders can contribute to the development of new regulations and that there is sufficient time for implementation. However, the amendments procedure has been criticized for its slow pace. In response to these concerns, a completely new version of the SOLAS convention was adopted in 1974. Despite the introduction of this new convention, amendments have continued to be made over the years to address emerging safety challenges and technological advancements. Thus, the SOLAS convention remains a dynamic and evolving framework for ensuring the safety of ships and their passengers (Cowley, 2006).

Chapter II-2 of the SOLAS convention indeed plays a critical role in ensuring fire safety onboard ships. This chapter addresses various aspects of fire prevention, detection, containment, and firefighting measures to mitigate the risk of fire incidents at sea.

- Division and separation: The regulations require ships to have thermal and structural boundaries that divide different areas of the ship, helping to contain fires and prevent their spread.
- Restriction of combustible materials: There are provisions aimed at limiting the use of combustible materials onboard to decrease the likelihood and seriousness of fires.
- Detection of fire: Requirements are in place for the installation and maintenance of fire detection systems to promptly identify and alert crew members to the presence of fires.
- Containment and extinction procedures: Procedures are outlined for containing and extinguishing fires once they occur, including the use of fire suppression systems and firefighting equipment.
- Means of escape: Special provisions ensure that adequate means of escape are available in the event of a fire, including clear pathways and exits for crew and passengers to evacuate safely.
- Availability of firefighting appliances: Regulations mandate the availability and proper maintenance of firefighting equipment such as extinguishers, hoses, and firefighting suits to enable effective response to fire incidents.
- Minimization of ignition sources: Measures are implemented to minimize potential ignition sources onboard, reducing the risk of fires starting in the first place.

Chapter II-2 has undergone significant amendments over the years to address emerging safety concerns and incorporate advancements in fire safety technology and practices. These revisions reflect ongoing efforts to enhance the fire safety standards for ships and ensure the protection of lives and property at sea and following are some brief highlights of these amendments.

The Titanic disaster in 1912 was a wake-up call for the international community to address safety concerns in maritime transportation. While the 1914 SOLAS Convention couldn't come into force due to World War I, its basic fire safety requirements laid a foundation for subsequent conventions. The tragic fire aboard the Morro Castle in 1934 underscored the urgency of improving fire safety measures on passenger ships. The subsequent investigation and lessons learned led to the development of non-combustible construction regulations, which are crucial components of modern fire safety regulations for passenger ships. World War II brought about advancements in maritime technology, which were incorporated into the 1948 SOLAS Convention. This convention introduced significant changes, such as the addition of dedicated parts (D, E, and F) in Chapter II exclusively focused on fire safety. Moreover, the 1948 SOLAS Convention extended its requirements to both passenger and cargo ships, highlighting a growing emphasis on fire safety across the maritime industry. The 1960 SOLAS Convention further refined fire safety regulations by applying certain passenger ship requirements to cargo ships, recognizing the importance of ensuring safety standards across all types of vessels.

The sequences of fires onboard worldwide passenger vessels in the 1960s served as a catalyst for significant changes in maritime safety protocols. The 1974 SOLAS Convention, which superseded previous iterations, notably addressed fire safety concerns by instituting dedicated chapters for construction requirements. Chapter II-1 focused on structural integrity, machinery, electrical systems, and stability, while Chapter II-2 specifically addressed fire protection, detection, and suppression measures. This division allowed for more comprehensive and targeted regulations to mitigate fire risks onboard ships. Key provisions of the 1974 SOLAS included mandates for new passenger ships to be constructed using non-combustible materials, as well as requirements for the installation of fixed fire sprinklers or detection systems. These measures aimed to enhance fire prevention and response capabilities, minimizing the potential for catastrophic incidents. Moreover, the convention also updated regulations for cargo ships, introducing specialized guidelines tailored to specific vessel types such as tankers. These tailored regulations acknowledged the unique fire hazards associated with different cargo types, thereby ensuring a more nuanced approach to fire safety in maritime transport. The 1981 Amendments and subsequent revisions not only refined existing regulations but also introduced new provisions to keep pace with emerging technologies and lessons learned from past accidents. The adoption of a new structure for SOLAS Chapter II-2, with a focus on the "fire scenario process," underscores a shift towards a more holistic and adaptable framework for addressing fire safety issues.

The fire aboard the Scandinavian Star passenger ship in 1990 was indeed a tragic event that highlighted the need for improved fire safety measures in the maritime industry. In response to this incident and other similar accidents, the International Maritime Organization (IMO) took significant steps to enhance fire safety regulations for passenger ships, as well as cargo ships and tankers. The comprehensive set of fire safety amendments adopted by IMO in December 1992 mandated the installation of modern fire safety features, such as automatic sprinkler and smoke detection systems, and the upgrading of fire safety bulkheads to non-combustible materials. These measures were aimed at bringing the safety standards for passenger ships closer to those of modern hotels. The 1996 amendments to SOLAS Chapter II-2, which came into force in 1998, further enhanced fire safety measures for passenger ships, cargo ships, and tankers. Additionally, the development and mandatory implementation of the International Code for the Application of Fire Test Procedures (FTP Code) standardized laboratory testing and type approval procedures for fire safety products installed on ships.

That's a great overview of the revisions made to SOLAS Chapter II-2 by the International Maritime Organization (IMO) in December 2000, which came into force on July 1, 2002. The restructuring to focus on the "fire scenario process" rather than ship type was a significant change aimed at enhancing safety measures. By starting with prevention, detection, and suppression, and progressing to escape, the regulations address the critical aspects of fire safety comprehensively. Moving specific system-related technical requirements to the International Fire Safety Systems Code (FSS Code) was a logical step to streamline the SOLAS regulations and provide clearer guidance to maritime stakeholders. The inclusion of purpose statements and functional requirements for each regulation further aids understanding and implementation for port and flag States. The addition of Part E, dedicated to human element matters such as training, drills, and maintenance issues, reflects the recognition of the crucial role played by human factors in ensuring maritime safety. Part F's introduction of a methodology for approving alternative or novel designs and arrangements acknowledges the evolving nature of maritime technology and encourages innovation while maintaining safety standards.

The FSS Code plays a crucial role in ensuring international principles for fire safety systems on ships, particularly those required by the revised SOLAS Chapter II-2. This separation of statutory requirements into the Convention and technical provisions into the FSS Code helps streamline regulations, making them more accessible for various stakeholders like equipment manufacturers and systems engineers. The FSS Code consists of 15 chapters, each focusing on specific systems and arrangements. Chapter I contains definitions and general requirements for approval of alternative designs and toxic extinguishing media. It's important to note that Chapter II-2 applies to ships constructed on or after July 1, 2002. However, there are provisions that also apply to ships built before this date, particularly regarding repairs, alterations, and modifications. For instance, ships undergoing repairs or modifications must continue to comply with previous requirements, and substantial alterations may require meeting the standards applicable to newer ships. Additionally, regulations cover specific areas such as cargo pump rooms in tankers and the installation of emergency escape breathing devices (EEBDs) and fire-extinguishing systems. Moreover, operational requirements outlined in Part E, including regulations for operational readiness, maintenance, instructions, onboard training, and drills, are also mandated for existing ships. Certain prohibitions and requirements for new installations on existing ships, such as the use of Halon and perfluorocarbons in fire-extinguishing systems and specifications for deep-fat cooking equipment, are also detailed. Passenger ships above a certain gross tonnage are mandated to comply with regulations for fixed local application fire-fighting systems, ensuring protection for specific machinery spaces without the need for extensive shutdown procedures or personnel evacuation. Overall, the FSS Code establishes comprehensive standards for fire safety systems on ships, ensuring a high level of safety for passengers, crew, and cargo.

The evolution of regulations surrounding fire safety at sea, particularly in response to incidents like the one aboard the Star Princess in 2006, underscores the maritime industry's ongoing efforts to enhance safety measures. The revisions to SOLAS Chapter II-2 and the International FSS code reflect a shift towards prioritizing casualty prevention and improving survivability in the event of an incident. One notable aspect of these amendments is the emphasis on alternative designs and arrangements, allowing for flexibility in meeting safety challenges while adhering to the regulations. This approach acknowledges the limitations of traditional prescriptive rules and recognizes the need for innovative solutions to address evolving risks. The introduction of Part F, Regulation 17, outlines a methodology for approving novel designs, ensuring that they meet or exceed the safety standards set by prescriptive rules. This includes conducting risk-based fire engineering analyses to demonstrate the safety performance of alternative designs.

Overall, these developments illustrate the maritime industry's commitment to continuous improvement in fire safety measures, driven by a combination of regulatory updates, technological advancements, and a proactive approach to design.

The Safety of Life at Sea (SOLAS) convention requires that fire drills be conducted at least once a month on ships, with some exceptions for short voyages and other specific circumstances. These drills must be as realistic as possible to ensure that the crew is well-prepared for any potential fire emergencies that may arise while at sea. The ship`s master and the company responsible for the ship`s operation is primarily responsible for ensuring compliance with SOLAS fire drill requirements. They must ensure that fire drills are conducted regularly and that all crew members are familiar with their roles and responsibilities in the event of a fire. Non-compliance with SOLAS fire drill requirements can result in serious consequences for ship owners and operators, including fines, detention of the ship, and even criminal liability in some cases. It is essential to take these requirements seriously and ensure that all necessary drills are conducted as required. While SOLAS does not provide specific guidelines for the conduct of fire drills, it does require that they be as realistic as possible. This means that drills should simulate actual fire scenarios, including the mobilization of crew, use of firefighting equipment, and communication with shore-based assistance if necessary. Ship operators have some flexibility in customizing their fire drill procedures to suit the specific needs of their vessels, if they ensure that the drills meet the minimum requirements set out in SOLAS. It is important to strike a balance between meeting these requirements and tailoring drills to the unique characteristics of each vessel. According to SOLAS, crew members should undergo regular training for fire drills to ensure that they are well-prepared to respond to fire emergencies. This training should be conducted at least once every three months, with additional training provided to new crew members as part of their initial familiarization with the ship`s fire safety procedures. On passenger ships, an abandoned ship drill and fire drill shall take place weekly. The entire crew need not be involved in every drill, but each crew member must participate in an abandoned ship drill and a fire drill each month. Passengers shall be strongly encouraged to attend these drills. Effective fire drills require thorough planning and coordination, clear communication with all crew members, and regular evaluation and feedback to identify areas for improvement. It is important for ship operators to foster a culture of safety on board and encourage active participation in fire drills to ensure that crew members are well-prepared for any potential emergencies. Classification societies play a crucial role in verifying compliance with SOLAS fire drill requirements through regular inspections and audits of ships. They assess the effectiveness of fire drills, the condition of firefighting equipment, and the overall fire safety management system to ensure that ships meet the necessary standards for fire safety at sea. Crew members play a crucial role in the success of fire drills by actively participating, following instructions, and providing feedback on their experiences. Their involvement in fire drills is essential for identifying any potential shortcomings in the ship`s fire safety procedures and ensuring that they are well-prepared to respond to fire emergencies while at sea.

In order to summarize the drill procedure onboard ships, Figure 2.1 depict the check list of on-board training, drills and inspections of fire appliances & life-saving appliances as an example. Also, SOLAS regulation number and frequency of the drill or training are included in Figure 2.1.

Requirement	SOLAS Regulations	Service company	Crew	Ship' s log	Intervals							
					Weekly	Monthly	3-Monthly	4-Monthly	6-Monthly	Annually	2-Yearly	5-Yearly
Watertight door drills	II-1/21 (II-1/23)		x	x	x2							
Damage control drill – passenger ships(applicable from January 2020)	II-1/19-1		x	x			x			x8		
Abandon ship drill and fire drill - cargo ships	III/19.3		x	x		x						
Abandon ship drill and fire drill - passengerships	III/19.3, III/30		x	x	x							
Abandon ship drill - lowering lifeboats	III/19.3.4.1, MSC/Circ.1578		x	x	x2	x3						
Abandon ship drill - launching lifeboats & rescue boats	III/19.3.4.3 & 19.3.4.6, MSC.1/Circ.1578		x	x		x1	x					
Abandon ship drill - free-fall lifeboat drill	III/19.3.4.4, MSC/Circ.1578		x	x			x					
Abandon ship drill - launch (or simulatedlaunch) free-fall lifeboats	III/19.3.4.4, MSC/Circ.1578		x	x					x			
Abandon ship drill - MES drill	III/19.3.4.8		x	x	x2	x3						
Abandon ship drill - MES training	III/19.3.4.8		x	x							x	
Abandon ship drill - testing of emergencylighting	III/19.3.4.9		x	x	x2	x3						
Enclosed Space Entry and Rescue Drills	III/19.3.3 & 19.3.6		x	x			x7					
LSA & fire on-board training	III/19.4.1 & .2		x	x	x2	x3						
Davit-launched liferaft training	III/19.4.3		x	x				x				
Launching appliances - inspect wire ropes	III/20.4 & MSC.402(96)	x	x							x		
Launching appliances - wire ropes renewed	III/20. 4 & MSC.402(96)	x	x									x4
Survival craft, rescue boats and launching appliances (visual inspection)	III/20.6.1 & MSC.402(96)		x	x	x							
Test run of lifeboat and rescue boat engines	III/20.6.2 & MSC.402(96)		x	x	x5							
Davit launched lifeboats - Moved fromstowed position	III/20.6.3		x	x	x3							
Testing of public address and general alarmsystem	III/20.6.4		x	x	x							
Davit launched lifeboats - Turned out fromstowed position	III/20.7.1		x			x						
Inspection of LSA including lifeboat equipment	III/20.7.2 & III/36.1		x			x						
Steering gear tests	V/26.1 & .2		x	x	x6							
Emergency steering drill	V/26.4		x	x			x					

1 Dedicated rescue boats launched monthly, if possible.
2 Passenger ships.
3 Cargo ships
4 When necessary due to deterioration of the falls or at intervals of notmore than 5 years.
5 In special cases the Flag may waive this requirement for ships constructedbefore 1 July 1986.
6 Within 12 hours before departure or weekly for ships which regularlyengage on voyages of short duration.
7 Every two months.
8 Passenger ships: activation of the shore-based support, if provided, toconduct stability assessments for the simulated damage conditions

Figure 2.1 : Example check list of onboard drills of fire appliances (INSB, 2020).

2.2 Fire Safety Literature Review with Focus on the Marine Field

2.2.1 Fire modelling

Fires in enclosed spaces can be particularly dangerous because of the limited ventilation, restricted airflow, and the potential for rapid escalation as heat and smoke accumulate. Compartment fires are particularly challenging because the enclosed space limits ventilation, allowing heat, smoke, and toxic gases to accumulate. This can indicate to rapid fire growing and a higher risk of flashover, where the entire contents of the room ignite simultaneously. Ventilation plays a crucial role in fire dynamics within compartments, as it affects the movement of heat and smoke and can influence fire behavior. Firefighters need to carefully manage ventilation to control the spread of fire and improve conditions for rescue and suppression efforts (Drysdale 1988).

Deterministic fire models are indeed essential tools for assessing the behavior and consequences of compartment fires. These models use mathematical equations based on fundamental principles of fire dynamics to simulate various aspects of fire development, including heat release rate, temperature distribution, smoke propagation, and movement of gases within a compartment (SFPE, 2016).

Indeed, the evolution of fire modeling has been quite fascinating. It began with semi-empirical and simple analytical models, often calculated by hand. These early models provided foundational insights into fire behavior but had limitations in terms of accuracy and scope. The development of zone models marked a significant advancement. These models divided the fire space into discrete zones, allowing for more detailed analysis compared to the hand-calculation models. Zone models became the first generation and the most widely used type of fire models due to their relative simplicity and computational efficiency. They were particularly valuable for understanding fire dynamics in confined spaces. However, the advent of Computational Fluid Dynamics (CFD) revolutionized fire modeling by enabling simulations based on first principles. CFD models solve the fundamental conservation equations of mass, energy, and momentum, providing a more comprehensive understanding of fire behavior. This approach, often referred to as field modeling or CFD modeling, allows for detailed simulations of complex fire scenarios, including interactions with structures, ventilation systems, and other environmental factors. CFD modeling has proven to be highly successful in addressing various fire safety challenges, such as optimizing vessel designs for fire evacuation, assessing the effectiveness of fire suppression systems, and predicting the spread of fire in different scenarios. Its ability to simulate fire phenomena with high fidelity has made it an indispensable tool in fire engineering and risk assessment (Novozhilov 2001).

Friedman's (1992) survey on computer models for fire and smoke provides valuable insights into the complexities and challenges of simulating fire behavior in various scenarios. The extensive coverage of different types of models reflects the multifaceted nature of fire modeling and the diverse requirements for different applications. The recommendation to use zone models for simpler geometries and field models for more complex structures underscores the importance of selecting appropriate modeling approaches based on the specific characteristics of the fire scenario being analyzed. Zone models offer simplicity and computational efficiency, making them suitable for basic scenarios with straightforward geometries, while field models provide greater flexibility and accuracy for more intricate environments. The discussion on fire representation, including options such as constant or time-varying heat release rates, highlights the need for flexibility in modeling approaches to accommodate different fire behaviors and dynamics. Understanding the factors influencing fire spread, such as radiation feedback and environmental conditions, is crucial for developing realistic simulations. The emphasis on empirical or analytical models derived from bench scale fire experiments underscores the importance of experimental validation and data-driven model development. Detailed experimental data enables the calibration and validation of fire models, enhancing their accuracy and reliability. Moreover, Friedman's identification of key uncertainties in fire modeling, such as incomplete combustion products and heat transfer mechanisms, highlights the challenges inherent in predicting fire behavior with precision. Addressing these uncertainties requires ongoing research efforts and improvements in modeling techniques to enhance the fidelity of fire simulations. Overall, Friedman's survey provides valuable guidance for researchers and practitioners involved in fire modeling, emphasizing the importance of selecting appropriate modeling approaches, leveraging experimental data, and addressing key uncertainties to improve the accuracy and reliability of fire simulations.

Olenick and Carpenter (2003) presents a significant advancement in the field of fire and smoke modeling, building upon the foundational work of Friedman (1992). By identifying and categorizing 168 computer-simulated programs across various categories, this survey provides a comprehensive overview of available tools for fire engineering and design. The inclusion of outdated models, alongside contemporary ones, ensures completeness and historical context, allowing users to understand the evolution of fire modeling over time. Notably, the expansion in the number of identified models since Friedman's survey reflects advancements in computing power, research, and practical knowledge in the field. The detailed information collected, including classification, description, cost, user’s guide, technical references, and developer contacts, empowers users to make informed decisions regarding the selection of appropriate fire models for specific applications. The emphasis on egress models, with features such as accounting for physiological effects and visualizing occupant movement, underscores the sophistication and practical relevance of the surveyed tools. The decision to make the survey data publicly available on the internet demonstrates a commitment to accessibility and transparency, enabling fire engineers, designers, and other stakeholders to access vital reference data easily. Moreover, the subsequent update of the database in 2007 reflects a dedication to maintaining relevance and accuracy considering evolving technologies and methodologies.

The SAFETY-FIRST project conducted by Ramsdale *et al.* (2003) examined various fire models for their suitability in applications concerning fire safety on large passenger ships. The focus was on both zone models and field models, each with its own set of strengths and limitations. Six zone models were reviewed in detail: HAZARD I (FAST), CCFM.VENT, CFAST, Harvard CFC V and VI, and FIREWIND. Each model was evaluated based on aspects like fire behavior, plume dynamics, heat transfer, ventilation effects, and consideration of chemical substances. The study emphasized the significance of the heat release rate of the design fire as a crucial input, along with parameters such as fuel composition and product yields affecting toxic gas concentrations. While no single model was found to possess all desired features, CFAST stood out due to its widespread usage and well-documented validation literature. However, the study advised caution regarding its applicability and sensitivity to input data. Seven field models were also examined, including general-purpose computational fluid dynamics (CFD) software like CFX, FLUENT, and STAR-CD, as well as fire-specialized models like JASMINE, KAMELEON FIRE 3D, SMARTFIRE, and SOFIE. These models demonstrated capabilities in simulating oxygen consumption, fire spread, post-flashover behavior, and other relevant parameters. The choice between zone and field models depends on factors like computational speed, ease of use, and the complexity of the fire scenario. Zone models offer faster execution and simpler operation but are limited in their applicability to specific cases. Field models, however, provide more flexibility and can handle complex situations, allowing for the prediction of parameters that zone models may struggle to compute, such as flame temperature and fire source geometry.

The study conducted by the Fire Safety Engineering Group at the University of Greenwich, focusing on fire evacuation simulations at sea, provides valuable insights into the complex dynamics of ship evacuations under various scenarios. By coupling the SMARTFIRE and maritime EXODUS models, the researchers were able to account for both fire impact on individuals and the effects of sea status on evacuation procedures. The scenarios examined underscore the importance of considering multiple factors, including fire presence, sea conditions such as heel angle, and mitigation measures like fire suppression systems. Each scenario revealed distinct challenges and outcomes, highlighting the need for comprehensive evacuation planning and safety measures in maritime environments. In particular, the introduction of a fire significantly affected evacuation times and outcomes, with fatalities observed near the fire location. The implementation of water mist fire suppression demonstrated promising results in reducing casualties, albeit at the expense of increased evacuation time. However, it's crucial to acknowledge the limitations of the study, such as the exclusion of toxic effects from fire products and certain assumptions regarding passenger behavior, like crossing in front of the fire room. These factors could potentially alter the results and underscore the importance of further research and refinement in ship evacuation modeling (Galea, 2004).

Shigunov (2005) marks a significant advancement in fire engineering, particularly in the realm of ship design. By offering a numerical method for fire modeling in multiple ship compartments. This study provides a practical tool that can be utilized in the assessment of various design alternatives. This is crucial in an industry where safety and efficiency are paramount concerns. One notable aspect of the method is its emphasis on speed and robustness. In engineering applications, especially in fields like ship design, computational efficiency is highly valued. Fire behavior can be significantly influenced by the structure of a vessel, including the materials used for compartment walls. By enhancing the modeling of these walls, the method provides a more realistic representation of fire spread and containment within a ship. Additionally, the efficient algorithm for pressure calculations enhances the method's accuracy and applicability. Pressure dynamics play a crucial role in fire scenarios, affecting factors such as smoke propagation and structural integrity. By incorporating an efficient algorithm for pressure calculations, the demonstration of the method's performance on two examples with available experimental results adds credibility to its efficacy. Being able to validate the numerical approach against experimental data enhances confidence in its predictive capabilities and further underscores its potential for practical application in ship design.

Salem (2006) provides the light on the landscape of fire modeling, particularly in terms of zone and field models, as well as their applicability in various scenarios. It's interesting to note the diversity in models identified, with 56 zone models and 25 field models being cataloged. The distinction between zone and field models seems crucial, with each having its own strengths and limitations. Zone models are particularly useful for their efficiency in simulating smoke movement in multi-compartment geometries, making them suitable for certain applications such as onboard ships where speed is essential. However, the limitation arises when considering the variability of fire effluents parameters across different scenarios. This underscores the importance of understanding the specific requirements of a given scenario when selecting a model. The relationship between zone models like CFAST, BRANZFIRE, and Raeume with a field model like FDS provides valuable insights into their relative strengths and weaknesses. While no single zone model emerges as universally applicable to all fire effluents parameters in all applications, the study suggests that a well-written zone code can still serve as a useful tool for comparative studies, particularly in scenarios where speed is a priority. Furthermore, exploration of explosion and evacuation models, particularly the identification of maritime EXODUS as suitable for maritime applications due to its ability to simulate factors like heel and the effect of fire effluent on passengers' movement, demonstrates the breadth of considerations in fire modeling beyond just smoke movement.

Jia *et al.* (2004) utilizes the CFD-based fire simulator SMARTFIRE for investigating the Swissair Flight 111 crash brought forth significant advancements in air crash investigations. The simulator's capability to navigate the intricate curved geometry of the aircraft fuselage, along with the labyrinth of cabling, ducting, and other utilities in the above-ceiling voids, provided a crucial advantage. By employing separate drawing and meshing software to refine simulation settings and incorporating data from experiments to determine heat release rates, material properties, fire spread rates, and material behaviors, Jia *et al.* (2024) was able to simulate various fire scenarios. The simulations encompassed scenarios ranging from ventilation airflow conditions before the fire ignition to fire flow modeling utilizing the initial ventilation flow conditions. These simulations played a pivotal role in the investigation, offering a better comprehension of the potential impacts, or their absence, of numerous variables associated with the in-flight fire.

Using Computational Fluid Dynamics (CFD), particularly Large Eddy Simulation (LES) codes like the Fire Dynamics Simulator (FDS) developed by the National Institute of Standards and Technology (NIST), offers an efficient means to predict various aspects of fires, such as plume appearances, dispersion of ignition products, and heat effects on surrounding objects. Ryder *et al.* (2004) demonstrated the efficacy of FDS through validation runs and applications in process safety. FDS excels in creating realistic models of process geometries, allowing for the evaluation of explosion and fire risks with distinct advantages over traditional CFD codes. It can produce transient solutions to fire and explosion growth using less sophisticated hardware, such as PC-type computers instead of UNIX workstations. Moreover, it can solve longer time histories (up to hundreds of seconds) with minimal computational resources and run time. Additionally, results can be analyzed, viewed, and tabulated in real-time within a PC environment. However, there are tradeoffs to consider. Rapid computations on PCs may require sacrificing grid resolution or sub-grid modeling, depending on the size of the modeled geometry. These tradeoffs should be carefully evaluated based on the specific requirements of the simulation.

The development of Fire and Smoke Simulator (FSSIM) sounds like a significant advancement in fire modeling, especially for scenarios involving complex ventilation and multiple compartments. Its foundation on MELCOR's thermal hydraulic routines provides a robust base for accurate simulations. The inclusion of features like remote ignition, multilayer heat conduction, and arbitrarily complex HVAC systems enhances its versatility and applicability to various real-world scenarios. The positive comparison with established models like CFAST and FDS in predicting fire behavior in single compartments with vent openings indicates the reliability and effectiveness of FSSIM. Its successful application in predicting fire and smoke spread onboard naval vessels demonstrates its practical utility in critical environments. Further development plans to incorporate detection and suppression systems, fire spread, progressive flooding, and integration with other software tools show a comprehensive approach to addressing broader aspects of fire safety and emergency response. The potential for runtime interaction with digital design documents for automated data extraction is particularly promising, streamlining the modeling process and improving efficiency (Floyd et al, 2015).

Nikolaou and Spyrou (2009) provides a comprehensive review of numerical fire modeling techniques applicable to passenger ships. They discuss various models suitable for simulating fire growth and smoke spread onboard ships, including the network model FSSIM and the zone model CFAST. While FSSIM is a simplistic network model treating each compartment as a single node, CFAST is recommended over other models due to its integration capabilities with risk analysis and its suitability for simulating fire scenarios onboard ships. Additionally, the review covers field models such as CFX by ANSYS, JASMINE by BRE, SMARTFIRE by the University of Greenwich, and FDS by the National Institute of Standards and Technology. These models offer more detailed simulations and are capable of handling complex scenarios, such as two-deck scenarios. A brief comparison between CFAST and FDS showed agreement in the early stages of fire but disagreement in the later stages. While CFAST is suitable for simpler scenarios with a limited number of compartments, FDS excels in simulating more complex cases and provides relevant parameters. However, the paper also highlights certain limitations and drawbacks of FDS, including the absence of material properties necessary for modeling solid combustion and the complexity of representing non-rectilinear shapes. Moreover, there is a noted need to reduce uncertainty in terms of both physical and numerical knowledge, as well as randomness in the fire modeling process. Despite these challenges, advancements in numerical fire modeling have significantly improved the understanding and prediction of fire behavior onboard passenger ships.

Yu *et al.* (2016) appears to be a novel method for simulating the expanding rule of ship cabin fire and smoke. By utilizing a combination of numerical calculation models centered on ventilation networks, field models, and zone models, the researchers aimed to accurately characterize ship cabin fire scenarios. The integration of these models into hybrid simulation technology allows for a comprehensive dynamic simulation of fire and smoke behavior in ship cabins. This approach enables researchers to analyze the plume scene features during a ship cabin fire incident, providing insights into the generation, development, and temporal migration of smoke. Verification of the proposed simulation method is planned to be conducted using miniature models, which can help validate the accuracy and reliability of the simulations. Overall, this hybrid simulation technology offers a promising avenue for understanding and predicting the characteristics of cabin fires on ships, laying the groundwork for further research in ship fire dynamics and smoke behavior.

Li *et al.* (2016) conducted a study on the characteristics of fire smoke flow in closed ship cabins, providing valuable insights into firefighting strategies. Their research focused on analyzing and verifying these flow characteristics, laying a theoretical foundation for addressing fires in ship cabins. One of the key findings seems to be the effectiveness of extinguishing ship fires in closed cabins as an emergency measure. Rapid evacuation of personnel and prevention of fire spread are highlighted as crucial initial steps. The study appears to have used small-sized ship cabins and heptane as the ignition fuel for their research, aiming to understand the fire smoke characteristics in closed compartments theoretically. Additionally, they developed a physical parameter model of fire smoke using MATLAB, which is likely helpful for further analysis and simulations. However, it's noted that the study's reliance on a constant heptane mass loss rate may introduce some discrepancies from real-world fire scenarios in enclosed spaces. This acknowledgment suggests avenues for further research and refinement of the model to better reflect actual conditions.

Using advanced simulation software like FDS (Fire Dynamics Simulator) allows researchers to model and analyze fire scenarios in detail. However, accurately predicting temperature distribution, especially in areas affected by incoming air, remains a challenge. Improving the accuracy of these simulations, particularly in predicting the behavior of cold layers influenced by airflow, could greatly enhance our understanding of cabin fire dynamics, and inform better fireproofing strategies. Zhu *et al.* (2011) utilized FDS with a Large Eddy Simulation turbulence model to simulate a full-scale cabin fire experiment designed by the U.S. Coast Guard. Such research efforts contribute significantly to enhancing fire safety standards in maritime environments.

Relying on historical fire accident data to inform fire simulation scenarios during the conceptual design phase is a pragmatic approach given the scarcity of specific data related to design fire and combustible materials. By focusing on areas like the machinery room, where fire incidents are more likely to occur based on historical data, designers can prioritize fire simulation efforts effectively. However, as technology advances and data collection methods improve, there's potential for greater integration of real-time data into the ship design process. This could involve leveraging sensors and monitoring systems to gather data on factors like material properties, environmental conditions, and operational parameters. Integrating this data into fire simulation frameworks could lead to more accurate and comprehensive risk modeling processes, enabling designers to better anticipate and address potential fire hazards throughout the ship's lifecycle. Additionally, ongoing research and development efforts in fire safety engineering and computational fluid dynamics will likely lead to further advancements in fire simulation tools, allowing for more sophisticated analyses and simulations that account for complex interactions between fire dynamics, structural design, and evacuation procedures. Ultimately, a multidisciplinary approach that combines historical data-driven insights with cutting-edge simulation technologies and real-time data integration will be key to continually improving fire safety in ship design and operations (Kang et al, 2017).

Johansson and Ekholm (2018) highlights the challenges faced by fire safety engineers when simulating fire scenarios using computational tools like FDS 5. Their round-robin study involved practitioners from eight Swedish consultancy firms who simulated the same scenario involving an 800 mm heptane pool in a three-room apartment. The findings revealed considerable variation among participants in how they specified the input file, selected input data, and chose devices within FDS. Notably, differences in describing the fuel and burner led to significant disparities in parameters such as mass loss rate and heat release rate. Additionally, errors in prescribing the fire resulted in variations in temperature increase, with discrepancies of 300 K in the fire room and 50 K to 150 K in nearby rooms. Nevertheless, the study also found that accurate predictions of temperature were possible when key factors such as heat release rate and wall boundary conditions were well-defined. Nonetheless, even with relatively well-defined input data, significant discrepancies persisted among participants' results. These discrepancies were attributed to four main factors: different assumptions, errors, inadequate familiarity with FDS, and insufficient understanding of fire dynamics. Addressing these factors is crucial for improving the consistency and reliability of fire simulations in the future.

It's fascinating how machine learning techniques are being explored to address the need for rapid and accurate fire predictions (Lattimer et al, 2020). Leveraging machine learning for fire prediction not only accelerates the process but also potentially enhances its fidelity. The comparison with computational fluid dynamics (CFD) results, showing machine learning's capability to provide predictions orders of magnitude faster, is particularly noteworthy. This efficiency could revolutionize hazard/risk assessments and mitigation strategy development, enabling faster decision-making and response planning. The discussion on dimensionality reduction techniques versus deep learning with neural networks offers valuable insights into the trade-offs involved. While dimensionality reduction may require more mathematical development, deep learning with convolutional neural networks seems to offer promising results in predicting spatial distributions of fire conditions.

2.2.2 Evacuation modelling

The VTT Technical Research Centre of Finland developed an advanced evaluation tool to quantify fire safety performance, which integrates fire dynamics and evacuation simulations. This tool, known as FDS+Evac, is built into the Dynamics Simulator (FDS) and allows for the simultaneous modeling of crowd flow and interactions between fire and evacuation processes. FDS+Evac considers how fire affects evacuees and vice versa, enhancing the accuracy of emergency scenario simulations (Hostikka *et al.,* 2007). FDS+Evac can simulate the movement of large groups of people, accounting for interactions and congestion, which is crucial for realistic evacuation scenarios. The tool models how fire conditions, such as smoke and heat, impact evacuees' movements and decisions. Conversely, it also considers how evacuees' actions can influence the development of fire and smoke spread. The tool incorporates rational decision-making processes, considering factors such as familiarity with the environment and presence of familiar people. It models how individuals make choices under stress or in groups, which often leads to more accurate predictions of evacuation behavior. FDS+Evac uses equations of motion to simulate individual human movements, considering forces like body interactions and friction with walls and other evacuees. These equations are solved using the FDS solver, ensuring a detailed and dynamic representation of human behavior during evacuations. The tool incorporates experimental data from Frantzich and Nilsson (2003) on moving speeds through smoke and uses the Fractional Effective Dose (FED) concept by Purser (2002) to assess the impact of heat and smoke toxicity on evacuees. The development of FDS+Evac included evacuation experiments to gather data on human behavior, flow rates, and decision-making processes. These experiments ranged from standard fire drills to more realistic evacuations simulating actual fire conditions. The primary focus of the validation was on human movement, comparing experimental results with those predicted by FDS+Evac and other existing software, ensuring the reliability of the tool. While FDS+Evac offers advanced modeling capabilities, its integration as a sub-program of FDS restricts its compatibility with other fire models. This limitation may affect its adaptability for various fire safety applications beyond those supported by FDS. FDS+Evac represents a significant advancement in fire safety modeling, particularly in terms of integrating human behavior with fire dynamics. Its ability to simulate large crowds, account for complex socio-psychological decision-making, and dynamically interact with fire conditions makes it a powerful tool for enhancing fire safety assessments. However, its reliance on FDS for fire modeling may limit its flexibility in some scenarios. Figure 2.2 shows the model of the cabin area including fire dynamics simulations and evacuation models.

Figure 2.2 : FDS+Evac model of the cabin area (Hostikka *et al.*, 2007).

Wang *et al.* (2014) conducted a study on passenger ship evacuation using simulation methods, drawing upon literature on passenger ship evacuation and the procedures set by the IMO. They presented an agent-based microscopic evacuation model known as CityFlow-M. This model was applied to a case involving a ROPAX passenger ship and was validated using data from a semi-unannounced assembly trial at sea. The results of the simulation showed a reasonable agreement with the experimentally measured data, indicating that CityFlow-M is a viable tool for simulating the assembly process on this type of passenger ship. The model is undergoing further development to enhance its accuracy and applicability. Future improvements include optimizing evacuation route assignments and incorporating additional parameters to better simulate human performance under specific conditions, such as lifting, trimming, and ship motions.

Zaman *et al.* (2016) examines 1200 GT passenger ships, which are characterized by their relatively small dimensions but have the capacity to carry over four hundred passengers and also accommodate cargo. The study involves calculations based on the IMO Interim guidelines and utilizes Agent-Based Modeling (ABM) for evacuation simulations. The results of these simulations have shown varying outcomes. Further analysis includes modeling fire scenarios to assess the impact of smoke and flames on the evacuation process, using Fire Dynamic Simulation (FDS) as a reference.

Tan *et al.* (2019) conducted a study focusing on the evacuation of passengers in the specific area of passenger ship staircases. This research fully accounted for scenarios involving personnel congestion and the presence of corners within the staircases. The study resulted in an improved mathematical model for simulating evacuations in staircases. The calculations derived from this model were consistent with real-world situations, indicating its reliability.

The significance of evacuation analysis has notably increased in early-stage ship design due to recent adjustments to the SOLAS Regulation II-2/13.3.2.7. These amendments mandate that both new and existing passenger and ro-ro ships conduct evacuation analyses from the project's inception. The current IMO Guidelines were scrutinized, and a comprehensive case study involving the evacuation of a 3600-person cruise ship was undertaken using both simplified and advanced methods (Nasso *et al.*, 2020). To achieve the advanced calculations, two different software tools based on virtual reality were employed, allowing a comparison with the results obtained from the simplified method. The relevant IMO Regulation, MSC.1/Circ.1533, issued in May 2016, which addresses the evacuation analysis of passenger ships, was thoroughly examined. The case study for the 3600-person cruise ship incorporated both basic and innovative methods, with the advanced analysis conducted using two multi-agent software tools certified by the IMO: AENEAS by DNV-GL and TraffGo, and EVI by the University of Strathclyde-Glasgow. The findings indicated a significant discrepancy between the simplified and advanced methods, particularly in terms of total evacuation duration. Specifically, the simplified analysis yielded a much shorter evacuation duration compared to the advanced methods. This highlights the importance of utilizing advanced, realistic simulation tools to obtain more accurate and reliable evacuation time estimates, which are critical for ensuring the safety and efficiency of passenger evacuations in emergency situations.

Xie *et al.* (2020) guided a study to develop a technique on uncertainty analysis of passenger travel time during ship evacuations under fire conditions. Recognizing the complexity and inherent uncertainty in such scenarios, they aimed to create a more efficient approach for assessing these uncertainties without requiring extensive simulation runs. Their method employs a surrogate model based on polynomial chaos expansion (PCE) integrated with the nested sampling technique. The proposed method leverages PCE to quantify uncertainties in passenger travel time. This approach reduces the number of necessary simulation samples by effectively handling multiple random parameters simultaneously. By using nested sampling within the PCE framework, the method efficiently deals with uncertainties, making it suitable for performance-based fire protection design in shipbuilding. The study found that initial passenger density in various zones significantly affects travel times during evacuation. The travel times were observed to follow approximately a normal distribution when input parameters were uniformly distributed. The safety factor in evacuation scenarios is highly dependent on the safety level, which in turn is influenced by the distribution types and parameters of the input variables. The sensitivity analysis revealed that travel time is notably influenced by the initial passenger density, particularly in areas such as restaurants and retail zones. These zones demonstrated a higher impact on evacuation efficiency compared to others. The width of exits also plays a crucial role in determining the sensitivity of travel time to initial passenger densities. For effective fire protection design, it is crucial to prudently determine the initial passenger densities in high-impact zones like restaurants and retail areas. The methodology enables designers to account for uncertainty in travel times without extensive computational efforts, improving the feasibility and reliability of safety assessments. Understanding the distribution and sensitivity of travel times can help in better planning and optimization of evacuation procedures, ensuring a higher safety margin in ship design and operation. In summary, Xie *et al.* (2020) presented a novel and efficient method to analyze the uncertainties in passenger travel time during ship evacuations under fire conditions. By using polynomial chaos expansion and nested sampling, their approach reduces the computational burden while providing robust insights into the factors influencing evacuation efficiency. This method enhances the ability to perform comprehensive uncertainty analyses in ship design, ultimately contributing to safer maritime operations.

2.2.3 Fire safety in passenger ships

Andersson and Daniel (2002) supervised a risk analysis study of smoke systems in accommodation spaces on passenger ships, utilizing the zone model CFAST (Jones *et al.*, 2005). The analysis focused solely on the smoke layer height as the criterion for measuring fire risk. However, considering only smoke layer height is insufficient for a comprehensive risk assessment. Radiation flux can impair passengers even if the smoke layer does not reach head height, indicating potential harm from thermal radiation exposure. Conversely, if the smoke layer reaches a passenger's head during a mild fire incident, the primary issue may be reduced visibility rather than a direct threat to life, suggesting that not all scenarios with smoke at head height are equally hazardous. The study did not account for firefighting effects due to the challenges of incorporating such dynamics into zone models. Furthermore, the applicability of zone models to structures with long corridors, large halls, and high atriums was not explored, as simulations in these areas are often questioned. Despite these limitations, the study offers valuable insights, particularly regarding the efficacy of active smoke control systems in managing fire risks.

Salem (2006) conducted a comparative study of three zone models—Raeume, CFAST, and BRANZFIRE, against the Fire Dynamics Simulator (FDS), which was used as a benchmark. The study revealed that these models produced somewhat different predictions under various geometries considered within shipboard scenarios. Some models performed better in certain scenarios, while others were more accurate in different contexts. The scenarios were designed to cover a wide range of shipboard areas occupied by passengers. Raeume was found to yield reasonable results in most cases (Salem, 2006). The study assumed a reasonable heat release rate (HRR) and considered wood combustion as the burning material in all simulations. The HRRs used were consistent with the range of experimental data on heat release rates for various burning items as summarized, which encompasses a large number of full-scale tests on different burning items (Särdqvist, 1993). Importantly, the study did not account for fire suppression effects when calculating fire consequences. The hazard was assumed to occur when one of the physical parameters, such as temperature, reached a critical value (e.g., 100°C). This approach did not consider the evacuees' reactions, their response, and behavior, which are crucial for assessing real-life fire scenarios. Consequently, the study produced the available safe egress time (ASET) the time before a given space becomes untenable but did not estimate the required safe egress time (RSET), the time required for passengers to evacuate a space. This omission prevented a direct comparison between ASET and RSET to fully assess the hazard associated with the design. Additionally, none of the studies attempted to quantify the impact of predicted fire circumstances on the strength of passengers during evacuation.

Spyrou and Nikolaou (2009) conducted a comprehensive investigation into the application of zone and field fire models for assessing fire scenarios onboard passenger ships. Their study primarily focused on two fire simulation tools: the zone model (CFAST) and the field model (FDS). While zone models like CFAST are useful for quick assessments and less computationally intensive simulations, they lack the sensitivity and detail needed for complex fire scenarios. Their insensitivity to the location of openings can be a limitation in accurately predicting fire behavior in interconnected spaces. Field models such as FDS offer a higher level of detail and accuracy, especially in transient fire scenarios and complex geometries typical of passenger ships. However, the extensive computational requirements necessitate careful consideration of the available resources and the desired accuracy of the simulations. In conclusion, this study highlights the importance of choosing the appropriate fire modeling tool based on the specific requirements of the scenario being simulated. While field models provide greater detail and accuracy, the computational demands are significant. Zone models, though less precise, can still be valuable for simpler or less resource-intensive applications. Therefore, the application of these fire simulation tools onboard ships require careful consideration of their strengths and limitations, particularly regarding the complexity of the ship's geometry and the specific fire scenarios being analyzed.

Salem (2010) investigates fire engineering tools in consequence analysis highlighted the evolution in fire safety design assessment for ships, driven by the introduction of Regulation 17 in the revised Chapter II-2 of the SOLAS convention of 1974. This regulation marks a pivotal shift from a prescriptive-based approach to a performance-based approach, which leverages scientific and technological advancements and encourages innovation in fire safety design. The performance-based approach necessitates the use of sophisticated fire engineering instruments to perform consequence analysis, a critical component of risk analysis techniques. Traditionally, many of these tools have been developed for simulating fire and smoke propagation in civil building compartments. However, this study raises concerns about the applicability of these models to the unique conditions and layouts found on ships. The research involves a thorough evaluation of existing fire modelling tools. This evaluation is conducted through comprehensive comparisons between representative zone models and a benchmark field model, specifically in the context of fire scenarios involving typical ship layouts. The goal of this work is to determine the effectiveness and accuracy of these tools in the maritime environment, ensuring that they can reliably simulate compartment fires aboard ships and thus contribute to the improved fire safety design of maritime vessels.

Salem (2019) conducted a thorough comparison of different fire models in predicting outputs related to a fire scenario on a vehicle-deck aboard a ROPAX ship. By using statistical analysis techniques, they were able to determine that each fire model had strengths in predicting specific outputs, with at least one model performing well for each concern. This suggests that there isn't a single best model overall, but rather an optimal model for each specific output of concern. This finding underscores the importance of considering various factors and selecting the most appropriate model for a given situation.

2.2.4 Fire protection onboard ships

Krystosik-Gromadzińska (2016) sheds light on the critical issue of engine room fire safety. The engine room presents a unique challenge due to its inherent characteristics, including limited space, high oxygen levels, numerous potential ignition sources, and the presence of various flammable materials. These factors create an environment where fires can quickly ignite and spread, leading to fully developed fires in a short span of time. Despite the impossibility of eliminating all potential fire hazards in the engine room, effective strategies can mitigate the risk and minimize the impact of fires. Key elements include proper design and arrangement of the engine room, adherence to safety protocols, and the application of experience-based practices. Both passive and active fire protection measures play vital roles in safeguarding the engine room. Passive methods involve structural features and materials designed to prevent or slow down the spread of fire, such as A-class divisions to compartmentalize the space and insulation of hot surfaces to reduce the risk of ignition. Active methods include the use of fire extinguishing systems and portable firefighting equipment, which can swiftly contain and extinguish fires as they occur. In conclusion, protecting the engine room from fire hazards requires a multi-faceted approach that combines effective design, rigorous safety measures, and the implementation of both passive and active fire protection methods. By addressing these aspects comprehensively, vessel operators can significantly enhance the safety and resilience of their engine rooms against the threat of fires.

Bolek and Ergin (2018) delves into the intricacies of LNG pool fires occurring on chemical/oil tankers, specifically examining how different pool aspect ratios and wind speeds influence flame characteristics. Employing a large eddy simulation approach coupled with the FDS code, the researchers conduct numerical investigations to understand these phenomena. Their findings reveal significant impacts of both pool aspect ratio and wind speed on flame characteristics. As the aspect ratio of the pool increases, there is a notable reduction in the mean flame height, accompanied by an increase in heat flux values. Additionally, the study identifies a positive correlation between wind speed and heat flux values, indicating that higher wind speeds contribute to heightened heat flux levels. This research sheds light on crucial factors influencing the behavior of LNG pool fires on chemical/oil tankers, offering valuable insights for safety measures and risk assessment in maritime operations involving LNG transportation.

Yang *et al.* (2018) offers a meticulous methodology for examining possible coincidence incidents within an offshore floating processing facility, exploring various ignition source placements and evaluating safety measures' efficacy using CFD code. The study predominantly relies on FDS, a specialized CFD tool tailored for analyzing fire dynamics, while also highlighting the disparities among FDS, FLUENT, and CFX.

Three key aspects are addressed in modeling the impact of accident scenarios: the maximum temperature induced by the fire, the duration of hazardous temperatures, and the extent of the hazardous zone. The findings underscore the gravity of LNG (liquefied natural gas) release as a significant hazard to both onboard personnel and assets. Additionally, even slight variations in ignition source locations can exacerbate the consequences of a fire, amplifying the potential risks.

Wang *et al.* (2018) focus on the vertical distribution of temperature rise provides valuable insights into how fire behaves in such confined spaces compared to open environments. The experiments conducted in a reduced-scale sealed engine room offer practical data on temperature gradients within the smoke layer, highlighting differences from open fires. The observed variations in the time taken to reach maximum temperature among various heights within the smoke layer emphasize the complexity of fire dynamics in enclosed spaces. This finding underscores the need for tailored strategies for fire suppression and rescue efforts in ship engine rooms to account for these nuances. The development of an empirical model to predict the vertical temperature slope distribution at the time of maximum temperature is a significant contribution. Such a model could be invaluable for ship designers, safety engineers, and emergency responders in assessing fire risks and designing effective mitigation measures for sealed engine rooms. Overall, this research not only enhances our understanding of fire behavior in sealed ship engine rooms but also provides practical tools for improving safety and emergency response protocols in maritime settings.

The SOLAS framework, which sets international standards for safety at sea, requires that materials like A-60 steel and alternatives such as FRD-60 Aluminum and FRP (Fiber-Reinforced Polymer) meet certain criteria, particularly in terms of their robustness and ability to maintain load-carrying capacity under fire exposure. Hulin *et al.* (2019) attempts to quantify robustness, a concept that is vital but often challenging to define and measure. By linking robustness to time to mechanical failure and acknowledging the influence of various factors like fire scenarios, load, and boundary conditions, the study provides valuable insights into how to assess and compare materials in terms of their ability to withstand fire-induced stresses. The requirement from SOLAS Chapter 2-II Regulation 17 to ensure an equivalent level of safety to steel construction even when using alternative materials underscores the importance of these tests and evaluations. By conducting full-scale tests on materials like A-60 steel, FRD-60 Aluminum, and FRP bulkheads under realistic fire conditions and comparing their performance against steel, authorities can ensure that ships remain safe even when using non-traditional materials.

Bellas *et al.* (2020) significantly contributes to the field of fire protection for ship machinery spaces. By utilizing CFD modeling with FDS, they were able to simulate various fire containment states as outlined by IMO. These scenarios included different types of fires using heptane and diesel oil, as well as exposed and obstructed fires. One notable aspect of their research is the analysis of both experimental and model uncertainties, which is crucial for assessing the reliability of the simulations. By understanding and quantifying these uncertainties, the study provides valuable insights into the performance of the FDS in modeling fire suppression scenarios. The findings of the study support the application of FDS in a performance-based design approach for water mist fire extinguishing systems in ship machinery spaces. This suggests that designers and engineers can use CFD modeling to predict the behavior of fires and the effectiveness of water mist systems in extinguishing them. This flexibility allows for the modeling of different machinery volumes and nozzle spacings beyond those prescribed by regulatory bodies like the IMO. Overall, this research contributes to improving fire safety in maritime environments by providing a robust method for designing and evaluating water mist fire extinguishing systems for ship machinery spaces. It offers a more tailored approach that considers specific ship configurations and fire scenarios, ultimately enhancing the safety and protection of both personnel and assets at sea.

2.2.5 Fire risk management

Themelis *et al.* (2012) aimed to develop a coherent probabilistic framework for assessing the fire safety of passenger ships. This framework is designed to enable efficient and sufficiently rational engineering evaluations of trial designs in relation to the SOLAS fire protection objectives. These objectives are centered around the principle that any fire occurring on board must be contained and suppressed effectively. The approach involves calculating failure probabilities for two critical aspects: insulation and extinguishment. By doing so, the framework provides a method for ranking alternative designs based on realistic design choices related to materials, geometry, ventilation, and fire safety systems. This probabilistic method is built on a series of analytical formulae, many of which are derived from first principles or have a strong foundation in fire engineering. This framework allows designers and engineers to evaluate the fire safety performance of different ship designs systematically and quantitatively. By incorporating probabilistic assessments, it provides a more nuanced understanding of the risks and safety measures needed, ensuring that passenger ships meet stringent fire safety standards in a rational and justifiable manner.

Xie *et al.* (2016) performed an advanced SFIS designed to provide timely and critical decision support for selecting appropriate suppression methods and firefighting tactics. The system is built around a BN, forming a novel intelligent identification model. This model can identify fires of varying sizes and can distinguish between solid fires and fuel oil fires. The study results demonstrate the effectiveness of the model and its robustness even in scenarios where one fire sensor fails. Moreover, the model's integration into Damage Control Systems (DCSs) significantly enhances situational awareness regarding damage and aids commanders in making prompt decisions. This is achieved by efficiently allocating the most suitable firefighting equipment and crew. The integration thus not only improves the identification and classification of fire types but also optimizes the overall firefighting strategy and response on ships.

The assessment of the current safety level of ships involves quantifying the risk associated with the operating world fleet. This process requires estimating and assessing the primary contributors to risk, specifically the frequency of maritime accidents and the extent of their consequences. Eliopoulou *et al.* (2016) further explored the potential relationship between accident rates and ship age, revealing complexities beyond initial assumptions. The present study shows that while the frequency of ship accidents has generally increased over the last decade, the overall safety level of various ship types has not significantly changed, as the average consequences of these accidents have remained relatively stable.

Zong *et al.* (2017) proposed a comprehensive risk assessment framework specifically designed for fire accidents in ship engine rooms. The framework integrates both the probability and consequences of fire incidents, aligning with standard risk assessment methodologies. The framework utilizes BN to model and compute the probability of failure events leading to fire accidents. BN is a graphical model that represents a set of variables and their conditional dependencies via a directed acyclic graph. GeNle software is employed to facilitate the construction and analysis of the Bayesian network. This tool helps in quantitatively assessing the failure probabilities by incorporating various input data and expert judgments. FDS is a CFD model developed by the NIST for simulating fire-driven fluid flow. It is used to simulate the development and spread of fire within the engine room. Through FDS, the framework models different fire scenarios to understand the potential impact, including the extent of damage, heat release rates, smoke production, and the effectiveness of fire suppression systems. ALARP method is applied to assess the overall risk level. This principle ensures that the risk is reduced to a level that is as low as reasonably practicable, balancing the cost of risk reduction measures against their benefits. By combining the probabilistic outcomes from the Bayesian network with the consequence analysis from the FDS simulations, the framework offers a holistic assessment of fire risks. This integrated approach allows for identifying critical areas and implementing effective risk mitigation strategies.

Wu *et al.* (2018) propose a probabilistic method for estimating fatalities in ship fire accidents, which is valuable for enhancing fireproofing safety in ship design and ensuring prompt responses to fire incidents. The method compares the ASET with the RSET. Estimating ASET is done using the FDS field model to simulate the fire development process. The FDS provides a detailed representation of how a fire evolves, including the spread of heat and smoke, which is crucial for determining how long safe egress is possible under different fire conditions. The RSET is calculated based on the guidelines provided by IMO. These guidelines take into account various factors such as crowd behaviors and the time required to navigate through corridors, stairs, and doors. RSET reflects the time needed for all occupants to evacuate safely, considering potential delays and obstructions. The method was validated by applying it to a real fire accident scenario, where the estimated fatality rate closely matched the actual outcomes, demonstrating the method's practical applicability and accuracy. Thus, Wu *et al.* (2018) offer a comprehensive and practical approach for fatality estimation in ship fire scenarios, integrating advanced simulation tools and established safety guidelines to improve emergency response and ship design safety measures.

