PILOT PROJECT "CONTAIN" – Exploring the Challenges of Containership Fires

Dansk Brand- og sikringsteknisk Institut

Jernholmen 12, 2650 Hvidovre · Tlf.: 36 34 90 00 ·

Fax: 36 34 90 