Baalisampang *et al.* (2018) conducted an extensive evaluate and assessment of fire and explosion incidents in maritime transportation from 1990 to 2015, aiming to pinpoint the causal and underlying factors of these incidents. Their study categorizes the causal factors into five main groups: human error, thermal reaction, electrical fault, mechanical failures, and unknown causes. The study reveals that human error is the predominant contributing factor, responsible for 48% of the accidents. Mechanical failures are the second most significant cause, accounting for 22% of the incidents. Deficient maintenance and inappropriate overhauls were identified as key contributors to mechanical failures, often leading to leaks and subsequent mechanical issues. Sources of ignition such as hot metal surfaces, static electricity, and electrical sparks and arcs play a critical role in triggering fires and explosions. Electrical faults are responsible for about 7% of the accidents, with electrical fires being a notable cause. Thermal reactions contributed to 14% of the accidents, primarily due to breaches of safety guidelines or policies. In summary, this study highlights the critical need for improving human performance, enhancing maintenance practices, and adhering to safety guidelines to mitigate fire and explosion risks in maritime transportation.

Zeńczak and Krystosik-Gromadzińska (2019) conducted a survey at the beginning of 2019 among engine room crew members employed by a European shipowner to analyze fire safety management in engine rooms. Their research was driven by statistics showing that most onboard fires originate in these spaces, posing significant risks to the vessel and its occupants. The primary cause of these fires is typically fueling leakage onto hot surfaces. The crew identified separators and auxiliary rooms as the highest-risk areas in the engine room. Key measures to improve fire safety included good crew education, proactive thinking, maintaining cleanliness and order, and participating in additional courses and training alarms. The respondents did not deem additional fire safety management tools necessary. However, they suggested that any new tools introduce should be concise, such as checklists on printed cards. Based on these insights, the researchers developed an example checklist for daily engine room inspections, aligning with the crew's recommendations for effective fire safety management. This checklist aimed to enhance the crew's ability to prevent fires efficiently by focusing on practical, actionable items derived from their direct experiences and insights.

The primary cause of machinery space fires on ships is often attributed to the release of flammable oil mist, which can encounter unprotected hot surfaces, leading to ignition. McNay *et al.* (2019) conducted a review of various regulatory and classification society requirements related to fire safety, as well as the use of FSAs by IMO as a rule-making tool. They also examined recommendations from accident investigations, advancements in fire safety technology, and existing research literature. The purpose of the review was to identify the most effective strategies for fire accident prevention and assess their cost-effectiveness. It was concluded that fire prevention efforts would be more efficient if the focus expanded beyond just detecting immediate events that occur just before ignition. A broader approach would address the systemic causes that lead to fire hazards in the first place, rather than only reacting to events at the point of ignition. By addressing these underlying systemic factors, fire safety measures could be improved, making them more cost-effective. The review suggests that by eliminating the root causes of fire hazards early, fire safety interventions can be implemented before reaching the critical point when ignition becomes inevitable. This proactive approach could prevent the occurrence of fires in machinery spaces and reduce the risk of catastrophic incidents. In summary, the review underscores the importance of taking a systemic approach to fire prevention in machinery spaces. Rather than focusing solely on detecting immediate fire risks, addressing the root causes and improving early intervention strategies would enhance fire safety and be more cost-effective in the long run.

Callesen *et al.* (2019) conducted an in-depth study on fire-related risks aboard container ships by analyzing fire accidents occurring between 1996 and 2017. They identified 39 confirmed fire incidents involving container ships within this period. Through their epidemiological hazard analysis, they pinpointed four types of hazardous cargo with significant fire risks: calcium hypochlorite, compressed charcoal briquette products, rechargeable batteries, and divinylbenzene. In their exploration of solutions to reduce fire detection times, Callesen *et al.* (2019) utilized CFD software for fire simulation modeling. They evaluated two detection methods: placement of temperature sensors and installation of optical smoke detectors. The results from these simulations provided insights into the effectiveness of each detection method in identifying fires at an early stage, thereby contributing to improved safety measures aboard container ships.

The procedure for evaluating fire safety of alternative ship design solutions, as described in MSC/Circ.1002, has proven to be inadequate for novel and large-scale designs. Evegren (2020) scrutinized the fire safety of alternative ship designs in terms of both functionality and applicability as a risk-based assessment procedure. This study identified several deficiencies based on comprehensive risk assessment research and involvement in over a dozen assessments. This study aims to enhance the robustness and reliability of fire safety assessments for alternative ship designs by addressing regulatory inconsistencies and advocating for a flexible, risk-based approach tailored to the specific hazards introduced by novel designs.

Pomeroy (2020) delves into the intricate nature of risk within the maritime domain, shedding light on the multifaceted influences of human factors, innovative solutions, and the complexities of engineered systems on maritime safety. Despite concerted efforts to mitigate risks, residual risk persists in any undertaking, particularly in the realm of complex engineered systems such as modern merchant ships. These residual risks are often shaped by human performance and technical complexities inherent in such systems. The paper outlines the challenges associated with residual risk and underscores the inherent limitations in achieving absolute safety, especially in environments characterized by high levels of complexity and novelty. In the context of maritime safety, where human factors and technical intricacies intersect, incidents can arise due to a myriad of factors that go beyond simple risk management protocols. In contemplating the future of ship safety, the paper emphasizes the need for effective regulation that encompasses not only technical standards but also factors related to human behavior, system dynamics, and risk management strategies. By acknowledging the interconnectedness of people, systems, and risk management practices, policymakers can strive towards a more comprehensive approach to ensuring maritime safety in the face of evolving challenges and technological advancements.

3. MATERIALS AND METHODS

3.1 Principles of Fire

Understanding the variables involved in a fire is indeed crucial for effective fire safety management. The concept of the fire triangle, which includes fuel, oxygen, and heat, provides a simple yet fundamental framework for comprehending the initiation and sustenance of fires. By controlling these variables, fire safety measures can be implemented to prevent or mitigate the impact of fires. In essence, a fire is sustained by a self-sustained oxidation reaction of a fuel, which releases heat and light. Without any one of the three elements, fuel, oxygen, or heat, a fire cannot be initiated or sustained. This understanding forms the basis for fire prevention and suppression strategies.

By comprehensively grasping the dynamics of the fire triangle, fire safety professionals can develop proactive measures such as proper storage of flammable materials, ensuring adequate ventilation to control oxygen levels, and implementing heat-resistant materials or fire suppression systems. Additionally, understanding how various factors influence the behavior of fires, such as environmental conditions and the properties of different fuels, enables the development of more effective fire safety protocols.

In summary, the fire triangle serves as a foundational concept in fire safety management, highlighting the interplay of fuel, oxygen, and heat in the initiation and propagation of fires. Through a thorough understanding of these variables, effective measures can be implemented to reduce the risk of fires and minimize their impact on lives and property. The fire triangle is depicted in Figure 3.1 (Della-Giustina,2014).

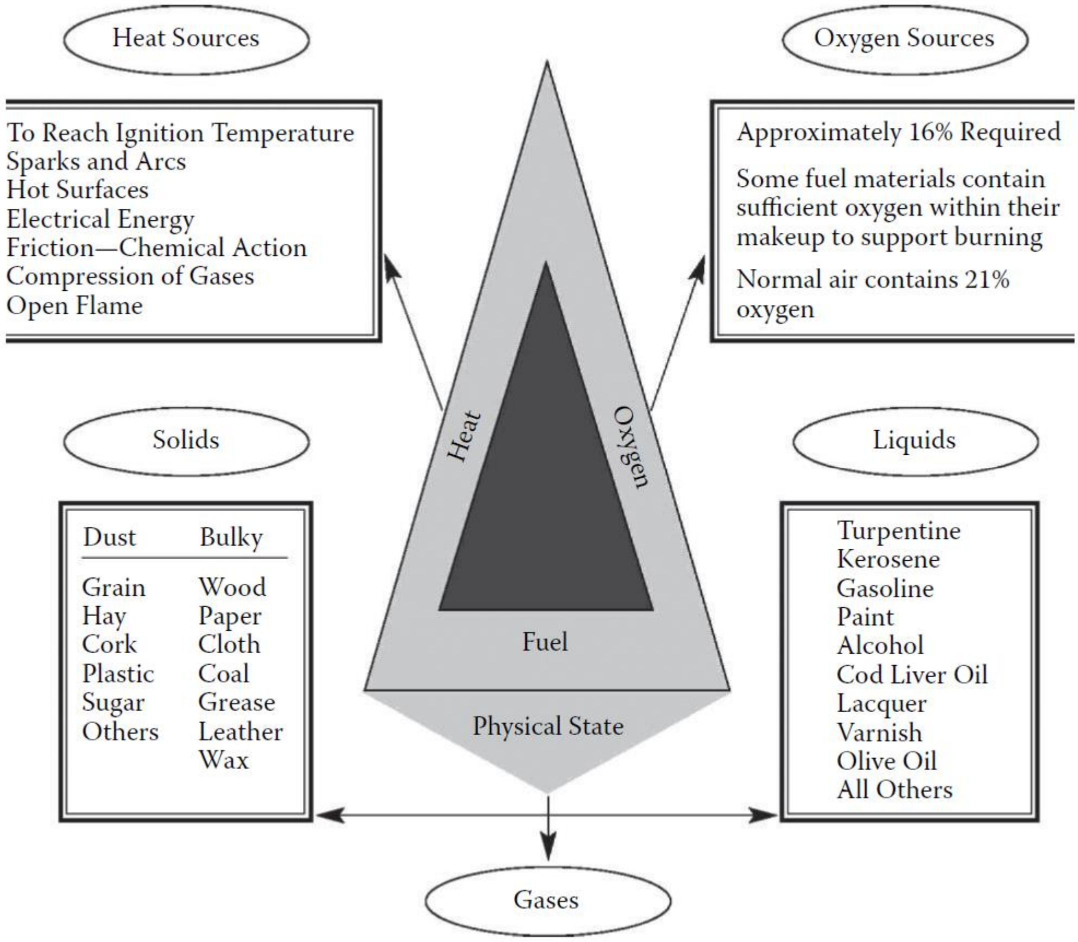

Figure 3.1 : Fire triangle (Della-Giustina,2014).

Absolutely, understanding the fire triangle is crucial for effective fire prevention and safety management. Each side of the triangle represents a critical element necessary for combustion: fuel, oxygen, and heat. By controlling or managing these elements, we can prevent fires from occurring or spreading.

1. Fuel: Fuel is any material that can undergo combustion. This can include solids, liquids, or gases. Common examples of fuel include wood, paper, gasoline, and natural gas. Fire prevention strategies related to fuel involve controlling or managing the availability of combustible materials. This might include proper storage procedures, minimizing sources of ignition near fuels, and using non-combustible materials where possible.

2. Oxygen: Oxygen is a critical component of combustion, as it is necessary for the chemical reaction to occur. Fire prevention strategies related to oxygen involve controlling the availability of oxygen. This might include proper ventilation systems to ensure adequate airflow, minimizing the use of oxygen-

rich materials in confined spaces, and maintaining equipment that relies on oxygen safely.

3. Heat: Heat is the energy necessary to initiate and sustain the combustion process. Heat can come from various sources, including open flames, electrical sparks, friction, and radiant heat. Fire prevention strategies related to heat involve controlling potential ignition sources and managing heat-producing activities. This might include regular maintenance of equipment to prevent overheating, implementing proper electrical safety measures, and controlling hot work activities such as welding or cutting.

By understanding the role of each side of the fire triangle and implementing appropriate fire prevention strategies, safety managers can effectively reduce the risk of fires in their facilities and protect both people and property.

Four main principles provide a comprehensive framework for understanding fire extinguishment (Bryan, 1982) as follows:

1. Control the fuel: This principle focuses on removing or altering the fuel source. Physically removing or separating the fuel from the fire prevents its continuous combustion. Additionally, diluting the fuel can also hinder its ability to sustain combustion. For example, removing stacks of wood pallets or closing valves to stop the flow of flammable liquids are methods of controlling the fuel.

2. Control the oxygen: Oxygen is essential for combustion, so controlling its availability can extinguish a fire. This can be achieved by inhibiting, displacing, or reducing the concentration of oxygen. Inhibiting oxygen involves creating a barrier between the flame and the atmosphere, such as using a blanket or foam. Displacing oxygen can be done by introducing inert gases like carbon dioxide, which lower the oxygen concentration to a level insufficient for combustion.

3. Control the heat: Heat is another critical component of combustion. By absorbing heat faster than it's generated, the combustion process can be disrupted. Water is an effective extinguishing agent because it can absorb large amounts of heat, thus cooling the fire and preventing further combustion.

4. Inhibit the chemical chain reactions: Combustion often involves complex chemical reactions. By introducing certain chemical agents into the fire, it's

possible to disrupt these reactions and prevent the fire from spreading. These agents interfere with the sequence of reactions by absorbing free radicals necessary for the continuation of combustion. Dry chemical extinguishing agents commonly found in portable fire extinguishers work by inhibiting these chemical chain reactions.

The overview of the five classes of fires and the appropriate extinguishing agents for each is crucial for personnel to quickly and effectively respond to different types of fires based on the fuel involved. Understanding the characteristics of each class of fire helps ensure the appropriate selection and application of extinguishing agents, minimizing damage, and maximizing safety. Globally, there are two main fire classification systems these are United States and European based classifications.

United States based fire classification is given in Table 3.1. The five classifications of fire are explained as Class A, B, C, D and K.

Table 3.1 : Fire classifications according to United States.

Fire Class	Symbol	Combustible	Example	Extinguishing agent
A		Freely burning combustibles	Wood, cloth, and paper	ABC/powder, water, water mist, foam
B		Burning liquid or gas	Gasoline, oil, and oil-based paint	ABC/powder, CO2, water mist, clean agent
C		Electrical fire	Wiring, fuse boxes, circuit breakers, machinery	ABC/powder, CO2, water mist, clean agent
D		Metallic fire	Magnesium, aluminum, sodium	Powder
K		Cooking or grease fire	Cooking oils, or fats in cooking appliances	Wet chemical, water mist

Class A fires involving ordinary combustible materials such as wood, paper, cloth, rubber, and some plastics. The common extinguishing agents for Class A fires are water (which cools and absorbs heat) and dry chemicals (which interrupt the chemical chain reaction).

Class B fires involving flammable and combustible liquids and gases like gasoline, oil, alcohol, and propane. Water is not suitable for Class B fires as it can spread the fire, so foam, carbon dioxide (CO_2), and dry chemicals are more effective. These agents work by smothering the fire, cooling the fuel, or displacing oxygen to interrupt combustion.

Class C fires involving energized electrical equipment. Water or conductive extinguishing agents are dangerous because of the risk of electric shock. Non-conductive agents like dry chemicals and inert gases are ideal for these fires. The equipment should be de-energized before applying Class A fire extinguishing methods.

Class D fires involving combustible metals like magnesium, sodium, titanium, powdered aluminum, potassium, and zirconium. These fires react differently to water or conventional extinguishing agents. Special dry powders or agents specific to the type of metal involved are used to smother or cool the fire.

Class E fires (sometimes not separately classified, as it overlaps with Class C in many regions) involving electrical equipment that is connected to a power source. The classification and extinguishing approach may vary, but the key consideration is that electrical equipment should be de-energized before applying to any extinguishing agents. Non-conductive agents are preferred.

Class F fires involving cooking oils and fats, commonly found in commercial kitchens. Class K fire extinguishers, which use agents that react with oils to form blanket-like foam, are specifically designed to address these fires effectively. These extinguishers prevent reignition and are required in many commercial kitchens for safety.

European based fire classification is given in Table 3.2. The six classes of fire are described as Class A, B, C, D, E and F.

Table 3.2 : Fire classifications according to Europe.

Fire Class	Symbol	Combustible	Features	Example	Extinguising agent
A		Solid substance	Glow and flames	Wood, paper, textiles	Water, foam, ABC powder, Novec
B		Liquids	Flames	Oil, gasoline, fats	Foam, CO2, ABC, BC Powder, Novec
C		Gases	Flames	Butane, propane, natural gas	CO2, ABC/BC powder, Novec
D		Combustible metal	Glow and flames	Magnesium, aluminium, sodium	Dry powder
E		Electric (liquids solid substances)	Glow and flames	Plastics	Novec, non-conductive agents
F		Oils and fats	Flames	Cooking oils, frying fats	Specific agents

Class A fires refer to fires involving ordinary combustible materials, such as: wood, paper, cloth, rubber, plastics etc. These materials are typically found in homes, offices, and other buildings. Class A fires can be put out using water or certain fire extinguishers designed for Class A fires, as water is effective in cooling down and extinguishing them. In fire safety classification, fires are grouped based on the type of material burning, and each class has specific extinguishing methods. Class A is the most common fire class encountered in residential and commercial settings.

Class B fires involve flammable liquids and gases, such as: gasoline, oil, paint, grease, solvents, propane, alcohol etc. These fires are different from Class A because they involve substances that burn hotter and more intensely. Class B fires cannot be extinguished with water, as water can spread the burning liquid, making the situation worse. To fight Class B fires, fire extinguishers specifically rated Class B (such as foam, CO2, or dry chemical extinguishers such as Fluorine-Free Foams, Aqueous Film

Forming Foam) are used. Additionally, fire suppression methods like smothering or using a foam blanket are often employed to eliminate oxygen and suppress the flames.

Class C fires involve electrical equipment that is energized, such as: electrical wiring, circuit breakers, fuse boxes, appliances, power tools, electrical panels etc. These fires are dangerous because they involve live electrical currents, making water a hazardous option for extinguishment. Using water in an electrical fire can result in electrocution. To extinguish a Class C fire, you should use fire extinguishers rated for electrical fires, such as: CO_2 (carbon dioxide) extinguishers and dry chemical extinguishers. Once the electrical power is shut off, the fire may be treated as a Class A or Class B fire, depending on the materials involved. It's essential to ensure the electrical source is disconnected before attempting to extinguish the fire safely.

Class D fires involve combustible metals that burn at very high temperatures, such as: magnesium, titanium, sodium, potassium, aluminum, lithium etc. These metals react differently to fire than common combustible materials. When they burn, they often produce intense heat, and water or standard fire extinguishers are ineffective—and can be dangerous—due to the violent reactions they cause when mixed with certain metals. To fight a Class D fire, you need specialized dry powder fire extinguishers designed for specific metals. The powder is used to smother the fire, cutting off the metal's access to oxygen and preventing the fire from spreading. Class D fires are less common but can occur in industries dealing with metals, such as manufacturing or welding. Always use the appropriate extinguisher and follow safety protocols in environments where these materials are handled.

Class E fire refers to electrical fires. In fire classification systems, Class E specifically applies to fires that involve electrical equipment, such as: wiring, circuit breakers, switches, electrical panel, appliances and machinery connected to electrical power sources etc. Class E fires are unique because they are caused by electrical hazards. Since water and certain extinguishing agents may pose a risk of electrical shock or further damage to electrical equipment, they should not be used. Instead, Class E fires are typically extinguished using dry chemical fire extinguishers, CO_2 fire extinguishers, or other non-conductive methods.

Class F fire refers to fires involving cooking oils and fats, which are typically found in commercial kitchens or environments with deep fryers, grills, or other cooking equipment. These types of fires are a particular concern because of the high temperatures of cooking oils and the potential for rapid spread. Key points about Class F fires include common fuels such as animal or vegetable oils and fats, used in frying and other cooking processes, risks these fires can start quickly and spread rapidly due to the high temperatures involved in cooking oils (often above 200°C or 400°F) and extinguishing agents for Class F fires, you should use a wet chemical fire extinguisher specifically designed for this purpose. The wet chemical agents are designed to cool the oils and form a barrier to prevent re-ignition.

Fires can indeed be categorized into different types based on various factors such as how they ignite and propagate. The four types are commonly recognized (Quintiere, 1998):

1. Diffusion flames: These occur when fuel and oxidizer mix at a molecular level before burning. This mixing typically happens in non-premixed conditions, where the fuel and oxidizer are introduced separately. Diffusion flames often have a blue color and are commonly seen in candles. In the case of a burning oil pool, the heat feedback to the pool maintains the evaporation of liquid into combustible vapor. This vapor mixes with oxygen in the air, forming a diffusion flame above the pool's surface. Similarly, in scenarios such as a piece of furniture burning, the process of pyrolysis occurs. Pyrolysis is indeed an irreversible chemical decomposition process induced by heat. During pyrolysis, the complex molecules in the furniture material are broken down into flammable vapors, which then diffuse and mix with oxygen in the surrounding air. This mixture of flammable vapor and oxygen ignites in the presence of a heat source, resulting in a diffusion flame. Understanding these processes is crucial for fire safety and firefighting strategies, as it helps in predicting fire behavior and determining the most effective methods for extinguishing or controlling the fire (Cowley, 2006).

2. Premixed flames: In contrast to diffusion flames, premixed flames occur when fuel and oxidizer are mixed before ignition. This mixture creates a homogeneous mixture that burns uniformly. Examples of premixed flames include gas stove burners and the flames in internal combustion engines. The pressure buildup behind the propagating flame can lead to two distinct phenomena. Deflagration occurs when the flame front travels at subsonic

speeds through the mixture. While still rapid, deflagrations are slower than detonations and are characteristic of many explosions in confined spaces. Detonation happens when the flame front travels at supersonic speeds through the mixture. Detonations are typically much more destructive and violent than deflagrations, causing shock waves and significant damage to the surrounding environment (Cowley, 2006).

3. Smoldering: Smoldering combustion is a slow, low-temperature, flameless form of combustion, often characterized by glowing embers and smoke. It typically occurs in materials like wood, peat, or coal when they are heated to the point of releasing combustible gases, but not enough to sustain an open flame. The transition from smoldering to flaming combustion occurs when the release of volatiles from the material exceeds a critical value and is ignited either spontaneously or by a pilot flame. This transition is crucial as it can dramatically alter the fire dynamics and increase the severity of the fire. Several factors influence smoldering combustion, including the physical and chemical properties of the material, its moisture content, orientation, and the direction of smoldering propagation. Upholstered furniture, mattresses, and garbage, especially when initiated by discarded cigarettes, are common scenarios where smoldering combustion occurs. It's important to note that smoldering combustion often results in incomplete combustion, leading to the production of toxic carbon monoxide instead of carbon dioxide, which poses significant risks to occupants in affected spaces. Understanding the factors and characteristics of smoldering combustion is essential for fire prevention and suppression efforts, particularly in scenarios involving materials prone to smoldering (Drysdale, 1988).

4. Spontaneous combustion: This type of combustion occurs without an external ignition source due to heat generated within a substance by chemical or biological processes. Common examples include piles of oily rags, compost piles, and certain types of organic materials. Spontaneous combustion indeed occurs when a substance undergoes slow oxidation when exposed to air, leading to ignition without the presence of an external heat source. The auto-ignition temperature, or spontaneous ignition temperature, represents the lowest temperature at which a substance will ignite spontaneously in the

presence of air and in the absence of an ignition source. A common example is lubricating oil sprayed onto a hot surface in a machinery space. When the oil reaches its auto-ignition temperature, it will ignite spontaneously in the presence of air, posing a fire hazard. Another aspect is self-heating spontaneous combustion, which occurs when heat is generated within the fuel itself. Certain fuels, such as coal, cotton seed, and oily rags, can generate heat through chemical reactions to the air. If the rate of heat generation exceeds the rate of heat dissipation, the temperature of the fuel will rise, leading to smoldering until the auto-ignition temperature is reached and spontaneous ignition occurs. Understanding the factors that contribute to spontaneous combustion, such as auto-ignition temperature and self-heating properties, is essential for fire prevention and safety measures, particularly in industries where materials prone to spontaneous combustion are handled or stored. Proper storage and handling practices, along with awareness of the risks associated with spontaneous combustion, are crucial for mitigating fire hazards in such environments (Cowley, 2006).

Fire development in a compartment follows a well-defined sequence of stages, each characterized by distinct physical and chemical processes that influence the fire's behavior and impact on its surroundings (Karlsson and Quintiere, 2000). Figure 3.2 illustrates stages of fire development in enclosed spaces in a temperature-time graph, which typically shows the progression from ignition through growth, flashover, fully developed fire, and finally decay.

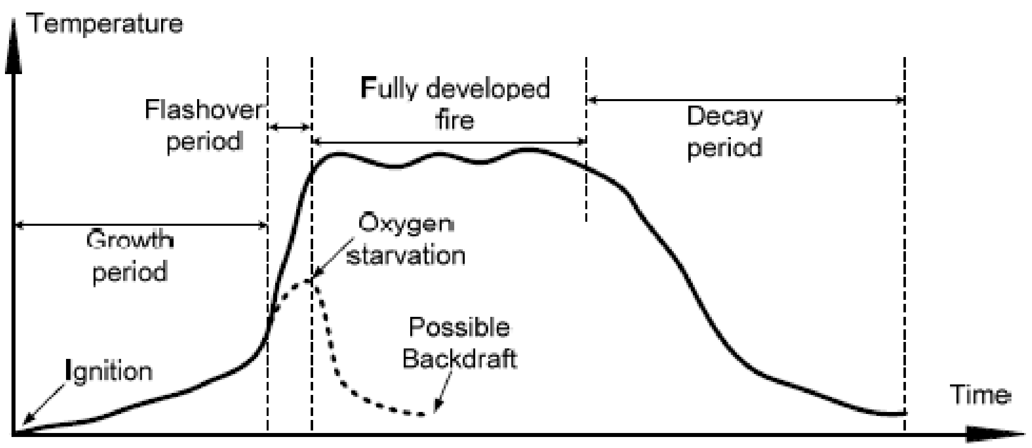

Figure 3.2 : Fire development stages (Drysdale, 1988).

Ignition is the initial phase where the exothermic process of combustion begins, resulting in heat release and a temperature rise. Ignition can be either piloted (e.g., by an open flame) or spontaneous. At this point, the fire is not significantly influenced by the enclosed space boundaries but depends on the nature of the fuel, which may burn with flaming or smoldering combustion.

After ignition, the fire enters the growth stage, characterized by the production of hot gases that rise due to buoyancy, forming a fire plume. This plume entrains fresh air, which helps sustain combustion. The hot gases spread horizontally when they reach the ceiling, forming a ceiling jet, and eventually descend along the walls, creating an upper layer of hot gases. This upper layer grows in volume and temperature as the fire continues to burn, leading to increased heating of the compartment's walls, ceiling, and floor. The fire at this stage is typically fuel-controlled, meaning the rate of combustion is primarily governed by the amount and type of fuel available. This critical transition marks the point where the compartment's temperature rapidly escalates, often exceeding 600°C or when the radiation heat flux to the floor reaches approximately 20 kW/m^2. Flashover signifies a sudden and intense spread of fire across all combustible surfaces in the compartment. The exact conditions for flashover can vary based on fuel properties, arrangement, and compartment geometry. It is defined by the International Standards Organization (ISO) as the rapid transition to a state where all surfaces are involved in the fire. In the fully developed fire stage, the fire reaches its peak intensity, with the highest fuel release rate and temperatures ranging typically from 700°C to 1200°C. The fire is often ventilation-controlled, meaning the availability of oxygen through openings becomes the limiting factor for combustion. This stage involves the most severe heat exposure to the compartment structure and contents. As the fuel within the compartment becomes depleted, the fire transitions from being ventilation-controlled to fuel-controlled once again in decay stage. The burning rate and energy release rate start to decrease, leading to a gradual decline in temperature. This phase continues until the fire eventually extinguishes due to the lack of sufficient fuel or oxygen.

3.2 Fire Safety Objectives

Organizations dedicated to fire safety focus on the assessment, preparation, and dissemination of fire safety requirements. This approach is the traditional and generally accepted method for achieving fire safety. In their deliberations, these organizations are influenced by fundamental questions concerning their objectives. Fire safety objectives are typically expressed in three ways: to protect life, to protect property, and to ensure that a disaster similar to one that triggered the fire safety activity never happens again. The first two objectives can be quantified, although they are rarely explicitly stated in numerical terms. The third objective, however, stems from the impact of major disasters, particularly those involving multiple fatalities, fires, and explosions, on fire safety requirements and legislation. While the aim of preventing a similar disaster from ever happening again is noble, it is ultimately unattainable. Even with the strictest precautions and faithful management of fire safety measures, there remains a remote possibility of a comparable disaster due to the inevitability of human and mechanical failure. Despite its unattainable nature, this objective reflects a significant additional aim, driven by the public's shock, concern, and anxiety following a major disaster. This societal involvement and demand for stringent safety measures highlight the third objective as a manifestation of societal risk or concern.

Designing fire safety for a specific hazard area, such as a building, factory, ship, or railway tunnel, involves a systematic process. This process comprises several interrelated steps that can be viewed as components of an overall fire safety system Rasbash *et al.* (2004). The fire safety design process is divided into steps that logically follow each other. The interaction between these steps is crucial for developing an effective fire safety system. Fire safety design steps are given in Figure 3.3 and the description of these steps are explained as follows:

1. Identify the hazard area: Determine the specific characteristics and constraints of the area under consideration, such as its layout, occupancy, and usage.
2. Establish fire safety objectives: Define what the fire safety system aims to achieve, such as protecting lives, preserving property, ensuring continuity of operations, and complying with legal requirements.
3. Hazard identification and risk assessment: Conduct a thorough analysis to identify potential fire hazards and assess the associated risks. This involves collecting data on materials, processes, and environmental factors that could contribute to a fire.

4. Determine performance criteria: Set performance benchmarks for the fire safety measures, including acceptable levels of risk and criteria for successful intervention and mitigation.
5. Design fire safety measures: Develop and plan specific fire safety measures, such as detection systems, suppression systems, and evacuation procedures. These measures should align with the established performance criteria.
6. Implement fire safety measures: Install and integrate the designed fire safety measures within the hazard area. This includes physical installations, procedural implementations, and ensuring compatibility with existing systems.
7. Test and validate measures: Conduct tests to ensure that the installed fire safety measures perform as expected. Validation may involve simulations, drills, and performance evaluations under various conditions.
8. Review and update: Continuously monitor the fire safety system's performance and make necessary updates based on new data, technological advancements, or changes in the hazard area.

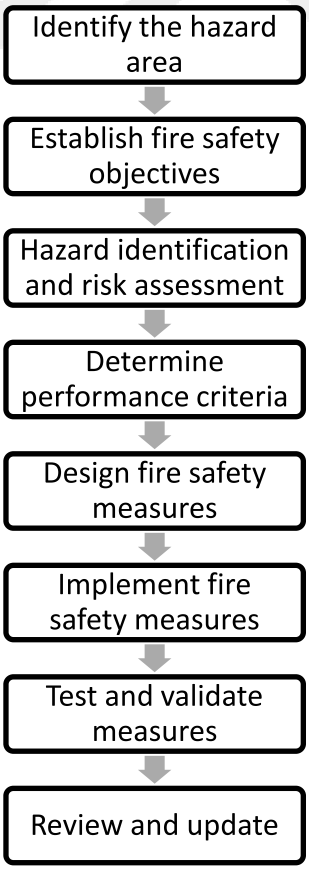

Figure 3.3 : Fire safety design steps (Rasbash et al, 2004).

3.3 Harmful Effects of Fire

In a fire, the toxicity of the products of thermal decomposition and combustion plays a significant role in the severity of the incident. When synthetic materials, commonly found in passenger ships due to their cost-effectiveness, durability, and aesthetic appeal, burn, they often release a range of toxic gases, including carbon monoxide, hydrogen cyanide, and other harmful compounds. These materials, often derived from petroleum-based sources, can result in highly toxic smoke and gases. Some of the most dangerous substances released during combustion include:

- Carbon Monoxide (CO): A colorless, odorless gas that interferes with the body's ability to transport oxygen, causing suffocation.
- Hydrogen Cyanide (HCN): This gas can inhibit cellular respiration and, at high concentrations, is potentially lethal.
- Acrolein and formaldehyde: These gases are irritants to the respiratory system, eyes, and mucous membranes and can cause long-term health problems.

The widespread use of materials like PVC (polyvinyl chloride), polyurethane foams, and styrene-based plastics in modern shipbuilding significantly contributes to the volume and toxicity of smoke. These materials, when exposed to fire, tend to release large quantities of toxic fumes, making it harder for people to breathe and increasing the likelihood of asphyxiation and poisoning. Moreover, the confined spaces in ships, especially in passenger vessels, can exacerbate the situation by limiting the airflow and allowing the toxic gases to accumulate. This environment makes it more difficult for passengers and crew to escape or find safe breathing zones, increasing the fatality rates. Fire safety regulations on passenger vessels, therefore, increasingly emphasize the importance of using low-toxicity materials for construction and decoration, improving ventilation, and developing effective fire suppression systems to reduce the risks posed by these toxic combustion products.

The use of flame retardants is indeed a common and necessary approach to reducing the flammability of materials, especially synthetic polymers, which are widely used in industries like shipbuilding, automotive, construction, and home furnishings. However, while these additives can help slow down the spread of fire, they often come with their own set of challenges and risks, particularly regarding the toxicity of their combustion products. Toxicity of flame retardant chemicals is that many traditional flame retardants, such as brominated and phosphorous-based compounds, have been linked to the release of toxic and potentially carcinogenic substances when they decompose under heat. For example, brominated flame retardants (BFRs) can release toxic gases like dibromo diphenyl ether and polybrominated dibenzodioxins (PBDD), which are harmful to both human health and the environment. And phosphorus-based flame retardants can generate highly toxic compounds such as phosgene, organophosphates, and other acidic products upon combustion, which can cause severe irritation to the respiratory system and other health hazards. Flame retardants often act by chemically altering the materials to make them less flammable. However, the presence of flame retardants can create different chemical reactions during the fire, potentially leading to the formation of more harmful and toxic products. In certain cases, they can inhibit the breakdown of polymer materials, which can cause the generation of highly toxic gases like hydrogen cyanide (HCN) or carbon monoxide (CO), which are already dangerous in fires. Many brominated and chlorinated flame retardants are not biodegradable, and their persistence in the environment can lead to long-term exposure risks, not just during fires but also throughout their lifecycle. Some of these chemicals accumulate in human tissues and wildlife, causing endocrine disruption, developmental toxicity, and potential carcinogenic effects. The balance between improving fire resistance and minimizing the toxic effects of combustion products is a complex one. The challenge is to assess the net benefit of flame retardants: reducing flammability and fire development while also considering the risks associated with the toxicity of decomposition and combustion products.

Developing safer alternatives is a research area that focuses on more eco-friendly flame retardants, such as those based on natural or inorganic materials (e.g., aluminum trihydrate, zinc borate, or melamine-based flame retardants). These alternatives tend to generate less harmful combustion products and have a better environmental profile. Balancing fire safety with health considerations is more stringent standards these are being developed to evaluate both the effectiveness of flame retardants and their toxicity profiles. For example, testing for toxic gas release, smoke generation, and environmental persistence during combustion is becoming a critical part of fire safety standards.

Key areas of research are the following:

- Non-toxic flame retardants: Focus on developing flame retardants that do not release harmful gases upon combustion and are biodegradable or less persistent in the environment.
- Fire-resistant materials: Research into inherently fire-resistant materials (e.g., silicone-based polymers) that do not require additives could reduce the need for flame retardants altogether.
- Advanced fire suppression technologies: Beyond material modification, improving fire detection, suppression systems, and ventilation can help mitigate fire hazards by preventing a fire from escalating in the first place.
- Designing for safety: Integrating safer material choices, better ventilation, and passive fire protection systems into buildings and ships can enhance fire safety without relying as heavily on flame retardants.

The use of flame retardants is essential for reducing fire hazards, but the trade-off between improving fire resistance and mitigating the toxic byproducts of combustion is crucial. The ideal approach lies in the development and adoption of safer, more sustainable materials and flame-retardant chemicals that not only prevent or slow down fire development but also minimize harmful health impacts during a fire. Striking this balance is key to ensuring safety for both people and the environment.

The three main parameters are critical in understanding the behavior of fires and the resulting toxic effects. These parameters directly influence both the combustion process, and the toxic hazards produced in a fire environment. Although the specifics of the parameters may vary depending on the fire scenario, these general factors provide valuable insights into fire dynamics and safety considerations. Based on the reference (Galaj and Saleta, 2022), the parameters are likely to include:

1. Chemical Composition and Structure of Materials:

- Influence on Combustion: The chemical makeup of the materials being burned plays a pivotal role in how a fire develops. For example, synthetic materials like plastics, foams, and certain polymers burn differently compared to natural materials like wood or cotton. Materials with a high carbon content, such as polyurethanes or polystyrene, may produce dense, black smoke with high concentrations of toxic carbon monoxide (CO), hydrogen cyanide (HCN), and other byproducts. On the other hand, materials rich in chlorine (like PVC) release harmful compounds such as hydrogen chloride (HCl) and dioxins when burned.

- Flame Retardants: As discussed, the presence of flame retardants in materials can also alter the combustion process. While flame retardants aim to reduce flammability, they may produce toxic gases when subjected to fire, depending on their chemical composition. For example, brominated flame retardants may release bromine-based toxicants, which contribute to respiratory issues.

2. Rate of Heating (Temperature Increase):

- Influence on Combustion: The rate at which a material is heated can impact both the intensity and the phase of combustion. Materials heated at a rapid rate may undergo a more violent combustion process, with higher peak temperatures, which can cause faster degradation and release a greater volume of toxic gases in a short amount of time. The temperature also influences the pyrolysis process (the decomposition of materials due to heat), where the chemical bonds break down and produce flammable and toxic gases.
- Influence on Toxicity: When materials burn quickly (i.e., a high heating rate), they may produce more smoke and harmful gases, leading to faster and more intense toxic exposure. For instance, high heating rates can result in the incomplete combustion of carbon-based materials, leading to the release of larger quantities of carbon monoxide, which is a deadly asphyxiant.

3. Oxygen Concentration (in the Room or Surrounding Environment):

- Influence on Combustion: Oxygen is a critical factor in any fire. The rate of combustion and the extent of material degradation depend on the oxygen concentration available. In an oxygen-rich environment, a fire will likely burn more intensely, leading to faster pyrolysis and more complete combustion of the materials. In contrast, in an oxygen-deficient environment (e.g., in a confined space), the fire may smolder, burn at lower temperatures, and produce more unburned gases.
- Influence on Toxicity: The oxygen level in the surrounding environment also directly affects the toxicity of combustion products. In oxygen-limited

conditions, incomplete combustion can lead to the generation of highly toxic products like carbon monoxide (CO), hydrogen cyanide (HCN), and acrolein. The lack of sufficient oxygen can prevent the full combustion of carbon, resulting in dangerous and sometimes invisible gases that pose significant risks to human health.

In summary, chemical composition is that different materials burn differently, releasing various toxic gases. The presence of additives such as flame retardants can influence the types of toxic gases released. Secondly, rapid heating accelerates the combustion process and can lead to the release of higher concentrations of toxic gases, as well as more intense fire development. Lastly, lower oxygen concentrations lead to incomplete combustion, generating more toxic gases like carbon monoxide and hydrogen cyanide, which are particularly hazardous in confined spaces. All these parameters are interrelated. For instance, the rate of heating can influence oxygen consumption, as intense fires rapidly deplete available oxygen. Similarly, the chemical composition of materials can dictate how they interact with oxygen in the environment and how efficiently they burn. The result is a complex relationship between material properties, fire dynamics, and the toxicity of combustion products, which underscores the importance of considering these factors in fire safety and prevention efforts. Understanding these parameters and their interactions is crucial for improving fire safety design, particularly in high-risk environments like ships, buildings, and passenger vehicles, where the goal is to minimize the hazards to human life and the environment while controlling fire development.

The main products of thermal decomposition and combustion that contribute to fatalities or incapacitation in fires are indeed critical to understanding fire safety. As highlighted, these can be categorized into three groups based on their effects on human health: narcotic (sleep-inducing) gases, irritants, and soot particles. Let's delve deeper into each of these categories:

- Narcotic (Sleep-Inducing) Gases:

These gases are responsible for the incapacitation of victims by disrupting normal oxygen transport or cellular respiration, leading to asphyxiation and loss of consciousness. These gases, even at relatively low concentrations, can incapacitate individuals quickly, preventing escape or intervention. The primary narcotic gases include:

- Carbon Monoxide (CO): A colorless, odorless gas that interferes with the blood's ability to carry oxygen. Carbon monoxide binds to hemoglobin much more effectively than oxygen, forming carboxyhemoglobin, which significantly reduces the blood’s oxygen-carrying capacity. Symptoms of CO poisoning include headache, dizziness, confusion, and eventually unconsciousness and death. Even low concentrations can be dangerous over time.
- Carbon Dioxide (CO2): While CO2 is a natural byproduct of combustion and is typically present in low concentrations, in high concentrations it can displace oxygen in the air, leading to hypoxia. As oxygen levels decrease, CO2 levels increase, which can cause dizziness, confusion, and in extreme cases, suffocation. CO2 is particularly dangerous in confined spaces, where it can rapidly accumulate.
- Hydrogen Cyanide (HCN): Released from materials that contain nitrogen (such as polyurethane foams, wool, and certain plastics), HCN disrupts the body's ability to use oxygen at the cellular level by inhibiting the enzyme cytochrome oxidase in the mitochondrial respiratory chain. This leads to cellular hypoxia. Symptoms of cyanide poisoning can include confusion, rapid breathing, convulsions, and death if exposure is prolonged, or concentrations are high.
- Oxygen Concentration Loss: During a fire, the consumption of oxygen in the combustion process, combined with the production of toxic gases, can rapidly reduce the available oxygen in a confined space. This results in hypoxia (low oxygen levels), which leads to dizziness, loss of consciousness, and eventual death if not corrected. Even moderate reductions in oxygen concentration can be incapacitating, especially in enclosed spaces such as cabins or rooms on ships.
- Nitrogen Oxides (NOx): Although nitrogen oxides, such as nitrogen dioxide (NO2), are typically present in smaller amounts, they can be produced during the combustion of materials that contain nitrogen, such as certain plastics and synthetic materials. Nitrogen oxides, particularly NO2, are narcotic at higher

concentrations, leading to symptoms similar to those of carbon monoxide poisoning.

2. Irritants:

These gases and particles irritate the respiratory system and mucous membranes, causing discomfort and, at higher concentrations, severe damage to the lungs and airways. They contribute to acute respiratory distress and may also exacerbate long-term health effects. Common irritants include:

- Inorganic Acid Gases (e.g., HCl, SOx, NOx):
  - Hydrogen Chloride (HCl): Released from burning materials containing chlorine (e.g., PVC), HCl is a potent irritant to the respiratory tract and eyes. Inhalation can cause coughing, wheezing, and shortness of breath. Prolonged exposure can lead to severe damage to the respiratory system.
  - Sulfur Oxides (SOx): Produced from the combustion of materials containing sulfur, such as certain industrial materials and fuels. SOx can irritate the eyes, nose, throat, and lungs, leading to coughing, difficulty breathing, and potentially causing long-term damage to the respiratory system.
  - Nitrogen Oxides (NOx): As mentioned earlier, NOx compounds, especially nitrogen dioxide (NO2), are both irritants and contributors to respiratory issues, causing inflammation of the airways and increased risk of asthma or chronic bronchitis.
  - Phosphoric Acids: Released from burning materials that contain phosphorus or phosphorus-based flame retardants. These acids can cause severe irritation to the respiratory tract and eyes, and prolonged exposure can lead to lung damage.
- Organic Irritants (e.g., Acrolein, Formaldehyde):
  - Acrolein: A byproduct of incomplete combustion, acrolein is an irritant to the eyes, nose, and throat. It can cause coughing, chest pain, and difficulty breathing. It is also highly toxic when inhaled at high concentrations.

- Formaldehyde: Released from burning materials containing formaldehyde or related compounds, this gas is a known carcinogen and irritant. It can cause irritation of the eyes, nose, and throat, and prolonged exposure can lead to more severe respiratory problems.

- Smoke Particles:

  Smoke is a complex mixture of gases, aerosols, and solid particles (soot), which can irritate the respiratory system and reduce lung function. Small particles in smoke, particularly those less than 10 micrometers in diameter (PM10), can travel deep into the lungs and cause long-term damage, including chronic obstructive pulmonary disease (COPD), asthma, and other pulmonary diseases.

3. Soot Aerosols and Particles:

- Soot is the fine black powder that results from the incomplete combustion of carbon-containing materials. These particles can be inhaled and may penetrate deep into the lungs, leading to respiratory distress and pulmonary damage. Soot particles are particularly dangerous because their small size allows them to travel into the upper respiratory tract and even enter the bloodstream, contributing to systemic toxicity.

- Health Effects of Soot: Inhalation of soot can cause immediate irritation to the throat and lungs, as well as long-term health problems. Prolonged exposure to soot and other fine particulate matter has been linked to cardiovascular diseases, lung cancer, and chronic respiratory conditions.

- Impact on Firefighters and Victims: Soot exposure is particularly dangerous for firefighters, who may encounter higher concentrations of soot in firefighting operations. Similarly, individuals trapped in burning environments are at risk of soot inhalation, which may lead to respiratory issues that persist long after the fire has been extinguished.

The combination of narcotic gases, irritants, and soot particles makes fires extremely hazardous to human health. These substances contribute to fatalities not only through asphyxiation (via CO, CO2, HCN) but also through direct damage to the respiratory system (via HCl, NOx, soot), leading to incapacitation and long-term health issues.

Fire safety measures, such as proper ventilation, fire suppression systems, and the use of low-toxicity materials in building and ship construction, are essential for reducing the severity of the toxic risks during a fire.

The symptoms of carbon monoxide poisoning are very similar to those associated with oxygen deficiency: shortness of breath, nausea, vomiting, headache and dizziness, general weakness, increased heart rate, and breathing rate. In severe poisoning, loss of consciousness, convulsions, coma, and consequently death occur. The toxic effect of carbon monoxide on the body is based on its ability to connect very easily with hemoglobin, the blood component responsible for transporting oxygen around the body:

$$HbO_2 + CO = HbCO + O_2 \tag{3.1}$$

As a outcome of their combination, carboxyhemoglobin is formed, which is unable to carry oxygen. Therefore, it leads to so-called oxygen starvation. The capability of hemoglobin to combine carbon monoxide is 210 times greater than that of combining with oxygen. Table 3.3 shows the dependence of the symptoms of carbon monoxide poisoning on the concentration in the atmosphere and the time spent in the environment containing it.

Table 3.3 : Symptoms of poisoning depending on the time of absorption and the concentration of carbon monoxide in the air.

Concentration mg/m^3	Concentration ppm	Absorption time min	Symptoms of poisoning
6	7.5	25	Reducing sensitivity to colors and light
50 – 60	63 – 75	120	Hearing disorders
60 – 80	75 – 100	300	Limiting the ability to perform psychological tests
100	125	480	Light symptoms of poisoning
232 – 464	290 – 580	300 – 360	Headache, dizziness, nausea
464 – 812	580 – 1015	240 – 300	Severe headache, shortness of breath, impaired muscle coordination, weakness, vomiting
812 – 1260	1015 – 1595	180 – 300	Severe headache, shortness of breath, vomiting, increased heart rate, weakness, fog in front of the eyes
1260 – 1720	1595 – 2150	60 – 180	Slow breathing and heart rate, coma interrupted by contractions
1800 – 2300	2250 – 2875	90	Headache, dizziness, shortness of breath, shortness of breath, collapse, may be fatal
3400 – 5700	4250 – 7125	20 – 30	Weak pulse, slow and cessation of breathing, death
5700 – 11,500	7125 – 14,375	2 - 15	Respiratory arrest, death

The hazardous effects of toxic gases in fires are indeed a critical concern for both victims trapped in the fire and responders, such as firefighters. The toxic gases produced during combustion can have rapid and deadly effects on the human body, often causing fatal outcomes before the fire itself can reach a person. Here's a breakdown of the key gases and irritants, emphasizing their mechanisms of toxicity and the risks they pose:

1. Hydrogen Cyanide (HCN): Hydrogen cyanide is one of the most toxic gases produced in fires, with a particularly fast-acting mechanism. It disrupts cellular respiration by inhibiting the enzyme cytochrome c oxidase in mitochondria, which is essential for oxygen use at the cellular level. As a result, cells cannot use oxygen, leading to hypoxia and tissue asphyxiation. Symptoms are mainly divided into two categories such as initial and severe exposure. Initial symptoms are headache, dizziness, and confusion. Severe exposure symptoms

are breathing difficulties, seizures, unconsciousness, and death. A concentration of 0.011% by volume can cause death in 30–60 minutes. A concentration of 0.025% leads to immediate death. Additional considerations have a characteristic almond odor, but this odor fades at dangerous concentrations. HCN can be absorbed through both the respiratory tract and skin, further complicating rescue efforts.

2. Sulfur Dioxide (SO2): Sulfur dioxide is a common component in fire gases, especially when materials containing sulfur, such as certain fuels or industrial materials, are burned. It is a strong irritant to the respiratory tract and mucous membranes, causing laryngeal spasm, swelling, and bronchoconstriction. Initial symptoms are coughing, chest tightness, and difficulty breathing. Then, severe exposure is that swelling of the larynx can cause suffocation. A concentration of 0.1%–0.3% by volume can lead to death from respiratory failure. Additional consideration acts rapidly, making it particularly dangerous in confined spaces where exposure can escalate quickly.

3. Phosphine (PH3): Phosphine, a highly toxic gas with a garlic-like odor, is released when materials containing phosphorus (e.g., some flame retardants, fertilizers) burn. It is absorbed through the respiratory tract and can cause severe neurological damage, respiratory distress, and systemic toxicity. Symptoms are initially headache, dizziness, nausea, vomiting and severely respiratory paralysis, seizures, and death. 0.10%–0.2% concentration in inhaled air causes death within 10 minutes. The rapid onset of toxic effects and the difficulty of detecting the gas (due to its smell) make it a silent killer in fire environments.

4. Hydrogen Chloride (HCl): Hydrogen chloride is released during the combustion of materials that contain chlorine, such as PVC. It is an extremely irritating gas, causing severe damage to the eyes, respiratory tract, and mucous membranes. Symptoms are initially eye and throat irritation, coughing, difficulty breathing and then severe inflammation, pulmonary edema (fluid in the lungs), and respiratory failure. 140 mg/m^3 is dangerous to human health. 1400 mg/m^3 is a lethal concentration. The pungent, sour odor of HCl makes it

recognizable, but at high concentrations, individuals may lose their ability to detect it before they are incapacitated.

5. Nitric Oxide (NO): Nitric oxide is a colorless, odorless gas produced during combustion, especially in materials that contain nitrogen. It can irritate the respiratory system, leading to bronchoconstriction and pulmonary edema. It can also react with oxygen to form nitrogen dioxide (NO_2), which is even more toxic. Initial symptoms are coughing, throat irritation, and difficulty breathing. Then, severe exposures are acute dyspnea (shortness of breath), cyanosis (bluish skin), blood-colored sputum, and even cardiovascular failure. High concentrations can lead to rapid paralysis of the respiratory and circulatory systems, causing death. Poisoning can occur in two phases. The first phase is respiratory irritation, cough, and mucosal inflammation. And the second phase is more severe respiratory symptoms, such as dyspnea, muscle pain, and cardiovascular collapse.

6. Other Irritating Organic Substances (Acrolein, Formaldehyde): Acrolein is a highly irritating substance released during incomplete combustion. It causes severe eye irritation, respiratory distress, and damage to the lungs. It is often associated with the burning of plastics and other organic materials. Formaldehyde is released from the combustion of materials containing formaldehyde-based resins (e.g., plywood, insulation materials). It causes eye irritation, respiratory issues, and long-term damage with repeated exposure.

The toxic and irritating gases produced during fires—such as HCN, SO_2, HCl, and NO—represent immediate threats to life. These substances have rapid, deadly effects, often incapacitating individuals before the fire itself can cause harm. Narcotic gases (like HCN) cause respiratory paralysis, while irritants (such as HCl and SO_2) lead to swelling, airway constriction, and suffocation. Acrolein and formaldehyde exacerbate respiratory damage and contribute to long-term health risks. Fire safety measures, including improved ventilation, fire suppression systems, and the use of low-toxicity materials, are essential in minimizing the risk posed by these toxic substances. Awareness of the potential dangers posed by these gases, and swift action during a fire, can help mitigate their deadly effects (Galaj and Saleta, 2022).

3.4 Fire Safety Analysis Methods

When studying the safety aspects of a large ship, addressing the entire system in its entirety can be highly impractical due to the complexity and scale. A more logical and manageable approach involves breaking down the ship into functional entities, which include various subsystems and components. This decomposition allows for a structured safety modelling process for each functional entity. By first modelling the safety of these smaller, manageable parts, one can then examine the interrelationships between these entities to develop a comprehensive system safety model. This model is essential for assessing the overall safety parameters of the ship. However, given the complexity and sophistication of large marine systems, formulating such a model often necessitates the use of approximations and relies on expert judgement to ensure its feasibility and accuracy (Pillay and Wang, 2003).

The fire safety analysis methods are categorized into two broad categories: qualitative and quantitative. The choice of method depends on factors like the availability of data, the need for precision, and the context of the assessment. The key goal of safety analysis is to assess and mitigate risks associated with the system. To achieve this, five critical questions need to be answered, which help identify potential hazards, assess their likelihood and severity, and ultimately provide guidance on measures to reduce risks to acceptable levels (Kim, 2005):

1. What can go wrong? - Identifying the potential hazards or failures.
2. How likely are these problems to occur? - Estimating the probability of hazard occurrence.
3. How severe might the potential problems be? - Understanding the consequences if hazards occur.
4. What lessons can/should be learned from the risk? - Extracting actionable insights to improve the system’s safety.
5. What measures need to be undertaken to reduce the risks and how can this be achieved? - Developing risk mitigation strategies.

In safety analysis, the choice between qualitative and quantitative approaches is influenced by the specific requirements of safety analysts and the nature of the available safety data. These analyses aim to assess the risks associated with a system by evaluating the probability of hazard occurrence and the potential consequences. A qualitative analysis typically involves descriptive assessments, expert judgment, and categorical evaluations of hazards without relying on numerical data. This approach is useful when precise data is unavailable or when a preliminary assessment is required to identify and prioritize hazards based on their perceived severity and likelihood. Conversely, a quantitative analysis employs numerical data and statistical methods to estimate the probabilities and impacts of hazards more precisely. This method provides a more detailed and measurable understanding of risks, which can be crucial for systems where safety is critical, and data is sufficient to support rigorous analysis. The prioritization of hazards is guided by their severity and occurrence probability. A severe hazard with a high probability of occurrence demands urgent and thorough attention to mitigate risks effectively. On the other hand, hazards that are unlikely to occur and have negligible consequences are typically given minimal attention, allowing resources to be allocated more efficiently towards addressing more significant risks (Aldwinckle and Pomeroy, 1983). In summary, the decision to use qualitative or quantitative risk analysis depends on the context of the assessment, the nature of the data, and the need for precision in evaluating and mitigating hazards.

3.4.1 Qualitative safety analysis

Qualitative safety analysis is a crucial process in marine design, aiming to enhance the safety and reliability of marine systems. This method involves a thorough examination of potential hazards and the implementation of strategies to mitigate these risks. The primary objectives of qualitative safety analysis include identifying hazards in the design, documenting and assessing the relative importance of identified hazards, providing a systematic compilation of data and aiding in the systematic assessment of overall system safety (Pillay and Wang, 2003). The process begins by systematically identifying possible hazards that could occur within the marine design. This step ensures that all potential risks are recognized early in the design phase. Once hazards are identified, they are documented and assessed for their potential impact. This assessment helps prioritize the hazards based on their severity and likelihood, allowing for a driven approach in identifying the most critical risks. Then, the objective involves gathering and organizing data systematically as a preparatory step for more detailed quantitative analysis. This compilation of data serves as a foundation for further, more precise safety evaluations. By compiling and analyzing data on identified hazards, qualitative safety analysis supports a comprehensive assessment of the overall safety of the marine system. This holistic view is essential for ensuring that all aspects of the system are considered in the safety evaluation. The process of qualitative safety analysis relies heavily on engineering judgment and experience. Experienced engineers use their knowledge and expertise to identify potential hazards, assess their significance, and determine appropriate safety measures. Based on the findings from qualitative safety analysis, various measures can be implemented to eliminate or control hazards. Incorporating qualitative safety analysis into the marine design process ensures that safety considerations are integrated from the beginning, leading to more robust and reliable marine systems. By systematically identifying and addressing hazards, the likelihood and consequences of accidents can be significantly reduced, contributing to the overall safety and effectiveness of marine operations.

3.4.2 Quantitative safety analysis

Quantitative Risk Analysis (QRA) indeed offers a systematic approach to evaluating risks associated with industrial processes or operations. By quantifying risks, organizations can make informed decisions regarding safety measures, maintenance strategies, and operational procedures. This approach enables a deeper understanding of the relationships between costs, benefits, and risk mitigation efforts. One of the key advantages of QRA is its ability to provide more nuanced insights compared to merely following regulations. While regulations offer a baseline for safety standards, they may not always capture the full complexity of risk scenarios or provide optimal solutions. QRA allows organizations to consider a broader range of factors, such as potential environmental impacts and commercial requirements, in their risk management strategies. By analyzing various risk scenarios and mitigation proposals, QRA helps optimize designs and operating procedures to balance safety, environmental concerns, and economic factors. This optimization process ensures that resources are allocated efficiently, minimizing costs while meeting both internal and external standards. The expansion of Quantitative Risk Analysis (QRA) beyond its origins in nuclear and chemical industries reflects a growing recognition of its applicability and benefits across various sectors. Factors such as commercial pressures, regulatory requirements, and public concerns have driven this trend, as organizations seek robust methods to manage risks effectively. At its core, QRA aims to provide a quantifiable description of risk, making it measurable against predefined criteria or values associated with a particular operation or design. Risk, being a multidimensional concept, encompasses both the frequency of hazards and their potential consequences. QRA involves estimating the likelihood and impacts of various hazard scenarios, considering not only individual risks but also societal and economic implications. In the broader context of risk assessment, QRA serves several key purposes:

- Assessing Risk to People: QRA helps evaluate the risk of fatalities or serious injuries to both the workforce and the public, ensuring a comprehensive understanding of human safety concerns.
- Identifying Risk Reduction Measures: By analyzing different hazard scenarios, QRA enables the identification of measures to reduce overall risk. This includes assessing the effectiveness of existing or proposed risk mitigation strategies.
- Selecting Safety Enhancements: QRA aids in the selection of preferred options for enhancing safety, allowing organizations to prioritize investments and interventions based on their potential risk reduction benefits.
- Setting Performance Standards: QRA supports the establishment of performance standards for design, monitoring, and auditing purposes, providing benchmarks for evaluating safety performance.
- Supporting Cost-Benefit Analysis: QRA assists in conducting cost-benefit assessments of safety expenditures, helping organizations make informed decisions about resource allocation and risk management investments.
- Decision Making on Risk Tolerance: QRA helps decision-makers determine whether the level of risk is tolerable based on predefined risk acceptance criteria, providing a framework for risk governance and decision-making.
- Assessing Environmental Risk: Beyond human safety, QRA also evaluates environmental risks associated with various activities or operations, contributing to sustainable and environmentally responsible practices.
- Evaluating Asset and Revenue Risks: QRA assesses risks to assets and revenue streams, allowing organizations to safeguard their investments and ensure business continuity.

Recognizing the inherent uncertainties in Quantitative Risk Analysis (QRA) results is crucial for making informed decisions. While QRA provides valuable insights into risk levels and potential consequences, it's essential to understand that these results may not always be precise, especially when assessing absolute figures. This acknowledgment becomes particularly important when QRA results are used as the basis for decision-making. When interpreting QRA results, it's essential to consider the specific circumstances and context of the decision or requirement at hand. While QRA can be useful for comparing different designs or scenarios, relying solely on absolute figures without scrutiny can lead to significant problems. Therefore, a thorough review of QRA results is necessary, considering the uncertainties inherent in the analysis. Given that there's no standardized method for conducting QRA, it's important to assess the sensitivity of the results to variations in the assumptions made during the analysis. This sensitivity analysis helps identify critical input data and areas where uncertainties may have a significant impact on the results. In cases where certain data inputs are deemed critical, conducting a more detailed analysis to improve confidence in the results may be necessary. Several methods are commonly used in QRA to estimate risk, each with its strengths and limitations. These methods include:

1. Event Tree Analysis (ETA): ETA is a graphical technique used to model the sequence of events that could lead to undesirable outcomes, allowing for the estimation of the probability of various scenarios (Yordanova, 2021).

2. Fault Tree Analysis (FTA): FTA is a deductive approach used to analyze the combinations of events that could lead to a particular undesired outcome, helping identify potential failure modes and their causes (Vesely et al, 1981).

3. Cause-Consequence Analysis (CCA): CCA examines the causal relationships between initiating events, system failures, and consequences, providing insights into the potential impacts of failures (Xin et al, 2020).

4. Failure Mode, Effects, and Criticality Analysis (FMECA): FMECA systematically identifies and evaluates potential failure modes of a system, assessing their effects and criticality to prioritize mitigation efforts (Lawson, 1983).

5. Risk Matrix Approach: The risk matrix method categorizes risks based on their likelihood and consequences, providing a qualitative assessment of risk levels (Basu, 2017).
6. Fuzzy Sets Theory: Fuzzy sets theory allows for the representation of uncertainty and vagueness in risk assessment, particularly useful when dealing with qualitative or subjective data (Kacprzyk, 2009).

By employing these methods and conducting sensitivity analyses, organizations can enhance the robustness of their QRA results and make more informed decisions regarding risk management and mitigation strategies.

3.5 Fire Modelling

The evolution of fire computer codes over the past decade has indeed been significant, with a notable shift towards more complex field models fueled by advancements in computer technology. These models play a crucial role in assessing the hazards associated with fires, encompassing both thermal and toxic aspects. Deterministic and probabilistic models represent the two primary categories, each with its own advantages and limitations.

A deterministic model is a mathematical model that does not consider randomness or uncertainty in its representation. In deterministic models, the outcome is entirely determined by the initial conditions and the model's equations or rules. These models assume that there is no inherent randomness in the system being modeled. Differential equations, algebraic equations, and logical models are often deterministic. Deterministic models, favored by many fire safety engineers, offer a clear advantage in providing concrete numbers that can be readily utilized for analysis. These models operate under the assumption that a given set of initial conditions will lead to a singular, predictable fire development. However, the inherent variability in fire behavior challenges this assumption, as no two fires are identical.

A probabilistic model is a type of stochastic model that explicitly uses probability distributions to describe uncertainty. In probabilistic models, the randomness is quantified using probability distributions, and the model makes probabilistic predictions about the outcomes. These models are used when there is a clear understanding of the underlying probability distributions that govern the system.

Examples of probabilistic models include Gaussian (normal) distributions, Poisson distributions, and Bayesian models. Probabilistic models, on the other hand, consider a range of potential fire developments, offering a more comprehensive perspective. Despite this advantage, their practical applicability is often restricted due to their complexity and computational demands.

A stochastic model is a mathematical model that incorporates randomness or uncertainty into its representation of a system or a process. Stochastic models assume that certain aspects of the system are governed by random variables or probabilistic events. Stochastic models are used to describe situations where outcomes are not completely predictable and where randomness plays a significant role. Examples of stochastic models include Markov chains, stochastic differential equations, and Monte Carlo simulations.

In summary, the main difference between stochastic and probabilistic models is that stochastic models introduce randomness or uncertainty into the modeling process, while probabilistic models specifically use probability distributions to quantify and predict outcomes. On the other hand, deterministic models do not account for randomness and assume that outcomes are entirely predictable based on known inputs and equations. It's important to choose the appropriate type of model based on the nature of the system being studied and the level of uncertainty or randomness involved.

Within deterministic modeling, there are two primary types: zone models and field models. Zone models, subdivided into one-layer, two-layer, and HVAC models, rely heavily on empirical correlations derived from laboratory-scale experiments. They are effective for simulating specific scenarios and are widely used for practical applications such as assessing the safety of occupied spaces. Field models, in contrast, involve solving governing conservation equations using numerical techniques, requiring fewer empirical relations. While more computationally intensive, they offer a higher level of detail and accuracy in simulating fire dynamics and behavior.

Ultimately, the choice between deterministic and probabilistic models, as well as between zone and field models, depends on the specific requirements of the analysis and the available computational resources. Types of computer fire modes are given in Figure 3.4.

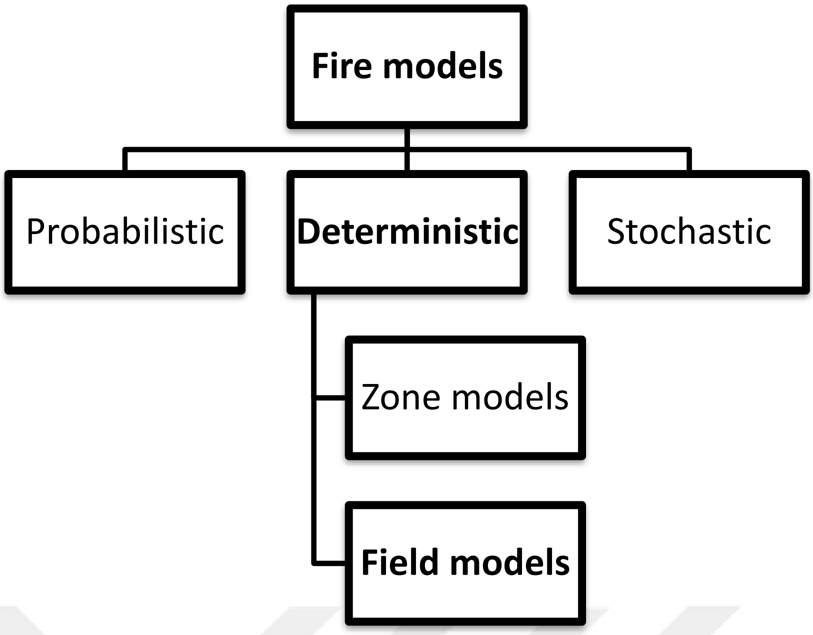

Figure 3.4 : Types of computer fire models.

3.5.1 Zone models

Zone models indeed offer a practical approach to simulate fire dynamics within compartments. By dividing the space into discrete zones, they simplify the computational complexity while still capturing the essential physics of fire behavior. This method leverages the observed stratification of gases within a compartment during a fire, with hot gases rising to form an upper layer and cooler gases staying near the floor as a lower layer. These layers are illustrated in Figure 3.5.

The basic principles underlying zone modeling involve applying conservation laws for mass, energy, and species to each zone. These laws yield a set of ODEs that govern the evolution of properties such as mass, volume, internal energy, density, and temperature within each zone over time. By solving these equations alongside the ideal gas law and definitions of density and internal energy, one can obtain time histories of the properties of interest for each zone. For instance, the conservation equations for mass, species, and energy provide insights into various parameters like upper- and lower-layer temperatures, layer height, compartment pressure, and gas concentrations (Shigunov, 2005). These equations, combined with the equation of state (ideal gas law), enable the derivation of densities. Karlsson and Quintiere (2000) have contributed significantly to the development and refinement of zone modeling techniques. Their work has enhanced our understanding of fire dynamics and improved the accuracy and efficiency of zone modeling approaches.

The equation of mass conservation, also known as the continuity equation, is a fundamental principle in fluid mechanics and thermodynamics. It can be expressed mathematically as:

$$\frac{dm}{dt} + \sum_{j=1}^{n} \dot{m}_j = 0 \tag{3.2}$$

where dm/dt is rate of mass change term and $\sum_{j=1}^{n} \dot{m}_j$ for the room illustrated in Figure 3.5 below assuming that the control volume is formed by the upper layer and the upper plume can be written as:

$$\sum_{j=1}^{3} \dot{m}_j = \dot{m}_{out} + \dot{m}_{ent} + \dot{m}_{sou} \tag{3.3}$$

where $\dot{m}_{out}$ the mass flow rate out of the room vent, $\dot{m}_{ent}$ the mass flow rate entrained into the fire plume and $\dot{m}_{sou}$ the mass flow rate produced by the fire source. The conservation of species implies the same principle of mass conservation for species i to a control volume. Thus, the equation of conservation of species i for which the mass fraction is given as Y_i can be written as:

$$m\frac{dY_i}{dt} + \sum_{j=1}^{n} m_j\left(Y_{ij}^{\cdot} - Y_i\right) = \dot{S}_i \tag{3.4}$$

where m is the mass of the layer, Y_{ij} is the mass fraction of species i leaving the control volume through a flow stream j, and $\dot{S}_i$ is the generation rate of species i from fire source.

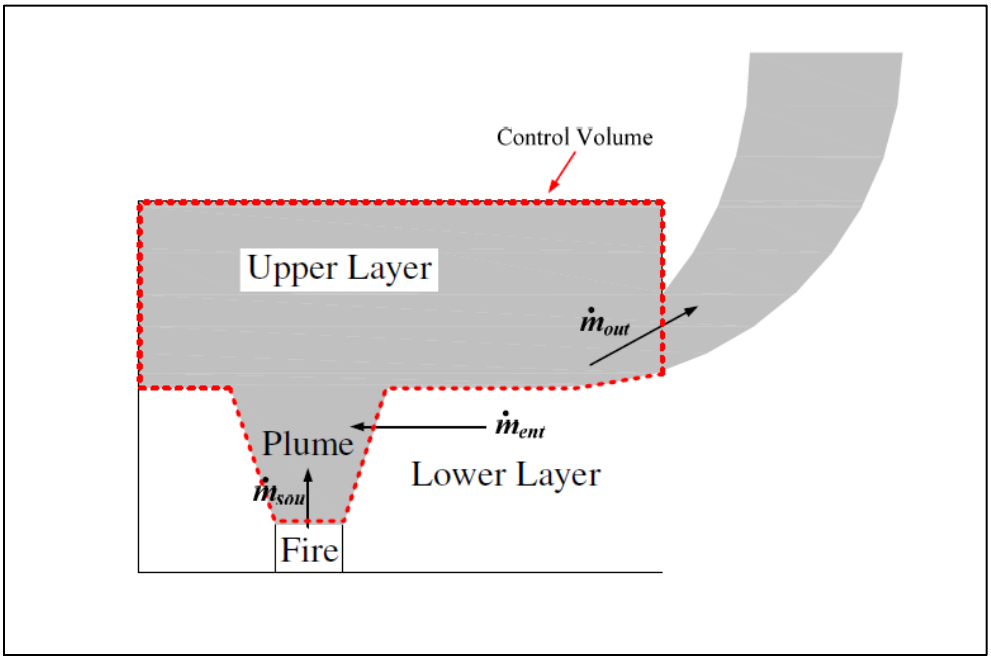

Figure 3.5 : The two layers (upper and lower) and the fire plume observed in enclosure's fire.

The conservation of energy for a control volume is applied with the equation of mass conservation and the equation of state $P = \rho RT$ and can be written as:

$$V c_p \frac{dT}{dt} - V \frac{dP}{dt} + c_p \sum_{j=1}^{n} \dot{m}_j \left(T_j^{\cdot} - T\right) = \dot{m}_{reac} \Delta h_c - \dot{Q}_{loss} \quad (3.5)$$

where V is the volume of the control volume, P is the global pressure in the room, T is the temperature of the gases in the control volume, T_j is the temperature of the gases crossing the boundaries of control volume through a flow stream j, $\dot{m}_{reac}$ is the mass rate of the reaction of gas fuel supplied, Δh_c is the effective heat of combustion, and $\dot{Q}_{loss}$ is the net rate of heat lost at the boundaries.

3.5.1.1 Sub-models

The conservation equations in zone models are crucial for simulating the behavior of physical systems within confined spaces. In this section, a breakdown of the essential sub-models related to source terms and transport terms. These sub-models interact with each other within the zone model framework, influencing the overall simulation results. The extent to which these terms are considered, and their inter-relationships determine the accuracy and sophistication of the model in predicting the behavior of the physical system under study.

3.5.1.2 Fire

In zone models, fires are typically prescribed with a Heat Release Rate (HRR), which represents the rate at which fuel is being burned. The fuel mass loss rate (MLR) or burning rate is related to the HRR and the heat of combustion of the fuel. This relationship allows for the calculation of how much fuel is being consumed per unit time. The availability of oxygen is crucial for combustion to occur. If there is not enough oxygen available, the fire is considered constrained, and it may not burn vigorously or completely. The needed oxygen supply can be calculated based on HRR and a constant value representing the heat released when 1 kg of oxygen is consumed. In an unconstrained fire, all burning typically occurs within the fire plume, which is the column of hot gases and flames rising from the fire source. However, in a constrained fire, where oxygen supply is limited, unburned fuel may flow to other areas, such as the upper layers of the compartment or adjacent compartments, to find sufficient oxygen to continue burning. It's worth noting that while zone models can simulate multiple fires in various locations within a compartment, they usually do not consider direct interaction between the plumes of these fires, even if they are in the same compartment. This simplification helps to keep the simulation computationally tractable while still providing valuable insights into fire behavior and smoke movement (Shigunov, 2005).

3.5.1.3 Heat transfer

Three different modes of heat transfer in fire problems are specifically conduction, convection, and radiation. While conduction is typically associated with solid materials rather than gases, in zone models like Raeume and CFAST, a simplified one-dimensional form of conduction is applied to account for heat transfer through walls, ceilings, and floors within the domain. This simplification helps in modeling the overall heat flow within space, even though convection and radiation are dominant between gas layers (Jones *et al.*, 2005).

3.5.1.4 Vent flows

Vent flow is indeed a critical aspect of fire modeling, as it plays a significant role in the movement of heat, smoke, and gases within a compartment. The sensitivity of vent flow to pressure changes makes it a key factor in understanding fire dynamics and designing effective fire safety systems. Horizontal flow through vertical vents, such as doors and windows. These openings provide pathways for heat and gases to escape or spread to adjacent compartments, influencing the fire's behavior and the safety of occupants. Vertical flow through horizontal vents, like hatches or ceiling holes, is particularly relevant in specialized environments like ships or during firefighting operations where roof venting is utilized. These vents allow for the release of hot gases and smoke from the upper portions of a compartment, aiding in ventilation and heat dissipation. Bernoulli's principle is a fundamental concept used to calculate vent flow, leveraging the pressure difference across the vent opening. This principle states that in fluid flow, an increase in the fluid's velocity is accompanied by a decrease in pressure, and vice versa. By applying Bernoulli's equation, engineers and fire safety professionals can estimate the flow rate of gases through vents based on the pressure differentials induced by the fire or mechanical ventilation systems. Understanding the pressure differentials generated by fires and ventilation systems is crucial for designing effective fire safety measures. Fires typically produce pressure changes on the order of 1 to 1000 Pa, while mechanical ventilation systems can induce pressure differences ranging from 1 to 100 Pa. These variations in pressure drive the flow of gases through vents, influencing the movement of heat and smoke within a compartment and ultimately affecting the fire's behavior and the safety of occupants. The formation of an upper layer enriched with heat and gases due to the fire's plume creates a buoyant force that pushes this layer upwards. As it expands, it displaces the lower, cooler layer, causing it to descend. When the upper layer reaches a vent, such as a door's soffit, a door plume is formed. This plume acts as a transitional zone between the fire compartment and the adjacent compartment. In the adjacent compartment, a new upper layer forms as heat and gases are transferred from the fire compartment through the vent. This process continues as the upper layer in each compartment expands and displaces the lower layer, creating a cyclical flow pattern. These opposing flows through the vent are driven by pressure and density differences resulting from temperature variations. The buoyancy of the hot gases in the upper layer, combined with the pressure differentials induced by the fire and ventilation systems, govern the movement of air through the vent. Understanding these dynamics is crucial for accurately modeling fire behavior and designing effective fire safety measures, particularly in scenarios involving compartmentalized spaces.

3.5.1.5 Fire suppression

In zone models, the influence of sprinklers on fires is typically addressed by simply reducing the heat release rate (HRR) without considering the detailed interaction between the water spray and combustion gases. This simplification may lead to inaccuracies in predicting fire behavior, as zone models often lack the capability to account for scenarios such as overwhelming fires or inadequately designed sprinkler systems. While some zone models neglect the effects of sprinklers entirely, others incorporate them by adjusting the HRR through suppression correlations. These correlations modify the existing HRR based on the effectiveness of the sprinkler system. By applying such adjustments, zone models attempt to approximate the impact of sprinkler activation on fire dynamics. However, it's important to note that despite these efforts, zone models may still have limitations in accurately capturing the complex dynamics of fire suppression by sprinklers. Detailed computational fluid dynamics (CFD) simulations or empirical models may be required for a more precise analysis of sprinkler effects in fire scenarios.

3.5.1.6 Limitations and assumptions

The limitations as outlined regarding zone models underscore the importance of cautious application and careful consideration of specific cases, particularly in scenarios like onboard passenger ships where compartment designs can vary widely. Some of these limitations are stated as follows (Jones *et al.*, 2005):

- Ideal Gas Assumption: The assumption of treating gas as an ideal gas with constant properties simplifies calculations but may not accurately represent real-world scenarios where gas behavior deviates from ideality.
- Sharp Boundary Assumption: Assuming a sharp boundary between upper and lower layers disregards the gradual transition that can occur, especially in rooms with significant stratification.
- Prescribed Pyrolysis and Heat Release Rate: Not accounting for feedback effects from flames or the possibility of flame spread can lead to inaccuracies in fire behavior predictions.
- Empirically Determined Entrainment Coefficients: Errors in empirically determined coefficients can compound in multicompartment scenarios, leading to significant discrepancies in remote compartments.
- Neglect of Wall Effects on Smoke Flow: Failure to consider downward flow along walls can result in underestimation of lower layer temperatures and concentrations.
- Uniform Radiation Assumption: Assuming uniform radiation from a single point disregards the complexities of fire dynamics and radiation patterns, potentially leading to inaccuracies.
- Ignoring Compartment Contents: Disregarding the influence of compartment contents on heat dissipation can lead to oversimplified predictions.
- Instantaneous Plume Impingement Assumption: Neglecting the time for gases to reach the ceiling overlooks important dynamics in fire behavior.
- Instantaneous Spread Assumption: Assuming instantaneous spread over the entire ceiling area may lead to overestimation, especially in compartments with high aspect ratios.

Given these limitations, it's crucial for practitioners to approach the application of zone models with a critical eye, considering the specific characteristics of the scenario at hand and validating results where possible. This level of caution becomes even more paramount in contexts like passenger ships, where compartment designs can introduce additional complexities.

3.5.2 Field models

Field models also known as Computational Fluid Dynamics (CFD) indeed employs field models, which discretize the domain into smaller units or control volumes. Control volume of the field model in an enclosed fire is illustrated in Figure 3.6. By applying conservation laws such as those for mass, momentum, energy, and species concentrations to these control volumes, CFD formulates a set of time-dependent, non-linear partial differential equations. The solution of these equations, along with an equation of state, yields predictions about the properties of fluid flow. Accuracy in CFD predictions depends on various factors, including the size and number of control volumes considered. Increasing the resolution by using smaller control volumes can improve accuracy but also increase computational costs. Conversely, larger control volumes may sacrifice detail but reduce computational expense. Achieving a balance between computational cost and desired accuracy is a crucial aspect of CFD modeling.

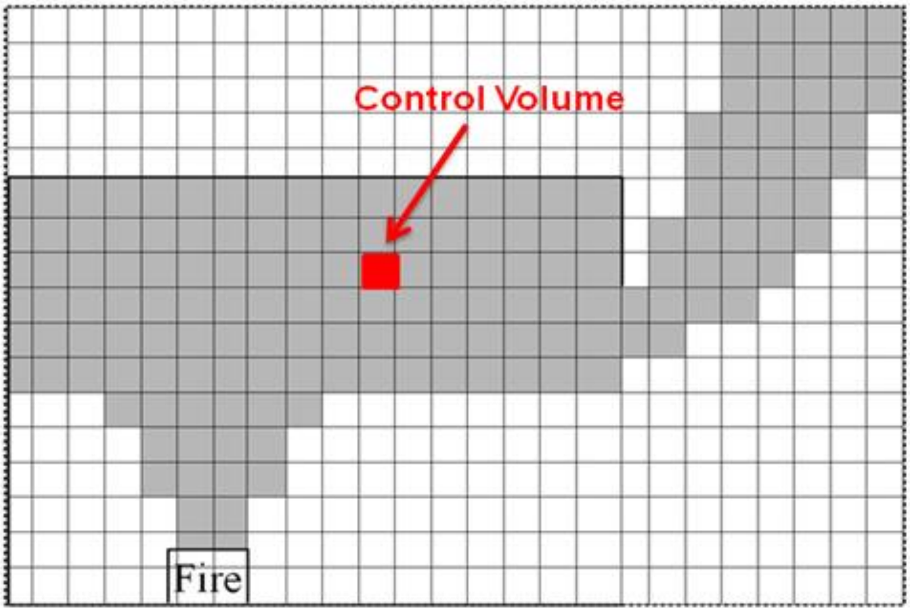

Figure 3.6 : The two layers and plumes in a room fire as divided by field models into small control volume.

For consistency, these equations are listed here in suffix notation (Versteeg and Malalasekera, 2007):

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial t}(\rho u_i) = 0 \tag{3.6}$$

where u_i is the velocity and ρ is the variable density noting that the density in a combusting flow is dependent on pressure, temperature and species concentration. The momentum equations can be written as follows:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_i}\left(\rho u_i u_j\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_i} + F_i \tag{3.7}$$

where p is the pressure, F_i represents the body forces including gravity and τ_{ij} is the viscous stress tensor:

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right) \tag{3.8}$$

The transport equations for species k can be written as follows:

$$\frac{\partial}{\partial t}(\rho Y_k) + \frac{\partial}{\partial x_i}(\rho u_i Y_k) = \frac{\partial}{\partial x_i}\left(\rho D_k \frac{\partial Y_k}{\partial x_i}\right) + \dot{\omega}_k \tag{3.9}$$

where Y_k is the mass fraction of a species k, D_k is the species diffusion coefficient in (m^2/s) which is usually considered a single value for all the involved species and $\dot{\omega}_k$ is the source (or sink) term representing the generation (or destruction) of a species due to chemical reactions.

The energy equations in its simplified form can be written as follows:

$$\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x_i}(\rho u_i h) = \frac{\partial}{\partial x_i}\left[\frac{\mu}{\sigma_h}\frac{\partial h}{x_i}\right] + \frac{\partial P}{\partial t} + S_{rad} \tag{3.10}$$

where h is the enthalpy, S_{rad} is the radiation loss or gain, σ_h is the mixture Prandtl number and μ is the dynamic viscosity.

3.5.2.1 Sub-models

In computational fluid dynamics (CFD), sub-models play a crucial role in solving the governing equations accurately. These sub-models are often derived from physical principles and empirical data to represent various phenomena that are not explicitly resolved in the simulation. Among the most important sub-models are those related to combustion, turbulence, and radiation (Versteeg and Malalasekera, 2007).

3.5.2.2 Combustion

Combustion models are essential for simulating the combustion process in engines, furnaces, and other combustion systems. These models typically involve equations that describe the chemical reactions, heat release, species transport, and other relevant phenomena occurring during combustion. They can range from simple empirical models to more complex detailed mechanisms, depending on the accuracy required and computational resources available. In the realm of non-premixed combustion modeling, various approaches are utilized to capture the intricacies of this complex phenomenon.

Simple chemical reacting system (flame-sheet) model simplifies combustion to a single fast chemical reaction with stoichiometric proportions of fuel and oxidant. It utilizes a mixture fraction to represent the mass fraction of fuel and oxidant. Transport equations for mixture fraction and enthalpy are solved, assuming negligible radiation and heat losses. Eddy Break-Up model considers the rate of fuel consumption to be controlled by flow properties, particularly turbulence. It expresses the reaction rate in terms of turbulence parameters like turbulent kinetic energy and dissipation rate. Its accuracy heavily depends on the predictions of the turbulence model. Eddy dissipation concept is an extension of the eddy break-up model, aiming to incorporate the significance of fine structures in turbulent flows where combustion chemistry plays a crucial role. Finite rate kinetics (laminar flamelet concept) approach focuses on kinetically controlled combustion applications where prediction of intermediate and minor species is essential. It models finite rate kinetics effects based on the laminar flamelet concept, considering the diffusion flame as a statistical ensemble of thin laminar flames. Turbulence effects are incorporated into flamelets, yielding a laminar flamelet library. Volumetric heat source model treats fire as a volumetric heat source, simplifying the combustion process by not requiring detailed combustion information. It focuses on simulating the resulting effects of combustion, such as heat and smoke production, based on prescribed inputs regarding the shape, size, and heat/mass production of the volume. Each model has its advantages and limitations, and the choice of model depends on the specific characteristics of the combustion problem being studied and the available computational resources.

3.5.2.3 Turbulence

In the context of fluid dynamics and the study of turbulence, solution methods to resolve the complex behavior of turbulent flows can indeed be classified into three main categories as follows:

- Direct Numerical Simulation (DNS): DNS involves solving the Navier-Stokes equations directly for all the scales of motion in a turbulent flow without any modeling approximations. It provides the most detailed and accurate representation of turbulence, capturing all the scales of motion and interactions. However, DNS requires extremely fine computational grids and time steps, leading to very high computational costs. This makes DNS feasible only for flows with relatively low Reynolds numbers or for small domains.
- Large Eddy Simulation (LES): LES resolves the large scales of motion directly and models the smaller scales of turbulence. The smaller, sub grid-scale motions are represented using sub grid-scale models. LES offers a good balance between accuracy and computational efficiency. It captures the most energetic and influential eddies while simplifying the treatment of smaller scales. While less computationally intensive than DNS, LES still requires significant computational resources, especially for high Reynolds number flows or complex geometries. Accurate sub grid-scale modeling is also critical for reliable results.
- Two-equation turbulence models: RANS focuses on solving the time-averaged Navier-Stokes equations, where the effects of turbulence are modeled rather than resolved. Turbulence models, such as the k-ε or k-ω models, are used to represent turbulent stresses. RANS is the most computationally efficient approach among the three methods. It is widely used in engineering applications for design and analysis due to its relatively low computational cost. RANS provides less detailed information about the turbulent flow structures compared to DNS and LES. The accuracy of RANS simulations heavily depends on the turbulence model used and may be less reliable for highly unsteady or complex flows.

In summary, the choice of methods depends on the specific requirements of the problem at hand, such as the desired level of detail, available computational resources, and the nature of the turbulent flow being studied.

3.5.2.4 Radiation

Radiation plays a crucial role in heat transfer during fire incidents, particularly near the fire source where temperatures are at their highest. The radiant heat transfer equation, which is an integro-differential equation, presents significant challenges in terms of solving it, even for relatively simple two-dimensional planar media. This complexity is exacerbated by the fact that radiant heat transfer occurs in non-isothermal and non-homogeneous media, necessitating the incorporation of these variations into the calculations. To manage these complexities, simplifying assumptions are often introduced, striking a balance between accuracy and computational efficiency. Various approaches to radiant heat transfer in fire problems have been proposed and are commonly encountered in the literature (Novozhilov, 2001) (Versteeg and Malalasekera, 2007). The overview of some approaches is given below:

- Radiation Transport Equation (RTE): The foundational equation for radiant heat transfer, accounting for emission, absorption, and scattering within the medium. Solving the RTE directly is often infeasible for practical fire scenarios due to its complexity.
- Discrete Ordinates Method (DOM): This method discretizes the angular domain into a finite number of directions, transforming the RTE into a set of coupled differential equations that are easier to solve numerically. It offers a good balance between accuracy and computational cost but can still be intensive for highly detailed simulations.
- Finite Volume Method (FVM): Often used for computational fluid dynamics, this method can also be applied to solve the RTE. It divides the domain into finite volumes and solves the radiative transfer in each volume. This approach can handle complex geometries and boundary conditions but requires careful grid resolution to maintain accuracy.

- Monte Carlo Method (MCM): This probabilistic method involves simulating the paths of many photons to statistically estimate radiative heat transfer. While very flexible and capable of handling complex media and boundary conditions, it is computationally expensive, particularly for large-scale fire simulations.
- Flux Method: This approach simplifies the RTE by integrating over angles to obtain radiative fluxes. While less accurate than methods that solve the full angular dependence, it significantly reduces computational requirements and can be useful for preliminary assessments or when detailed angular resolution is unnecessary.
- P1 and Higher-Order P-N Approximations: These methods approximate RTE by expanding the intensity in terms of spherical harmonics. The P1 approximation, or differential approximation, is the simplest, reducing the RTE to a diffusion-like equation. Higher-order approximations provide better accuracy at the cost of increased complexity and computational effort.

These approaches each offer a trade-off between computational efficiency and the accuracy of the results. The choice of method depends on the specific requirements of the fire scenario being modeled, including the complexity of the geometry, the degree of detail needed, and the available computational resources. By understanding and applying these methods appropriately, it is possible to achieve a practical balance that meets the needs of fire safety analysis and design.

3.5.2.5 Boundary conditions

Boundary conditions are crucial in computational fluid dynamics (CFD) simulations as they define the limits and interactions at the edges of the computational domain. These conditions can include various physical phenomena such as the flow of air through openings (doors, windows), heat transfer through walls, or the introduction of external sources or sinks like fires or suppressants. The primary types of boundary conditions in CFD are:

- Dirichlet Boundary Conditions: These specify the exact values of variables at the boundaries. For example, setting a fixed velocity or temperature for air entering through a door or window.

- Neumann Boundary Conditions: These define the gradients of variables at the boundaries. An example is setting the gradient of velocity or temperature to zero along a plane of symmetry, ensuring no flux across that boundary.
- Source/Sink Boundary Conditions: These represent the addition or removal of mass, momentum, or heat within the domain. An example is defining a fire as a volumetric heat source, which adds heat to the computational domain.

In this study, Fire Dynamics Simulator (FDS) is selected for simulation purposes. FDS is developed by the National Institute of Standards and Technology (NIST) and this is specifically designed for simulating fire dynamics and predicting the movement of smoke and heat. It is widely recognized and used in fire protection engineering and research.

3.5.3 Evacuation modelling

Over the past two decades, computer simulation models for evacuation analysis have significantly evolved from simple 'hydraulic' and 'ball-bearing' models to complex behavioral models with adaptive capabilities. Today, there are over 40 different evacuation models tailored for various environments, including aircraft, buildings, trains, and ships. These models share common elements in representing the geometric environment, population, and evacuee behavior, which are critical in defining the nature of an evacuation model (Sharp *et al.*, 2003).

Originally developed at the University of Edinburgh and maintained by IES Scotland, SIMULEX focuses on the physical aspects of evacuation through detailed spatial representation. It is designed as a tool for fire safety engineers, architects, and marine engineers to aid in the design of vessel layouts. SIMULEX is capable of simulating the evacuation of large numbers of people from multi-floored structures (Thompson *et al.*, 1996). Both are discrete step models. EVACSIM, developed in 1995, is used for modeling evacuation flows in various public and private facilities, including buildings, stadiums, passenger terminals, and offshore oil platforms (Soma *et al.*, 1995). EVAC was developed to comply with both IMO and Norwegian regulations and uses a coarse network method for geometry representation, focusing on escapeways linked by decision points (Drager and Orset, 1999). Part of the EXODUS suite from the Fire Safety Engineering Group (FSEG) at the University of Greenwich, maritime EXODUS is designed for marine applications. This model is flexible and can incorporate new data, such as human performance under conditions of list and roll, which are currently being researched in collaboration with Canadian entities (Galea *et al.*, 1999). Although the current version lacks specific data on the deployment of escape systems and vessel abandonment, these aspects can be integrated once data becomes available. Developed by the Ship Stability Research Centre (SSRC) at the Universities of Glasgow and Strathclyde, Evi is a state-of-the-art passenger evacuation simulation tool for ships. It can simulate real-time evacuation scenarios on large cruise ships, accounting for various incidents such as fire, collision, flooding, and cargo shift, while considering ship motions in a sea environment. Evi's capabilities include evaluating evacuation times, identifying bottlenecks, assessing layout designs, conducting sensitivity analyses, and supporting crisis management through training and effective evacuation planning (Vassalos *et al.*, 2001). These models reflect the technological advances and varying purposes for which they were developed, ranging from design tools to compliance with specific regulations. The availability of computing power at the time of their development also influenced their methodologies and capabilities.

4. FIRE PROTECTION SYSTEMS

Fire protection systems are crucial for ensuring both life safety and property safety. These systems can be categorized broadly into three main areas: detection, extinguishment, and compartmentation. While these categories are distinct in purpose, they often overlap in practice, as actions taken to protect life may also protect property, and vice versa.

- Fire Prevention
- Risk Assessment: Identifying potential fire hazards and implementing measures to mitigate them.
- Fire Safety Education: Training occupants on fire prevention techniques and the proper use of fire safety equipment.
- Ship Design and Construction
- Fire-Resistant Materials: Using materials that resist ignition and slow the spread of fire.
- Compartmentation: Dividing vessels into sections with fire-resistant barriers to prevent the spread of fire and smoke.
- Structural Integrity: Ensuring that the ship structure can withstand fire for a certain period, providing time for evacuation and firefighting.
- Fire Detection and Alarm Systems
- Smoke Detectors and Alarms: Installing systems that provide early warning of a fire, allowing for prompt evacuation and response.
- Automatic Fire Detection Systems: Utilizing advanced detection technologies (e.g., heat sensors, flame detectors) to identify fires quickly.
- Fire Suppression Systems

- Sprinkler Systems: Installing automatic sprinklers that activate to control or extinguish fires.
- Fire Extinguishers: Strategically placing fire extinguishers for immediate use in controlling small fires.
- Means of Egress
- Evacuation Planning: Designing clear and accessible escape routes to ensure safe evacuation of occupants.
- Emergency Lighting: Ensuring pathways are illuminated during power outages to facilitate safe egress.
- Fire Service Access
- Crew Connection: Providing easy access for firefighters or fire safety related crews to connect equipment.
- Access Decks and Lines: Designing and maintaining access routes depending on fire safety plan. Captain, chief engineer and crews (seafarers, greasers etc.) access the location of fire source.
- Emergency Response Planning
- Fire Drills: Conducting regular drills to practice evacuation procedures and ensure readiness.
- Emergency Communication Systems: Establishing systems for communicating with occupants and coordinating emergency responses.
- Smoke Control Systems
- Smoke Ventilation: Installing systems to control and remove smoke, improving visibility and air quality during a fire.
- Pressurization Systems: Maintaining positive pressure in stairwells and escape routes to keep them smoke-free.
- Fire Safety Management
- Maintenance of Fire Protection Systems: Regularly inspecting and maintaining fire safety equipment to ensure proper functionality.

- Fire Safety Policies: Developing and enforcing policies that promote fire safety awareness and compliance with regulations.

By addressing these key areas, fire safety engineering aims to protect both lives and property, recognizing that improvements in one area often benefit the other. This holistic approach ensures comprehensive fire protection and resilience against fire-related incidents. This summary classifies the considerations involved in fire safety engineering under the two headings of active and passive provisions (Malhotra, 1984).

- Active fire protection
    - Alarm
    - Smoke control
    - Firefighting or control
    - Dangerous contents
    - External firefighting
    - Fire safety management
- Passive measures
    - Compartmentation
    - Flammability
    - Escape routes
    - Structural integrity

4.1 Active Fire Protection Systems

Mainly, active fire protection includes detection and suppression systems. To ensure life safety through evacuation, it is necessary to ensure that means are available for detection and control of a fire. Control is needed both to reduce the production of smoke to allow more efficient evacuation and to keep temperatures down in the structure to reduce subsequent damage.

4.1.1 Detection and control systems

Systems installed for fire detection can be categorized into manual, automatic, or a combination of both. Manual fire detection systems require human intervention to activate the alarm. One common example is the traditional frangible glass panel. When broken, this panel triggers the fire alarm system. Despite their simplicity, manual systems have limitations. They rely on someone noticing the fire and assessing its severity, which can be problematic in situations where people are not always present. Automatic fire detection systems operate without human intervention. These systems use sensors to detect excessive heat or smoke. When triggered, they can directly activate fire-fighting measures, such as the fusible head of a sprinkler, or indirectly initiate fire control and evacuation procedures. Advanced technologies in automatic systems include low-power lasers and infrared sensors for smoke detection. Automatic systems often combine heat and smoke detection sensors to enhance reliability. However, the effectiveness of these sensors can be influenced by the vessels' normal ambient conditions and usage. For example, kitchens or smoking areas pose challenges, although modern computer controls have mitigated many of these issues. For all but the smallest and least occupied vessels, it is crucial that detection devices are integrated into a comprehensive system. This system should identify the fire's source or the point where the alarm was activated, initiate fire control measures, such as closing roller shutter doors to isolate compartments, deploying smoke curtains, or activating automatic venting systems, trigger evacuation procedures and automatically notify the local fire brigade of the fire outbreak.

By combining these features, fire detection systems can provide robust protection, ensuring rapid response and minimizing potential damage and danger.

Ensuring clear visibility and safe evacuation during a fire is crucial to prevent smoke from descending below 2.5 to 3 meters above the floor level within the first 15 minutes. This requirement arises due to the dual hazards posed by smoke: its toxicity and the disorientation it causes by impairing visibility. Effective smoke control can be achieved through forced venting to manage smoke generation or by using smoke curtains to create reservoirs that contain smoke in the early stages. In certain scenarios, natural venting can be sufficient to control smoke without additional measures. However, in warehouses where the stored contents might produce toxic smoke early in a fire, it is necessary to contain the smoke within specific areas until the roof can vent naturally. This containment needs to last long enough to ensure that visibility remains clear for evacuation, typically a brief period due to the low human occupancy and direct access to fire exits in such buildings. In contrast, large open-plan structures like shopping malls and atriums pose more significant challenges for smoke control. The volume of smoke produced, and the required ventilation levels can be substantial, necessitating precise calculations as outlined (Hansell and Morgan, 1985). For these buildings, the implementation of an automatic smoke venting system that activates upon fire detection is essential. This system can employ either natural or forced draft ventilation but must be automatic and consider the access needs of fire brigades and the risk of falling cladding. Forced draft systems require a reliable standby power supply to ensure their effectiveness during an emergency.

Appendix A shows the image of fire detection and control systems.

4.1.2 Extinguishing systems

Fire suppression and extinguishment have evolved significantly with advancements in technology and understanding of the combustion process. The traditional fire triangle — fuel, heat, and oxygen — has been the basis of fire control methods for centuries. The idea is simple: if you remove or reduce one of these components, the fire will stop burning. For example, extinguishers that release water or foam work by cooling the heat or smothering the fire to limit oxygen.

However, as fire suppression systems and research progressed, it became clear that combustion isn't just about these three components. There's a crucial aspect of fire behavior that's chemical in nature. Combustion involves complex reactions between the fuel and oxygen, and if this "chain reaction" can be interrupted, combustion can be stopped even if fuel, heat, and oxygen are still present.

This led to the development of the fire tetrahedron, an expansion of the fire triangle to include a fourth component: the chemical chain reaction. In the fire tetrahedron, combustion is seen as a process requiring fuel, heat, oxygen, and a chemical reaction. Halon extinguishers and modern dry chemical agents, for example, work by disrupting this chain reaction, preventing the fire from sustaining itself.

The fire tetrahedron model offers a more comprehensive framework for understanding fire suppression, providing a way to design systems that target all four aspects of combustion. This has led to more advanced and efficient fire control methods, capable of dealing with different fire types and environments.

In summary, by targeting not just fuel, heat, or oxygen, but also the chemical reactions that keep fire burning, fire suppression technology has become much more effective, allowing for a wider range of approaches to extinguish or control fires.

Extinguishing agents are water, foam, carbon dioxide (CO2), dry chemical powders and halon and clean agents.

Water is the most used fire extinguishing agent due to its several desirable properties. However, it also has some limitations. The effectiveness of water in extinguishing fires is primarily due to its ability to cool the fuel below the temperature at which it can produce flammable vapors, a process known as cooling. Additionally, water can extinguish fires through smothering, dilution, and emulsification. Water has a high specific heat capacity, which means it requires a significant amount of heat to change from a liquid to a gas. When applied to a fire, water absorbs a substantial amount of the fire's heat. If enough water is used, it can absorb sufficient heat to lower the temperature of the fuel below the point at which it releases flammable vapors, causing the fire to be extinguished. Furthermore, when water turns into steam, it continues to absorb heat, making it an effective extinguishing agent even in its gaseous form. When water is converted to steam, its volume increases approximately 1,600 times. This expansion helps displace oxygen from the fire area, which is crucial for combustion. By reducing the oxygen available to the fire, the steam helps smother the flames, aiding in extinguishing the fire through oxygen depletion. To maximize water's effectiveness, it is best to apply it in a spray form rather than a stream. Sprayed water absorbs heat more quickly and efficiently. This principle is utilized in sprinkler systems, which discharge water in a spray pattern to cover a larger area and cool the fire more rapidly. Water can also extinguish fires through dilution and emulsification. Dilution involves adding water to a burning liquid, cooling it and reducing vapor production. Emulsification occurs when immiscible liquids mix, forming an emulsion that retards the release of flammable vapors. However, these methods are generally less effective and come with risks such as spills and boil overs, which can spread the fire and cause injuries. Water's primary advantage as a fire suppression agent is its availability and low cost, particularly in areas with a municipal water supply. However, water has several limitations such as weight, electrical conductivity, property damage and freezing. To address these limitations, various design methods and the selection of alternative extinguishing agents can be employed. For example, other suppression agents, such as foam, dry chemicals, or gaseous agents, can be used in situations where water limitations are problematic. In summary, while water is an effective and widely used fire extinguishing agent due to its cooling and smothering properties, its limitations must be considered. Proper application methods and alternative agents can help mitigate these limitations, ensuring effective fire suppression in a variety of scenarios.

The essential elements used in fire suppression systems, particularly in dealing with flammable liquid spills and fires. Here's a breakdown of the key points:

- Foam Concentrates: These are used to create foam solutions when mixed with water. Foam is particularly effective in fighting fires involving flammable liquids, such as oil or gasoline, because it helps to smother the fire, preventing the fuel from encountering oxygen, which is necessary for combustion.
    - Low-expansion foam forms a thicker blanket of foam with a lower volume of air mixed in.
    - High-expansion foam produces foam with more air, creating a larger volume of foam, which is useful for suppressing fires in confined spaces or large areas.
- Wetting Agents: These additives reduce the surface tension of water, allowing it to penetrate combustible materials more effectively. When added to water, wetting agents make the water spread and absorb into the materials more easily, improving the water's ability to control deep-seated fires, such as those in wood or other porous substances.
- Antifreeze: In colder climates, antifreeze is added to water used in fire suppression systems to lower the freezing point. This ensures that water-based systems, including sprinkler systems or hoses, remain operational even in freezing temperatures, preventing the water from freezing and rendering the system useless during a fire.

Carbon dioxide (CO2) finds its place in various commercial applications, from carbonating beverages to serving as a fire extinguishing agent. Its properties make it particularly suitable for extinguishing fires, especially in kitchen environments and industrial settings. In fire extinguishing systems, CO_2 can be employed in two primary ways: total flooding and local application. Total flooding systems are utilized to protect enclosed spaces such as kitchens, where the entire area is filled with CO_2 to extinguish fires. Local application involves directing CO_2 specifically at the source of the fire, such as deep fryers. One critical aspect to consider when working with CO_2 is its phase transition. At room temperature and pressure, CO_2 can exist in vapor or solid form (dry ice). If the pressure drops below a certain threshold, dry ice can form and block pipelines, impeding the flow of CO_2. The mechanism of CO_2 in fire extinguishing involves diluting the oxygen concentration around the fire. By reducing the oxygen available for combustion, the rate of heat generation decreases, eventually leading to the fire's extinction. Additionally, CO_2's high vapor density enables it to blanket the surface of fuels, physically separating oxygen from the fuel and further suppressing combustion. While CO_2 may not provide as significant a cooling effect as water pound-for-pound, its ability to remove heat from the surroundings during sublimation contributes to its effectiveness in extinguishing fires. Overall, CO_2 serves as a valuable fire suppression agent due to its unique combination of properties.

Dry chemical extinguishing agents work effectively by disrupting the combustion process through a combination of smothering, cooling, and breaking the combustion chain reaction. When applied directly to the flaming area, they can swiftly extinguish fires. This effectiveness is comparable to halons, which also work by interrupting the combustion chain reaction. Common dry chemical agents used in fire suppression systems include sodium bicarbonate, potassium bicarbonate, urea-potassium bicarbonate, and monoammonium phosphate. These agents may include additives such as metallic stearates, tricalcium phosphates, and silicones to improve characteristics like flow, storage, and water repellence, and to prevent caking. Multipurpose dry chemical agents, often based on monoammonium phosphate, are versatile and can be used to extinguish fires involving ordinary combustibles, energized electrical equipment, and flammable liquids. However, regular dry chemical agents, which lack penetrating abilities, are not as effective against ordinary combustibles unless accompanied by water to address subsurface burning. It's crucial to avoid mixing dry chemical agents unless explicitly specified, as incompatible combinations can generate hazardous substances like CO_2, leading to container explosions and caking of the agent.

Halon is indeed a fascinating fire extinguishing agent with unique properties. Its effectiveness in disrupting the chemical combustion chain reaction rather than simply removing heat or smothering the fire sets it apart. This mechanism allows it to suppress fires quickly and efficiently. The fact that it leaves no residue after discharge and is electrically nonconductive makes it highly suitable for protecting electronic and electrical equipment. Its noncorrosive nature further adds to its appeal, ensuring that sensitive materials are not damaged during a fire suppression event. However, the environmental concerns associated with halon, particularly its depletion effect on the ozone layer, have led to a re-evaluation of its usage. This has prompted the exploration of alternative fire suppression agents and the development of new products to replace halon in existing systems. It's interesting to note the ongoing research into using different test gases, such as sulfur hexafluoride (SF6), in acceptance testing as a potential alternative to halon. This demonstrates the commitment to finding environmentally friendly solutions while maintaining the effectiveness of fire suppression systems. As technology advances and environmental awareness grows, the fire protection industry continues to evolve, seeking innovative solutions that balance safety, effectiveness, and sustainability. SOLAS 1974, Reg.II-2/10 permits the use of halons as fire extinguishing media on ships built before October 1, 1994. The phase-out date for Halon systems on ships built before this date has not been fully established under SOLAS, but the focus is on ensuring that existing systems are properly maintained and tested until they are replaced. Halon's environmental impact, particularly its role in depleting the ozone layer, is a significant concern. Halon testing (such as using Halon for functional checks or discharges for maintenance purposes) is prohibited due to the harmful effects it can have on the ozone layer if released into the atmosphere. Alternative fire suppression systems are encouraged, as they provide more environmentally friendly solutions to fire safety onboard. The European Commission has a strict stance on Halon usage. It considers the supply of Halon to non-EU flagged ships in EU ports to be an illegal export, due to Halon’s harmful environmental impact. If halon is discharged or used in a non-EU flagged ship while in an EU port, it cannot be refilled with Halon. This can lead to the ship being detained until a new fire suppression system is installed, which could be an environmentally safer alternative like FM-200, Novec 1230, or CO2 systems. When Halon is released from a system onboard a ship, and if that ship is flagged outside the EU, it cannot be refilled with Halon in an EU port. This means ships would face detention in the port until they have replaced their Halon-based system with a compliant, environmentally friendly fire suppression system. This policy encourages the replacement of Halon systems with modern alternatives, which are more environmentally sound and comply with both international and EU regulations.

Novec 1230 Fire Protection Fluid chemical clean agent suppression system uses a colorless, non-toxic fluorinated ketone containing carbon, fluorine, and oxygen. Novec 1230 fluid is a sustainable clean agent, providing a replacement for halon and hydrofluorocarbon extinguishing agents. A more environmentally friendly solution, Novec 1230 fluid is often used in data centers and other electronic-heavy facilities due to its ability to suppress fires by removing heat without causing disruptions and damage to sensitive electronic equipment.

FM-200 chemical clean agent suppression system uses a hydrofluorocarbon (HFC) compound containing hydrogen, fluorine, and carbon. The clean agent is stored in cylinders as a liquid and pressurized with nitrogen, saving up to seven times the space of a CO2 system or an inert gas system. FM-200 is suitable for applications where space is at a minimum and for frequently trafficked areas as its non-reactive, non-corrosive, and non-conductive.

The role of automatic fire suppression systems are discussed, specifically automatic sprinkler systems, in various types of buildings or hazards. Here's a clearer explanation of the topic:

Automatic sprinkler systems are indeed the most commonly used fire suppression method in buildings. They are designed to detect and respond to fires by releasing water. When a fire breaks out, heat from the flames causes the sprinkler heads to activate, releasing water at a controlled rate. These systems are designed to do at least two things:

- Contain the fire: By distributing water in the area of the fire, sprinklers can help limit its spread, keeping it from becoming uncontrollable.
- Extinguish the fire: In many cases, if the system is properly designed and there is sufficient water supply, it can fully extinguish the fire.

Sprinklers operate at a predetermined temperature, meaning that each sprinkler head is designed to activate at a specific temperature. This temperature threshold ensures that sprinklers only release water when a fire is detected, preventing unnecessary water damage. The water flows to the sprinklers through a network of pipes installed in the ceiling or walls. These pipes are pressurized and, when a sprinkler is activated, they allow water to flow to the sprinkler head. Although sprinkler systems are the most common, not all hazards are compatible with water. For example, in areas with electrical equipment or certain chemicals, water might be inappropriate due to the risk of electrical shock or chemical reactions. In such cases, alternative suppression methods (like gas-based systems or dry chemical systems) may be used. In summary, automatic sprinkler systems are a critical safety feature in many buildings, providing both containment and extinguishment capabilities for fires. However, they may not always be appropriate, depending on the nature of the hazard. Absolutely, it is highlighted that the dual purposes of sprinkler systems are succinctly. The primary function of sprinkler systems is to extinguish fires. Upon detecting a fire, the sprinklers release water, aiming to suppress or extinguish the flames before they can spread further, minimizing property damage, and potentially saving lives. Even if the sprinkler system doesn't fully extinguish the fire, it plays a crucial role in controlling its size. By containing the fire and limiting its growth, the sprinklers buy time for occupants to evacuate safely and for firefighting crews to arrive and take over suppression efforts. Additionally, when integrated with a fire alarm system, sprinkler systems offer an added layer of protection. By acting as initiating devices, they can quickly alert occupants to the presence of a fire, facilitating timely evacuation and enhancing overall safety. Ultimately, the combined benefits of sprinkler systems—fire suppression, fire size control, and integration with fire alarm systems—significantly contribute to property protection and life safety in the event of a fire.

Portable fire extinguishers can be valuable tools for quickly and effectively suppressing small fires, especially when they're still in the incipient stage. They provide a means for individuals to take immediate action to control a fire before it escalates, potentially preventing further damage and harm. However, it's crucial to emphasize the importance of proper training and judgment when using portable fire extinguishers. While they can be effective in the right circumstances, attempting to extinguish a fire without adequate training or when the fire has already grown beyond the incipient stage can be extremely dangerous. In such cases, the priority should always be on safe evacuation and prompt notification of the fire department. In summary, while portable fire extinguishers can be effective firefighting tools, their use should be guided by proper training, sound judgment, and a clear understanding of their limitations. Additionally, timely notification of professional firefighting services is essential in any fire emergency to ensure a coordinated and effective response. There are six common agents used in portable extinguishers: water-based, carbon dioxide (CO_2), dry chemicals, halon, dry powder and foam.

Appendix B shows the images of fire extinguishing systems.

4.2 Passive Fire Protection Systems

Passive fire protection systems on ships are crucial for enhancing safety and preventing the spread of fire. These systems are designed to contain fires, protect structural integrity, and ensure the safety of passengers and crew without requiring any active intervention. These passive fire protection systems are integrated into the design and construction of ships to enhance overall safety and compliance with international maritime safety regulations, such as those stipulated by the International Maritime Organization (IMO) under the Safety of Life at Sea (SOLAS) Convention.

4.2.1 Fire resistant materials

Fire-resistant bulkheads and decks are constructed using materials that can withstand high temperatures and prevent the spread of fire between compartments. Fire-resistant insulation materials are used in walls, ceilings, and around critical equipment to slow the spread of fire and heat. Specially designed fire doors are installed in compartments to create barriers that can withstand fire for a specified period, preventing it from spreading to other areas. These are used in specific areas to maintain visibility while still providing a barrier against fire. Ensuring that escape routes such as stairways and corridors are protected with fire-resistant materials to allow safe evacuation. Lifeboat and muster stations are often protected with fire-resistant materials to ensure they remain accessible in the event of a fire.

Appendix C gives fire reactions of materials.

4.2.2 Compartments

The compartmentalization of large structures is a critical aspect of fire safety, designed to limit the spread of fire and facilitate phased evacuations onboard ships. This strategy involves dividing the ship into sections both vertically and horizontally. The goal is to confine a fire to a specific compartment, thereby preventing it from spreading to other parts of the structure and allowing for an organized evacuation process. Initially, only the decks within the fire-affected compartment are evacuated, while the remaining decks above and below the fire zone are evacuated later. The criteria for compartmentalization, such as maximum deck areas or volumes, are somewhat ambiguous and often rooted in historical precedents rather than contemporary fire-fighting advancements. One significant issue that needs attention is the spread between horizontal compartments due to the failure of decks or bulkheads. To mitigate this risk, steel decks and bulkheads onboard ships should be equipped with either sprinkler protection or intumescent coatings. Additionally, it is crucial to ensure that the integrity of compartmentalization is maintained following any repairs, remedial work, or renovations. Any modifications should be carefully managed to uphold the original fire safety standards and prevent compromising the compartmentalized design of the structure.

Appendix D gives the visualization of compartmentalization.

4.2.3 Smoke control systems

Smoke and Fire Curtains are used to control the movement of smoke and fire within large open spaces, directing them towards extraction points and preventing their spread. Installed in ventilation and air conditioning ducts to prevent the spread of fire and smoke through the ship's ventilation system. Also, special seals are used where cables and pipes pass through bulkheads and decks to prevent fire from spreading through these openings. Fire-resistant emergency lighting and clearly marked escape routes and fire safety equipment locations are critical for ensuring safe evacuation during a fire.

Appendix E shows smoke control systems such as fire curtains.

4.2.4 Surface protection

Intumescent coatings are applied to structural steel and other materials; these coatings expand when exposed to heat, providing an insulating barrier that protects the material from fire. When exposed to heat, intumescent paint systems expand and form an insulating layer of aerated carbon, akin to the char layer that forms on timber during combustion. This process enhances fire resistance by creating a barrier that protects the underlying material from high temperatures. One significant advantage of these paints is that they can be applied to exposed steelwork, serving both as a fire-protective measure and a final architectural finish. However, there are some drawbacks associated with intumescent paints. Maintenance is a critical concern; regular inspections are necessary to ensure the integrity of the paint layer. If a fire occurs, the paint layer must be replaced, as it would have already expanded and charred, losing its protective capability. Additionally, while intumescent paints are effective against fires, they also resist the impacts of blasts and hydrocarbon fires, providing a comprehensive protective solution for structural elements in hazardous environments.

Appendix F shows the visual of steel coatings and surface protection systems.

4.2.5 Fire safety plans and training

Comprehensive fire safety plans detailing the passive and active fire protection measures, evacuation procedures, and regular crew training on fire safety protocols.

Effective fire safety training is essential for preparing personnel to respond appropriately in the event of a fire. Key components of training should include:

- Fire Prevention Education: Training on fire hazards, safe practices, and how to prevent fires in the workplace (e.g., electrical safety, handling of flammable materials).
- Fire Extinguisher Use: Hands-on training on how to use fire extinguishers, identifying the correct type for different fire classes (e.g., Class A, B, C, D, K).
- Evacuation Procedures: Familiarizing staff with evacuation routes, exits, assembly points, and how to assist others during an evacuation.
- Emergency Response Protocols: Training in the roles of fire wardens, reporting fires, coordinating with emergency responders, and performing first aid if necessary.
- Regular Drills: Conducting fire drills that simulate different scenarios (e.g., nighttime fire, fire in specific areas, or fire involving hazardous materials) to ensure readiness.

- Post-Incident Review: After any fire drill or actual emergency, conduct debriefings to assess the effectiveness of the response and identify areas for improvement.

Hermansson and Papamatthaiou (2021) discuss the essential skills for crew members to acquire during fire safety training onboard ships. The authors categorize these skills into three primary areas:

- Practical skills: These involve hands-on ability to respond to fire-related emergencies.
- Theoretical skills: These include knowledge of fire safety procedures, regulations, and principles.
- Social skills: These refer to communication, teamwork, and leadership abilities required during an emergency response.

The study also emphasizes that several factors significantly impact the effectiveness of fire safety training onboard, particularly:

- Safety culture: A positive safety culture promotes proactive safety measures and adherence to protocols.
- Leadership: Strong leadership ensures proper guidance and the effective implementation of safety practices.
- Knowledge: The depth and accuracy of knowledge regarding fire safety procedures and regulations are crucial.

Moreover, the study identifies a gap between the fire safety training conducted onboard and the relevant safety regulations and rules. This gap suggests that onboard training might not fully align with the regulatory standards that should be followed, potentially reducing its effectiveness. In response to these findings, the study provides suggestions for improving fire safety training onboard. These suggestions are focused on addressing the factors that influence training and ensuring that the skills which are considered most important (practical, theoretical, and social) are adequately developed in the crew members. This can lead to enhanced preparedness and better fire safety outcomes in emergencies.

Appendix G gives an example of a fire safety plan.

4.3 Fire Protection Systems in This Study

In this chapter, active and passive fire protection systems are explained. In the case studies that provide in this study, active and passive fire protection systems are taken into consideration when establishing scenarios. In the case study of Turkish domestic passenger vessel from Sehir Hatlari includes fire rated bulkheads in the compartmentation and fire extinguishing systems called as sprinklers depending on scenarios. In the case study of electric vehicle spaces onboard ship, only fire rated deck includes the scenario.

5. FIRE INCIDENTS ONBOARD SHIPS

5.1 Fire Incident Historical Data

No ship can operate 100% safely or be completely error-free. Hazard classification and risk evaluation are primarily targeted on assessing risk levels and identifying the greatest fire hazards on board. Properly conducted analyses can reduce failure risk to an acceptable level and enhance ship reliability in critical conditions. Therefore, risk assessment applications are of great importance to safeguard the system reliability in ships. A thorough analysis of historical ship incident data can inform amendments to regulations and decrease the theoretical accident risk. Maritime safety is not only of primary environmental importance but also has a considerable commercial aspect. An apparent safety level is a critical component of the package offered by operators to their customers (Barlas et al, 2017).

It is well known that onboard fires are among the main ship accidents, leading to loss of life and property. If fire on board is not extinguished, it can lead to catastrophic consequences, total actual loss, and severe victims. The data was collected from the Global Integrated Shipping Information System (GISIS), a database provided by the International Maritime Organization (IMO), containing casualty and incident data reported by IMO member states. We analyzed various types of ships reporting serious and very serious fire casualties from January 2000 to December 2022 (GISIS, 2023). In GISIS, fire casualty reports are classified into four categories: very serious, serious, less serious, and unspecified. Total loss of the ship and/or loss of life can be defined as very serious fire casualties. Serious fire casualties are fatalities to ships which do not qualify as "very serious fire casualties" and which involve a fire and/or explosion, resulting in immobilization of main engines, extensive accommodation damage, severe structural damage, etc. In this study, only very serious and serious reported casualties are investigated. The serious and very serious fire incidents of different types of ships between January 2000 and December 2022 are given in Table 5.1.

Table 5.1 : Different types of ships reporting serious and very serious fire casualties between 2000 and 2022.

Ship Type	Total	Percentage
Tanker	78	24.1%
Ro-Ro/Ferry/Pass.	54	16.7%
General cargo	45	13.9%
Fishing Vessel	43	13.3%
Bulk/Ore Carrier	34	10.5%
Others	30	9.3%
Container	30	9.3%
Tug/Supply Vessel	9	2.8%

Ro-Ro/Ferry/Passenger ships accounted for 16.7% of marine casualties globally from 2000 to 2022. However, one must consider not only the number of incidents but also the incidence rate. The average occurrence rates of ship types recording serious and very serious fire fatalities between 2000 and 2022 are shown in Table 5.2. The average rate describes the number of fire casualties per 1,000 ships over a 22-year period. It is calculated by dividing the casualty numbers by the average number of ships. The average incidence rate of fire casualties for RoRo/Ferry/Passenger ships from 2000 to 2022 is 6.82, meaning that, on average, 6.82 out of every 1000 such ships reported serious or very serious fire fatalities. During the same period, the average incidence rate for all other ship groups was 3.58. Therefore, the incidence rate for RoRo/Ferry/Passenger ships is almost twice that of all other ship types.

Table 5.2 : The incidence rates of different types of ships reporting serious and very serious fire casualties between 2000 and 2022.

Ship Type	Average Incidence Rate	Average Number of Ships
Ro-Ro/Ferry/Pass.	6.82	7907
Tanker	5.42	14380
General cargo	2.53	17784
Fishing Vessel	1.86	23000
Bulk/Ore Carrier	2.63	12941
Container	5.38	5574
Tug/Supply Vessel	0.43	20804

5.2 Serious Incidents with Passenger Ships Around the World

5.2.1 Star Princess

The incident aboard the Star Princess in 2006 was a tragic reminder of the potential dangers posed by fire on cruise ships. The fire, likely sparked by a discarded cigarette, spread rapidly due to combustible materials on the balconies and inadequate fire protection measures. The thick black smoke generated made evacuation challenging, resulting in one fatality and several injuries. Investigations by multiple authorities highlighted several deficiencies in fire safety regulations, particularly regarding external areas such as balconies. Recommendations were swiftly issued to improve fire protection arrangements, including proposals for amendments to the SOLAS Convention and the FSS Code. These proposed changes aimed to enhance balcony safety by mandating non-combustible materials for partitions, restricting combustible materials, and requiring the installation of fire detection and extinguishing systems for balcony furniture.

The response to this incident underscores the importance of continuous evaluation and improvement of safety standards in the maritime industry to prevent similar tragedies in the future.

The description highlights a critical gap in current maritime safety regulations. While SOLAS regulations govern the construction, fire protection, detection, and extinction measure onboard vessels, they do not specifically address the combustibility of materials used in external areas like balconies. This oversight poses a significant risk, as demonstrated by the Star Princess fire, where combustible materials readily ignited and fueled the blaze, leading to rapid spread and difficulty in containment. The incident underscores the need for immediate international action to address fire risks in external areas such as balconies. With the increasing prevalence of balconies on modern passenger vessels, it's crucial to ensure that fire protection measures are comprehensive and not limited to internal areas covered by existing regulations. Addressing this issue requires collaboration among maritime authorities, cruise ship operators, and regulatory bodies to implement measures that mitigate the risk of fires in external areas. This may involve updating SOLAS regulations to include requirements for balcony materials' combustibility, as well as mandating the installation of fire detection and suppression systems in balcony areas. By closing this regulatory gap and implementing proactive safety measures, the maritime industry can prevent future incidents and safeguard the lives of passengers and crew onboard cruise ships. Photos of Star Princess after fire are given in Figures 5.1, 5.2 and 5.3 (MAIB, 2006).

Figure 5.1 : View of Star Princess after fire incident.

Figure 5.2 : Melted aluminium structure of Star Princess.

Figure 5.3 : Melted polycarbonate partition of Star Princess.

5.2.2 Nordlys

The incident involving the coastal express steamer Nordlys in September 2011 was a tragic event that resulted in two fatalities, several injuries, and significant damage to the vessel. The investigation conducted by the Accident Investigation Board Norway (AIBN) revealed a series of factors contributing to the incident and identified several areas for improvement in safety procedures and vessel maintenance. Here's a summary of the key findings and recommendations from the AIBN report:

- Probable Cause of the Fire: The investigation concluded that the fire likely started due to a diesel leakage igniting upon contact with an un-insulated indicator valve on the starboard main engine. This leakage was attributed to a fatigue fracture in the feed pipes for a fuel injector pump, which was loose because the fastening bolts were not sufficiently tightened during a recent replacement.

- Inadequate job specification for the replacement of the fuel injector pump. Lack of insulation on hot surfaces in the engine room.
- Failure to set the water-based fire-extinguishing system to automatic mode and insufficient training for the crew.
- Failure of the emergency generator due to insufficient cooling, with prior issues not adequately addressed.
- Lack of procedures and training for dealing with personnel loss.

The AIBN proposed seven safety recommendations, including:

- Requiring all vessels to prepare an overview of hot surfaces in the engine room.
- Proposing prohibitions on the use of extinguishing agents that pose risks to human life.
- Implementing requirements for automatically released fire-extinguishing systems.
- Increasing focus on insulation of hot surfaces during inspections of passenger ships.
- Revising maintenance systems to ensure crew reliance on job specifications.
- Introducing routines for training to deal with personnel loss.
- Consulting with authorities to ensure watertight integrity of bulkheads between cargo holds.

Following the accident, the shipping company implemented several measures, including installing a new water-mist system as the main fire-extinguishing system, altering the arrangement for controlling dampers in the emergency generator room, and improving emergency exits from the engine room. Management development programs and officer conferences focused on crew compliance with procedures, and cooperation with the University of Bergen initiated to map safety culture on board. By addressing these recommendations and implementing necessary changes, both the regulatory authorities and the shipping company aim to enhance safety standards and prevent similar incidents in the future. The photo of Nordlys is given in Figure 5.4 (AINB, 2013).

Figure 5.4 : View of Nordlys after fire ignition.

5.2.3 Al Salam Boccaccio

The sinking of the M/V AL SALAM BOCCACCIO 98 in 2006 was a tragic event with devastating consequences. From the sequence of events described, it's evident that a combination of factors contributed to the disaster, including a fire outbreak, failure to follow emergency procedures, inadequate response from the crew and master, as well as external factors such as weather conditions. Several key points stand out from the analysis:

- Fire Outbreak: The fire that started, possibly in a passenger's luggage, initiated a chain reaction of events leading to the sinking. The lack of rigorous screening for flammable materials and inadequate fire protection measures for cargo contributed to the severity of the situation.
- Ineffective Emergency Response: Emergency procedures were not adequately followed by the crew and master. Confusion, unclear instructions, and a lack of decisive action hindered proper response efforts. Additionally, the refusal to seek external assistance or initiate an abandoned ship order further exacerbated the situation.
- Stability Issues: The accumulation of water on the car-deck due to firefighting efforts, coupled with the shifting cargo, created an unstable list condition. Uncertainty about ballast operations and ineffective corrective measures worsened the vessel's stability.

- Master's Role: The master's failure to accept recommendations from officers, reluctance to seek assistance, and refusal to initiate abandoned ship procedures played a significant role in the disaster. Lack of effective leadership and decision-making contributed to the loss of lives.
- Safety Management System (ISM): The ISM system onboard failed to function effectively due to non-compliance with established procedures, particularly by the master. This raises concerns about the practical implementation of safety protocols onboard ships.
- Search and Rescue Operations: Delays in SAR operations further compounded the tragedy, potentially resulting in additional loss of life.

The investigation highlights systemic failures in safety protocols, emergency preparedness, and leadership onboard the vessel. Addressing these issues requires a comprehensive approach involving stricter regulations, improved training for crew members, enhanced safety protocols, and better oversight mechanisms to prevent similar incidents in the future. The photo of Al Salam Boccaccio is given in Figure 5.5 (Panama Maritime Authority, 2006).

Figure 5.5 : View of Al Salam Boccaccio.

5.2.4 Lindy Lou

The incident involving the narrowboat Lindy Lou is a tragic reminder of the potential dangers associated with inadequate safety measures, especially on vessels where occupants may be more vulnerable to fire hazards due to limited escape routes. The sequence of events leading to the fire underscores the importance of proper installation and maintenance of heating appliances, as well as the necessity of early warning systems like smoke alarms. The lack of specific standards for solid fuel stove installations on boats highlights a regulatory gap that needs to be addressed to ensure the safety of occupants. The proposal for a new standard by the British Standards Institution (BSI) is a step in the right direction towards mitigating such risks in the future. Additionally, the absence of smoke alarms on Lindy Lou raises concerns about the current regulations regarding safety equipment on recreational craft. The recommendation to fit smoking alarms on boats with overnight accommodation, as suggested by the Boat Safety Scheme (BSS), is a sensible measure that could potentially save lives in similar situations. By advocating for changes to international standards such as the ISO standards, and implementing recommendations for safety equipment like smoke alarms, authorities can enhance the safety protocols for habitable small craft and help prevent similar tragedies from occurring in the future. The photo of Lindy Lou is given in Figure 5.6 (MAIB, 2007).

Figure 5.6 : View of Lindy Lou while fire investigation.

5.2.5 Emerald Princess

The incident involving the crew member's fatal injury aboard the Emerald Princess due to a burst nitrogen cylinder underscores the critical importance of proper maintenance and inspection protocols for high-pressure cylinders on ships. The Transport Accident Investigation Commission's findings highlight several deficiencies in the maintenance and inspection procedures:

- Corrosion Assessment: Severe external corrosion significantly compromised the integrity of the nitrogen cylinder, leading to its failure. This emphasizes the necessity of thorough corrosion inspections by competent personnel before any remedial work or reintegration into service.
- Quality Assurance: Despite having been surveyed just two weeks prior, the failed nitrogen cylinder and others were not deemed fit for service. This highlights a gap in the effectiveness of the survey process and the need for consistent and rigorous standards for assessing the condition of high-pressure cylinders.
- Global Standards: The absence of consistent global standards for maintaining, inspecting, and testing high-pressure cylinders on ships is identified as a pressing issue. Urgent action is recommended to develop such standards to ensure the safety of maritime operations worldwide.
- Immediate Safety Measures: The operator took immediate safety actions to prevent similar accidents across the fleet, indicating a proactive approach to addressing safety concerns.
- Recommendations for Improvement: The Commission issued recommendations to relevant stakeholders, including the equipment manufacturer, classification societies, industry associations, and regulatory authorities like Maritime New Zealand. These recommendations focus on enhancing training, raising awareness, and advocating for improved safety standards at the international level.

Overall, the key lesson from this inquiry is the paramount importance of rigorous inspection, maintenance, and adherence to global standards to prevent similar accidents in the future and ensure the safety of maritime personnel. The photo of Emerald Princess is given in Figure 5.7 (TAIC, 2018).

Figure 5.7 : View of Emerald Princess.

5.2.6 Norman Atlantic

A detailed account of the tragic events surrounding the M/V NORMAN ATLANTIC fire and the subsequent rescue operations and investigations are given in this section. The incident, which occurred in December 2014, involved multiple SAR authorities, primarily Greek and Italian, with Albania also playing a minor role. The rescue efforts resulted in the saving of 452 individuals, while unfortunately, 11 lives were lost, and several others remained missing.

The investigation, conducted by DIGIFEMA along with participating bodies from Germany and Greece, aimed to ascertain the causes and circumstances surrounding the fire and subsequent events. However, there were challenges faced during the investigation, including restrictions imposed by the Italian Judicial Authority, which affected the ability of participating entities to carry out certain investigative activities.

Despite these challenges, evidence was gathered from inspections on board, interviews with crew members and company staff, and documentation provided by the Italian Judicial Authority. Technical consultants, appointed by DIGIFEMA, also contributed reports on the fire's development and electrical systems.

The investigation sought to draw conclusions and make recommendations based on the gathered evidence. The process underscores the complexities and difficulties involved in maritime incidents, especially when multiple jurisdictions and legal authorities are involved. The photo of Norman Atlantic is given in Figure 5.8 (MIT, 2014).

Figure 5.8 : View of Norman Atlantic after fire incident.

5.2.7 Insignia

On December 11, 2014, at around 09:09, a fire broke out in the Diesel Generator Room of the vessel INSIGNIA, located in Castries, St. Lucia. The fire originated at the free end of the No. 4 diesel generator due to fuel oil encountering a hot surface. The fuel oil leaked from a loose flange connection in the low-pressure fuel oil piping system, with the probable ignition source being an exposed section of the exhaust manifold due to insulation gaps. The fire was intense, producing significant heat and smoke, but it was extinguished within approximately 30 minutes after burning until the available fuel was consumed. At the time of the fire, INSIGNIA had approximately 300 passengers on board, with the rest participating in shore excursions. Unfortunately, four of the vessel's engineers and three Wärtsilä service technicians were performing maintenance in the Diesel Generator Room. One engineer and two technicians were unable to escape and died due to smoke inhalation. Three members of the ship’s fire team were treated for smoke inhalation, but there were no other injuries to the crew or the surviving technician. The primary damage from the fire was contained within the Diesel Generator Room, affecting the control systems of the four diesel generators. The ship's emergency generator provided electrical power during and after the fire, but ventilation and air conditioning systems were temporarily shut down. Approximately 300 passengers who were on board during the fire were safely evacuated to the pier as temperatures inside the ship rose due to the ventilation system shutdown. Prestige Cruise Services LLC organized charter flights to transport all 652 passengers to Miami, Florida, United States.

Based on the findings and conclusions provided:

- Immediate Cause of the Fire: The fire originated from atomized fuel oil spraying from a loose flange connection in the low-pressure fuel oil piping system on the No. 4 diesel generator. The probable ignition source was a gap in the insulation for the exhaust manifold.
- Contributing Factors: The absence of spray screens over the flanged connections for the fuel oil system on DG4, as required by SOLAS regulations, was identified as a contributing cause. The lack of these screens increased the risk of fuel oil spraying, encountering a hot surface and igniting.
- Functionality of Fire Systems: The ship's fire detection, suppression, and containment systems worked effectively, enabling the crew to promptly detect, contain, and extinguish the fire.
- Casualties: Three individuals, including one of INSIGNIA's engineers and two Wärtsilä service technicians, died due to smoke inhalation. The heavy smoke and high temperatures in the Diesel Generator Room contributed to the exhaustion of the firefighting crew and hampered the search efforts.
- Response and Evacuation: The response of INSIGNIA's Master and crew to the fire and the subsequent evacuation of passengers were deemed appropriate.
- Safety Training: The safety training for Wärtsilä service technicians could have been more robust, particularly regarding awareness of emergency egress routes within the ship's engineering spaces.
- Maintenance Communication: Wärtsilä's system of relying on Service Letters and Technical Bulletins without updating the Vasa 32 Operations Manual posed a potential gap in ensuring awareness of maintenance recommendations among ship's engineers. Ambiguous recommendations, lacking specific torque requirements, also contributed to implementation challenges.

These conclusions highlight various factors contributing to the fire incident, the response to it, and areas for improvement in safety protocols, training, and maintenance communication to prevent similar incidents in the future. The photo of Insignia is given in Figure 5.9 (Republic of the Marshall Islands, 2014).

Figure 5.9 : View of Insignia.

5.2.8 Peejay V

The incident involving the PeeJay V on January 18, 2016, illustrates the critical importance of safety measures and equipment on passenger vessels. The rapid escalation of the fire in the engine room underscores the need for effective fire detection and suppression systems, as well as proper crew training in emergency response procedures. The crew's initial attempt to suppress the fire with a CO2 extinguisher highlights the importance of having appropriate firefighting equipment onboard. However, the ineffectiveness of the CO2 system due to air entering the engine room through various openings, including an unclosed cable duct, underscores the significance of regular maintenance and inspection of safety systems to ensure their functionality. The inability to access all life jackets and deploy the flotation raft due to the fire further emphasizes the necessity for adequate emergency preparedness and equipment accessibility. The fact that passengers were forced to enter the water without life jackets highlights the potential dangers that can arise in emergency situations when safety equipment is not readily available. Overall, this incident underscores the need for comprehensive safety protocols, including effective fire detection and suppression systems, regular maintenance of safety equipment, thorough crew training in emergency procedures, and ensuring the accessibility of life-saving apparatuses. By addressing these factors, similar incidents can be mitigated or prevented, ultimately enhancing the safety of passengers and crew aboard passenger vessels.

The incident involving the PeeJay V highlights several critical safety issues and lessons for maritime operations:

- Early Detection and Response: Prompt detection of fires aboard vessels is crucial for effective firefighting and preparation of life-saving equipment. Without a fire detection and alarm system, the crew had limited time to respond adequately.

- Crew Training and Familiarity: Crew members must be thoroughly trained in using onboard firefighting systems. In this case, insufficient knowledge about the CO2 fixed fire-fighting system hindered its effectiveness.

- Effectiveness of Fire-Fighting Systems: Even if firefighting apparatus like CO2 systems are functional, they rely on the ability to seal off the affected area. The design flaw in the engine room, preventing complete closure, rendered the system ineffective.

- Proper Equipment Placement: While the placement of life-saving equipment was appropriate, the speed at which the fire escalated hindered access to a significant portion of it. This underscores the importance of considering accessibility in emergency scenarios.

- Regulatory Oversight: The incident also raises concerns about regulatory oversight. Maritime rules should require vessels to have adequate fire detection and alarm systems, especially considering passenger capacity and operating range.

- Operator Understanding: Both vessel builders and operators need a thorough understanding of safety systems. Lack of comprehension regarding the CO2 fire-fighting system's operation contributed to the incident.

In response to these findings, recommendations should focus on improving fire detection systems, enhancing crew training, addressing design flaws in fire-fighting equipment, ensuring proper equipment placement for accessibility, and strengthening regulatory requirements for vessel safety standards. The photo of PeeJay V is given in Figure 5.10 (TAIC, 2016).

Figure 5.10 : View of PeeJay V.

6. METHODOLOGY

This chapter presents the methodology used to investigate fire safety onboard passenger ships. The purpose of this chapter is to understand the crucial fire safety parameters and fire protection systems during a fire incident onboard ship.

6.1 Data Collection and Analysis Methods

In this study, among the data collection methods case studies are a quantitative research method that provides an in-depth understanding of a particular subject, event, or phenomenon within its real-life context. Incident historical data refers to records and information related to specific events or incidents that have occurred in the past. This type of data is often used in various fields, including emergency management, healthcare, public safety, and business continuity, to analyze patterns, assess risks, and improve future responses. Components of the data sets:

- **Description:** Reported fire casualties onboard all types of ships.
- **Reason:** The data set is established due to present the frequency of fire incidents for different types of ships. Depending on the incident rate, this study focuses on passenger ships.
- **Source:** International Maritime Organization Global Integrated Shipping Information System (GISIS)
- **Timeline:** 22 years from January 2020 to December 2022
- **Location:** Worldwide
- **Casualties and damages:** Fire casualty reports are classified into four categories such as very serious, serious, less serious and unspecified. Total loss of the ship and/or loss of life can be defined as very serious fire casualties. Serious fire casualties are fatalities to ships which do not qualify as "very serious fire casualties" and which involve a fire and/or explosion, resulting in immobilization of main engines, extensive accommodation damage, severe

structural damage, etc. In this study, only very serious and serious reported casualties are investigated.

- **Response actions:** Data set is not derived depending on response actions by fire protection systems, crew, fire department, cost guards or others.
- **Root cause analysis:** In this historical fire incident data, root causes are not written in all the reported events. Due to that, only selected fire incidents in Chapter 5 are examined depending on the root cause of the fire incidents.
- **Outcome:** Total 323 fire incidents are reported by IMO member. In Table 5.1 incident numbers and percentages are given depending on ship types.

Overall, incident historical data is a valuable resource for understanding past events, informing decision-making, and enhancing preparedness for future incidents.

After using these data sets, the next step is assessing fire safety risk onboard passenger ships. The risk assessment is evaluating potential risks based on past incidents to inform future planning and preparedness. The average incident data approach involves analyzing historical data on incidents (like accidents, security breaches, or service disruptions) to identify patterns and trends. This approach helps organizations understand the frequency, severity, and causes of incidents, enabling them to improve safety, reduce risks, and allocate resources effectively. In this study, the frequency of fire incidents for each ship type is given in Chapter 5 depending on deriving the average number of fire related events.

6.2 Fire Modelling Methods

The evolution of fire modelling methods over the past decade has indeed been significant, with a notable shift towards more complex field models fueled by advancements in computer technology. These models play a crucial role in assessing the hazards associated with fires, encompassing both thermal and toxic aspects. Deterministic and probabilistic models represent the two primary categories, each with their own advantages and limitations.

A deterministic model is a mathematical model that does not consider randomness or uncertainty in its representation. In deterministic models, the outcome is entirely determined by the initial conditions and the model's equations or rules. These models assume that there is no inherent randomness in the system being modeled. Differential equations, algebraic equations, and logical models are often deterministic. Deterministic models, favored by many fire safety engineers, offer a clear advantage in providing concrete numbers that can be readily utilized for analysis. These models operate under the assumption that a given set of initial conditions will lead to a singular, predictable fire development. However, the inherent variability in fire behavior challenges this assumption, as no two fires are identical.

A probabilistic model is a type of stochastic model that explicitly uses probability distributions to describe uncertainty. In probabilistic models, the randomness is quantified using probability distributions, and the model makes probabilistic predictions about the outcomes. These models are used when there is a clear understanding of the underlying probability distributions that govern the system. Examples of probabilistic models include Gaussian (normal) distributions, Poisson distributions, and Bayesian models. Probabilistic models, on the other hand, consider a range of potential fire developments, offering a more comprehensive perspective. Despite this advantage, their practical applicability is often restricted due to their complexity and computational demands.

A stochastic model is a mathematical model that incorporates randomness or uncertainty into its representation of a system or a process. Stochastic models assume that certain aspects of the system are governed by random variables or probabilistic events. Stochastic models are used to describe situations where outcomes are not completely predictable and where randomness plays a significant role. Examples of stochastic models include Markov chains, stochastic differential equations, and Monte Carlo simulations.

In summary, the main difference between stochastic and probabilistic models is that stochastic models introduce randomness or uncertainty into the modeling process, while probabilistic models specifically use probability distributions to quantify and predict outcomes. On the other hand, deterministic models do not account for randomness and assume that outcomes are entirely predictable based on known inputs and equations. It's important to choose the appropriate type of model based on the nature of the system being studied and the level of uncertainty or randomness involved.

Within deterministic modeling, there are two primary types: zone models and field models. Zone models, subdivided into one-layer, two-layer, and HVAC models, rely heavily on empirical correlations derived from laboratory-scale experiments. They are effective for simulating specific scenarios and are widely used for practical applications such as assessing the safety of occupied spaces. Field models, in contrast, involve solving governing conservation equations using numerical techniques, requiring fewer empirical relations. While more computationally intensive, they offer a higher level of detail and accuracy in simulating fire dynamics and behavior.

Ultimately, the choice between deterministic and probabilistic models, as well as between zone and field models, depends on the specific requirements of the analysis and the available computational resources.

The former rely mostly on empirical correlations between specific variables derived from laboratory scale experiments. Zone models are subdivided into one-layer, two-layer, and HVAC models, depending on the type of problem they are attempting to solve. Field models assume fewer empirical relations and attempt to solve the governing conservation equations (mass, momentum, and enthalpy) using numerical techniques. Different types of models used to calculate and predict smoke movement are discussed during a fire onboard passenger ship, each with its own specific limitations and applications.

- One-Layer Models: These models simulate the movement of smoke in regions that are far from the fire's origin. They are capable of handling large, complex buildings with multiple floors and rooms. They treat the smoke as a homogeneous layer (i.e., a single, uniform zone), and assume that the conditions (temperature, smoke concentration, etc.) are uniform throughout the layer. These models are especially useful for large-scale building designs where detailed simulations of smoke in every individual room or floor are not necessary.

- Two-Layer Models: These models are typically used for smaller, more confined spaces, such as small rooms or enclosures. They assume a distinction between the hot, smoke-filled upper layer (often referred to as the "hot layer") and the cooler, relatively smoke-free lower layer (the "cold layer") within a room. They are limited by the assumption that the enclosure has no vertical shafts or significant vertical smoke movement. These models are useful for predicting smoke behavior in the immediate vicinity of the fire and provide a more detailed simulation compared to one-layer models, but they are not suitable for large or complex buildings.

- HVAC Models: It focuses specifically on how smoke moves through a building's ventilation system. They are similar to one-layer models in their approach, but with an added focus on airflow and the dynamics of HVAC systems. These models simulate how the HVAC system interacts with smoke, influencing its spread and affecting the overall fire and smoke control strategies. HVAC models are particularly useful when evaluating the role of ventilation systems in managing smoke spread during a fire.

Each of these models has its own set of assumptions and is best suited for specific types of fire scenarios and building designs. For large buildings or complex fire simulations, one-layer models might be the most efficient, while two-layer models are better for understanding smoke behavior in smaller, confined spaces. HVAC models are specialized for systems where ventilation plays a critical role in smoke control.

This thesis employs a field model for fire modelling. Field (or CFD) models split the domain into multiple smaller control volumes to calculate the flow. With the advancements in computer science, field models have become increasingly common and are now extensively used (Rasbash et al, 2004). The conservation laws of mass, momentum, energy, and species concentrations are applied to each of these control volumes. Solving the equations, along with the equation of state, provides predictions of fluid flow properties with an accuracy level dependent on the size and number of the control volumes considered.

Combustion models are essential for simulating the combustion process in engines, furnaces, and other combustion systems. These models typically involve equations that describe the chemical reactions, heat release, species transport, and other relevant phenomena occurring during combustion. In the context of fluid dynamics and the study of turbulence, solution methods to resolve the complex behavior of turbulent flows can indeed be selected as Large Eddy Simulation among Direct Numerical Simulation (DNS) and Reynolds-averaged Navier-Stokes (RANS) turbulence models. Large Eddy Simulation resolves the large scales of motion directly and models the smaller scales of turbulence. The smaller, sub grid-scale motions are represented using sub grid-scale models. LES offers a good balance between accuracy and computational efficiency. It captures the most energetic and influential eddies while simplifying the treatment of smaller scales. While less computationally intensive than DNS, LES still requires significant computational resources, especially for high Reynolds number flows or complex geometries. Accurate sub grid-scale modeling is also critical for reliable results.

Radiation plays a crucial role in heat transfer during fire incidents, particularly near the fire source where temperatures are at their highest. The radiant heat transfer equation, which is an integra-differential equation, presents significant challenges in terms of solving it, even for relatively simple two-dimensional planar media.

Boundary conditions are crucial in computational fluid dynamics (CFD) simulations as they define the limits and interactions at the edges of the computational domain. These conditions can include various physical phenomena such as the flow of air through openings (doors, windows), heat transfer through walls, or the introduction of external sources or sinks like fires or suppressants. Source/Sink boundary conditions are selected these represent the addition or removal of mass, momentum, or heat within the domain. An example is defining a fire as a volumetric heat source, which adds heat to the computational domain.

Lastly, the structure of a whole passenger ship is very complex to model all details in a model. Mainly, the detailed shapes of each piece of equipment on this deck are irregular. Therefore, since the fire modelling tool is used for investigating the fire within the vessel and cube-shaped meshes are used for building physical models, the structure information of the actual deck should be simplified. Most of these little pieces of equipment are disregarded while creating the numerical model since they may not have a significant impact on the spread of fire. Since the deck contains a lot of small equipment, such gas bombs, oil tanks, and high-pressure containers, an explosive phenomenon might easily occur when a fire starts. This could make the fire more destructive. To make the calculation simpler, this would be disregarded due to the complexity of explosibility. Therefore, during the early stages of the fire's development within the deck, people's movements have very little bearing on the distribution of flow. Human action can therefore be disregarded. However, due to human interference, the fire's course will be unpredictable in its later stages. The consequences of human behavior will not be discussed in this study. Last but not least, the ignitability of the fuel system is disregarded in order to streamline the model computation.

6.3 Fire Risk Assessment Methods

When studying the safety aspects of a large ship, addressing the entire system in its entirety can be highly impractical due to the complexity and scale. A more logical and manageable approach involves breaking down the ship into functional entities, which include various subsystems and components. This decomposition allows for a structured safety modelling process for each functional entity. By first modelling the safety of these smaller, manageable parts, one can then examine the interrelationships between these entities to develop a comprehensive system safety model. This model is essential for assessing the overall safety parameters of the ship. However, given the complexity and sophistication of large marine systems, formulating such a model often necessitates the use of approximations and relies on expert judgement to ensure its feasibility and accuracy (Pillay and Wang, 2003). To apply safety analysis methods effectively and efficiently in the design for safety process, it's essential to comprehend both qualitative and quantitative safety analysis concepts.

Quantitative Risk Analysis (QRA) indeed offers a systematic approach to evaluating risks associated with industrial processes or operations. By quantifying risks, organizations can make informed decisions regarding safety measures, maintenance strategies, and operational procedures. This approach enables a deeper understanding of the relationships between costs, benefits, and risk mitigation efforts. One of the key advantages of QRA is its ability to provide more nuanced insights compared to merely following regulations. While regulations offer a baseline for safety standards, they may not always capture the full complexity of risk scenarios or provide optimal solutions. QRA allows organizations to consider a broader range of factors, such as potential environmental impacts and commercial requirements, in their risk management strategies. By analyzing various risk scenarios and mitigation proposals, QRA helps optimize designs and operating procedures to balance safety, environmental concerns, and economic factors. This optimization process ensures that resources are allocated efficiently, minimizing costs while meeting both internal and external standards. The expansion of Quantitative Risk Analysis (QRA) beyond its origins in nuclear and chemical industries reflects a growing recognition of its applicability and benefits across various sectors. Factors such as commercial pressures, regulatory requirements, and public concerns have driven this trend, as organizations seek robust methods to manage risks effectively. At its core, QRA aims to provide a quantifiable description of risk, making it measurable against predefined criteria or values associated with a particular operation or design. Risk, being a multidimensional concept, encompasses both the frequency of hazards and their potential consequences. QRA involves estimating the likelihood and impacts of various hazard scenarios, considering not only individual risks but also societal and economic implications. In the broader context of risk assessment, QRA serves several key purposes:

- Assessing Risk to People: QRA helps evaluate the risk of fatalities or serious injuries to both the workforce and the public, ensuring a comprehensive understanding of human safety concerns.
- Identifying Risk Reduction Measures: By analyzing different hazard scenarios, QRA enables the identification of measures to reduce overall risk. This includes assessing the effectiveness of existing or proposed risk mitigation strategies.
- Selecting Safety Enhancements: QRA aids in the selection of preferred options for enhancing safety, allowing organizations to prioritize investments and interventions based on their potential risk reduction benefits.
- Setting Performance Standards: QRA supports the establishment of performance standards for design, monitoring, and auditing purposes, providing benchmarks for evaluating safety performance.
- Supporting Cost-Benefit Analysis: QRA assists in conducting cost-benefit assessments of safety expenditures, helping organizations make informed decisions about resource allocation and risk management investments.
- Decision Making on Risk Tolerance: QRA helps decision-makers determine whether the level of risk is tolerable based on predefined risk acceptance criteria, providing a framework for risk governance and decision-making.

- Assessing Environmental Risk: Beyond human safety, QRA also evaluates environmental risks associated with various activities or operations, contributing to sustainable and environmentally responsible practices.
- Evaluating Asset and Revenue Risks: QRA assesses risks to assets and revenue streams, allowing organizations to safeguard their investments and ensure business continuity.

Recognizing the inherent uncertainties in Quantitative Risk Analysis (QRA) results is crucial for making informed decisions. While QRA provides valuable insights into risk levels and potential consequences, it's essential to understand that these results may not always be precise, especially when assessing absolute figures. This acknowledgment becomes particularly important when QRA results are used as the basis for decision-making. When interpreting QRA results, it's essential to consider the specific circumstances and context of the decision or requirement at hand. While QRA can be useful for comparing different designs or scenarios, relying solely on absolute figures without scrutiny can lead to significant problems. Therefore, a thorough review of QRA results is necessary, considering the uncertainties inherent in the analysis. Given that there's no standardized method for conducting QRA, it's important to assess the sensitivity of the results to variations in the assumptions made during the analysis. This sensitivity analysis helps identify critical input data and areas where uncertainties may have a significant impact on the results. In cases where certain data inputs are deemed critical, conducting a more detailed analysis to improve confidence in the results may be necessary.

Among the several methods, event tree analysis (ETA) is selected for this study to assess the fire safety risk onboard ships. This ETA method is a graphical technique used to model the sequence of events that could lead to undesirable outcomes, allowing for the estimation of the probability of various scenarios (Yordanova, 2021).

7. CASE STUDIES

In this thesis, three different passenger vessels are selected as case studies.

The first one is from Istanbul public maritime transportation company called Sehir Hatlari. As an Istanbul Metropolitan Municipality entity, the fleet of Sehir Hatlari publicly transports 40 million passengers annually. Among 30 vessels in the fleet, 600-passenger capacity vessels are selected as a case study depending on building year and fire protection systems. This group of vessels are the newest among the fleet and have a wide range of fire protection systems such as fire-rated bulkheads and fire extinguishing systems.

Due to the exponential growth on production and transportation of electric vehicles (EVs) globally, fire safety evaluation of electric vehicle spaces onboard ships is examined in the second part of the case study. In this study, the selected deck of transported electric vehicles are analyzed with fire dynamics simulations.

Lastly, ro-ro passenger ship is selected as a case study to evaluate fire safety from the point view of risk management. In this case, fire location

7.1 Fire Modelling of Turkish Domestic Vessel

A Turkish domestic passenger vessel called as Sehir Hatlari is operation inland sea public transportation in Istanbul as an entity of Istanbul Metropolitan Municipality. Selected ferry among the fleet is named SH SUTLUCE with 9564009 IMO number.

7.1.1 History

Şehir Hatları, Istanbul's premier public sea transportation provider, offers essential services across the Bosphorus Strait, Princes' Islands, and Golden Horn. Renowned for its modern operations and rich history, Şehir Hatları stands as a symbol of Istanbul's maritime heritage. The origins of Şehir Hatları date back to 1844 during the Ottoman Empire, initially managed by the Hazine-i Hassa Ferries Administration under the Ottoman Navy Ministry. It began by connecting key points such as Sirkeci, Princes’ Islands, Pendik, and Yeşilköy, along with ports in Istanbul, Izmit, Gemlik, and Tekirdağ. Over the years, the company underwent several name changes such as Fevaid-i Osmaniye Administration (1862), Idare-i Aziziye (1871), Idare-i Mahsusa (1878) and Ottoman Seyr-i Sefain Administration (1910). In 1933, the Seyr-i Sefain Administration saw the formation of AKAY Administration, focusing on the Marmara line, including Princes’ Islands, Anatolian Side piers, and the Yalova line. By 1937, AKAY Administration evolved into Şehir Hatları under the State Maritime Roads Management Directorate.

The unification of Istanbul’s ferry services under Şehir Hatları began in 1941 with the integration of Haliç Vapurlari Sirketi, which operated on the Golden Horn line. In 1945, Sirket-i Hayriye, established in 1851 for Bosphorus line services, was nationalized, transferring its operations to Şehir Hatları. This consolidation streamlined ferry services across Istanbul.

Since 1945, Şehir Hatları has managed ferry operations on the Bosphorus, Marmara, and Golden Horn lines. It operated under the Turkish Maritime Corporation established in 1983 and later the General Directorate of Maritime Enterprises of Turkey, formed in 1948. A significant change occurred in 2005 when Şehir Hatları was transferred to the Istanbul Metropolitan Municipality by the Privatization High Council of Turkey. This transition marked a new era, leading to the construction of five new passenger ferries, a modern car ferry, and three Golden Horn ferries with panoramic visibility. Additionally, restoration projects for older ferries and piers were undertaken, with some piers being rebuilt entirely.

In 2010, the Istanbul Metropolitan Municipality established the Istanbul Şehir Hatları Corporation to address traffic issues and enhance sea transportation efficiency. This initiative aimed to further integrate and modernize Istanbul’s maritime transport infrastructure.

Şehir Hatları, with its deep-rooted history and continuous modernization, remains a crucial component of Istanbul's public transportation network. Its evolution from the Ottoman-era beginnings to a contemporary municipal corporation reflects its enduring significance and commitment to serving the city's residents and visitors. (Sehir Hatlari, 2023).

7.1.2 Fleet overview

Şehir Hatları has totally 30 passenger vessels that are divided into 6 categories depends on the capacity of the vessel: 2100, 1800, 1700, 1500, 700 and 600 passengers and each category have 5, 5, 1, 11, 5 and 3 ferries respectively (Sehir Hatlari, 2023). From Figure 7.1 to 7.6 depict the images of each vessel category. Depending on Ayci and Barlas (2015) and Ayci (2015), the reason for the capacity change is related to operational expenses of the vessels and occupancy rate of the lines. The propulsion system alternatives of passenger ships used in public transportation same as Sehir Hatlari are analyzed in terms of fuel consumption and investment costs (Roland et al, 2021). As well as passenger vessels, Şehir Hatları invest in Sea Taxi that is operating for private sea transportation including 6-10 passenger capacity. In the next studies, Sea Taxi will be analyzed.

Figure 7.1 : 2100 passenger capacity vessels.

Figure 7.2 : 1800 passenger capacity vessels.

Figure 7.3 : 1700 passenger capacity vessels.

Figure 7.4 : 1500 passenger capacity vessels.

Figure 7.5 : 700 passenger capacity vessels.

Figure 7.6 : 600 passenger capacity vessels.

7.1.3 Model validation

Before running the fire dynamics simulations of the case study parameters, the model has to be validated and verified by an experimental study. Steckler *et al.* (1989) conducted a number fire tests inside a compartment to study fire-induced flows. The experimental data gathered from these fire tests have been used as part of the validation for fire dynamics simulations. The data signifies non-spreading fires in small compartments. A series of 45 experiments were accomplished by Steckler *et al.* (1989) to investigate fire induced flows in a compartment 2.8 m * 2.8 m in plane and 2.18 m in height. The 0.3 m diameter burner was supplied with commercial grade methane at fixed rates producing constant fire strengths of 62.9 kW. Model of Steckler experiment is depicted in Figure 7.7. Depending on burner type and geometry of the case study, experiments by Steckler *et al.* (1989) are performed as a validation study.

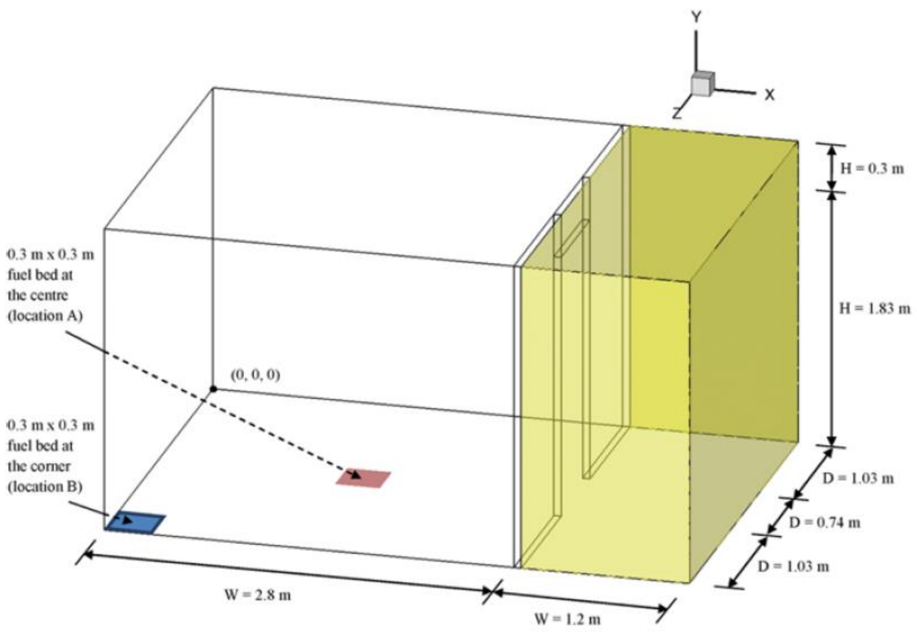

Figure 7.7 : Model of Steckler *et al.* (1989) experiment.

Initially, the comparison of heat release rate between fire dynamics simulations with 4 different mesh sizes and experiments are given in Figure 7.8. In fire dynamics simulations, heat release rate is zero at zero and significantly increases to around 60 kW at approximately 20 seconds. Experiment and FDS results are validated in terms of heat release rate and mesh sizes at heat release rate are not affected mainly.

In the model, there are 19 thermocouples that are placed height from 0 to 1.8 m from bottom to top. In order to validate the model and running mesh dependencies, temperatures on these thermocouples for experiments and fire dynamics simulations are illustrated in Figure 7.9. The differences on temperatures between experiment and FDS results is approximately 10%. As a result of grid resolution, grid size is selected as 0.1 m according to Figure 7.9.

The simulation results match well with the experimental data, despite some initial differences these are reasonable due to the response time of the temperature sensor used in the experiment. The recorded values are delayed from the true temperature during the early stages of the fire due to the extremely high rate of temperature increase. As the temperature increase rate decreases, the variations disappear.

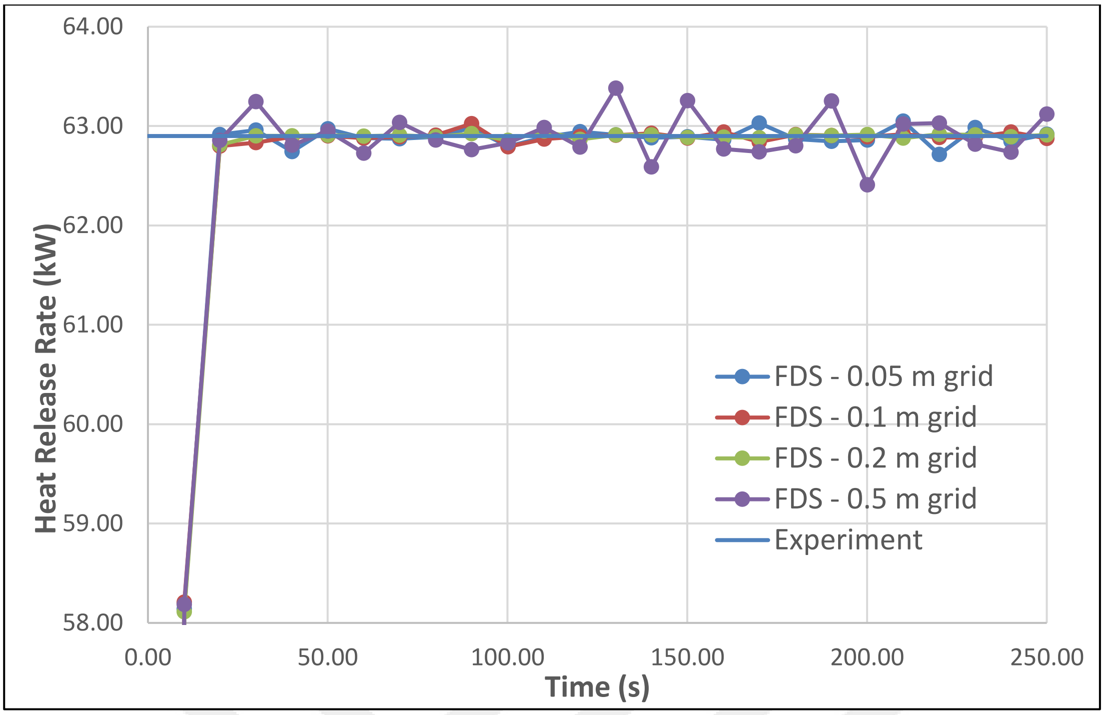

Figure 7.8 : Heat release rate results of experiment and fire dynamics simulations.

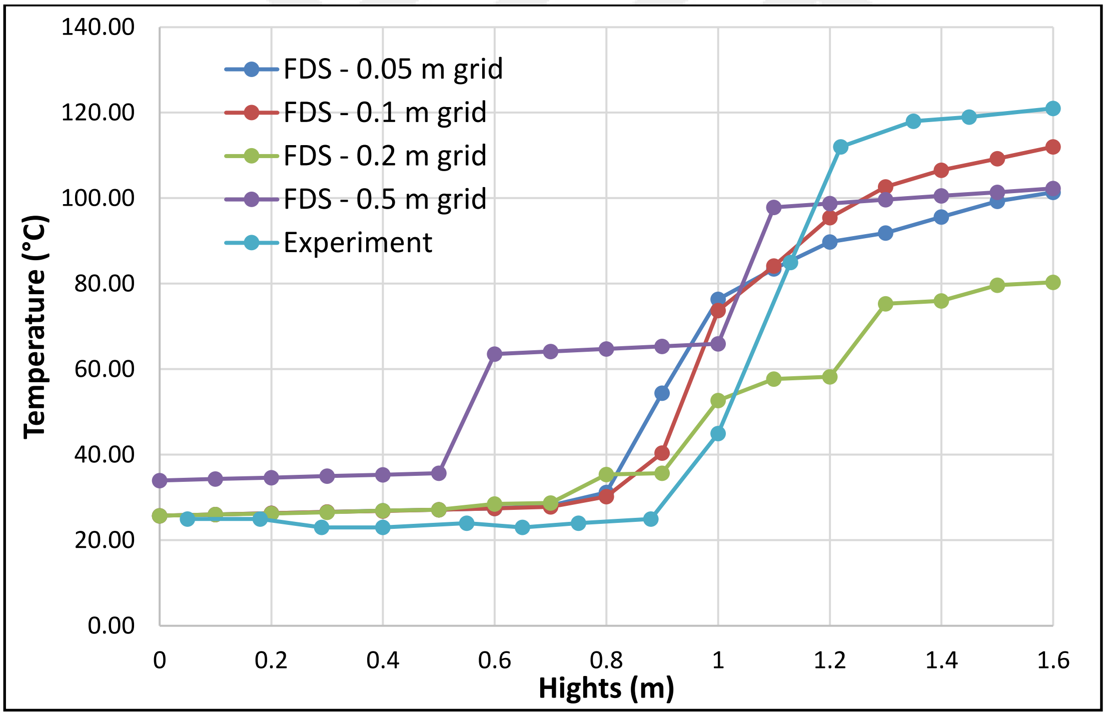

Figure 7.9 : Temperatures on thermocouples in experiments and fire dynamics simulations with different mesh sizes.

In addition to grid resolution of Steckler *et al.* (1989) experiments, the characteristic fire diameter (D^*) is calculated according to below equation 7.1 (McGrattan et al, 2013):

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{\frac{2}{5}} \tag{7.1}$$

where $\dot{Q}$ is the total heat release rate of the fire, ρ_∞ is the air density (kg/m^3), c_p is the air specific heat ($kJ/kg \cdot K$), g is the gravitational constant (m/s^2) and T_∞ is the ambient temperature (K). Depending on the calculation, D^* is calculated 0.1 m grid size that is aligned with the Steckler *et al.* (1989) experiment results.

7.1.4 Materials and methods

In this study SH SUTLUCE passenger vessel from Istanbul's Sehir Hatlari fleet, which has the lowest passenger capacity, was chosen for research. The specifications are provided in Table 7.1 and a photograph of SH SUTLUCE is depicted in Figure 7.10 (Sehir Hatlari, 2023). Also, the current photographs of SH-SUTLUCE are added to the Appendix H.

Table 7.1 : Technical specification of SH SUTLUCE (IMO: 9564009).

Building year	2009
Passanger capacity	600
Gross Tonnage (ton)	175.4
Net Tonnage (ton)	69.2
Lenght Overall (m)	41.97
Beam (m)	8.5
Depth (m)	2.8
Freeboard (m)	0.754
Main Engine Type	D16C-BMH VOLVO PENTA
Power	2X641BHP

In terms of fire safety, the fire control and safety plan of SH SUTLUCE passenger vessel is given in Figure 7.11 for profile view, Figure 7.12 for upper deck plan view, Figure 7.13 for main deck plan view and Figure 7.14 for lower deck plan view.

Figure 7.10 : A photograph of SH SUTLUCE.

Figure 7.11 : Profile view of SH SUTLUCE from fire control and safety plan.

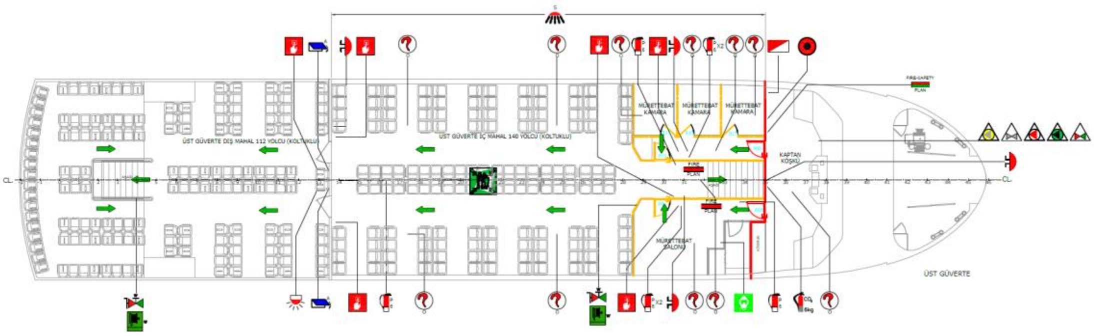

Figure 7.12 : Upper deck plan view of SH SUTLUCE from fire control and safety plan (252 seats for passenger, cabins for crew and captain bridge).

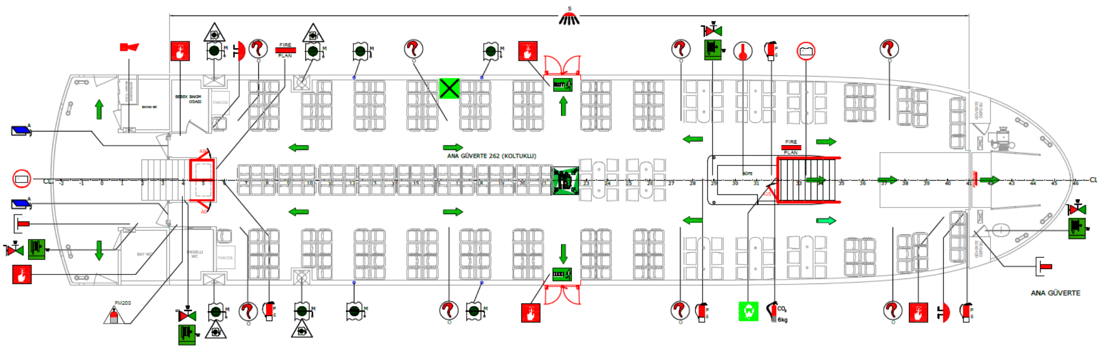

Figure 7.13 : Main deck plan view of SH SUTLUCE from fire control and safety plan (262 seats for passenger and sneak bar).

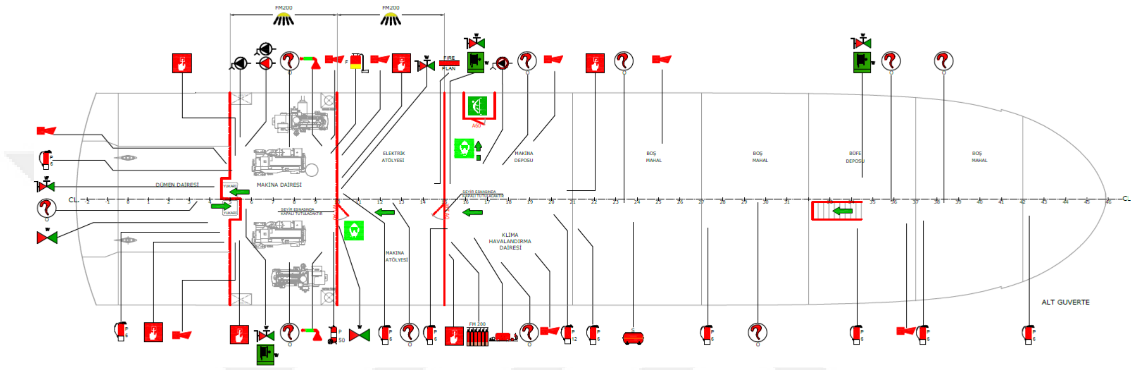

Figure 7.14 : Lower deck plan view of SH SUTLUCE from fire control and safety plan (helm station, engine room, electrical, mechanical and air conditioning workshops and warehouses).

In general, the structure of a whole passenger ship is very complex to model all details in a model. In the first step, this study focuses on the lower deck of selected passenger vessels depending on Bashan et al (2020) that evaluates twenty common risks in ship engine rooms and fire risks appear among the 5 most significant hazards. Mainly, the detailed shapes of each piece of equipment on this deck are irregular. Therefore, since the FDS tool is used for investigating the fire within the vessel and cube-shaped meshes are used for building physical models, the structure information of the actual deck should be simplified as follows:

a) The intricate layout of the deck: most of these little pieces of equipment are disregarded while creating the numerical model since they may not have a significant impact on the spread of the fire.

b) Explosibility: since the deck contains a lot of small equipment, such gas bombs, oil tanks, and high-pressure containers, an explosive phenomenon might easily occur when a fire starts. This could make the fire more destructive. To make the calculation simpler, this would be disregarded due to the complexity of explosibility.

c) The impact of human activity on the spread of the fire: during the early stages of the fire's development within the deck, people's movements have very little bearing on the distribution of flow. Human action can therefore be disregarded. However, due to human interference, the fire's course will be unpredictable in its later stages. The consequences of human behavior will not be discussed in this study.

d) The ignitability of the fuel system is disregarded in order to streamline the model computation.

In this case, the simplified structure and the final model are shown in Figure 7.15. The overall length of the model is 41.1 m, the width is 8.5 m, and the height is 2.8 m. The whole deck is separated by fire rated bulkheads into four main zones: helm station, engine room, mechanical and electrical workshop, and warehouses respectively. The length between each fire rated bulkheads is 4.3 m. Two diesel engines are in the center of the engine room. In each fire, rated bulkheads have three door openings. In addition, ladder and service openings are modelled based on the current situation of the passenger ship. The study assumes that the openings are stable and not changed during the life of vessels. In this control volume, boundary conditions and mesh figure for the case of fire dynamics simulation are depicted in Figure 7.16.

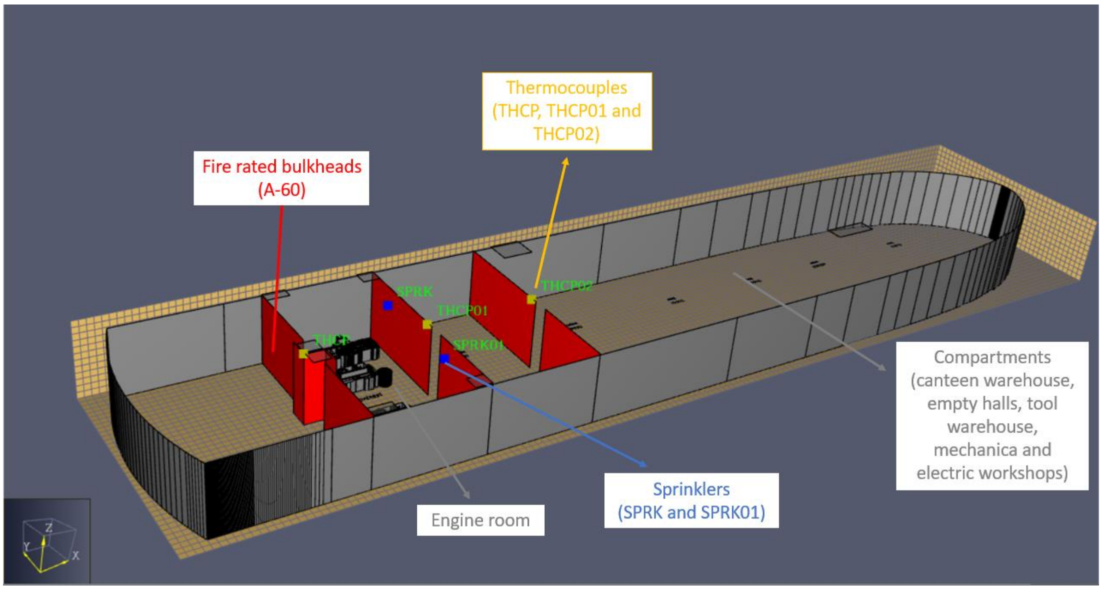

Figure 7.15 : Geometric model structure of the lower deck for SH SUTLUCE.

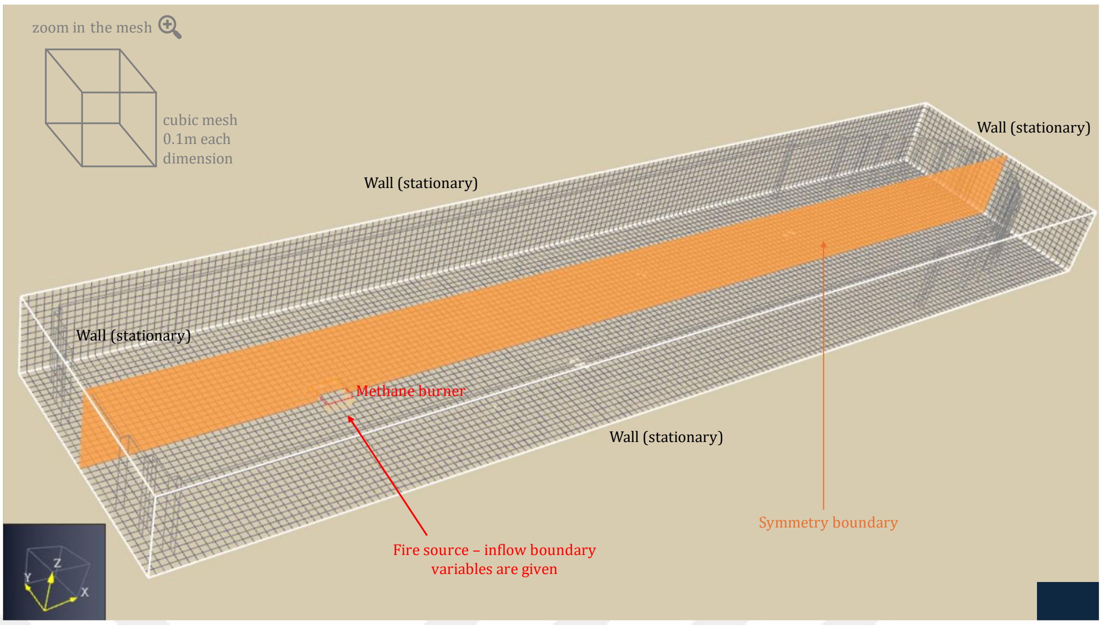

Figure 7.16 : Boundary conditions and mesh figure for the case of fire simulation.

The fire source is located in the center of the engine room and its cuboid dimension is 1m x 1m x 0.25m. Therefore, the maximum heat release rate is 3460 kW (Su and Wang, 2013). The fire in its growth stage and during its decay period can be described by a t^2 curve. Methane reaction is used in the fire modelling and specific heat of combustion is determined as 50 MJ/kg Ergin and Sulus (2009), Bolek and Ergin (2018). The well-known Very-Large Eddy Simulation is used based on the concept of filtering a larger part of turbulent fluctuations compared to the standard Large Eddy Simulation (Labois and Djamel, 2011).

From the perspective of fire protection systems, extinguisher systems such as sprinklers and structural systems such as fire-rated bulkheads and decks are concentrated in this study. On the other hand, fire detection and alarm systems are ignored to simulate. The sprinklers are generic industrial type, and the activation temperature is 93.33 °C. In order to determine the arrangement of sprinklers, geometrical shape method is used. The geometrical shape method is the simplest and most widely used spacing method because it provides the highest uniformity for the system (Dwomoh et al, 2014). Different geometrical layouts of sprinklers are depicted in Figure 7.17.

In conclusion, the main parameters of fire simulation are given in Table 7.2.

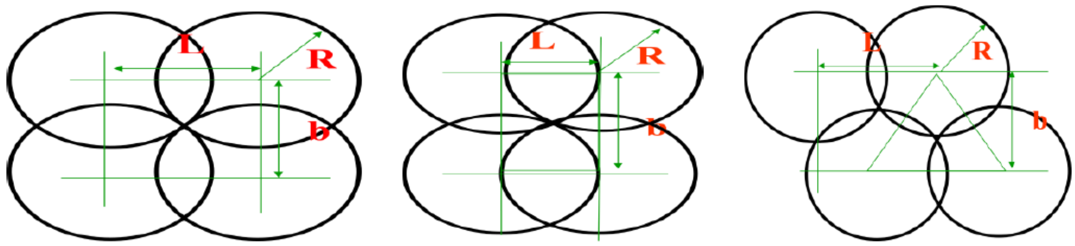

Figure 7.17 : Different geometrical layouts of sprinklers (Dwomoh et al, 2014).

Table 7.2 : Main parameters of the fire simulation.

Fire source	Volume	Max heat release rate	Reaction	Specific heat of combustion
	1m*1m*0.25m	3460 kW	methane	50 MJ/kg
Fire extinguishing system	Type	Arrangement method	Quantity	Activation temperature
	generic industrial	geometrical shape method	1, 2 or 4 depends on scenarios	93.33 °C
Fire rated bulkheads	Material		Thickness	
	Steel		0.01m	
Mesh	Mesh geomety	Mesh size	Quantity of mesh	
	cubic	0.25*0.25*0.25 m^3	76,608	

7.1.5 Results

In order to analyze fire safety onboard passenger ships with the case of SH SUTLUCE, several scenarios are derived in terms of fire fatality level. Table 7.3 shows the details of the fire simulation scenarios. Scenario 1 is divided into 3 main categories depending on quantity and arrangement of sprinklers. To determine the end time of the simulation, each scenario was run up to the stabilization point; therefore, the end time was specified as 280s, 480s, and 300s for scenarios 1, 2, and 3, respectively. In each scenario, simulations were run until heat release rate, temperature, and pressure parameters stabilized.

Table 7.3 : Scenarios of the fire simulations.

Scenario	Fire Extinguisher System (Sprinklers)	Fire-rated Bulkheads and Deck	Number of Sprinkler Nozzles	Simulation Time	Scenario Fatality
Scenario 1a	Yes	Yes	1	280	Best
Scenario 1b	Yes	Yes	2	280	Best
Scenario 1c	Yes	Yes	4	280	Best
Scenario 2	No	Yes	-	480	Medium
Scenario 3	No	No	-	300	Worst

Heat release rate – time graphs for each scenario are illustrated in Figure 7.18. In the first few seconds, heat release rates increase dramatically for all scenarios and continue fluctuating at roughly the same level, that is the determined maximum heat release rate in the simulation; 3460 kW. Total energy of the control volume is another crucial factor in fire dynamics simulations. In Figure 7.19, the total energy vs time chart is analyzed for each scenario. Similar to the heat release rate, total energy dramatically increases with the ignition of the fire in the compartment. After almost 50s for all scenarios, the average total energy converges to zero value. In the worst scenario, this convergence starts mainly after 100s, and the total energy is approximately doubled than other scenarios at 50s.

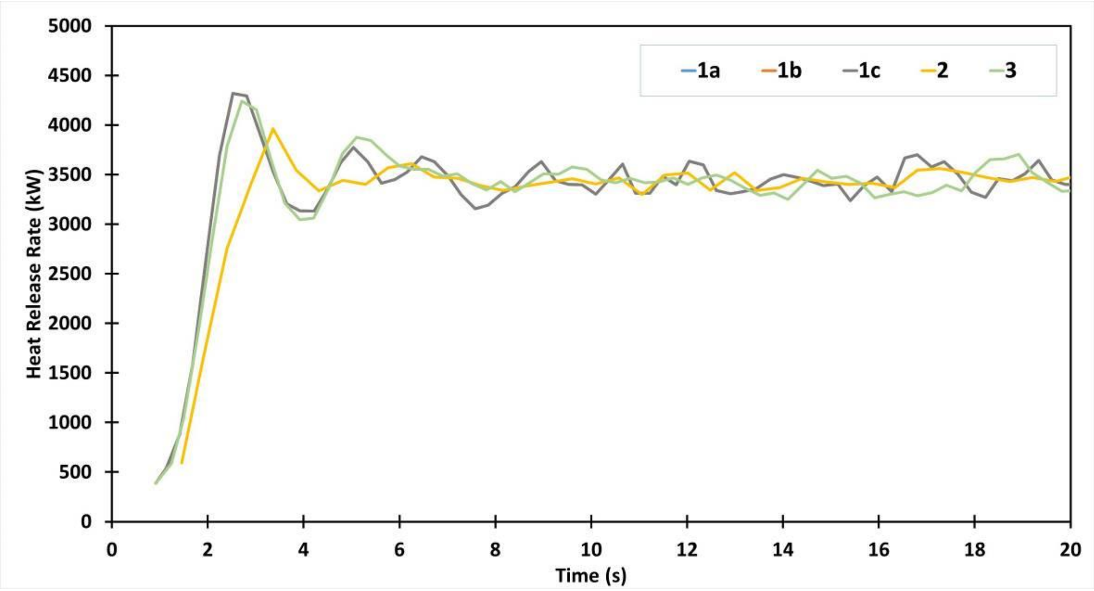

Figure 7.18 : The heat release rates (HRR) of three different scenarios.

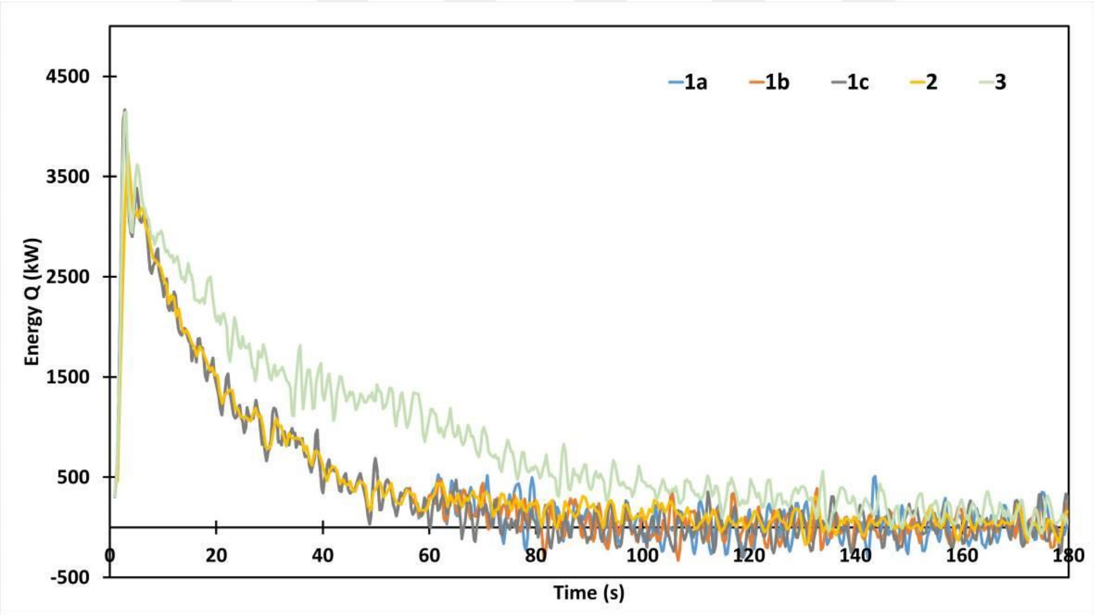

Figure 7.19 : Total energy (Q) of three different scenarios.

In the scenarios, thermocouples were placed into the mid-top of each fire-rated bulkhead in the lower deck. Figure 7.20 demonstrates the location of thermocouples in the lower deck. The fire source in the engine room is colored red and fire-rated bulkheads are colored as dark red in the figure.

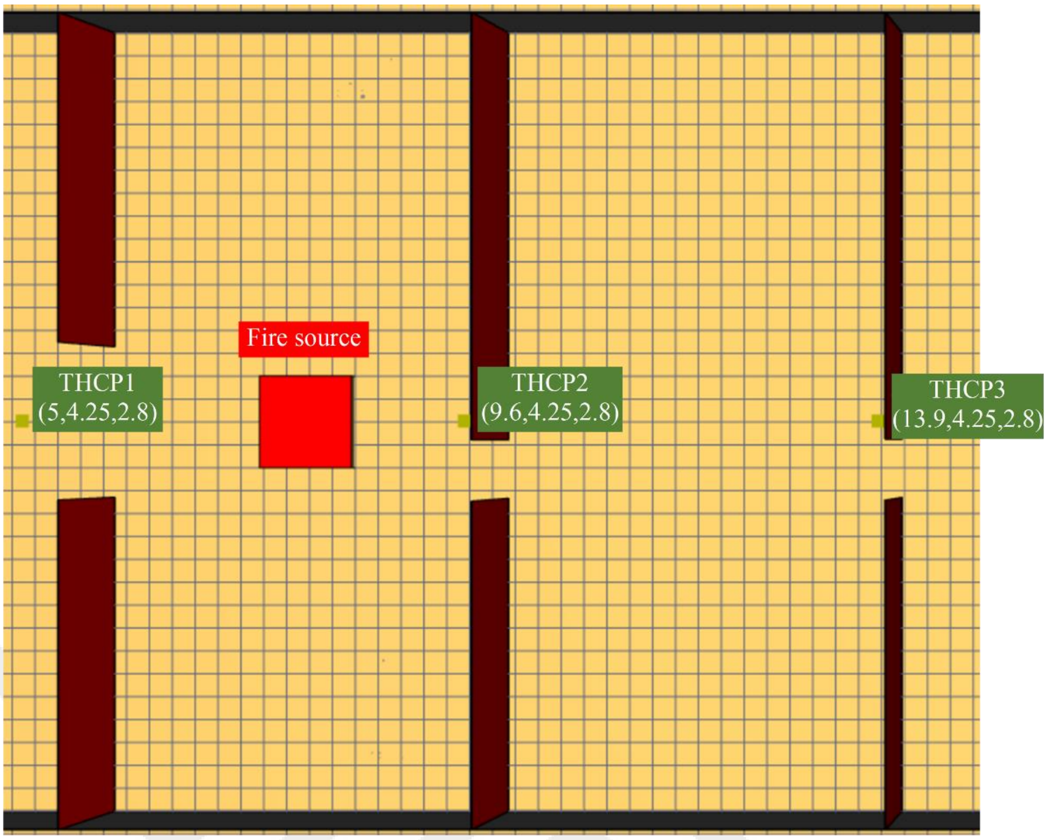

Figure 7.20 : Arrangement of the thermocouples in the lower deck.

The measured temperatures on the thermocouple 1 (THCP1) are given in Figure 7.21. THCP1 is the most critical one that reaches more than 500 °C for all scenarios expect scenario 3 that is the worst one. Fire-rated bulkheads cause the closed compartments, and this leads to the temperature increase in THCP1. The enclosed volume of the deck in scenario 3 is higher than the other scenarios. At the end of the simulation, THCP1 stabilizes at approximately 400 °C for all scenarios.

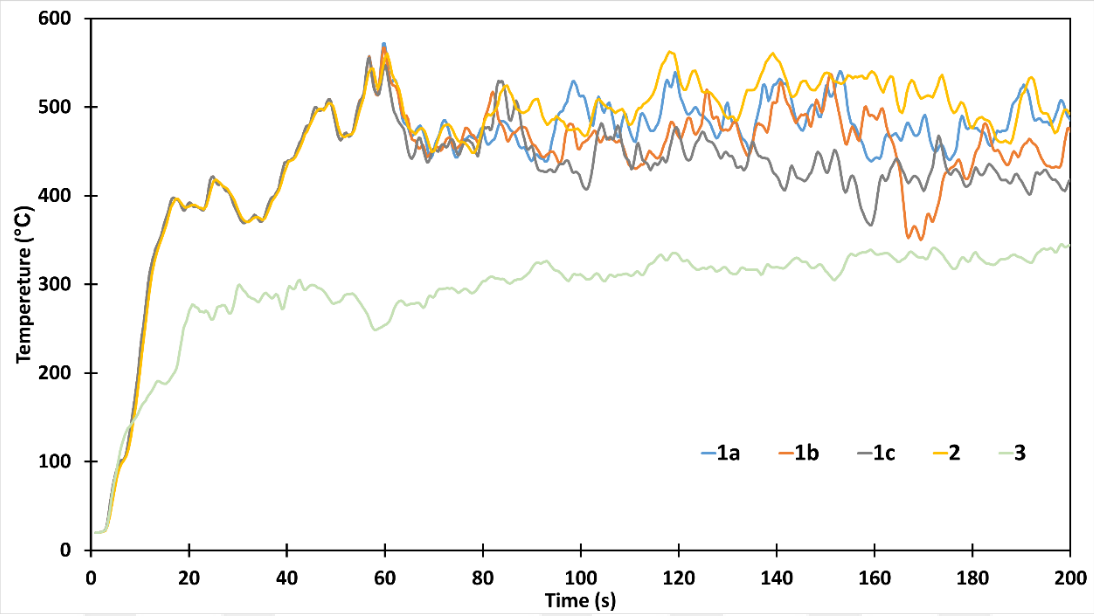

Figure 7.21 : The temperature change of the thermocouples in each scenario for THCP1.

The temperature change on the thermocouple 2 (THCP2) is given in Figure 7.22. The maximum temperature on THCP2 is almost 300 °C. Same as THCP1, the temperature is increasing slowly in the scenario 3 at the beginning phase of the fire. After the 100s, the figures are stabilized for all scenarios at the level of approximately 150 °C.

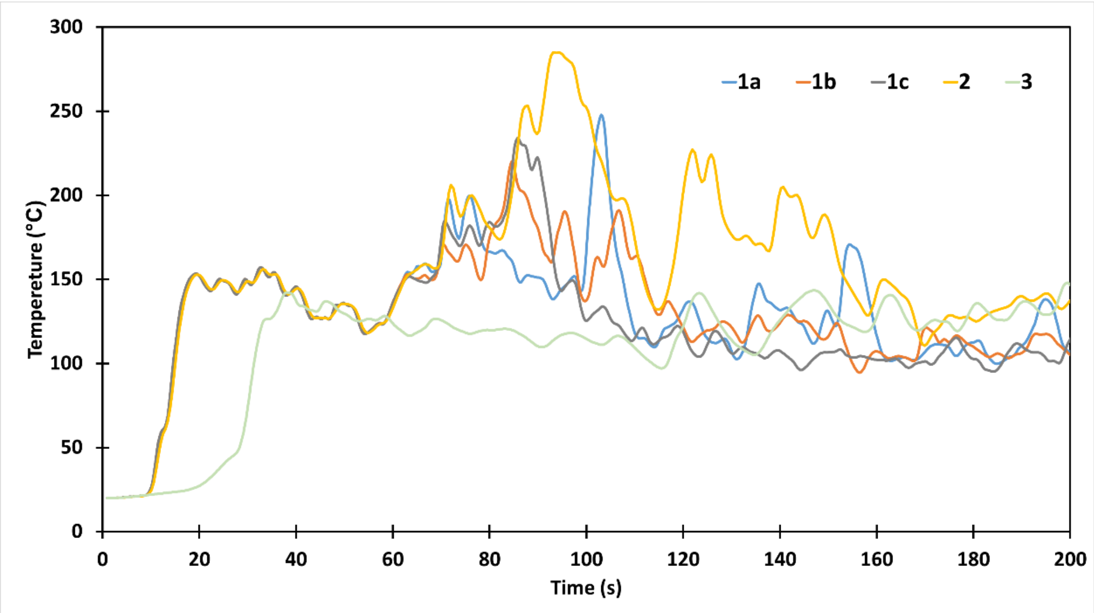

Figure 7.22 : The temperature change of the thermocouples in each scenario for THCP2.

The temperature change on the thermocouple 3 (THCP3) are given in Figure 7.23. The maximum temperature on THCP3 is almost 180 °C. Same as other thermocouples, the temperature increases slowly in the scenario 3 at the beginning phase of the fire. After the 100s, the figures are stabilized for all scenarios at the level of approximately 120 °C.

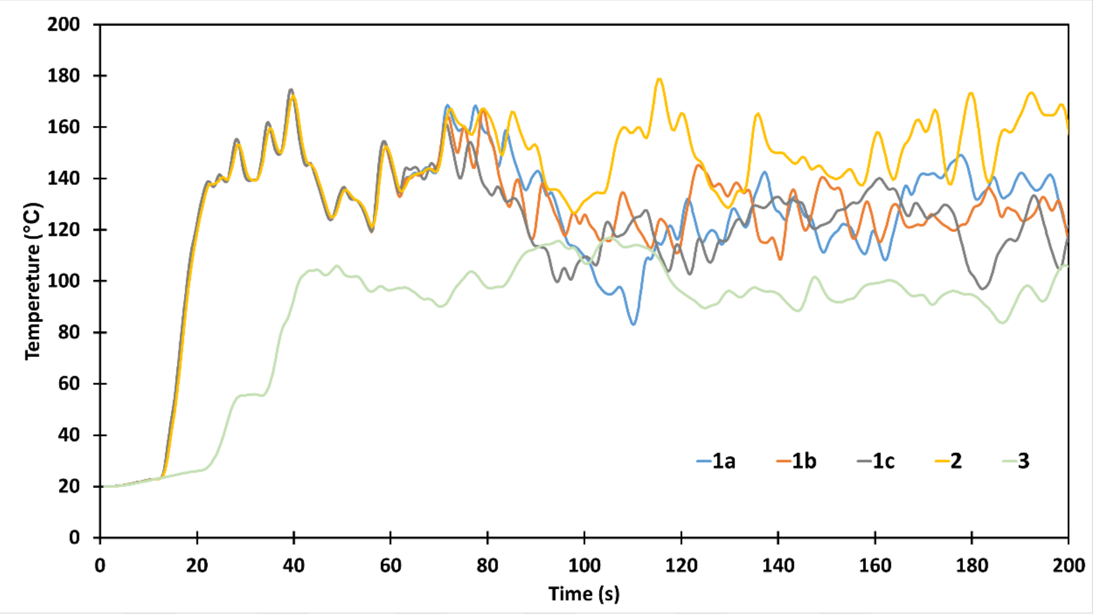

Figure 7.23 : The temperature change of the thermocouples in each scenario for THCP3.

In the 3 best scenarios called scenario 1a, 1b and 1c, the arrangement and number of sprinklers are derived from each scenario. The arrangements of scenario 1a, 1b and 1c are given in Figure 7.24, 7.25 and 7.26 respectively. The arrangement of sprinklers is determined according to geometrical shape method. In scenario 1a, one sprinkler nozzle is placed in the center of the engine room. This location is above the fire source. In scenario 1b, 2 sprinkler nozzles are located in the right and left sides of the center. Lastly, scenario 1c have 4 sprinkler nozzles these are placed in the right, left, front and back sides of fire source in the engine room. All sprinkler nozzles are in the upfront of the fire source and is located in 2.8m height in z-direction.

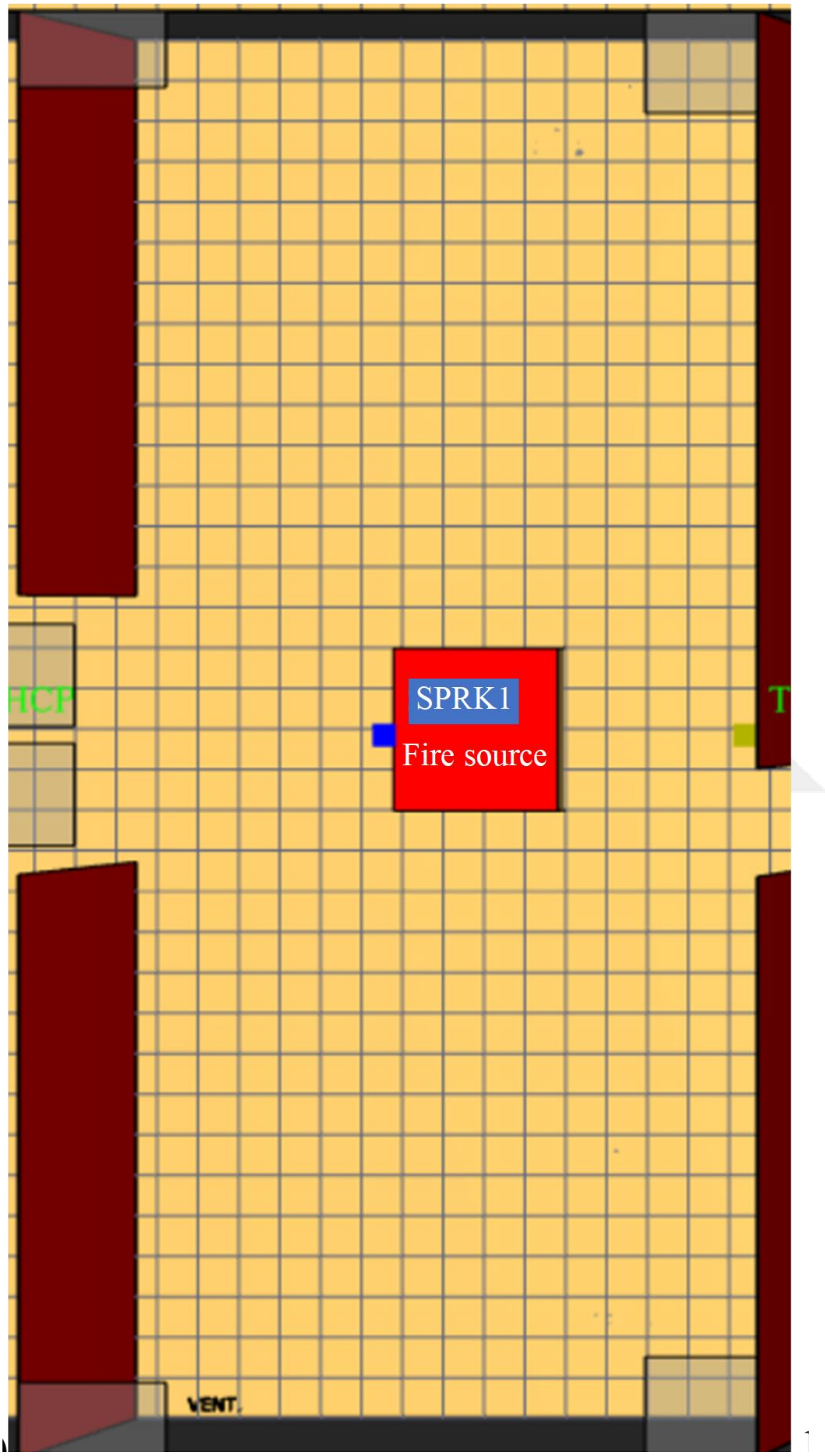

Figure 7.24 : Arrangement of the sprinklers in the engine room for scenario 1a.

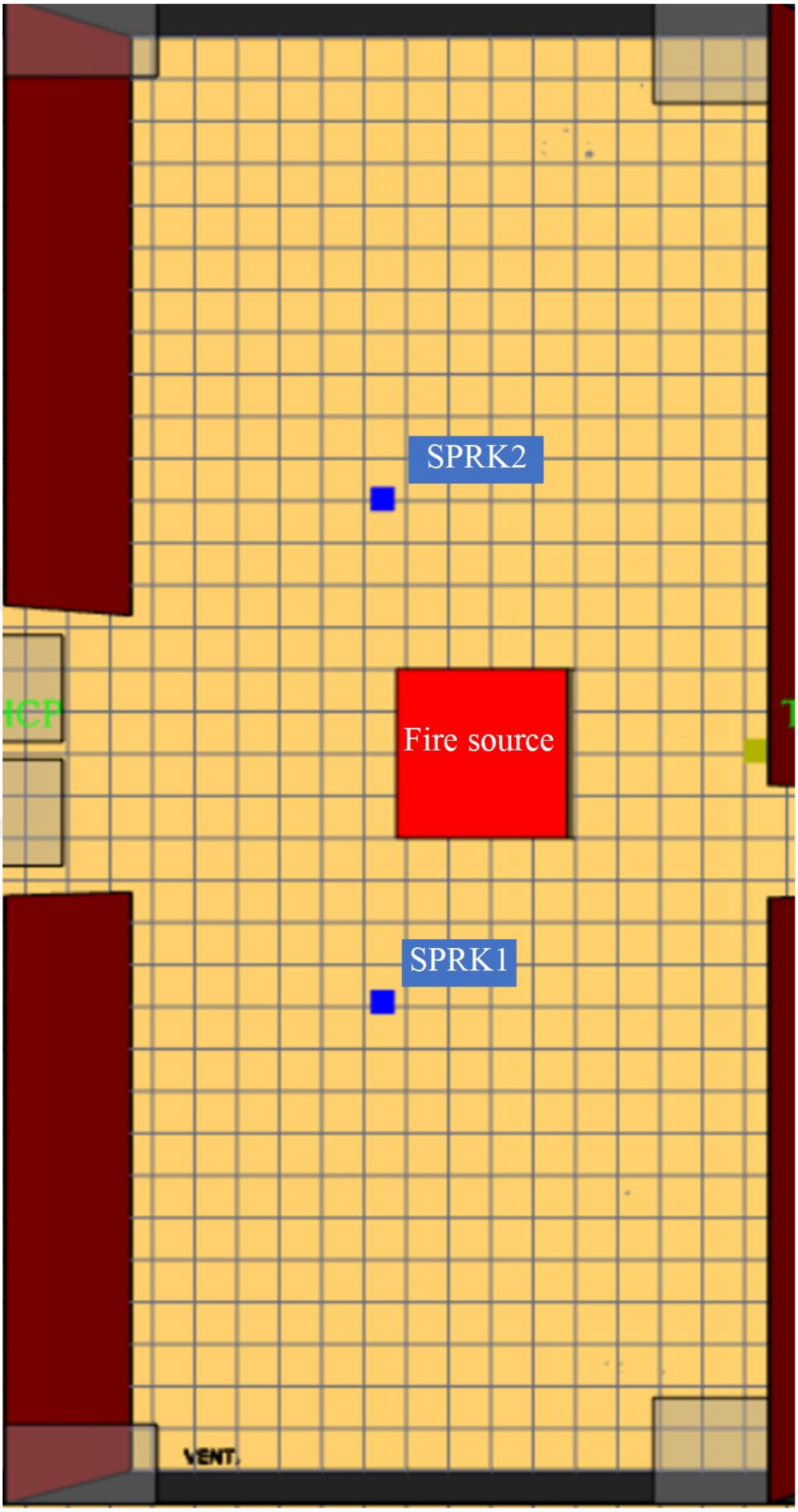

Figure 7.25 : Arrangement of the sprinklers in the engine room for scenario 1b.

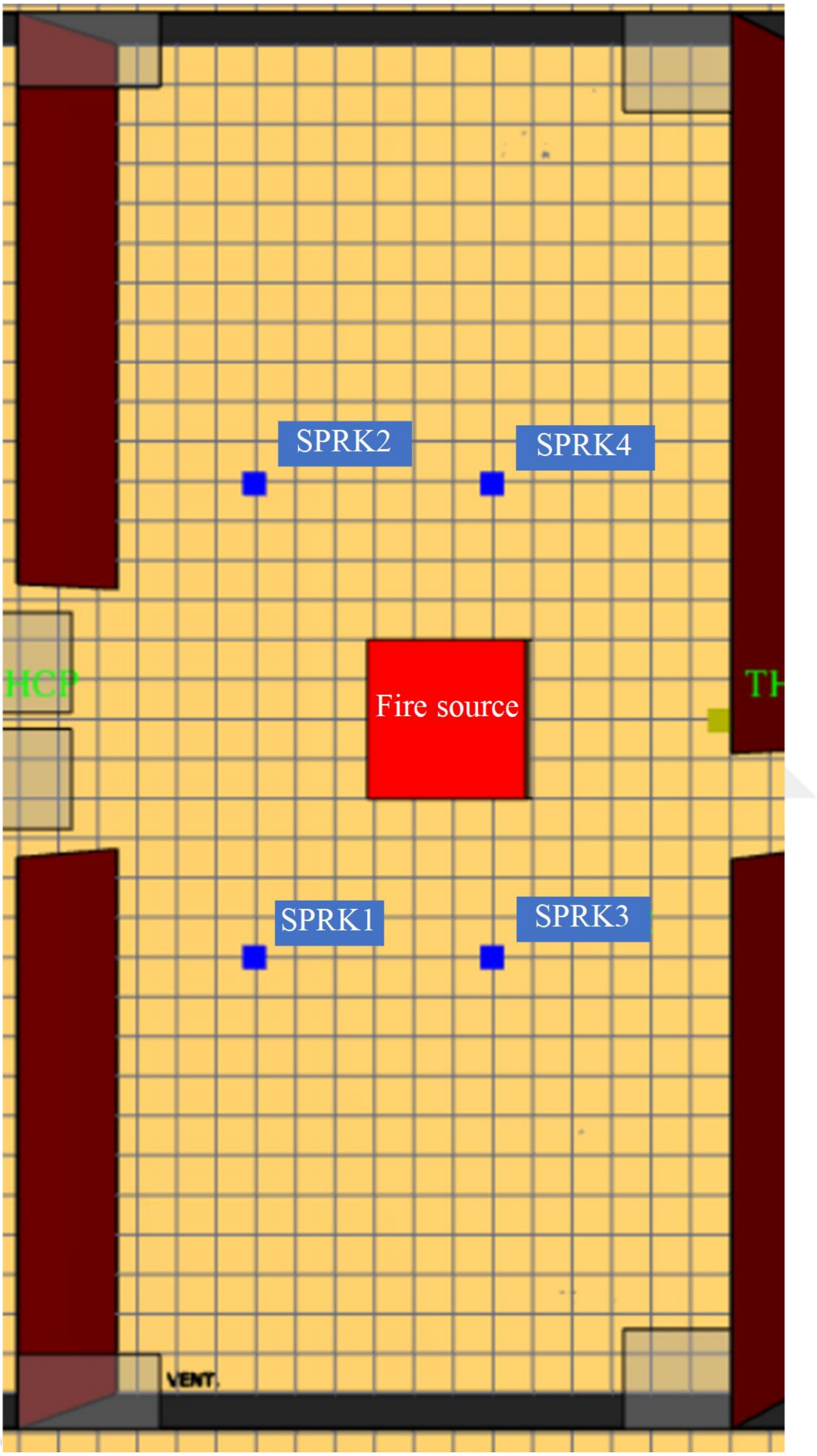

Figure 7.26 : Arrangement of the sprinklers in the engine room for scenario 1c.

The temperature change of sprinkler nozzles for scenario 1a, 1b and 1c are illustrated in Figure 7.27, 7.28 and 7.29 respectively. The sprinkler activation temperature 93.33 °C is plotted into the figures. In scenario 1b and 1c, temperature can reach 160°C even though scenario 1a has 180°C maximum nozzle temperature. The characteristic of graphs is the same due to the selecting same fire source and sprinkler type as generic industrial. In scenario 1a, SPRK1 is activated at around 60s and in scenario 1b, SPRK1 is activated at around 70s and SPRK2 is activated at around 50s. Lastly, SPRK1 and SPRK3 are activated at almost 75s and SPRK2 and SPRK4 are activated at approximately 50s in scenario 1c.

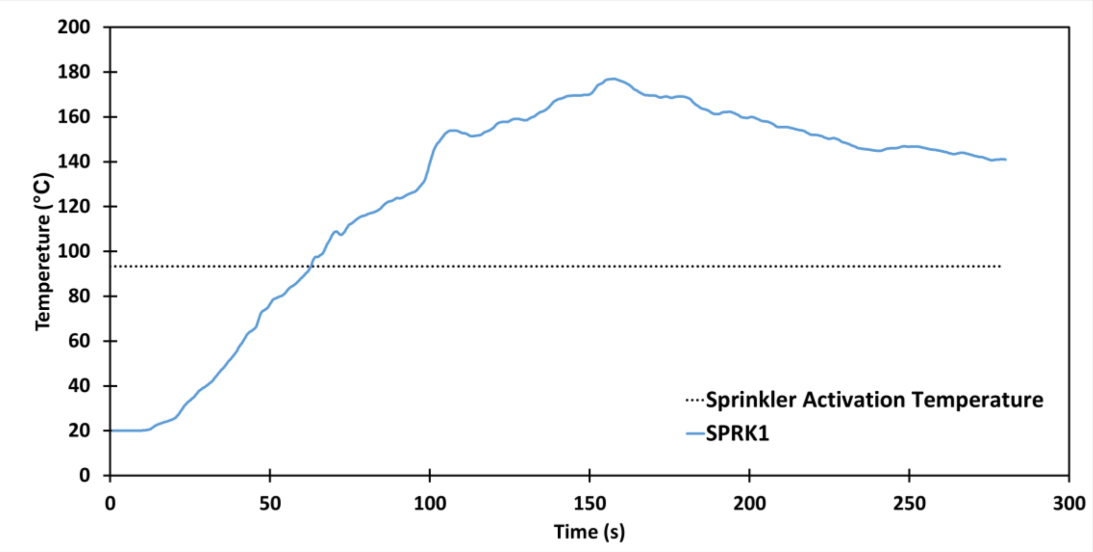

Figure 7.27 : The temperature change of sprinklers in scenario 1a.

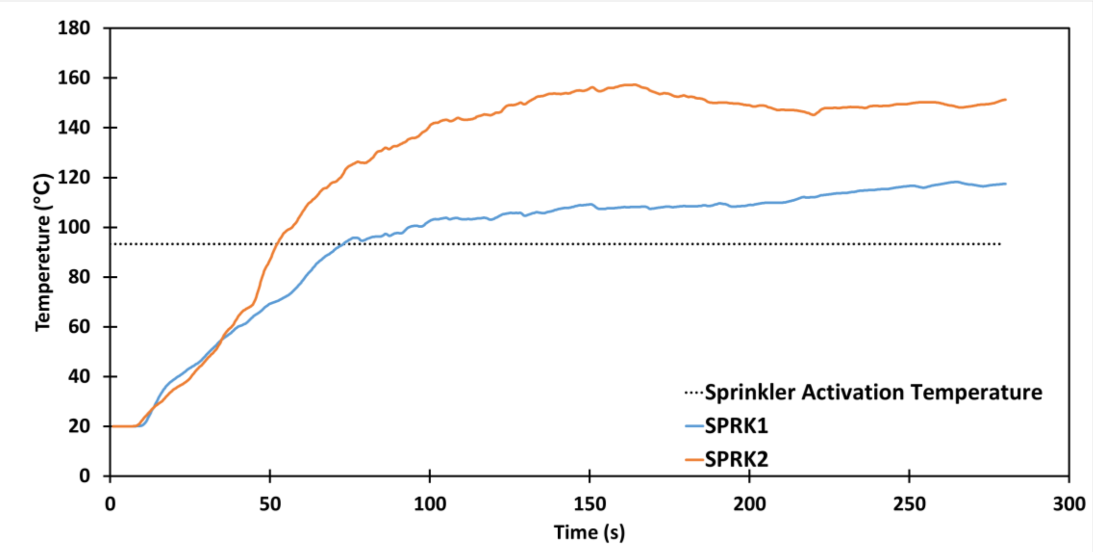

Figure 7.28 : The temperature change of sprinklers in scenario 1b.

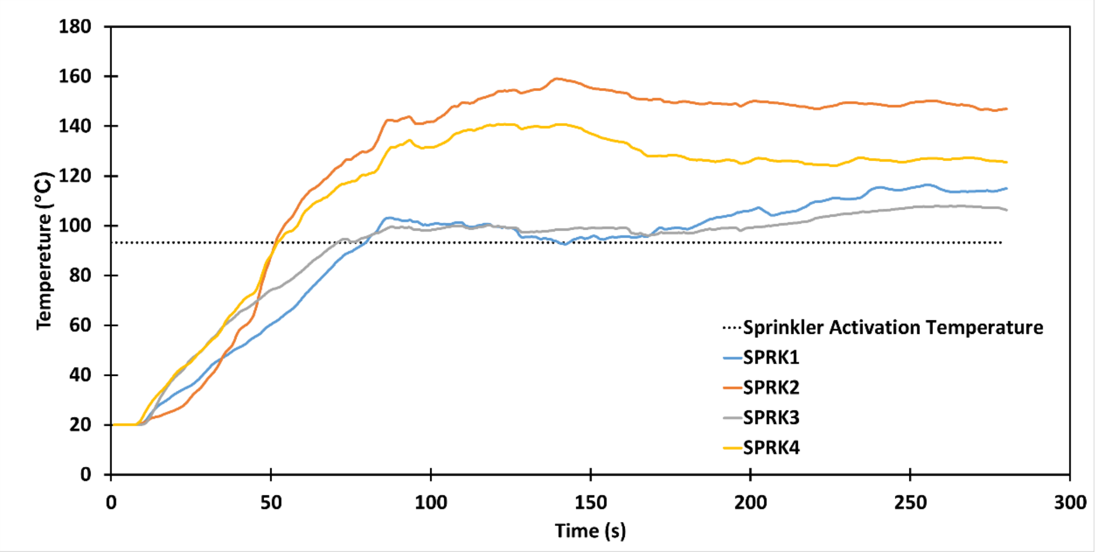

Figure 7.29 : The temperature change of sprinklers in scenario 1c.

The temperature distributions on y=4.25m at t=50s for scenarios 1a, 1b, 1c, 2 and 3 are depicted in Figure 7.30, 7.31, 7.32, 7.33 and 7.34 respectively. Time is selected depending on the activation of the sprinklers. In the scenarios, sprinklers break out after 50s. In only scenario 3, temperature along the ship length is distribution and other zones such as workshop areas, warehouses in the lower deck are affected by the fire by engine room. This indicates that fire rated bulkheads play a crucial role for the compartmentation even though only 50s last. Characteristics of temperature distributions are almost same for scenarios 1a, 1b and 1c. Since sprinkler numbers and arrangements do not affect the temperature due to the fact that these are activated soon. Finally, the most critical output for life safety is that the temperature level at 50s is reached to more than 400 °C, this level can lead to life and property safety issues in the control volume.

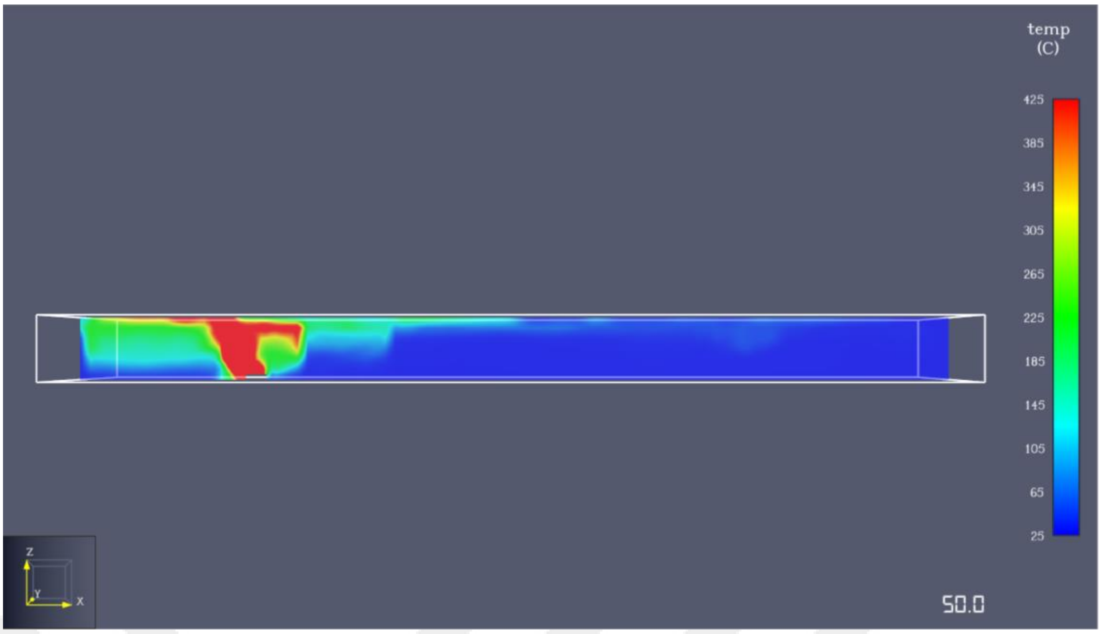

Figure 7.30 : Temperature distribution at y=4.25m at t=50s for scenario 1a.

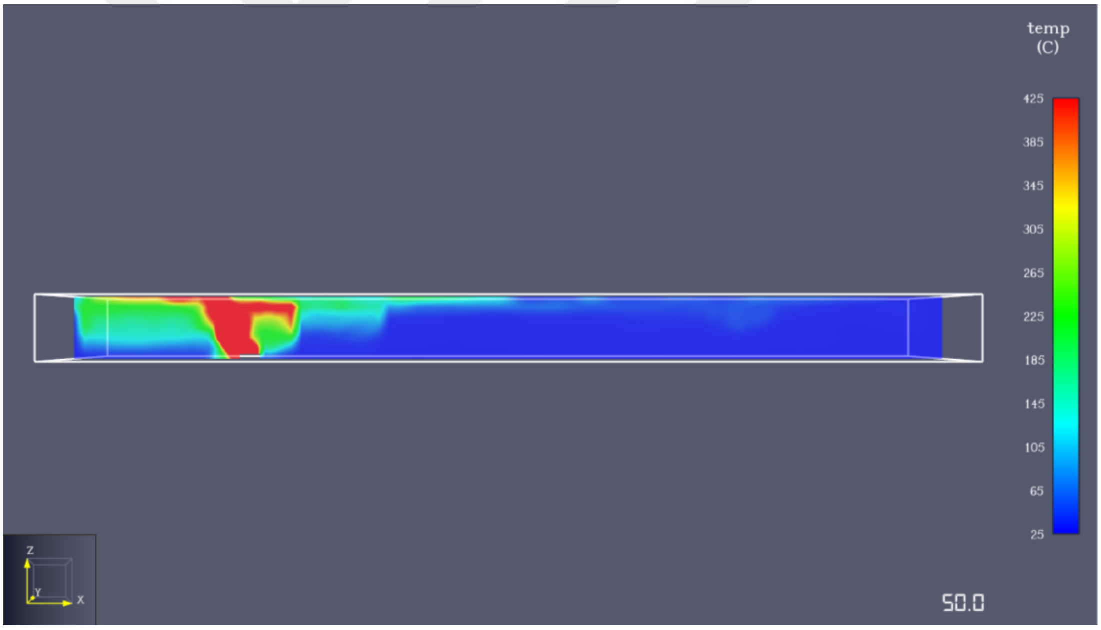

Figure 7.31 : Temperature distribution at y=4.25m at t=50s for scenario 1b.

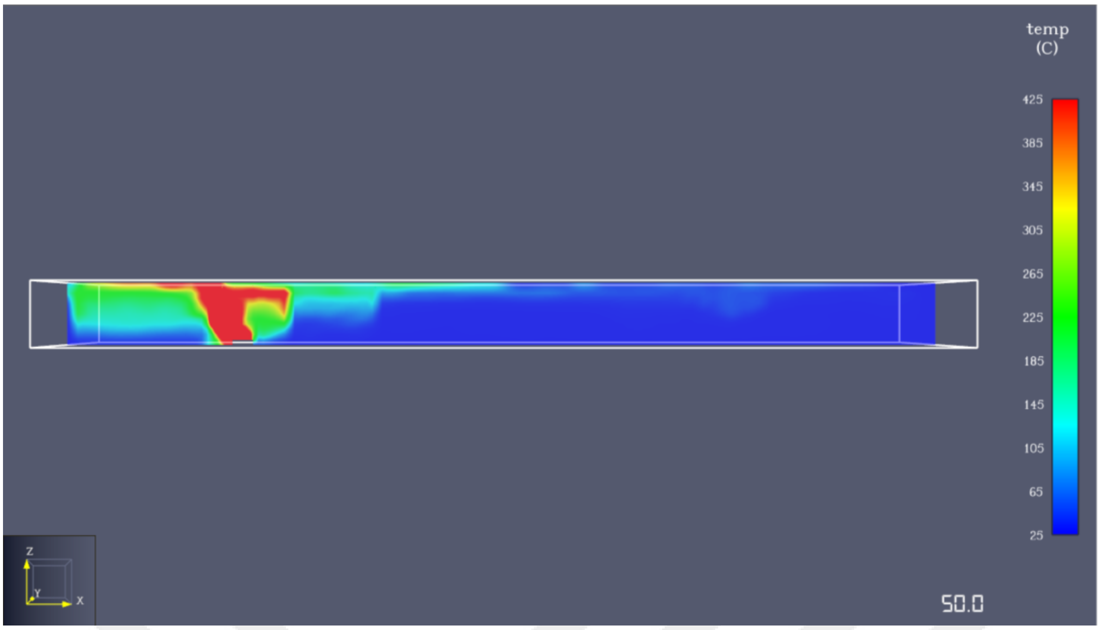

Figure 7.32 : Temperature distribution at y=4.25m at t=50s for scenario 1c.

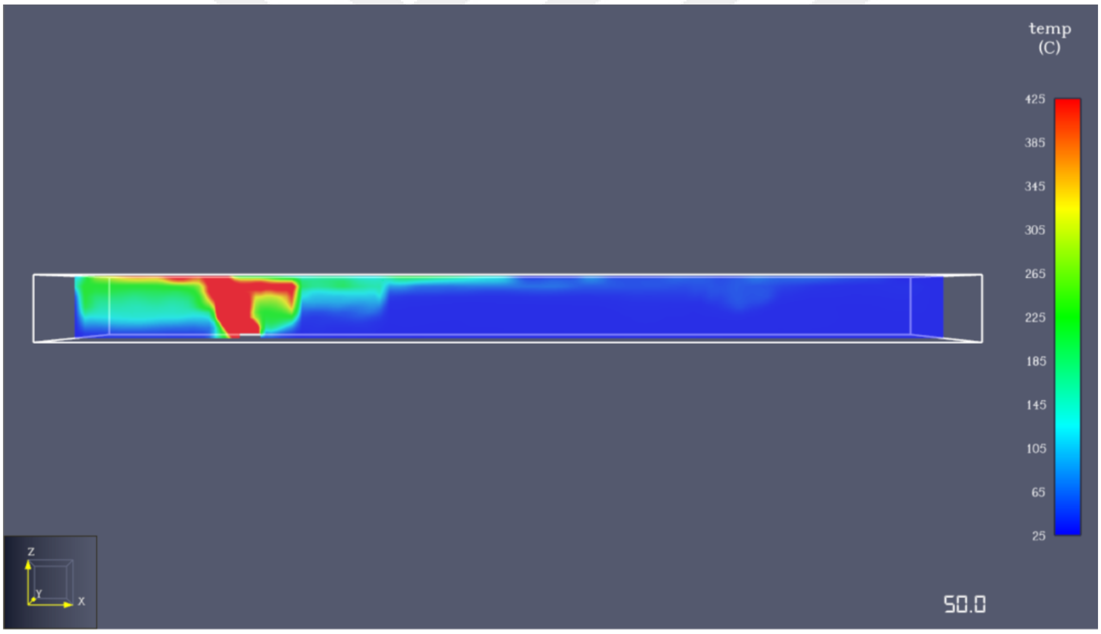

Figure 7.33 : Temperature distribution at y=4.25m at t=50s for scenario 2.

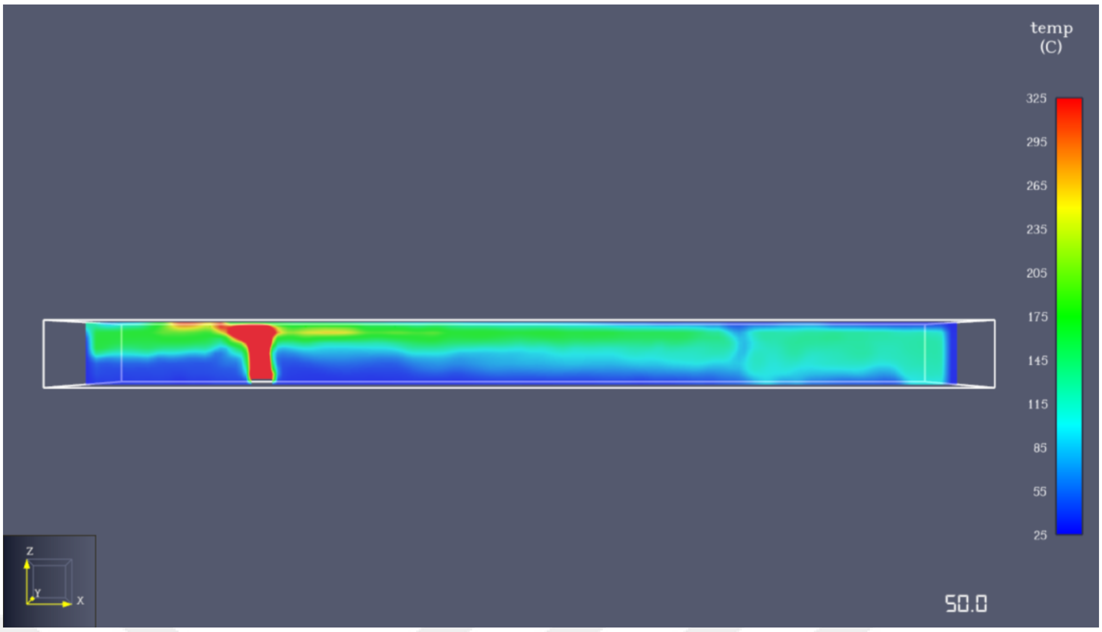

Figure 7.34 : Temperature distribution at y=4.25m at t=50s for scenario 3.

Figures 7.35, 7.36, 7.37, 7.38 and 7.39 represent the temperature distribution on 4.25m at y-direction at 150s along the lower deck for scenarios 1a, 1b, 1c, 2 and 3 respectively. Even though, characteristics of the temperature distribution at time 150s are almost similar to previous results at time 50s. However, the temperature of other zones increases dramatically to almost 300 °C in Figure 7.38 for scenario 3 that is lack of fire-rated bulkheads. In addition, differences between scenario 3 and others last the same until the end of simulation. Lastly, sprinkler effects on the scenarios 1a, 1b and 1c is noticed in Figures 6.34, 6.35 and 6.36. While comparing scenario 1a and 1b this means that one sprinkler nozzle and two sprinkler nozzles, high temperature volume in the engine room of scenario 1a is higher than scenario 1b. In conclusion, the number of sprinklers in the engine room has a positive effect on the temperature level. Otherwise, there is no significant difference between scenario 1b and 1c. To sum up, the two sprinklers scenario called as 1b is the optimum solution in this case.

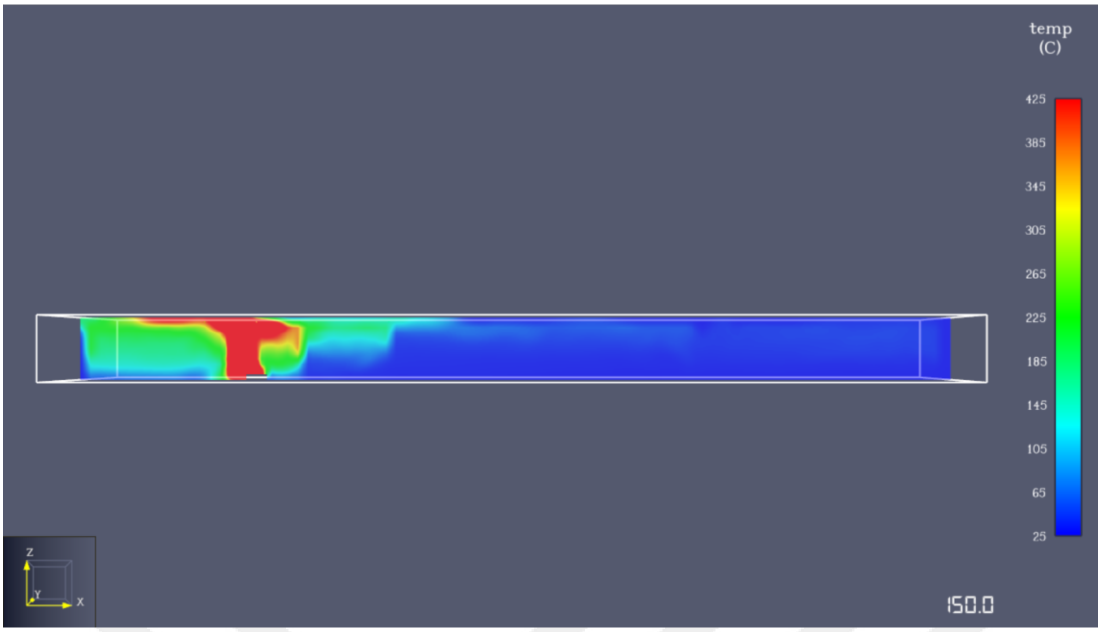

Figure 7.35 : Temperature distribution on y=4.25m at t=150s for scenario 1a.

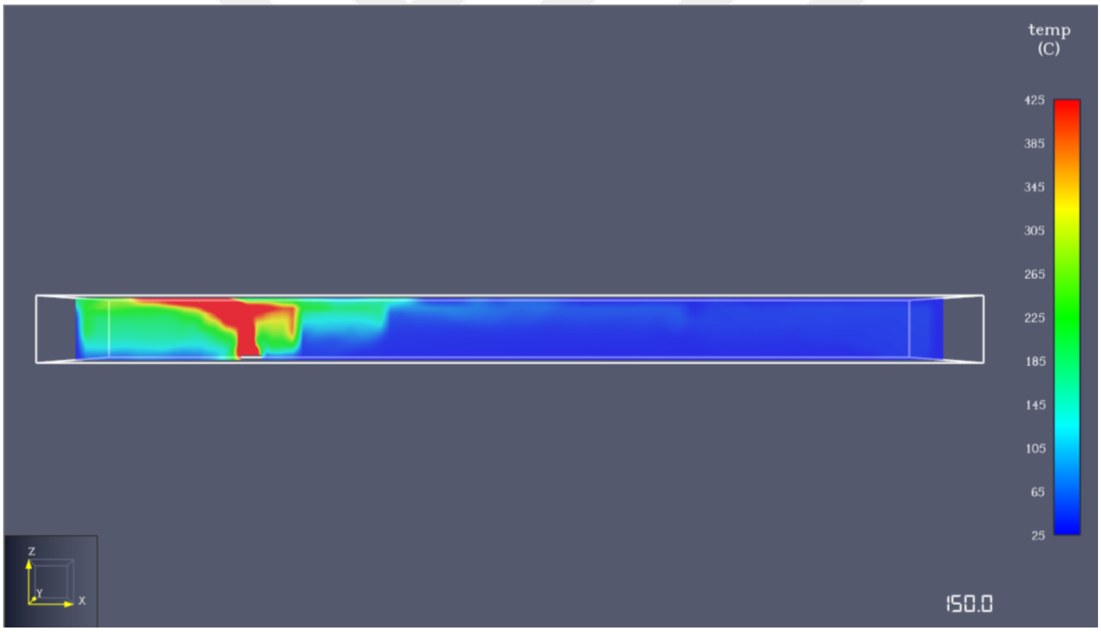

Figure 7.36 : Temperature distribution on y=4.25m at t=150s for scenario 1b.

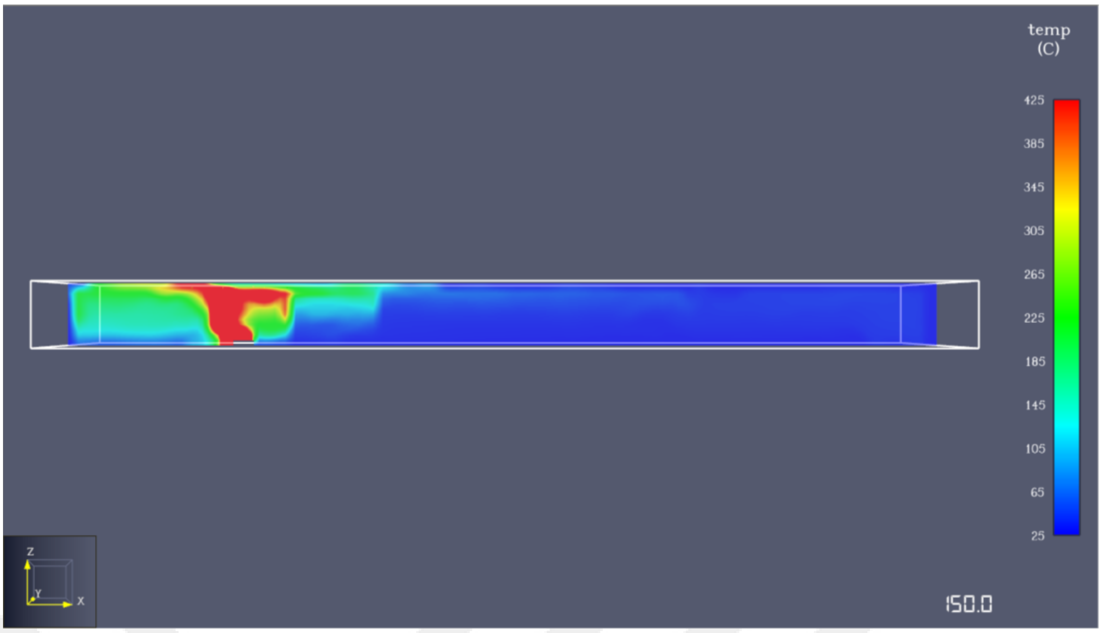

Figure 7.37 : Temperature distribution on y=4.25m at t=150s for scenario 1c.

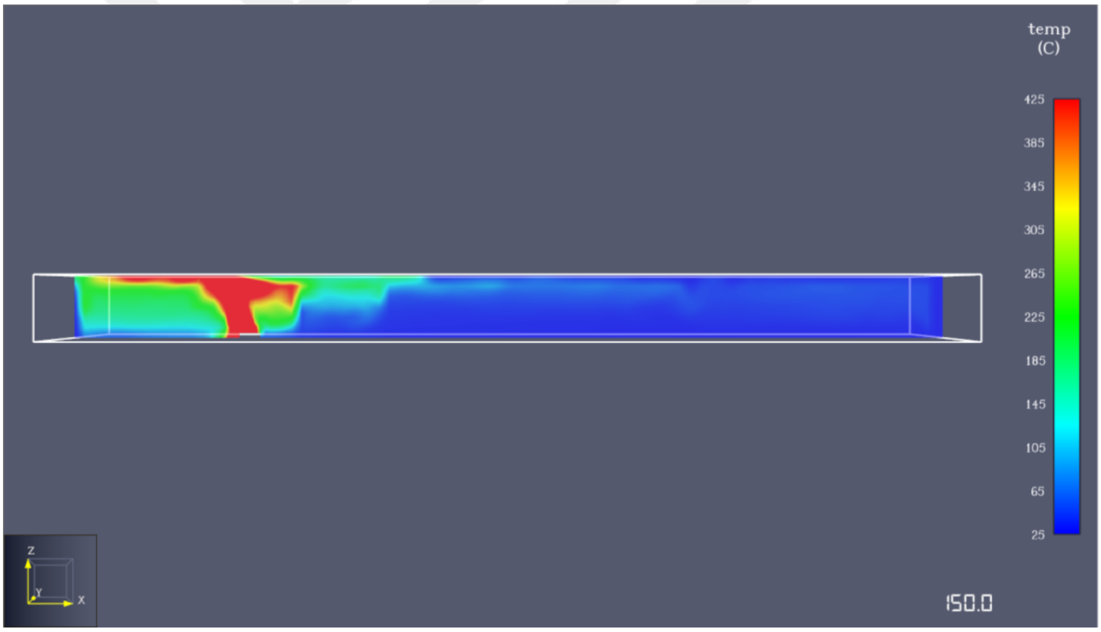

Figure 7.38 : Temperature distribution on y=4.25m at t=150s for scenario 2.

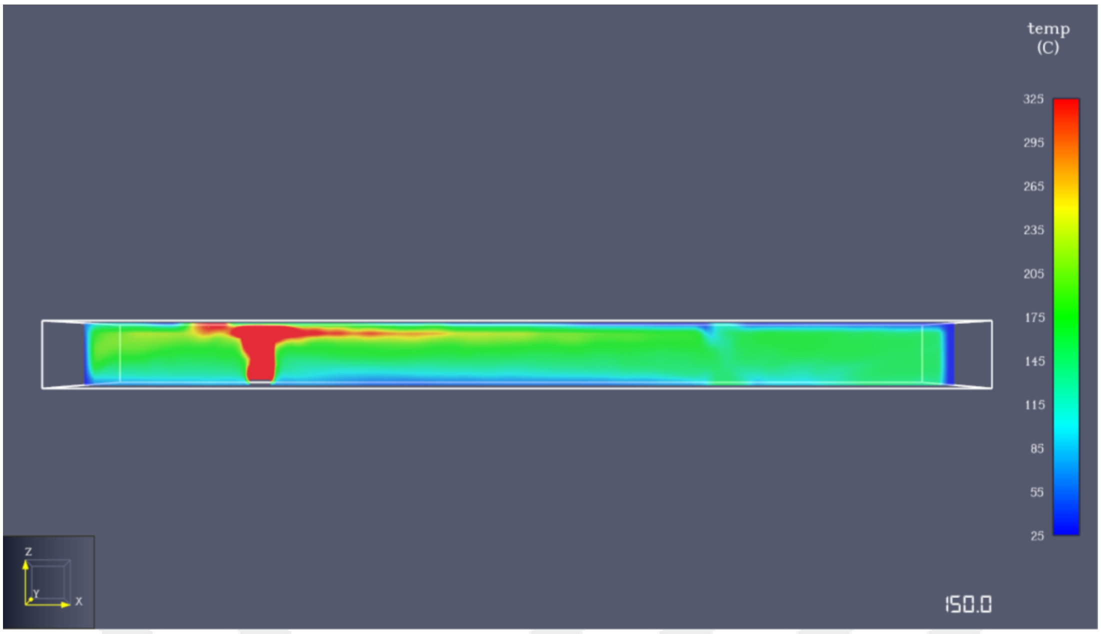

Figure 7.39 : Temperature distribution on y=4.25m at t=150s for scenario 3.

Temperature distribution on the fire-rated bulkhead that is located on 5.4m in x-direction at 100s for scenario 1a, 1b, 1c, 2 and 3 are given in Figure 7.40, 7.41, 7.42, 7.43 and 7.44 respectively. This bulkhead is crucial in terms of fire safety due to the separation engine room from helm station. In these figures, the positive effect of sprinklers is shown when comparing scenario 1c and 2. Additionally, fire-rated bulkhead effects can be shown in Figure 7.42.

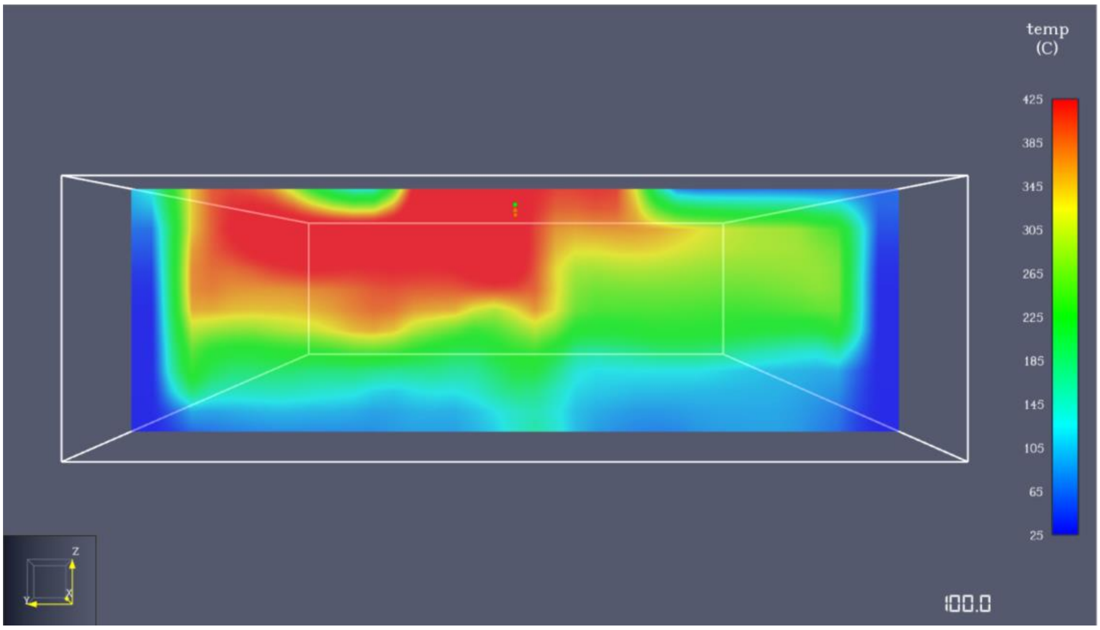

Figure 7.40 : Temperature distribution on x=5.4m at t=100s for scenario 1a.

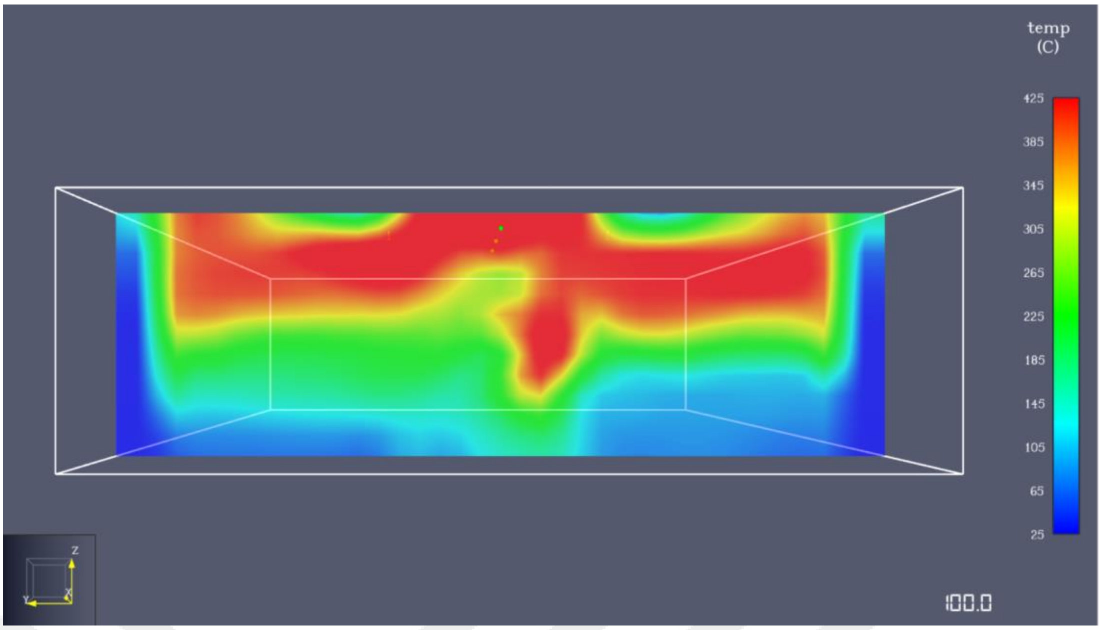

Figure 7.41 : Temperature distribution on x=5.4m at t=100s for scenario 1b.

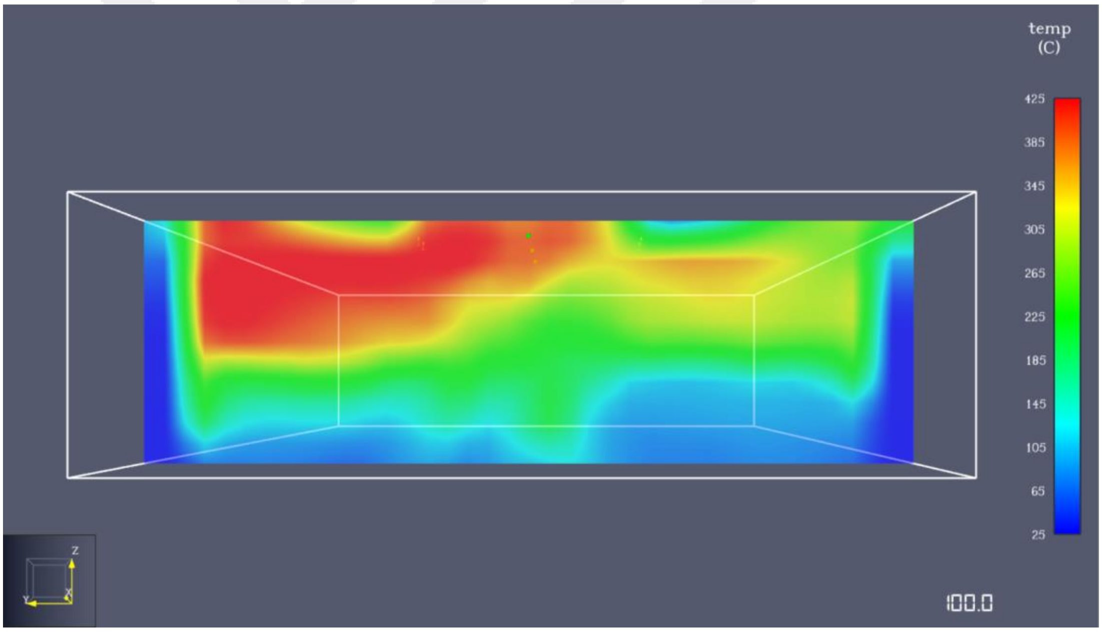

Figure 7.42 : Temperature distribution on x=5.4m at t=100s for scenario 1c.

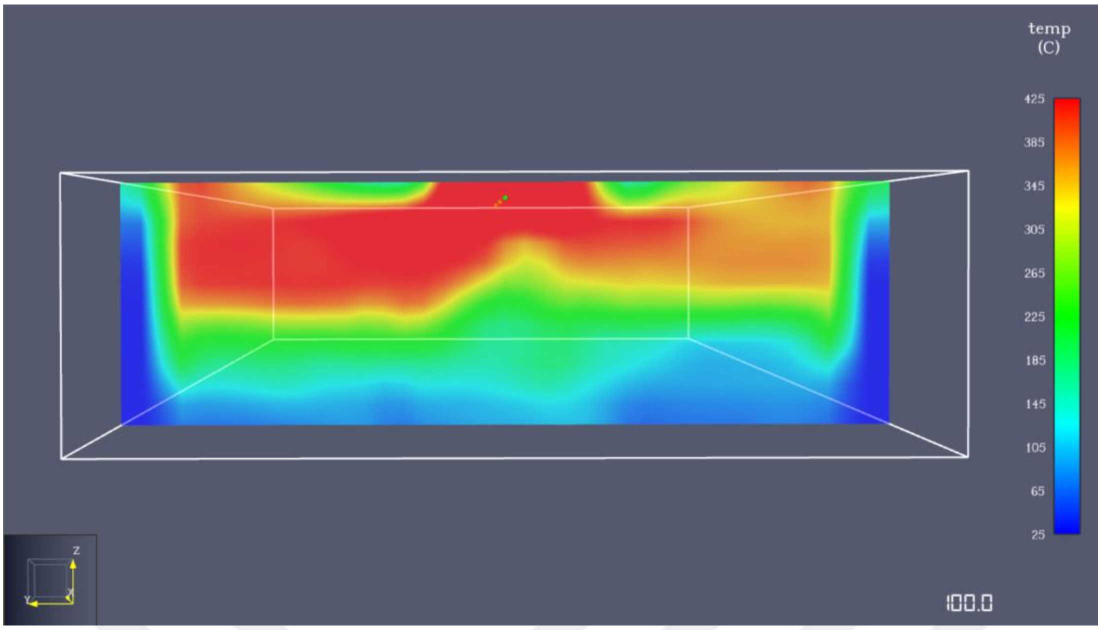

Figure 7.43 : Temperature distribution on x=5.4m at t=100s for scenario 2.

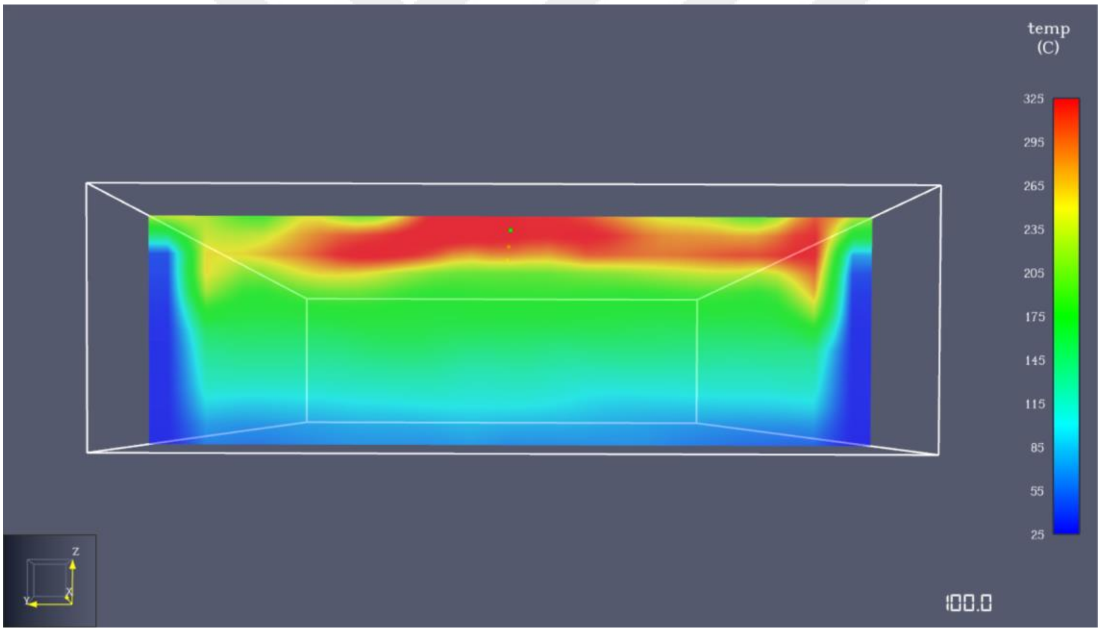

Figure 7.44 : Temperature distribution on x=5.4m at t=100s for scenario 3.

Temperature distribution on the fire-rated bulkhead that is located on 5.4m in x-direction at 250s for scenario 1a, 1b, 1c, 2 and 3 are given in Figures 7.45, 7.46, 7.47, 7.48 and 7.49 respectively.

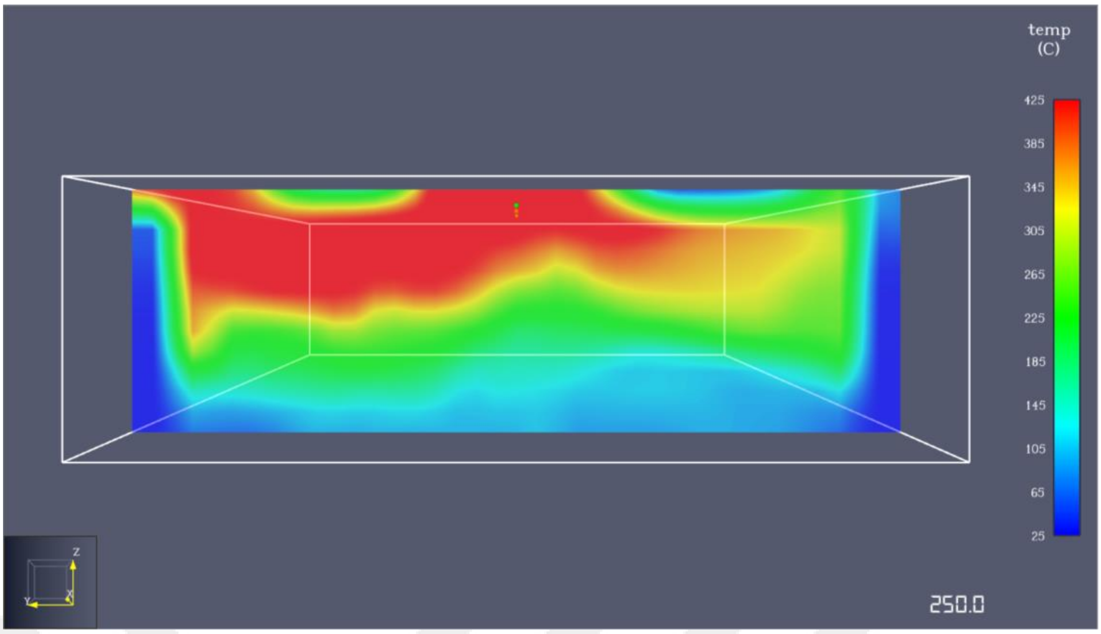

Figure 7.45 : Temperature distribution on x=5.4m at t=250s for scenario 1a.

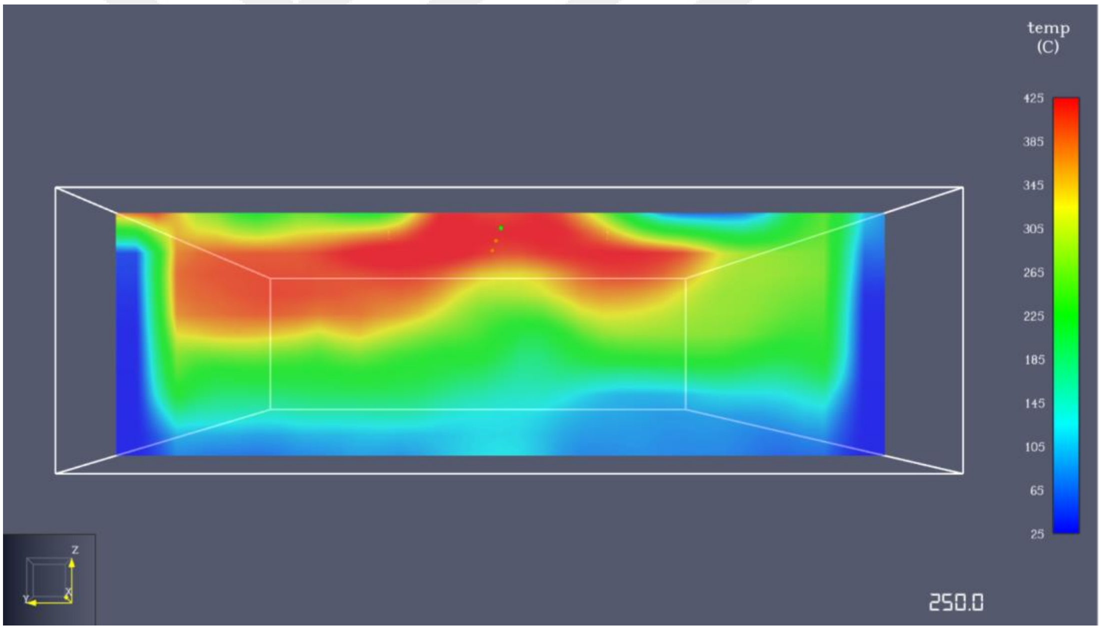

Figure 7.46 : Temperature distribution on x=5.4m at t=250s for scenario 1b.

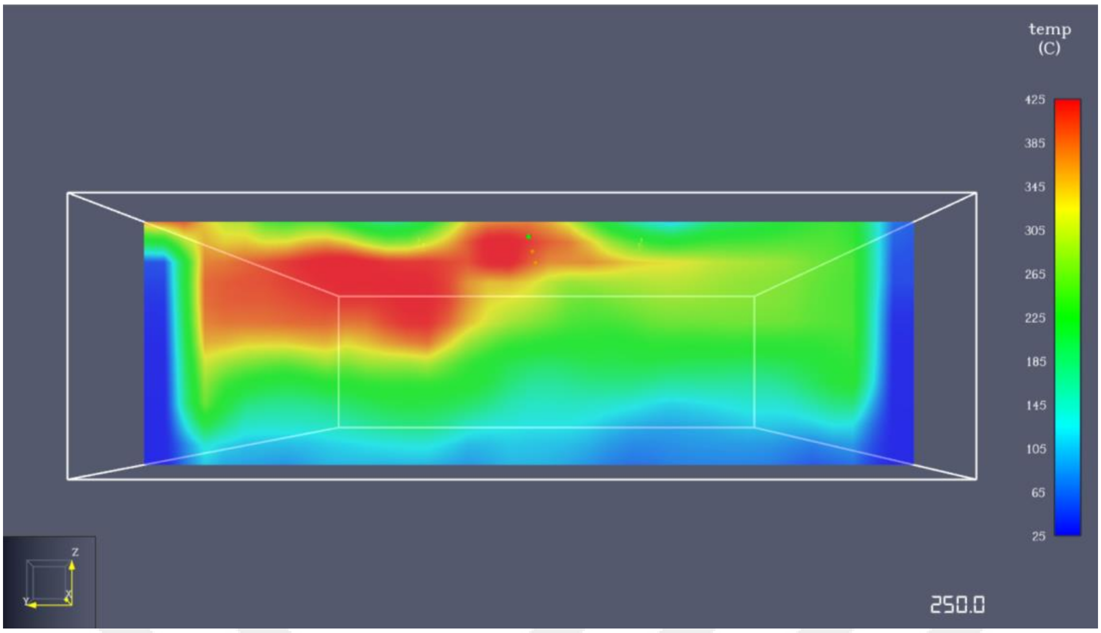

Figure 7.47 : Temperature distribution on x=5.4m at t=250s for scenario 1c.

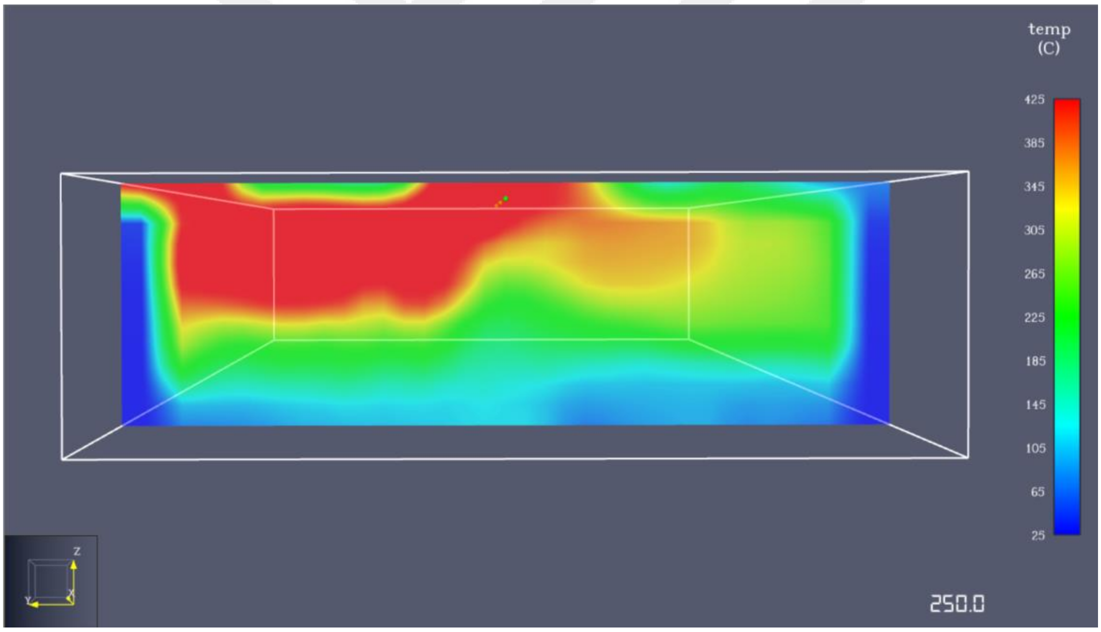

Figure 7.48 : Temperature distribution on x=5.4m at t=250s for scenario 2.

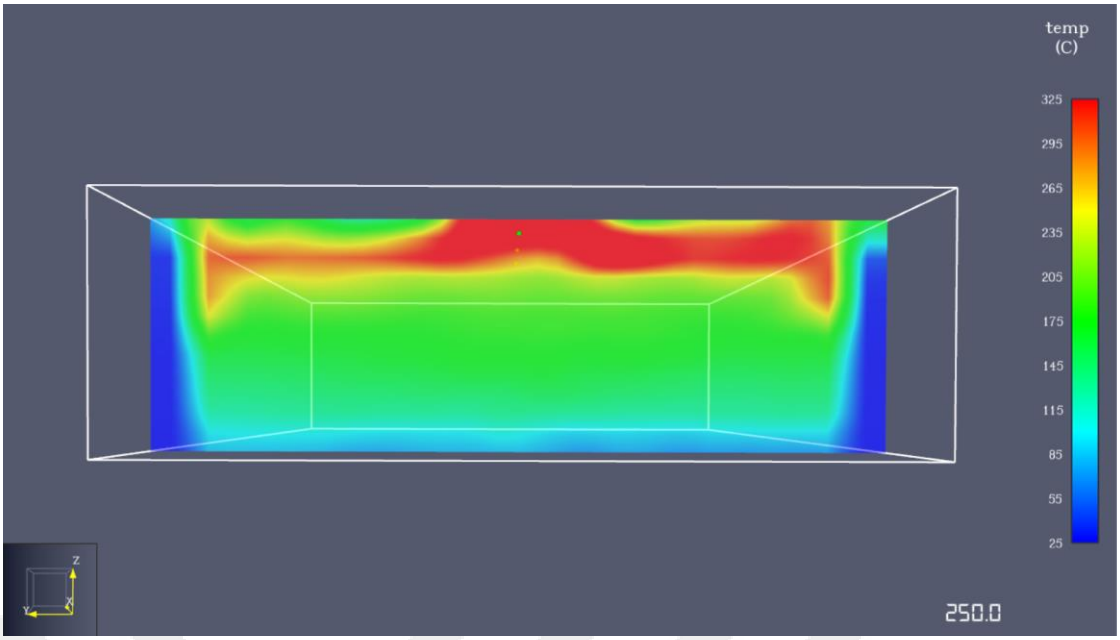

Figure 7.49 : Temperature distribution on x=5.4m at t=250s for scenario 3.

Temperature distributions on the fire-rated deck are placed in 2.8m z-direction at 100s for scenarios 1a, 1b, 1c, 2 and 3 are given in Figures 7.50, 7.51, 7.52, 7.53 and 7.54 respectively. This plane in the z direction is a significant obstacle for spreading fire along the ship vertically. If this fire-rated deck collapses due to the temperature increase, passenger compartments would be in danger in terms of fire safety. Due to this fact, the temperatures on this plane take a crucial place to evaluate fire safety onboard ships. While comparing temperature distribution, sprinkler effect is significantly shown in Figure 7.50 and Figure 7.51 for scenarios 1c and 2. Also, fire-rated bulkheads provide positive impact on spreading fire, smoke and temperature along the vessel.

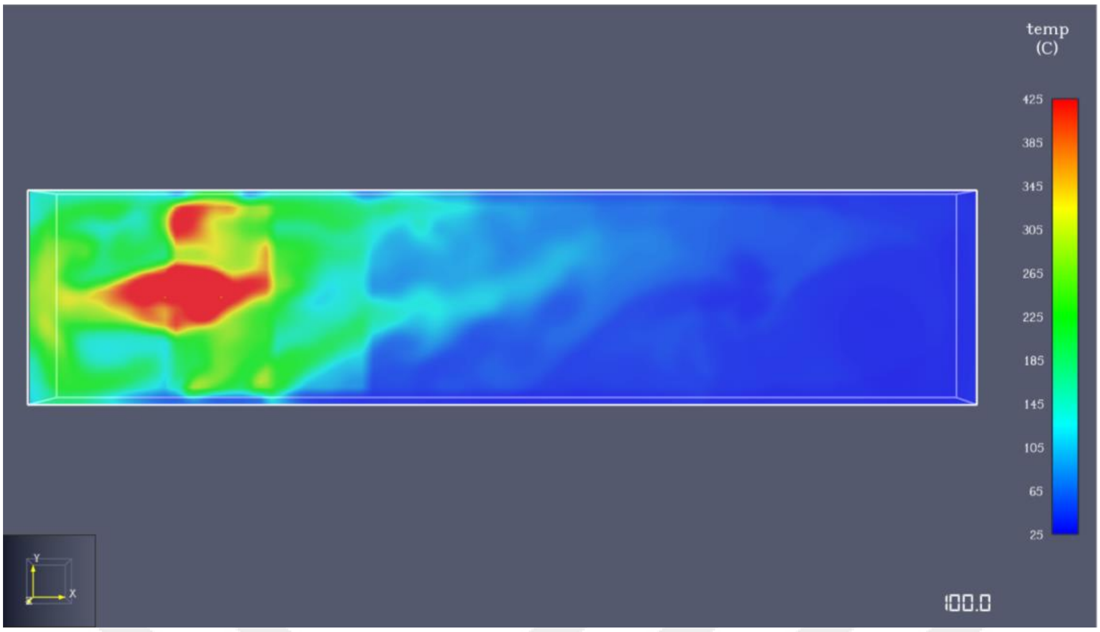

Figure 7.50 : Temperature distribution on z=2.8m at t=100s for scenario 1a.

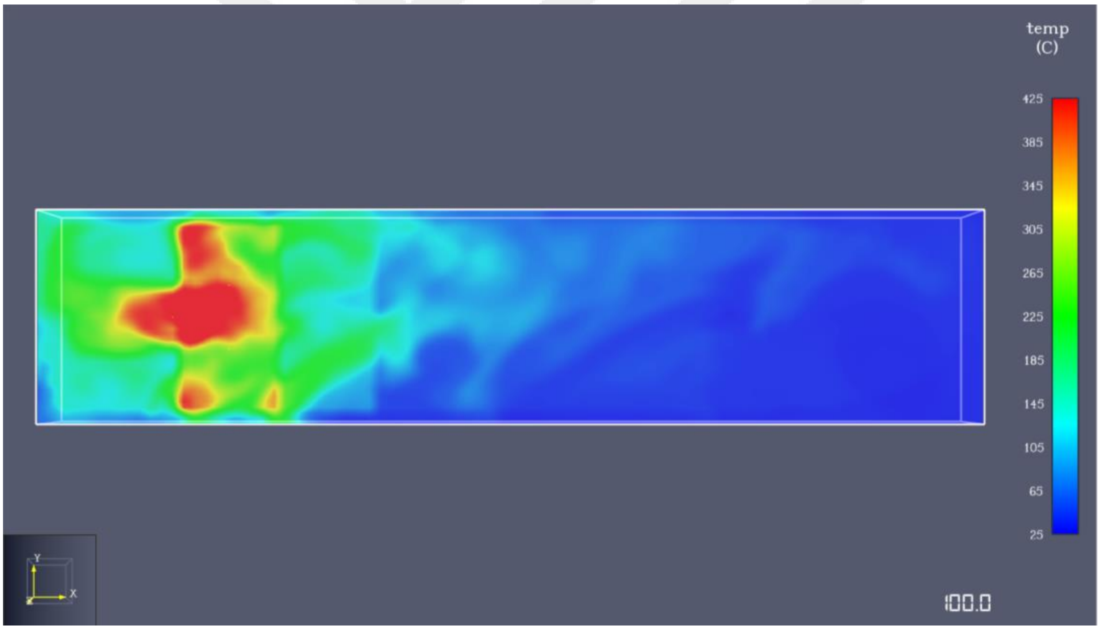

Figure 7.51 : Temperature distribution on z=2.8m at t=100s for scenario 1b.

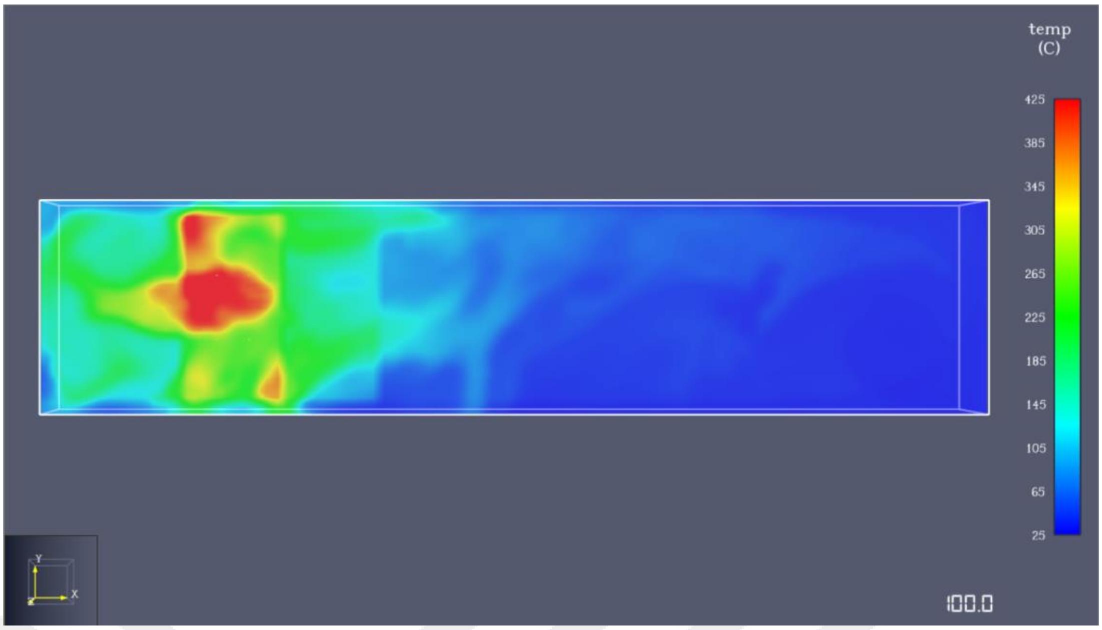

Figure 7.52 : Temperature distribution on z=2.8m at t=100s for scenario 1c.

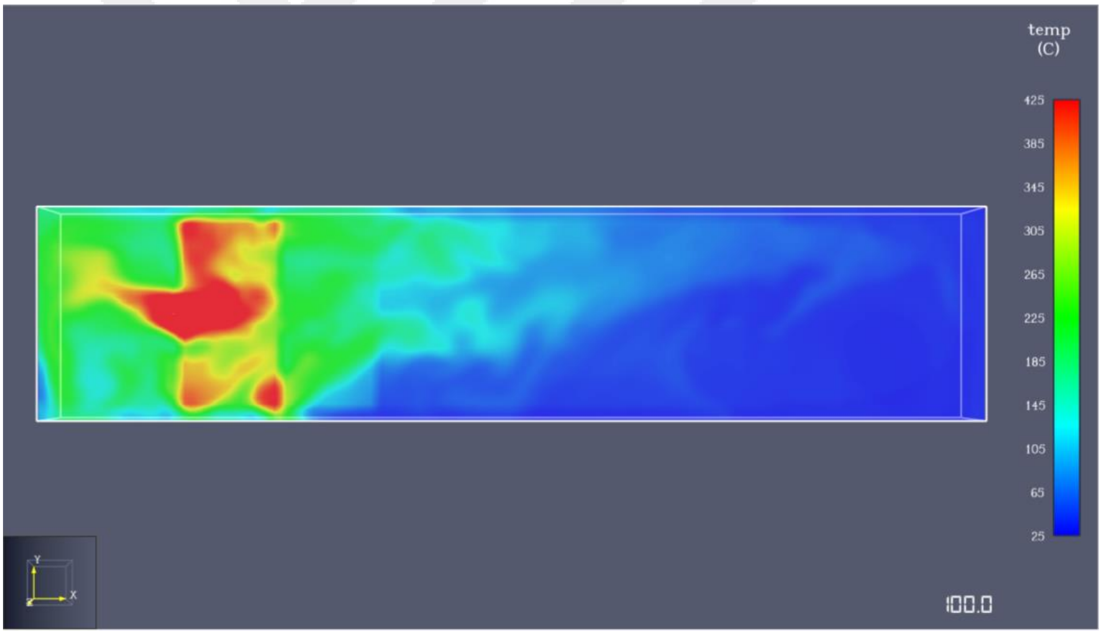

Figure 7.53 : Temperature distribution on z=2.8m at t=100s for scenario 2.

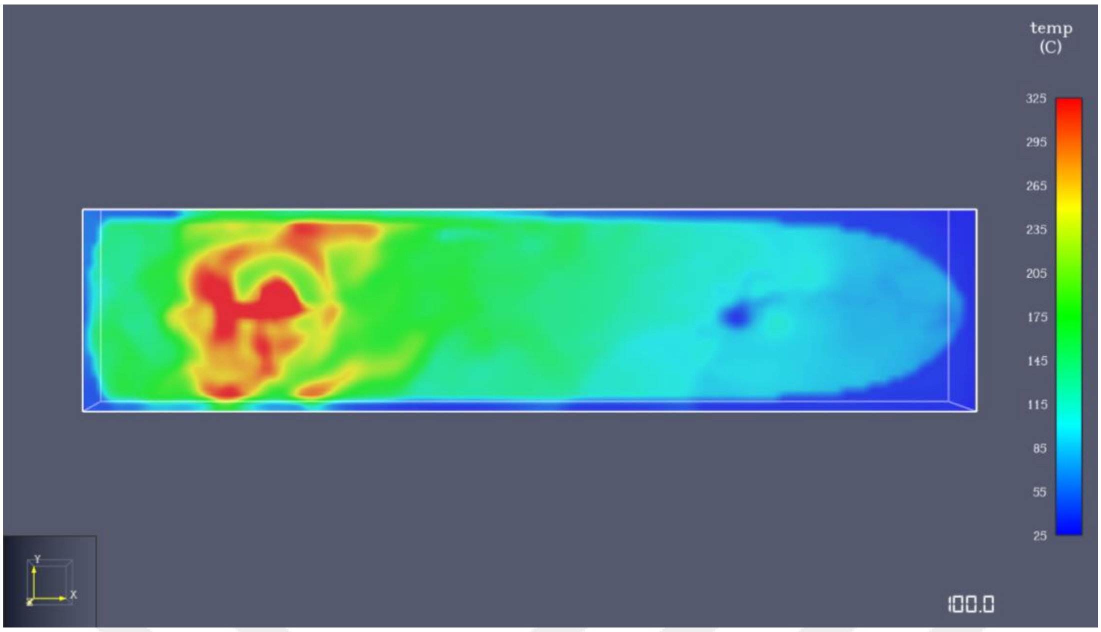

Figure 7.54 : Temperature distribution on z=2.8m at t=100s for scenario 3.

Temperature distributions on the fire-rated deck is placed in 2.8m z-direction at 200s for scenarios 1a, 1b, 1c, 2 and 3 are given in Figures 7.55, 7.56, 7.57, 7.58 and 7.59 respectively. This plane in the z direction is a significant obstacle for spreading fire along the ship vertically. If this fire-rated deck collapses due to the temperature increase, passenger compartments would be in danger in terms of fire safety. Due to this fact, the temperatures on this plane take a crucial place to evaluate fire safety onboard ships. While comparing scenarios 1a and 1b, there is not significant impact on the temperature in terms of one and two sprinkler arrangements. However, temperature increase along the deck for scenario 3 is wider than other scenarios due to the absence of fire-rated bulkheads in the scenario.

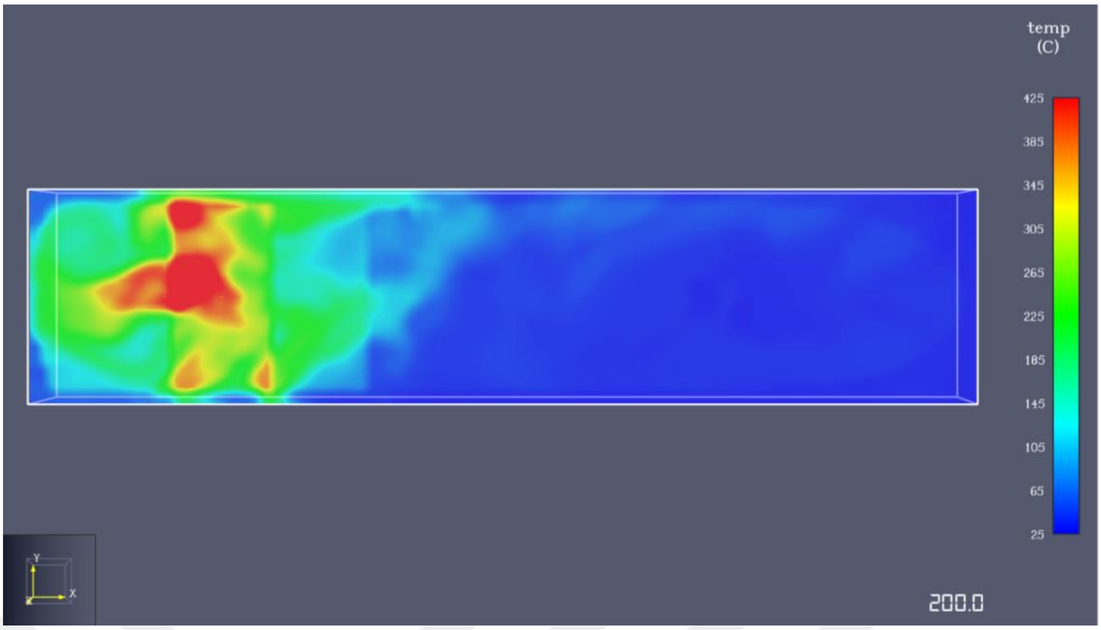

Figure 7.55 : Temperature distribution on z=2.8m at t=200s for scenario 1a.

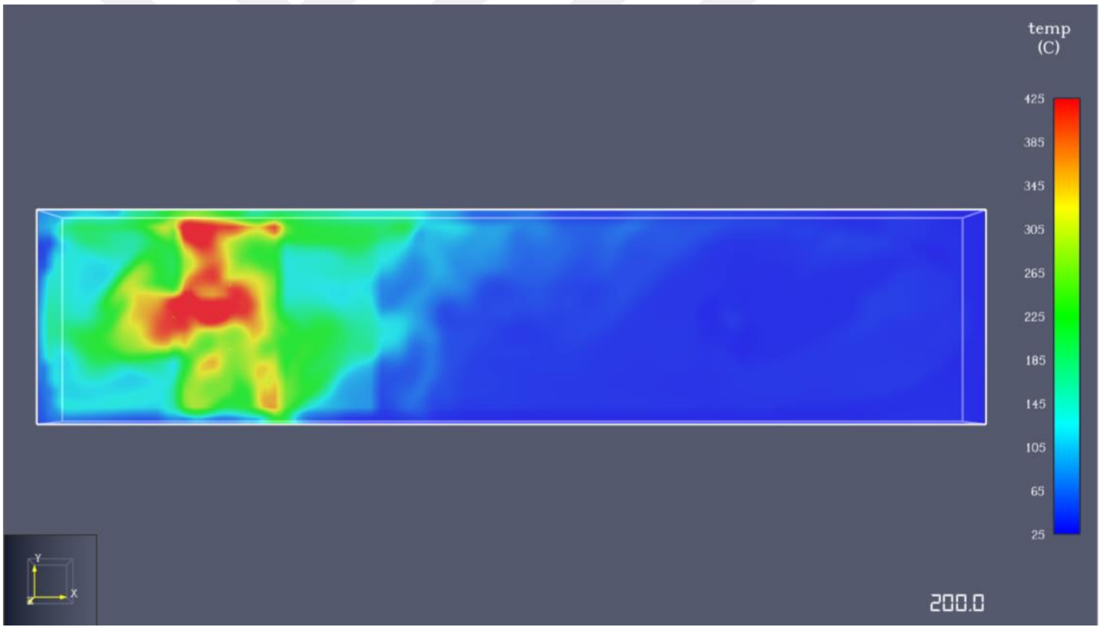

Figure 7.56 : Temperature distribution on z=2.8m at t=200s for scenario 1b.

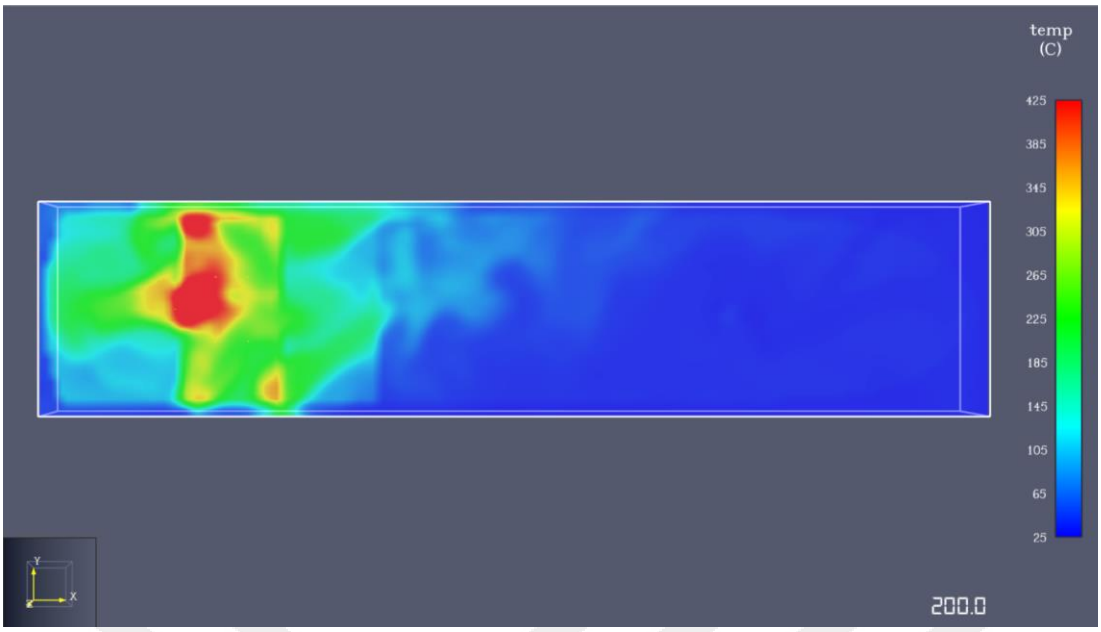

Figure 7.57 : Temperature distribution on z=2.8m at t=200s for scenario 1c.

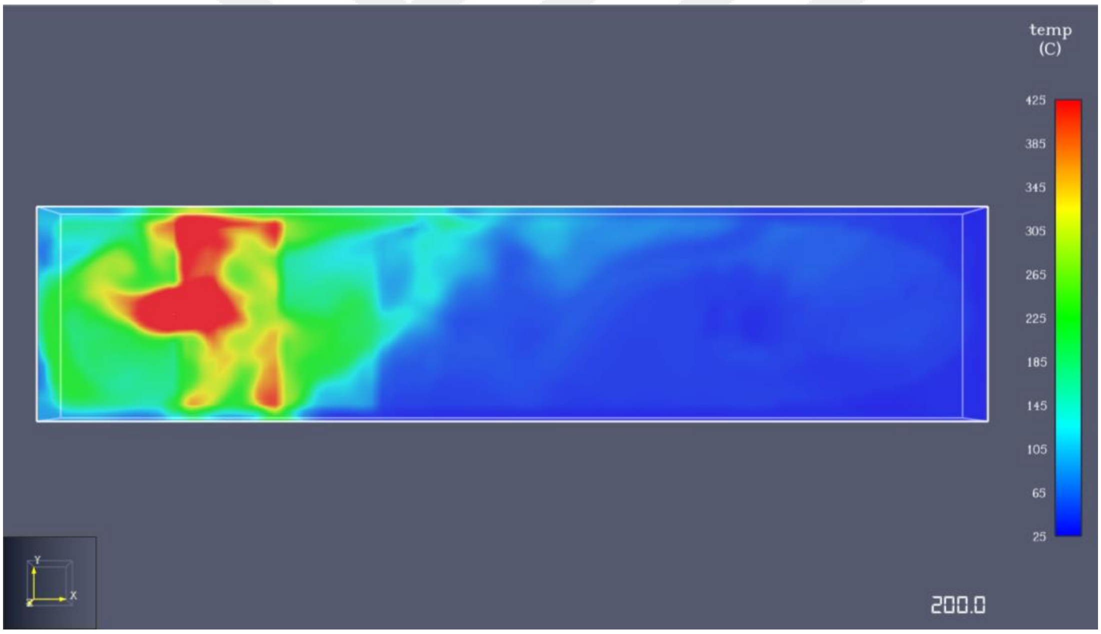

Figure 7.58 : Temperature distribution on z=2.8m at t=200s for scenario 2.

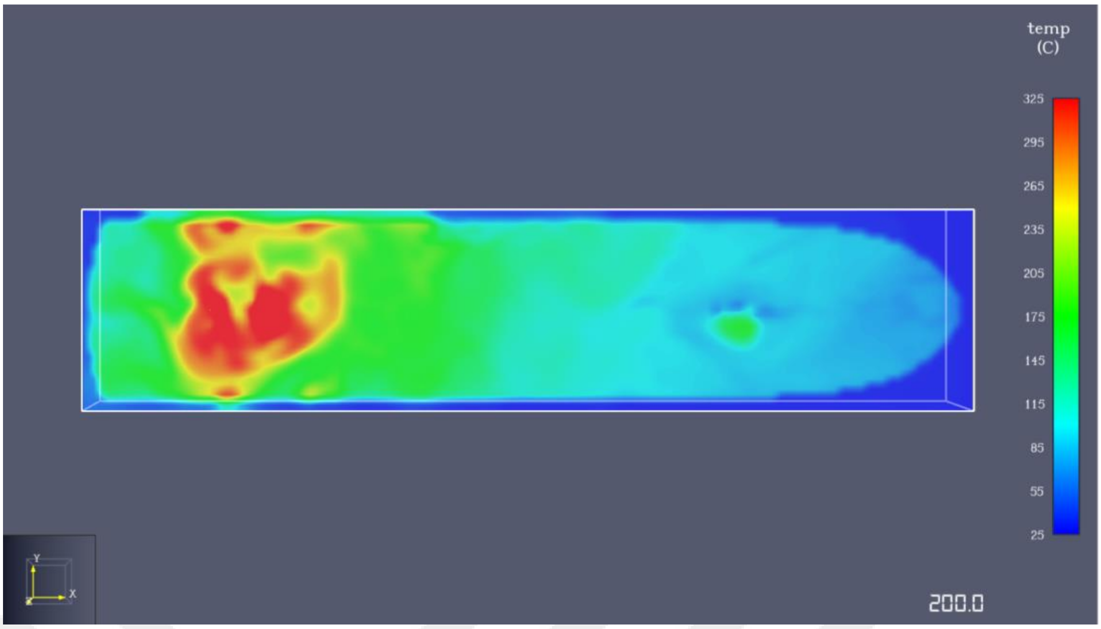

Figure 7.59 : Temperature distribution on z=2.8m at t=200s for scenario 3.

7.2 Fire Modelling of Electric Vehicle Spaces Onboard ROPAX Vessel

7.2.1 Background of electrical vehicle transportation

Electric vehicle (EV) markets are growing exponentially as sales exceeded 10 million cars in 2022 globally and the percentage of EVs in total car sales increased three and a half times in three years, from around 4% in 2020 to 14% in 2022. EV sales are expected to continue strongly through the coming years. Figure 7.60 depicts the parabolic growth of the global sales volume of EVs between 2016 and 2023 (IEA, 2023). As the growth trend in EV sales continues exponentially, the sales number of EV globally overtakes 30 million quantities within recent years (Statista, 2023).

The global demand for Pure Car Carriers (PCCs) is experiencing significant growth, largely driven by the increasing internationalization of car transportation. These specialized vessels, which are designed specifically to transport cars, stand apart from traditional roll-on/roll-off (ro-ro) vessels due to their ability to carry a larger number of vehicles at once. PCCs typically feature multiple parking decks above the main deck, allowing for efficient vehicle storage and handling. As the market for PCCs expands, new challenges are emerging, particularly concerning fire safety during the shipping process. A study (Fu et al., 2023) highlights the importance of identifying and evaluating risk factors that could lead to fire accidents on these ships. The researchers propose a fire risk evaluation model, utilizing the entropy weight TOPSIS method to assess and rank the various risk factors associated with fire hazards.

This growing demand for PCC vessels is reflected in the large number of orders being placed. In March 2023 alone, 143 orders were placed for PCCs, which significantly outpaces the 26 orders for traditional ro-ro vessels. This trend indicates a substantial increase in the demand for specialized car carriers, with 76 orders in 2022, doubling the number from 2021. Additionally, by the end of the first quarter of 2023, 29 orders had already been placed, suggesting that the total number of orders for PCCs will exceed those of the previous year, marking a continued surge in demand for this type of vessel. This expansion indicates a key shift in the global car transportation industry, where specialized, efficient, and safe transport options like PCCs are becoming increasingly vital.

In the world, almost 80 million vehicles are produced annually and approximately 40% of the vehicles are transported via marine transportation. For the near future projection, both produced vehicles and marine transportation ratio on vehicles are assumed to be doubled (Statista, 2023). Therefore, a part of the vehicle transportation via marine, EV plays a crucial role depending on exponential growth on EVs global sales. Among the risks such as floating, grounding, structural failures or collisions, fire safety takes a significant place to be considered due to the fact that EVs or charging stations led to fire incidents onboard ships. Lithium-ion batteries, commonly used in EVs, have the potential to catch fire under adverse conditions, posing serious risks to both passengers and crew. Based on this risk assessment, the subject of fire safety onboard ships that transport EVs reveals as a challenging and paramount issue to be analyzed and solved. This study focuses on the issue from the perspective of fire dynamics simulations.

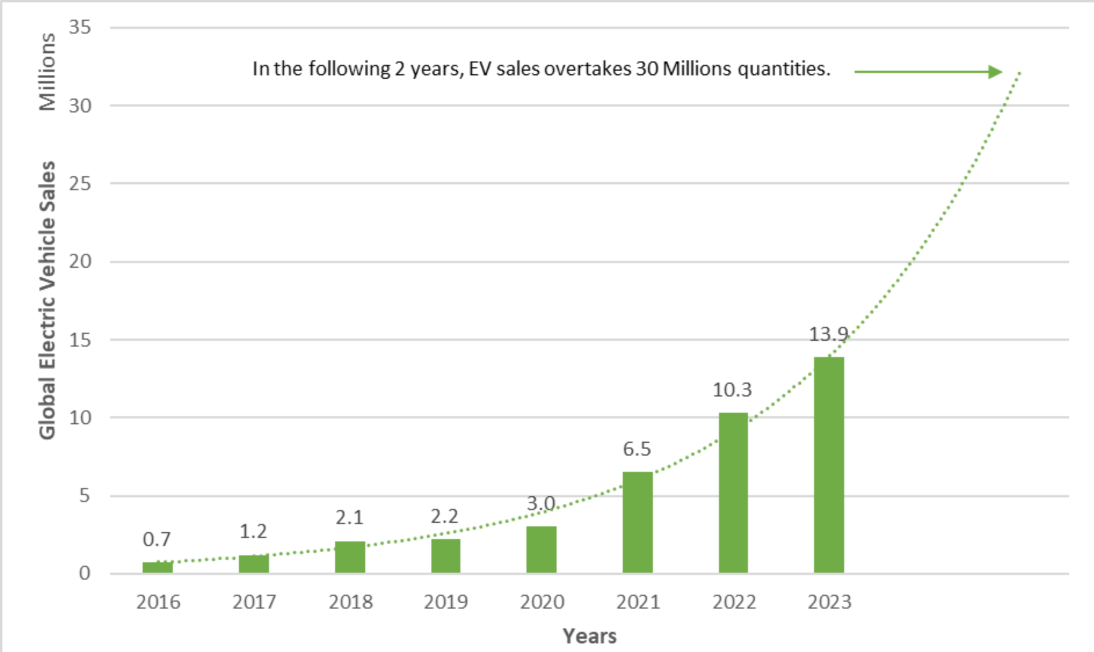

Figure 7.60 : Global electric vehicle sales, 2016-2023 (IEA, 2023).

Lithium-ion batteries have the potential to catch fire under adverse conditions due to exposure to the conditions of energy creation, storage, and use. Although rare, fires and accidents caused by these batteries can be very dangerous. Therefore, it is important to take every precaution to prevent lithium-ion battery fires. When Li-ion cells generate more heat than they are able to effectively dissipate, they may experience thermal runaway, which is the rapid, uncontrollable release of heat energy that could cause fire or explosion.

There have been many reports of EV fires in the last few years. When an EV is involved in a fire, investigating the incident often reveals the battery as the primary cause. The safety of transporting EVs is a major concern for the shipping and insurance companies since some accidents have been reported owing to the thermal runaway of EVs (Zhang et al, 2019). Also, there are also some fire accidents of EVs occurring globally as reported by the general media. For example, a fire on a ferry carrying almost 3,000 cars off the coast of the Dutch island of Ameland has left one sailor dead and 22 other crew members hurt in July 2023 (BBC, 2023). Therefore, if a fire accident occurs on the deck, the fire may spread to other combustible materials and eventually cause serious consequences, so the transportation of EVs by ship should be handled carefully.

From the perspective of novelty of the study is that applications of performance-based design and fire dynamics simulation tools to the EVs spaces onboard ROPAX ships with a case study provide the prediction of temperature levels along the enclosed space. This case study examines the fire safety of electrical vehicle spaces of ferries. The aims of the study are as follows:

- Performance-based fire safety design on ships includes electrical vehicles,
- Outline strategies for mitigating fire risk, particularly on electric vehicle spaces on vessels,
- Simulate fire dynamics inside the control volume and track crucial components such as temperature.

The literature review is detailed analyzed in terms of fire safety regulation onboard ships, fire modelling and performance-based design depending on fire dynamics simulations in the next section. In summary, fire regulation onboard ships are mainly based on the Safety of Life at Sea (SOLAS) in Chapter II-2. Additionally, UK Government, Maritime & Coastguard Agency and Nippon Kaiji Kyokai publish guidelines for the specifically EVs and its transportation via maritime. Fire modelling with fire dynamics simulations is the main part of the literature review section. Among the probabilistic, deterministic, and stochastic fire modelling approaches, deterministic ones such as field and zone models are examined in detail and mathematical equations of field model selected for the case study is given. Lastly, the fire dynamics simulations for specifically passenger ships, Ro-Ro vessels and ROPAX vessels including EVs spaces are reviewed literally.

7.2.2 Materials and methods

In this case study, one ship is selected as a case study for simulating fire dynamics. In this case, the capacity of the vessel is 800 passengers, 90 cars and 60 trucks. Table 7.4 indicates the technical specifications of the vessel below. In general, the structure of a whole ship is very complex to simulate all detailed information in a model. In the first step, this study focuses on electric vehicles space onboard ships. Mainly, the detailed shapes of each piece of equipment on this deck are irregular. Therefore, FDS software is used for investigating the fire and cube-shaped grids are used, the structure information of the real deck should be streamlined as follows:

a) The complex structure in the deck: as some small equipment or electrical vehicles have a small effect on the flame spread, most of these components are ignored during development of numerical models. Electrical vehicles in the compartments simplify with two cubic fire sources.

b) Explosibility: There are many small pieces of equipment and devices within the compartments, so they can easily cause explosions in the event of a fire. This can increase the destructive power of fire. However, due to the complex nature of explosives, this will be omitted to simplify the calculations.

c) Human impact on fire development: For the whole fire spreading process within the deck; in the early stages, the movement of people has a small effect on the flow distribution. Therefore, the impact of human actions will be ignored.

d) Active fire protection systems such as fire extinguishing sprinklers and detections are ignored in this study.

Table 7.4 : Technical specification of the ROPAX vessel.

Ship type	ROPAX
Length (m)	146
Beam (m)	22
Depth (m)	14
Draught (m)	6.26
Gross tonnage (t)	6,825
Deadweight tonnage (t)	3,790
Capacity	800 passengers 90 cars 60 trucks

For the CFD simulations, it is necessary to assume some initial conditions of external and internal parameters. For the environment, it is assumed that the air temperature is 20 °C, ambient pressure is 1013 hPa, and relative air humidity is 40%. A propane gas burner is taken as the combustion material (Sun et al, 2020). The well-known Very-Large Eddy Simulation (V-LES) is used based on the concept of filtering a larger part of turbulent fluctuations compared to the standard LES (Labois and Djamel, 2011). It can be concluded that VLES model has better predictions of the swirling flow field for both the mean and the root mean results than the LES models (Tiwari et al, 2020). Therefore, the maximum heat release rate is 7000 kW per EV (Brzezinska and Braynt, 2022). The fire in its growth stage and during its decay period can be described by a t2 curve and total simulation time is taken as 1000s. Geometry of the ship is simplified and determined the length of 145m, the width of 23m and the height of 5m. Instead of the complex geometry of the EV, two cuboid fire sources geometry are determined 4x3x2 m3 depending on vehicles geometry. Each fire source is combusted at the beginning of the simulation.

To select the grid resolution for the fire dynamics simulation, it's essential to consider the non-dimensional ratio of the characteristic fire diameter (D*) to the nominal size of a grid cell (dx). This ratio helps determine the appropriate resolution of the computational grid. The greater the ratio, the finer the resolution required for accurate simulation results. The characteristic fire diameter (D*) depends on factors such as the heat release rate ($\dot{Q}$) and ambient conditions according to equation as below:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{\frac{2}{5}} \tag{7.2}$$

where $\dot{Q}$ is the total heat release rate of the fire, ρ_∞ is the air density (kg/m3), c_p is the air specific heat (kJ/kg·K), g is the gravitational constant (m/s2) and T_∞ is the ambient temperature (K). Depending on the calculations, a cubic mesh is used with 0.5m dimension (McGrattan et al, 2013).

In conclusion, the main parameters of fire dynamics simulation are given and summarized in Table 7.5 and geometry of the EV space in the ROPAX ship is shown in Figure 7.61. In this control volume, boundary conditions for the case of fire dynamics simulation are depicted in Figure 7.62.

Table 7.5 : Main parameters of the fire simulation.

Initial temperature	20 °C
Initial pressure	1013 hPa
Initial humidity	40%
Fire reaction	Propane
Turbulence model	Very-Large Eddy Simulation (V-LES)
Maximum heat release rate	7000 kW per EV
Fire source dimensions	4m*3m*2m
Control volume	145m*23m*5m
Mesh size	0.5m

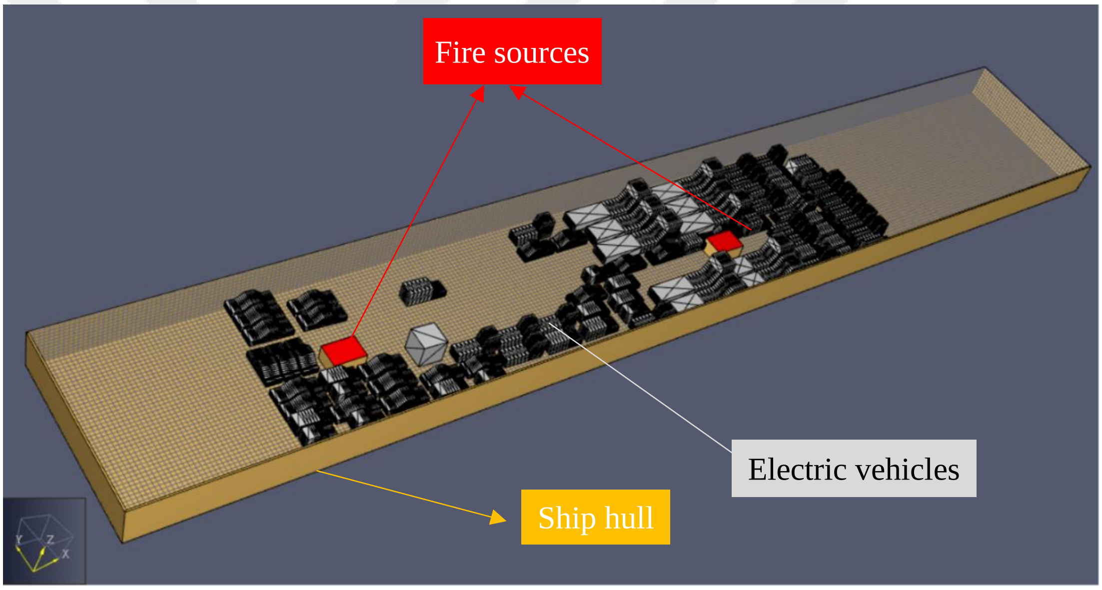

Figure 7.61 : Geometry of the fire simulation space in ROPAX.

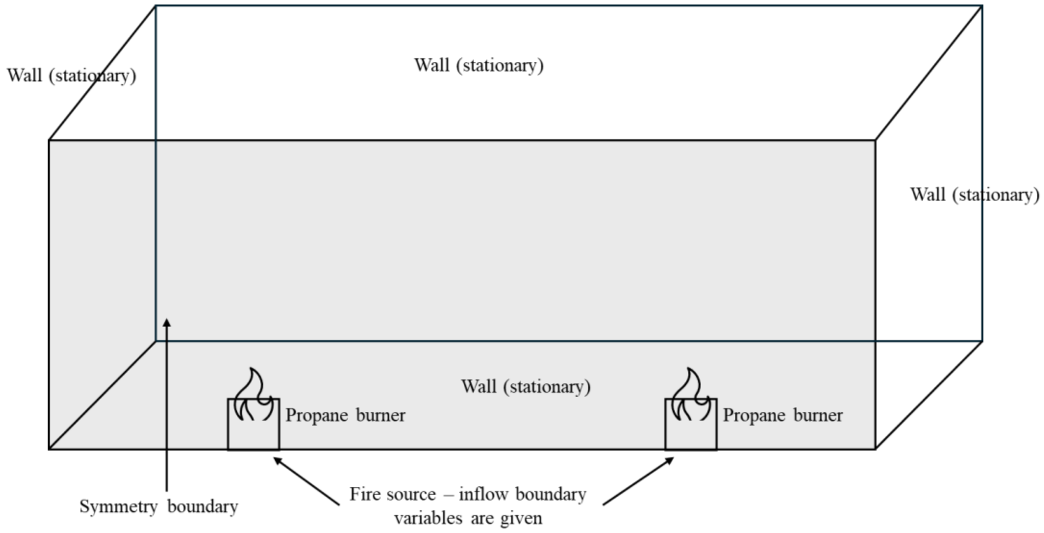

Figure 7.62 : Boundary conditions for the case of fire simulation.

7.2.3 Results

In this case study, heat release rate and pressure in the control volume are analyzed for the initial results of the simulation. Figures 7.63 and 7.64 present the heat release rate and pressure changes in the control volume along the time respectively. In Figure 7.63, heat release rates reach almost 240 MW value at the early phase of the fire. After the fluctuation around 160 MW that is calculated as a maximum heat release rate while designing simulation, heat release rate stabilizes to zero around 150s. Figure 7.63 demonstrates the pressure changes at time steps and almost 40 kPa pressure in the control volume are calculated. To sum up, in the compartment fires, due to the lack of combustible materials, fire burns itself out. After approximately 300s, all these critical parameters are stabilized.

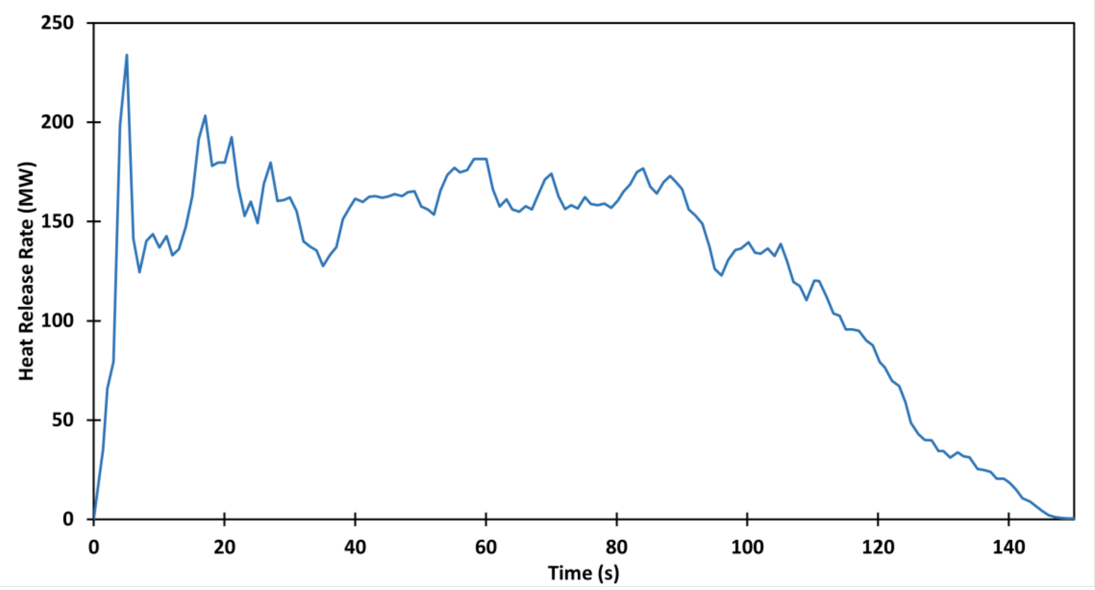

Figure 7.63 : Heat release rate (MW) vs Time (s) graph of the simulation.

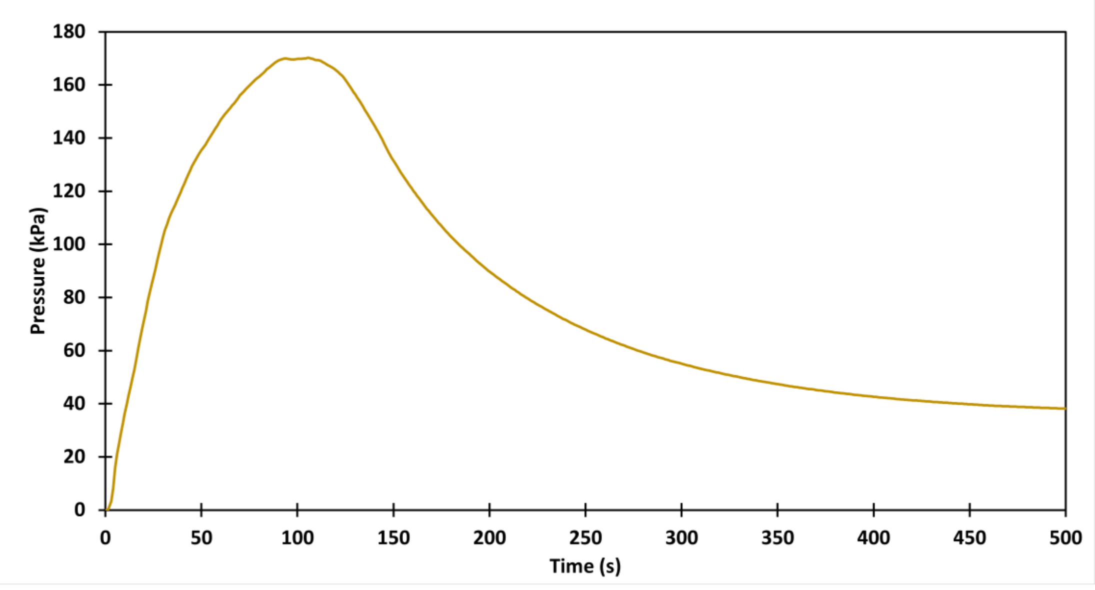

Figure 7.64 : . Pressure (kPa) vs Time (s) graph of the simulation.

Temperature distributions along the control space are significant to evaluate the severity of the fire incident. Due to that, plates in x-direction (10m), in y-direction (11.5m) and in z-direction (4.5m) are specified aligning with center of fire sources to track the temperature distribution. Figure 7.65 indicates the temperature distribution in x-direction (lengthwise in the compartment) at time steps as 50s, 100s, 150s and 200s. At the early stage of the EV space, temperature dramatically increases to almost 1000 °C. Structural elements of the vessel, EVs and equipment in the space can be ignited and lose of their functions by this temperature level organically. Due to the fact that, this temperature level onboard ferries, the spaces or compartments of EV transportation in the ferries have to be designed with structurally resistance materials to the fire. In this study, the ignition and explosibility are ignored due to decrease complexity of the case study.

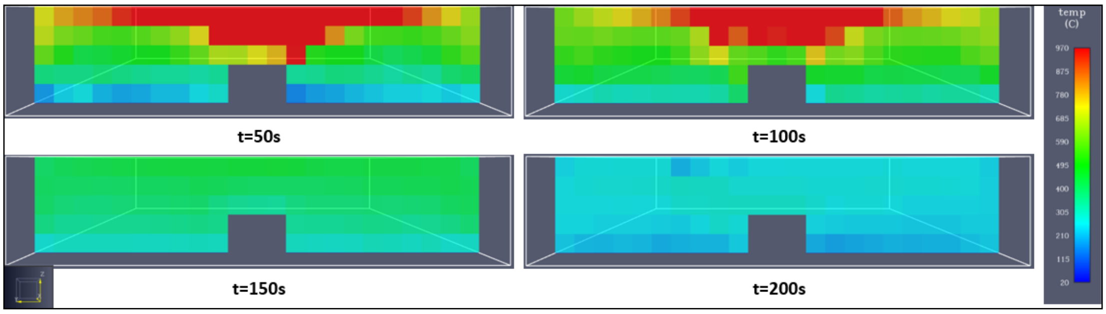

Figure 7.65 : Temperature distribution on x=10m at 50s, 100s, 150s and 200s.

Temperature distribution on y=11.5m and z=4.5m at six different time steps such as 50s, 100s, 150s, 200s, 250s and 300s are depicted in Figure 7.66 and Figure 7.67 respectively. In these figures, interaction between two fire sources starts after 100s and this is harmonized at following time steps. Same as Figure 7.65, the planes exceed the critical temperature level for space quickly. In the first 50s, temperature distribution shows that EV fires have a significant impact on the surrounding elements such as structural steels, other vehicles, machinery, equipment etc. Therefore, Figure 7.68 presents the 3D perspective view of the thermal distribution in the control volume at the time of 75s, 125s, 175s and 225s.

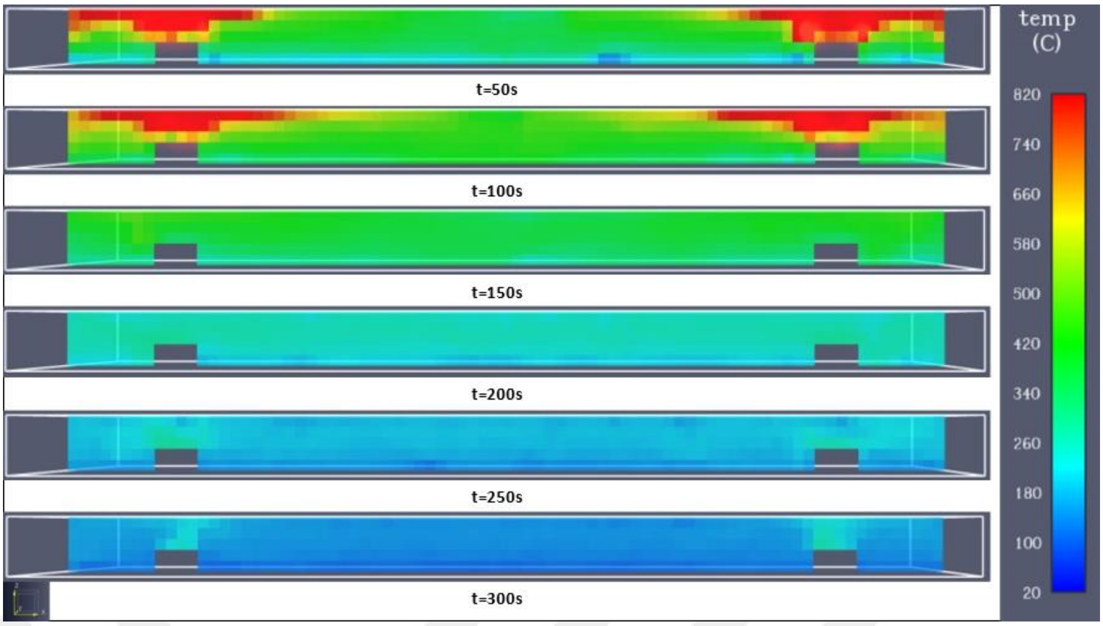

Figure 7.66 : Temperature distribution on y=11.5m at 50s, 100s, 150s, 200s, 250s and 300s.

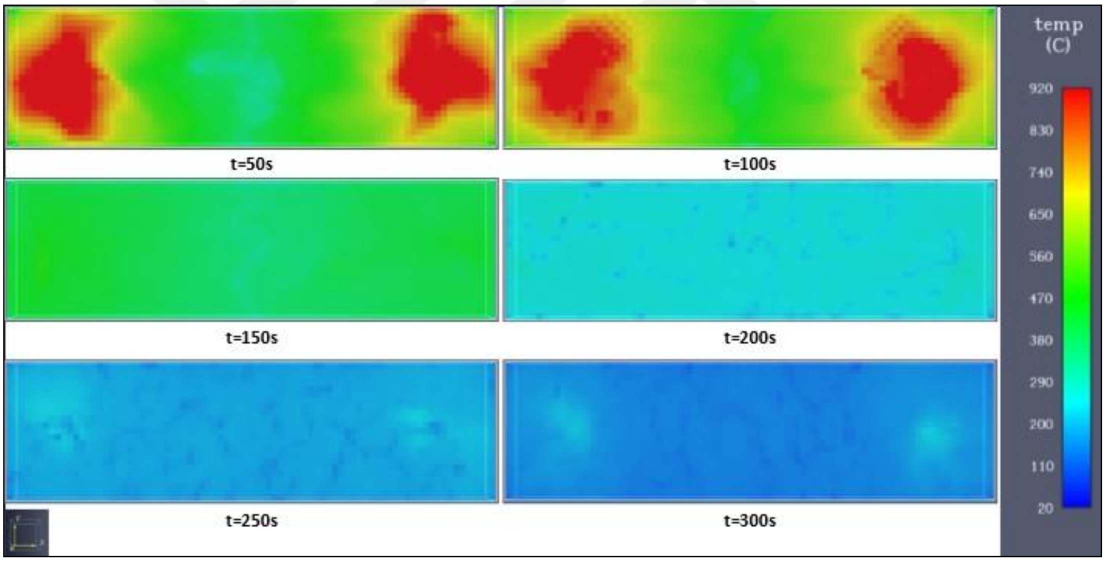

Figure 7.67 : Temperature distribution on z=4.5m at 50s, 100s, 150s, 200s, 250s and 300s.

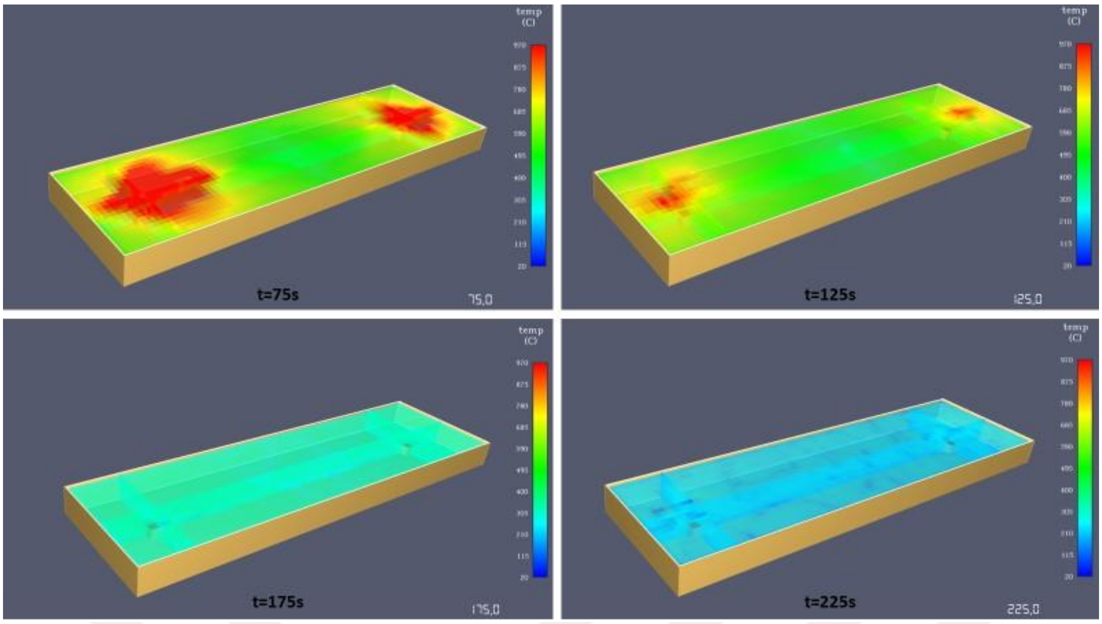

Figure 7.68 : Temperature distribution on 3D perspective view at time 75s, 125s, 175s and 225s.

In addition to the figures related to the temperature distribution, thermocouples are placed on different locations as a center of fire source, y, and z planes. There are 6 thermocouples on the fixed directions of x=10m and y=11.5m and derived by the z direction. From top to bottom direction, thermocouple 1 is placed on z=4.5m that is the top of the EVs space deck and other ones are arranged by 0.5m dimension successively. Figure 7.69 is depicted the location of the thermocouples in the EVs space.

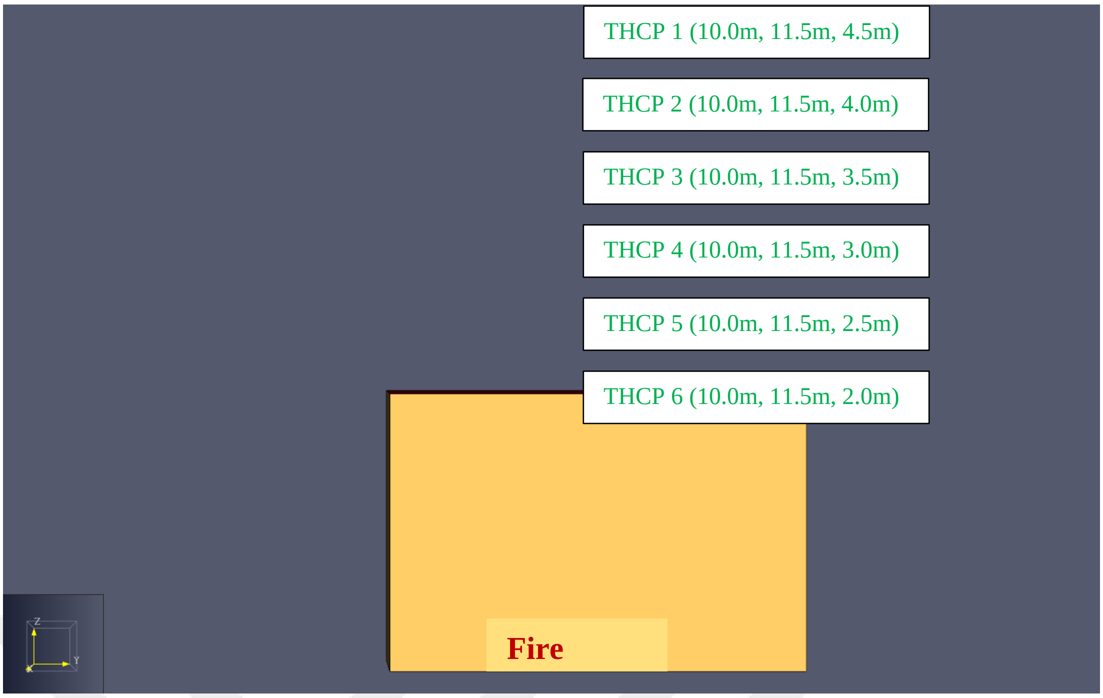

Figure 7.69 : Arrangement of thermocouples.

Temperatures on the thermocouples are given in Table 7.6. As reviewing the temperatures on the selected thermocouples, extremely increase in the initial time steps are realized. For each thermocouple reaches the maximum temperature levels on the time between 30s and 40s and after 50s the temperatures are decreasing step by step. Even though the value of the temperature is deriving from location to location, the characteristic of graph is mainly like all thermocouples. Also, the maximum temperatures and the average values reach around 1200 °C and 700 °C respectively.

Table 7.6 : Temperatures on the thermocouples.

	Temperature (°C)					
Time (s)	**THCP1**	**THCP2**	**THCP3**	**THCP4**	**THCP5**	**THCP6**
0.0	20.00	20.00	20.00	20.00	20.00	20.00
2.5	55.50	124.56	248.53	371.33	448.35	428.81
5.0	827.38	951.40	988.54	986.84	931.92	814.62
10.0	989.19	1026.85	1031.24	1020.27	936.27	823.27
20.0	1083.84	1083.67	1046.55	986.97	904.71	819.17
30.0	1126.80	1155.26	1148.79	1113.64	1053.46	963.59
40.0	1131.28	1182.13	1191.42	1169.16	1082.68	939.76
50.0	1086.06	1148.32	1180.33	1164.19	1094.51	973.85
100.0	917.61	943.53	940.91	914.16	846.28	767.28
150.0	903.83	856.74	835.24	797.39	645.97	408.01
200.0	794.06	687.63	598.86	461.81	392.11	345.73
250.0	287.22	292.13	295.30	297.19	295.84	300.27
300.0	216.61	226.27	230.74	234.73	243.66	283.96
Tmax	1186.72	1233.68	1217.59	1184.57	1098.82	998.97
Tmean	743.08	745.66	731.08	685.24	608.15	539.08

Temperature of gas in the control volume is another crucial parameter to investigate fire scenario for the EV spaces onboard ferries. The combustible material such as propane burners in this study is directly affected by the gas distribution and the temperature of it. Gas temperature distribution 3D view at different time steps such as 75s, 125s, 175s and 225s are depicted in Figure 7.70. Same as the temperature distribution, gas temperature also reaches 1200 °C early times. Then, the gas temperature decreases in each time step to approximately 500°C, 300 °C and 100 °C respectively in Figure 7.69. In summary, by understanding the dynamics of gas temperature, maritime engineers can develop effective fire safety measures to mitigate risks and ensure the safety of passengers, crew, and cargo in maritime environments.

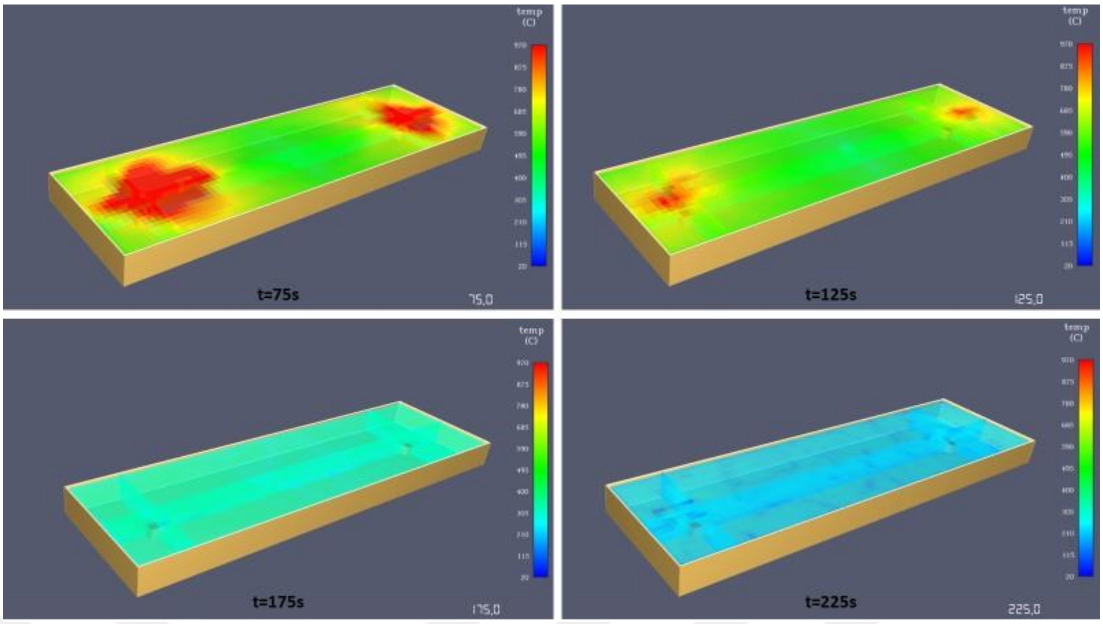

Figure 7.70 : Gas temperature distribution on 3D perspective view at time 75s, 125s, 175s and 225s.

In this case study, fire safety analysis of EV spaces onboard ships is examined using a fire dynamics simulation method known as the field model. By using performance-based design and fire dynamics simulation tools to predict the temperature level of the incident, this study brings novelty to the fire safety analysis of EV transport onboard ROPAX ship. Due to the fact that, the sales volume of EV is increasing significantly, transportation of EV is trend topic in terms of marine safety. Also, serious, and very serious fire incidents' rate among ships cannot be ignorable according to historical data. Crucial parameters in fire safety such as temperature, pressure, heat release rate and total energy are examined to reveal severity of the EV spaces onboard ships. Extra high temperature levels around 1200°C, especially in the early stage of the EV fire incidents, are the main output of this study. These temperatures in the transportation, accommodation or technical spaces inside the vessel cause severe results in terms of life and asset safety. Additionally, structural stability of vessels is mainly affected from the high temperature and structural and insulation products have to be resistant to the temperature level. Lastly, extinguishing, detection and evacuation topics should be designed depending on crucial temperature increase in the initial stage of fire incident. Fire dynamics simulations indicate that temperature reaches to the peak level in approximately 40s.

The rapid growth of the EV market in the world brings with the risk of major fire accidents during the transport of EVs by ships. In recent years, several ships have suffered major accidents as a result of fires during EV transport, most of them were total losses. Transportation of EV onboard ships need extra precautions in terms of fire unlike internal combustion engine-powered vehicles. As known, EV battery fires ignite quickly and intensively in the initial phase of fires. For this reason, it is necessary to prevent and intervene very strictly while the fire is still at the beginning. Finally, from the perspective of insurance companies, regulations should be specified for EV transported onboard ships to mitigate fire safety risks.

Incorporating these recommendations into this study efforts can contribute to the development of more robust fire safety measures for EV transportation onboard ships. By addressing these key areas, stakeholders mitigate fire safety risks and ensure the safety of passengers, crew, and assets in maritime environments. Additionally, implementing regulations specific to EV transportation onboard ships can further enhance safety standards and minimize the occurrence of fire incidents.

7.3 Risk Modelling Onboard Ro-Ro Passenger Ship

7.3.1 Background

In addition to fire dynamics simulations, fire risk modelling tools are implemented to the selected case studies. In previous chapters, fire risk modelling methods such as qualitative and quantitative risk analysis are detailed in fire safety analysis methodology sub-section. Depending on this literature review, quantitative risk analysis is selected to implement in case studies.

A fire risk model onboard passenger ships is a systematic approach used to assess and manage the risk of fire. It involves identifying potential fire hazards, evaluating the likelihood of fire occurrences, and determining the potential consequences. The goal is to enhance the safety of passengers, crew, and the ship itself.

Quantitative analysis of fire safety involves the use of mathematical, statistical, and computational methods to assess and improve fire safety onboard ships and other structures. This approach helps to identify risks, evaluate the effectiveness of fire safety measures, and optimize safety strategies. Key elements of quantitative fire safety analysis include:

- Fire Risk Assessment: Evaluating the likelihood and potential consequences of fire incidents. This involves identifying hazards, determining the probability of fire occurrences, and assessing the potential impact on people, property, and operations.

- Fire Modeling: Using mathematical models to simulate fire behavior and smoke movement within buildings. Fire modeling helps predict the development of fires, the spread of smoke, and the impact on building occupants.

- Evacuation Modeling: Analyzing the movement of people during fire emergencies. This includes modeling the evacuation process to ensure safe and timely evacuation from buildings.

- Performance-Based Design: Developing fire safety strategies based on performance objectives rather than prescriptive codes. This approach uses quantitative analysis to ensure that fire safety measures meet specific performance criteria.

- Statistical Analysis: Utilizing historical fire data to identify trends, common causes of fires, and the effectiveness of fire safety interventions. Statistical methods help in making data-driven decisions to enhance fire safety.

- Cost-Benefit Analysis: Assessing the economic efficiency of fire safety measures by comparing the costs of implementing safety features with the expected benefits in terms of reduced fire losses and improved safety.

- Uncertainty Analysis: Quantifying the uncertainty in fire safety assessments and modeling results. This involves using probabilistic methods to account for the variability and uncertainty in input data and model predictions.

- Optimization: Applying mathematical optimization techniques to find the best fire safety solutions under given constraints. This can involve optimizing the placement of fire detectors, designing efficient evacuation routes, or selecting cost-effective fire suppression systems.

The chain of events laying ground for the design of the event tree was based on the risk model developed in FIRESAFE II and constituted the following tiers (Leroux et al, 2018):

1. FIRE: Ignition/start of the fire.
2. Space type: The fire development, detection, and firefighting possibilities depend on the type of passenger ship spaces such as engine room (ER), open closed passenger spaces (CPS), open passenger spaces (OPS). Fire in a certain space was in the current study considered as a separate event.
3. Detection: The detection can either be 'early' or 'late'. Early detection refers to enough time to succeed with first response, e.g., with a handheld fire extinguisher before the conditions become untenable in the direct vicinity of the fire.
4. First response: Firefighting with a handheld extinguisher. Can be successful or unsuccessful.
5. Decision: The terms 'early' and 'late' are used to describe if the decision to activate a fixed extinguishing system is early enough to extinguish the fire or if only fire suppression is possible.
6. Extinguishment: Only possible following an early decision. Following a late decision, only suppression of the fire was assumed to be possible.
7. Containment: Fire and smoke spread can be avoided, allowing safe stay on board.
8. Evacuation: In case of failure of extinguishment and failure of containment, evacuation of the ship is necessary.

As in FIRESAFE II (Leroux et al, 2018), the terms 'early detection' and 'late detection' as well as 'early decision' and 'late decision' were included in the model. This was done to capture the dynamics of a fire, i.e., earlier detection and decision, the greater the likelihood of a successful response. The chain of events is given in Figure 7.71.

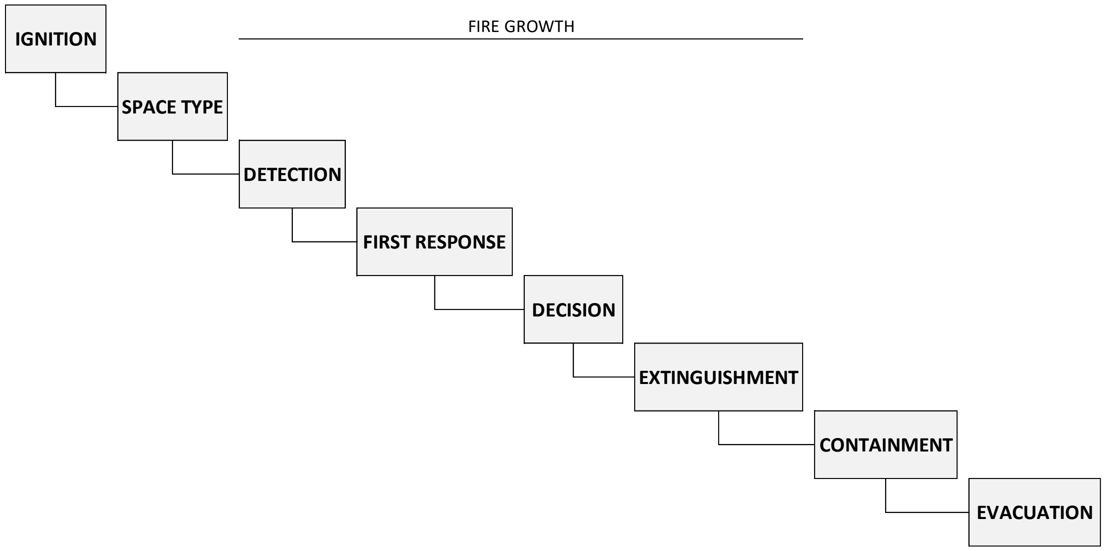

Figure 7.71 : Chain of events (Leroux et al, 2018).

7.3.2 Results

Event tree analysis (ETA) utilizes decision trees to graphically model the possible outcomes of an initiating event capable of producing an end event of interest. This type of analysis can provide (1) qualitative descriptions of potential problems (combinations of events producing various types of problems from initiating events) and (2) quantitative estimates of event frequencies or likelihoods, which assist in demonstrating the relative importance of various failure sequences (Henley and Kumamoto, 1996). ETA may be used to analyze almost any sequence of events but is most effectively used to address possible outcomes of initiating events for which multiple safeguards are in line as protective features.

As a case study of event tree analysis, passenger ships are selected to evaluate fire safety with event tree analysis method. Depending on Leroux *et al.* (2018), the main breakdown is the fire ignition location such as closed passenger spaces, open passenger spaces and weather deck. Figures 7.72, 7.73 and 7.74 show the event tree analysis of closed passenger spaces, open passenger spaces and weather deck respectively. In each scenario, 21 different scenarios are derived depending on detection, decision, suppression, containment and evacuation performances. Scenarios from A to U describe event analysis for each scenario. When the combination of these, total 63 scenarios are taken into consideration for a passenger ship that is selected as a case study.

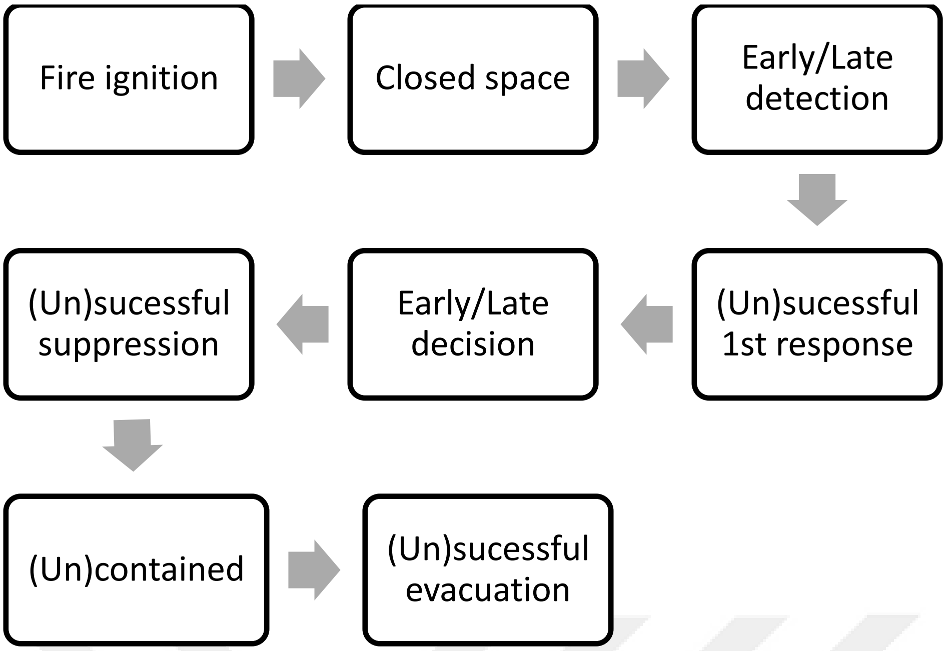

Figure 7.72 : Event tree analysis of closed passenger spaces.

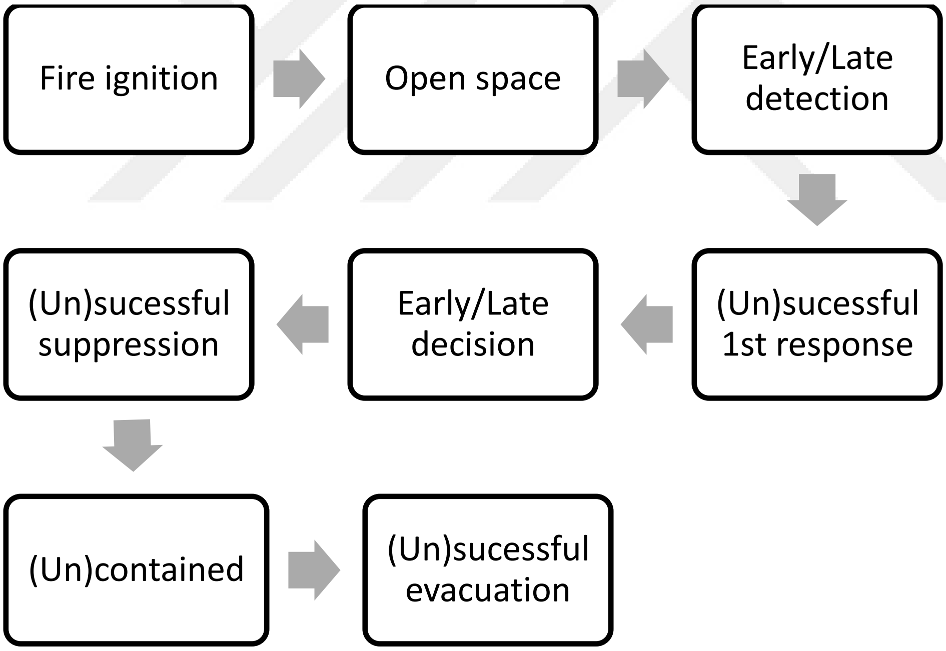

Figure 7.73 : Event tree analysis of open passenger spaces.

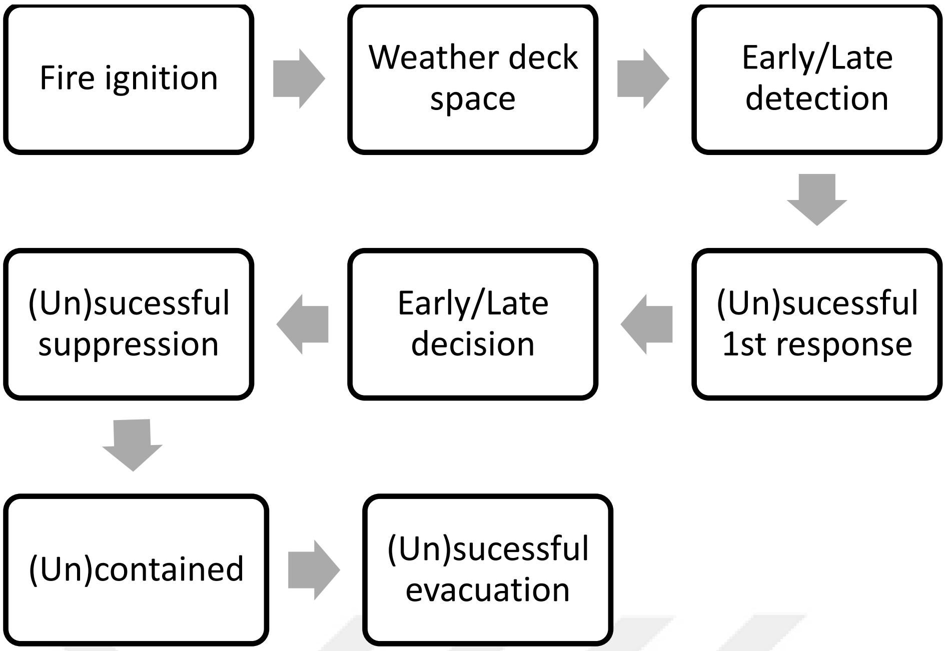

Figure 7.74 : Event tree analysis of weather deck.

As well as the event tree analysis, descriptions of the scenarios are given below:

- Scenario A: This scenario explains the successful early detection of fire in the original space and successful 1st response to the fire and finish the fire incident there. The path of scenario A is depicted in Figure 7.75.
- Scenario B: This scenario starts with early detection and the 1st unsuccessful response to the fire. Then the early decision is taken by the crew and successfully extinguished by the manual or automatic suppression systems in the fire origin space. The path of scenario B is depicted in Figure 7.76.
- Scenario C: This scenario starts with early detection and unsuccessful 1st response to the fire. Then the early decision is taken by the crew but unsuccessfully extinguishing. Finally, the fire is contained into the fire origin space by using successful structural fire protection actions such as compartmentation. The path of scenario C is depicted in Figure 7.77.
- Scenario D: This scenario starts with early detection and an unsuccessful 1st response to the fire. Then an early decision is taken by the crew but unsuccessfully extinguishing. After failure of the containment of fire in the fire origin spaces, evacuation is successfully done. The path of scenario D is depicted in Figure 7.78.

- Scenario E: This scenario starts with early detection and unsuccessful 1st response to the fire. Then an early decision is taken by the crew but unsuccessfully extinguishing. After failure on the containment of fire in the fire origin spaces, evacuation is unsuccess. The path of scenario E is depicted in Figure 7.79.

- Scenario F: This scenario starts with early detection and an unsuccessful 1st response to the fire. Then the crew takes the decision lately, but suppression works successfully. Finally, the fire is contained inside the space. The path of scenario F is depicted in Figure 7.80.

- Scenario G: This scenario starts with early detection and an unsuccessful 1st response to the fire. Then the crew takes the decision lately, but suppression works successfully. After the fire is not contained in the space that fire is ignited, evacuation is done successfully. The path of scenario G is depicted in Figure 7.81.

- Scenario H: This scenario starts with early detection and unsuccessful 1st response to the fire. Then the crew takes the decision lately, but suppression works successfully. After the fire is not contained into the space that fire is ignited, evacuation is done unsuccessfully. The path of scenario H is depicted in Figure 7.82.

- Scenario I: This scenario starts with early detection and unsuccessful 1st response to the fire. Then the crew takes the decision lately and suppression does not work successfully. Finally, fire is successfully contained. The path of scenario I is depicted in Figure 7.83.

- Scenario J: This scenario starts with early detection and unsuccessful 1st response to the fire. Then the crew takes the decision lately and suppression does not work successfully. After the fire is not contained in the space that fire is ignited, evacuation is done successfully. The path of scenario J is depicted in Figure 7.84.

- Scenario K: This scenario starts with early detection and unsuccessful 1st response to the fire. Then the crew takes the decision lately and suppression does not work successfully. After the fire is not contained into the space that fire is ignited, evacuation is not done successfully. The path of scenario K is depicted in Figure 7.85.

- Scenario L: This scenario starts with late detection and unsuccessful 1st response to the fire. Then the crew takes the decision early and the suppression is done successfully. The path of scenario L is depicted in Figure 7.86.
- Scenario M: This scenario starts with late detection and unsuccessful 1st response to the fire. Then the crew takes the decision early, but the suppression is not done successfully. Finally, the fire is contained in the fire origin space. The path of scenario M is depicted in Figure 7.87.
- Scenario N: This scenario starts with late detection and unsuccessful 1st response to the fire. Then the crew takes the decision early, but the suppression is not done successfully. Also, fire is not contained successfully but successful evacuation is done. The path of scenario N is depicted in Figure 7.88.
- Scenario O: This scenario starts with late detection and unsuccessful 1st response to the fire. Then the crew takes the decision early, but the suppression is not done successfully. Also, fire is not contained successfully, and unsuccessful evacuation is done. The path of scenario O is depicted in Figure 7.89.
- Scenario P: This scenario starts with late detection and unsuccessful 1st response to the fire. Then the crew takes the late decision, but the suppression is done successfully. Lastly, fire is contained successfully. The path of scenario P is depicted in Figure 7.90.
- Scenario Q: This scenario starts with late detection and unsuccessful 1st response to the fire. Then the crew takes the late decision, but the suppression is done successfully. Also, fire is not contained successfully. Lastly, successful evacuation is done. The path of scenario Q is depicted in Figure 7.91.
- Scenario R: This scenario starts with late detection and unsuccessful 1st response to the fire. Then the crew takes the late decision, but the suppression is done successfully. Lastly, fire is not contained successfully, and successful evacuation is not done. The path of scenario R is depicted in Figure 7.92.

- Scenario S: This scenario starts with late detection and unsuccessful 1st response to the fire. Then the crew takes the late decision, and the suppression is not done successfully. Lastly, fire is contained successfully. The path of scenario S is depicted in Figure 7.93.
- Scenario T: This scenario starts with late detection and an unsuccessful 1st response to the fire. Then the crew takes the late decision, and the suppression is not done successfully. Also, fire is not contained successfully but successful evacuation is done. The path of scenario T is depicted in Figure 7.94.
- Scenario U: This scenario starts with late detection and unsuccessful 1st response to the fire. Then the crew takes the late decision, and the suppression is not done successfully. Also, fire is not contained successfully, and successful evacuation is not done. The path of scenario U is depicted in Figure 7.95.

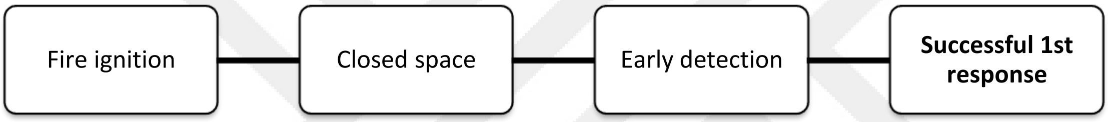

Figure 7.75 : Event tree analysis of Scenario A.

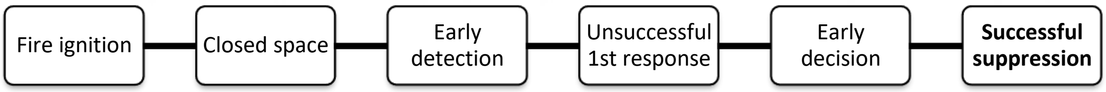

Figure 7.76 : Event tree analysis of Scenario B.

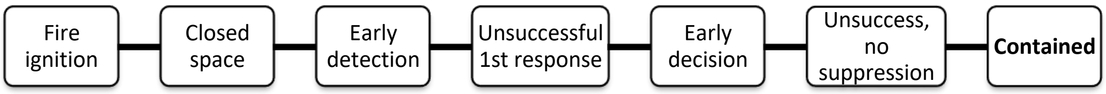

Figure 7.77 : Event tree analysis of Scenario C.

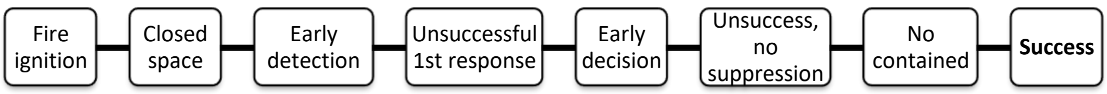

Figure 7.78 : Event tree analysis of Scenario D.

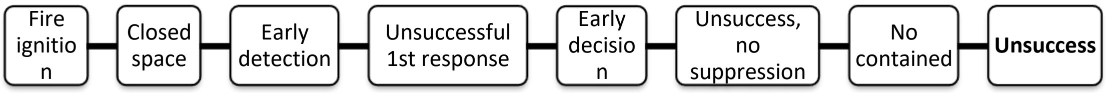

Figure 7.79 : Event tree analysis of Scenario E.

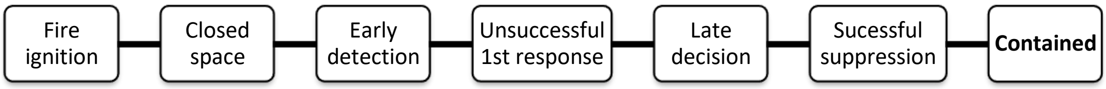

Figure 7.80 : Event tree analysis of Scenario F.

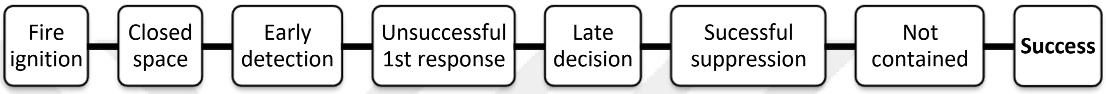

Figure 7.81 : Event tree analysis of Scenario G.

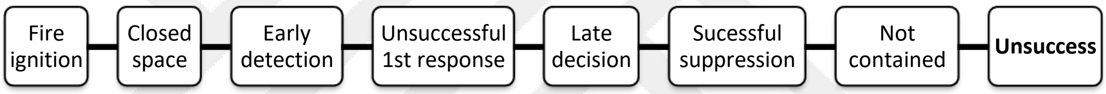

Figure 7.82 : Event tree analysis of Scenario H.

Figure 7.83 : Event tree analysis of Scenario I.

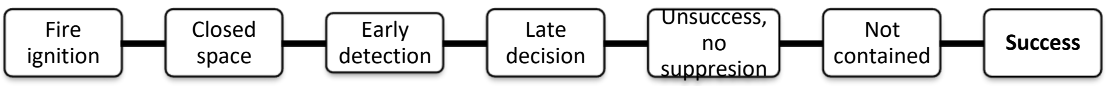

Figure 7.84 : Event tree analysis of Scenario J.

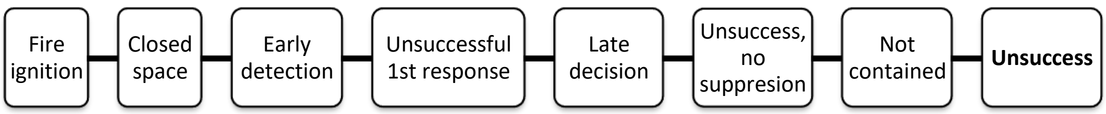

Figure 7.85 : Event tree analysis of Scenario K.

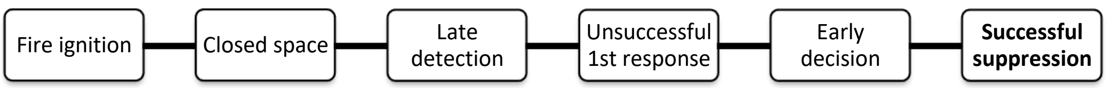

Figure 7.86 : Event tree analysis of Scenario L.

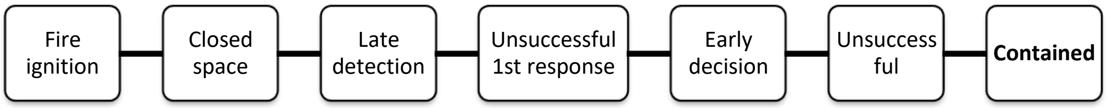

Figure 7.87 : Event tree analysis of Scenario M.

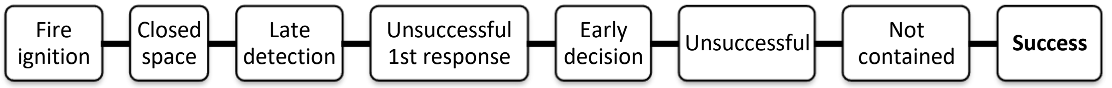

Figure 7.88 : Event tree analysis of Scenario N.

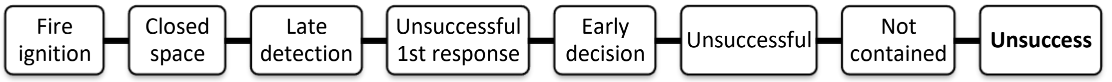

Figure 7.89 : Event tree analysis of Scenario O.

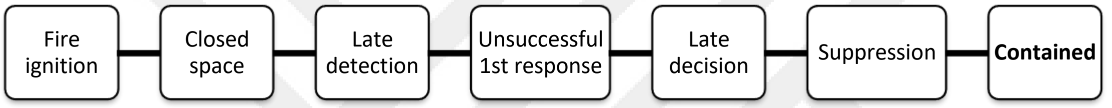

Figure 7.90 : Event tree analysis of Scenario P.

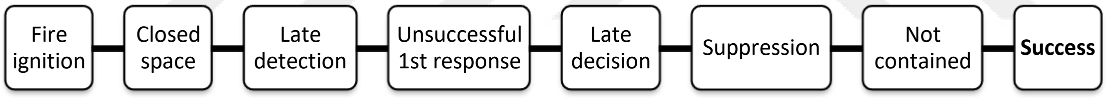

Figure 7.91 : Event tree analysis of Scenario Q.

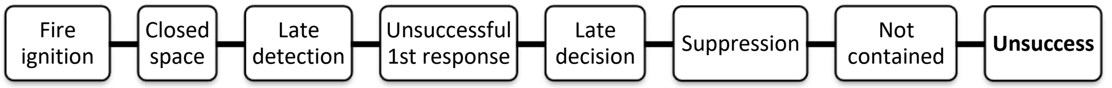

Figure 7.92 : Event tree analysis of Scenario R.

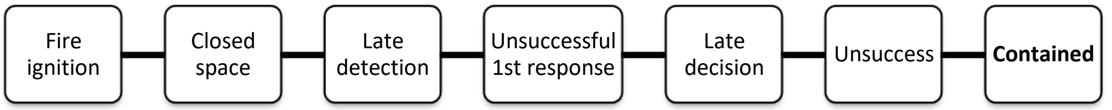

Figure 7.93 : Event tree analysis of Scenario S.

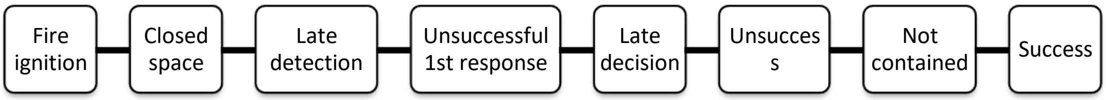

Figure 7.94 : Event tree analysis of Scenario T.

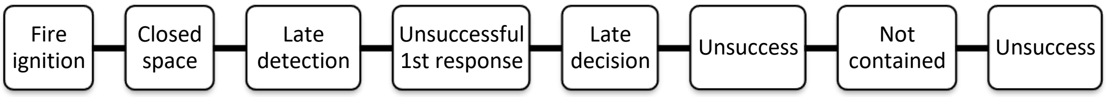

Figure 7.95 : Event tree analysis of Scenario U.

7.4 Discussions

In this thesis, three main cases are selected for fire modelling with Fire Dynamics Simulator FDS and fire risk assessment with Event Tree Analysis method. The first case study focuses on Istanbul's public maritime transportation company, Şehir Hatları. As an entity of the Istanbul Metropolitan Municipality, Şehir Hatları transports 40 million passengers annually. Among the 30 vessels in the fleet, the study selects the 600-passenger capacity vessel called SH-SUTLUCE based on their building year and fire protection systems. These vessels are the newest in the fleet and feature a wide range of fire protection systems, including fire-rated bulkheads and fire extinguishing systems. The second case study examines the fire safety of electric vehicle (EV) spaces onboard ROPAX passenger ships, prompted by the exponential growth in the production and transportation of EVs globally. The selected deck for transporting electric vehicles is analyzed using fire dynamics simulations. Lastly, Ro-Ro passenger ship is selected for fire risk assessment with event tree analysis.

Before selecting these case studies, fire incidents historical data sets are examined with the perspective of probabilistic approaches. Even though Ro-Ro/Ferry/Passenger ships are placed second among all types of ships with 16.7% of marine serious and very serious fire casualties globally from 2000 to 2022, the incidence ratio per 1,000 ships of Ro-Ro/Ferry/Passenger ships have the highest rate with 6.82 serious and very serious fire incidents per 1,000 Ro-Ro/Ferry/Passenger ships globally. Depending on this severe number of passenger ships give the direction to this thesis to analyze and evaluate fire safety onboard three types of passengers ships; passenger ferry, ROPAX and Ro-Ro passenger ships.

In this thesis, fatal fire incidents onboard passenger ships are selected and analyzed the investigation reports of these incidents called as Star Princess, Nordlys, Al Salam Boccaccio, Lindy Lou, Emerald Princess, Norman Atlantic, Insignia and Peejay V. After all severe fire incidents, codes and regulations have to be reviewed depending on the investigation reports. For example, in Star Princess fire proposed changes aimed to enhance balcony safety by mandating non-combustible materials for partitions, restricting combustible materials, and requiring the installation of fire detection and extinguishing systems for balcony furniture. Therefore, the reasons for the fatal fire improve the perspective of fire prevention systems and risk management studies. For instance, in Star Princess fire incident, the fire was only sparked by a discarded cigarette in the balcony and in Nordlys the fire occurred due to a diesel leakage igniting upon contact with an un-insulated indicator valve on the starboard main engine. After all investigation reports analyzed in detail, three cases are designed to fire dynamically. For instance, an engine room is the critical point for the fire incident depending on knowhow from Nordlys, then the origin place of fire selects as engine room for SH SUTLUCE case. In chapter 7, the simulation parameters and case study details are given in the previous sub-sections.

As well as the design of the structure, fire protection systems have to be taken into account while designing and operating passenger ships. In the case called SH SUTLUCE, both active and passive fire protection systems are simulating in the scenarios. Active fire protection systems called sprinklers are placed inside the engine room diverse by one, two and four nozzles. Also, passive fire protection systems called fire-rated bulkheads and decks are integrated into the simulations. As a result, these two protection systems complement each other for the fire safety onboard ships. In this case, scenarios including fire-rated bulkheads directly affect the temperature level of the other compartments. These are technical zones such as electrical, mechanical and air conditioning workshops. In the design phase of passenger ships, performance-based design of fire safety tools such as fire dynamics simulator have to be used as well as the minimum criteria of related regulations. On the other hand, training to increase fire safety awareness of crews plays a critical role in the operation stages. In interviews with stakeholders from ship owner companies and crews, these kinds of training and awareness activities support them for fire incidents. Fire risk assessment case takes a significant place to determine events during the fire onboard Ro-Ro passenger ships. Combining fire modelling and fire risk assessment methods in a passenger ship give a chance to establish a performance-based ship design in the design phase and a fire safety plan in the operation phase. Thus, an integrated fire safety and protection scenario can be created depending on the result of fire dynamics simulations and fire risk assessment analysis along the lifetime of passenger ships.

8. CONCLUSIONS AND RECOMMENDATIONS

This study emphasizes the critical importance of fire safety onboard ships, particularly passenger ships, given their high fire occurrence rate compared to other vessel types. Fire incidents at sea can result in significant loss of life and property, making it essential to explore and implement effective fire prevention and safety measures. The thesis focuses on fire safety regulations, fire dynamics simulations, fire protection systems, and risk management strategies, particularly onboard passenger vessels.

The study highlights the role of SOLAS (Safety of Life at Sea) and the International Fire Safety Systems (FSS) Code in establishing fire safety standards on ships. Despite these detailed regulations, fire safety remains a challenge, as shown by incidents reported globally, especially on passenger ships. This highlights a gap between regulations and real-world safety performance, reinforcing the need for ongoing improvements in fire prevention and response strategies. A statistical analysis of serious and very serious fire incidents between 2000 and 2022 via Global Integrated Shipping Information System (GISIS) by the International Maritime Organization (IMO) revealed that passenger ships have the highest fire occurrence rate. The fire occurrence rate per 1,000 vessels is 6.82 for passenger ships, this finding justifies the focus on passenger vessels in the study and points to a critical area for intervention in maritime fire safety practices.

In this study, three case studies from passenger ships are selected in order to evaluate fire safety practices.

- **Domestic Public Marine Transportation Passenger Ferry:** In this study, SH SUTLUCE passenger ferry from the fleet of Şehir Hatları that is a public marine transportation entity of Istanbul Municipality is analyzed using computational fluid dynamics simulations. This ferry has a 600-passenger capacity, 41.97m in length, 8.5m in beam and 2.8 in depth. This study examines fire safety in the engine room with 5 different scenarios called best, medium and worst depending on whether fire extinguishing sprinklers and fire-rated bulkheads or not. The simulations emphasize the importance of fire-resistant bulkheads and decks in containing fires and preventing structural collapse. Moreover, the study explores how the number of fire extinguishing nozzles affects the temperature and the speed of fire suppression. The optimal recommendation was two nozzles for maximum effectiveness.

- **ROPAX Passenger Ship with Electric Vehicles:** Due to the exponential growth of electric vehicles market in recent years, marine transportation of electric vehicles has crucial risks from the perspective of ship safety. Among the risks such as floating, grounding, structural failures or collisions, fire safety takes a significant place to be considered since EVs or charging stations led to fire incidents onboard ships. In this case study, one ROPAX passenger ship including electric vehicle spaces is selected to analyze fire safety using fire modelling. This vessel is 146m in length, 22m in beam, 14m in depth and has 800 passengers, 90 cars and 60 trucks capacity. Electric vehicle deck is selected for fire ignition in the fire dynamics simulations. The simulation reveals that fire temperatures could exceed 1200°C, requiring fire-resistant materials to protect critical areas and avoid catastrophic ignition or structural failure.
- **Ro-Ro Passenger Ship:** From the fire risk assessment approach, one generic Ro-Ro passenger ship is selected to assess fire risk by using Event Tree Analysis (ETA) from quantitative risk analysis methods. This method tracks the sequence of events from fire detection to evacuation, considering various scenarios to evaluate fire risk. The analysis shows the importance of fire detection, compartmentalization, user response, and evacuation procedures in minimizing the consequences of a fire on board.

All above case studies advocate performance-based fire safety design on passenger ships, which incorporates both fire dynamics simulations and fire risk assessment methods. By focusing on these models, ship design and operations can be optimized for better fire prevention and emergency response. This approach allows for better optimization of fire safety features, ensuring that ships are built with fire risks in mind, and that fire protection systems are tailored to the specific needs and characteristics of each vessel.

Both active (extinguishing systems) and passive (structural elements like fire-resistant bulkheads and decks) fire protection systems are essential for preventing the spread of fires and maintaining the integrity of the vessel. The study emphasizes that regular inspections and maintenance of these systems are necessary to ensure their proper functioning during an emergency.

Advanced fire dynamics simulations and fire risk assessment tools guide the design and operation of passenger vessels. These simulations provide invaluable insights into how fires spread and how they can be effectively controlled or contained in different scenarios, especially with emerging technologies such as electric vehicles.

The study highlights the importance of crew training in fire safety. The application of tools like Event Tree Analysis (ETA) can help simulate different fire scenarios, allowing the crew to prepare for various emergencies and improve their decision-making processes during a real incident. This training is crucial in ensuring a quick and coordinated response to fire outbreaks.

This study stresses the need for a holistic approach to fire safety that integrates fire dynamics simulations, risk assessments, regulatory frameworks, and crew preparedness. By addressing the vulnerabilities specific to passenger ships, especially those with electric vehicles, and by continuously evolving fire safety strategies to meet emerging challenges, the study offers valuable insights for improving maritime fire safety practices. This performance-based design approach not only enhances safety but also contributes to the development of more resilient and fire-safe passenger ships in the future.

For future research, the following ones are recommended:

- Performance-based fire safety analysis onboard passenger ships are a developing research area, and fire dynamics simulations can be applied to other ship types such as containers, fishing vessels or tankers.
- The inclusion of other compartments to the fire dynamics simulation, such as atriums, upper decks, galleries, etc., is suggested.
- The selection of different types of fire origin within the control volume can give more diversified results.

- Exploration of diverse sprinkler types and activation temperatures should be included in scenarios involving malfunctioning systems.
- Other fire risk assessment techniques or probabilistic methods can be integrated into the study.
- Smoke propagation can be added to the study, including the materials that led to the smoke in the control volume. For instance, antiskid coatings can be considered for smoke concentration and implicit evacuation.
- Fire safety evaluation of Sehir Hatlari's new investments Deniz Taxi.
- Event Tree Analysis method integration to a Domestic Passenger Ship company in Turkey.
- Establish the attained fire safety index using probabilistic approaches.

In addition to the above recommendations, human factor analysis can be added to the study for future research. The evacuation model and fire detection system design are affected directly by human factors. For the evacuation modeling, a simulation tool dedicated to the fire safety industry called PathFinder is advised to be integrated. In addition, performance-based fire safety analysis onboard passenger ships are a developing research area, and fire dynamics simulations can be applied to other ship types such as containers, fishing vessels or tankers. Lastly, smoke propagation can be added to the study, including the materials that led to the smoke in the control volume. For instance, antiskid coatings can be considered for smoke concentration and implicit evacuation.

The authors believe that undertaking these suggested investigations can yield valuable insights and contribute to the enhancement of fire safety measures on passenger ships.

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APPENDICES

APPENDIX A: Fire detection and control systems

APPENDIX B: Fire extinguishing systems

APPENDIX C: Fire resistance materials

APPENDIX D: Fire compartmentation

APPENDIX E: Fire and smoke control systems

APPENDIX F: Surface protection systems

APPENDIX G: Fire safety plans

APPENDIX H: Photographs of SH-SUTLUCE

APPENDIX A : Fire detection and control systems

Figure A.1 : Fire detection and control systems.

APPENDIX B : Fire extinguishing systems

Figure B.1 : Fire extinguishing systems.

Figure B.2 : Portable fire extinguishers.

APPENDIX C : Fire resistance materials

Figure C.1 : Fire reaction test and fire resistance materials.

APPENDIX D : Fire compartmentation

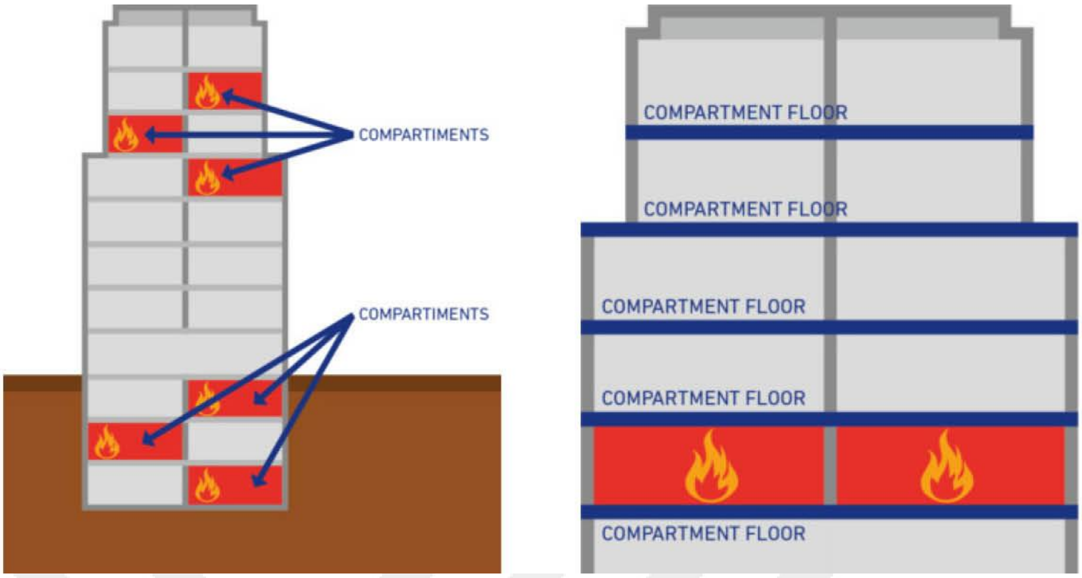

Figure D.1 : Fire compartmentations.

APPENDIX E : Fire and smoke control systems

Figure E.1 : Fire curtains and doors from control systems.

APPENDIX F : Surface protection systems

Figure F.1 : Surface protection coatings to the steel structure.

APPENDIX G : Fire safety plans

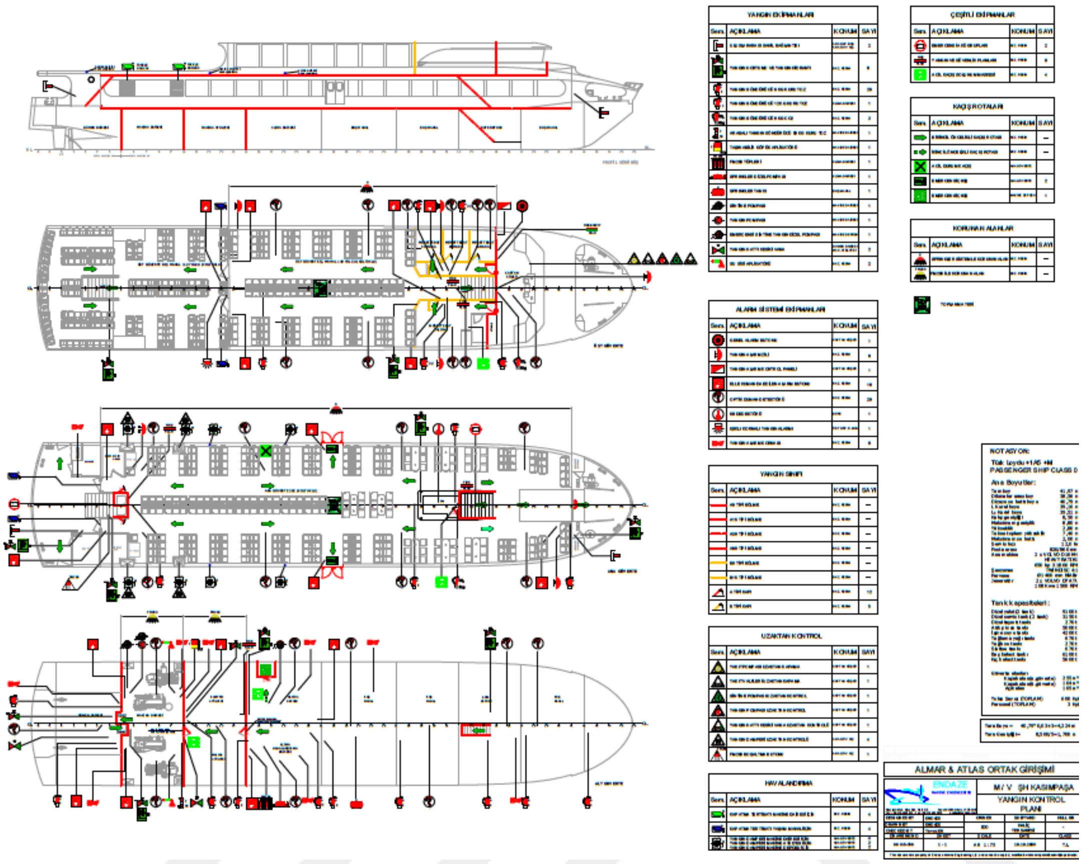

Figure G.1 : An example of fire safety plan drawings.

APPENDIX H : Photographs of SH-SUTLUCE

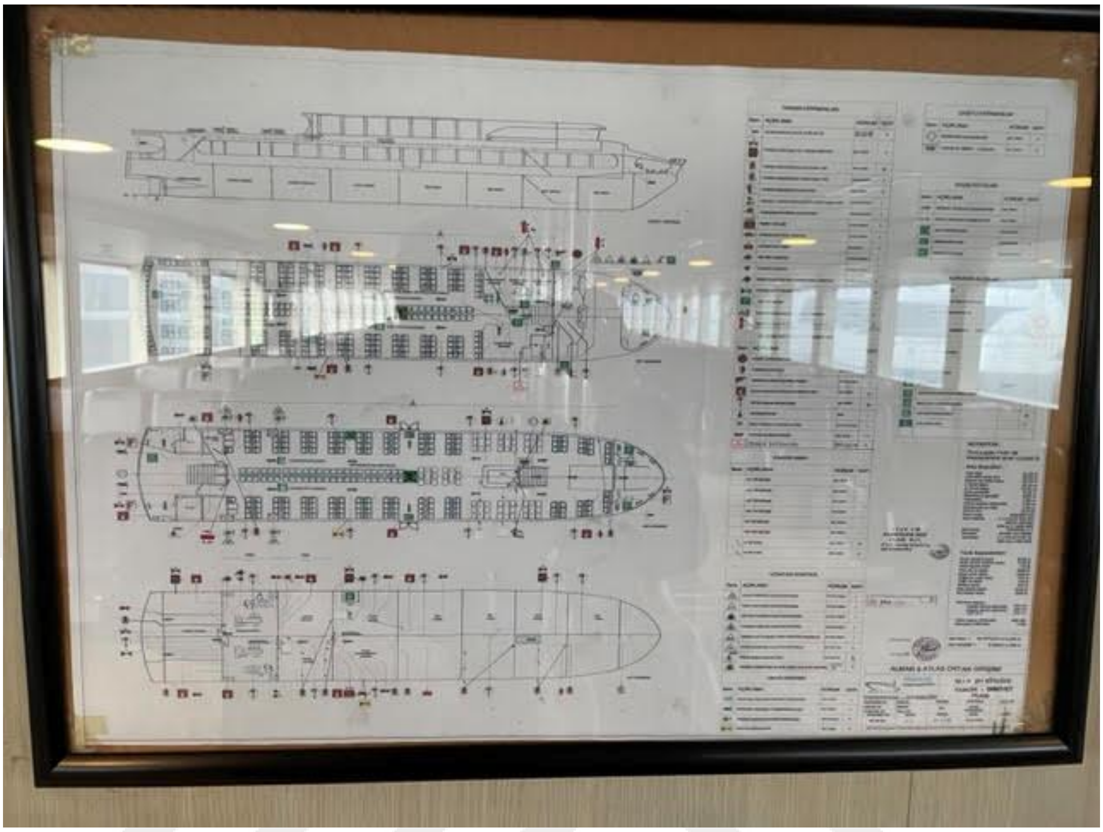

Figure H.1 : Fire safety plan drawing onboard SH-SUTLUCE ferry.

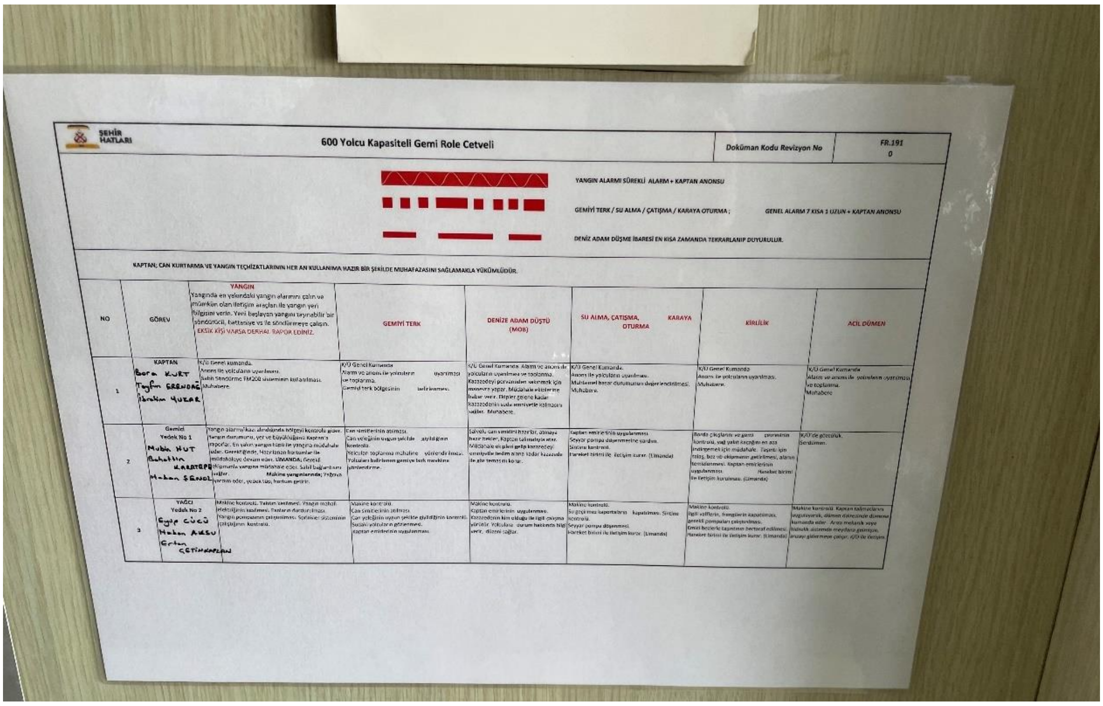

Figure H.2 : Muster list of SH-SUTLUCE.

Figure H.3 : Fire safety control panel of SH-SUTLUCE.

Figure H.4 : Control panel of SH-SUTLUCE.

Figure H.5 : Control panel of fire sprinklers and valves in SH-SUTLUCE.

Figure H.6 : Fire extinguishing system components in SH-SUTLUCE.

Figure H.7 : Passenger seats in the main deck of SH-SUTLUCE.

Figure H.8 : Passenger seats in the upper deck of SH-SUTLUCE.

Figure H.9 : Master cabin of SH-SUTLUCE.

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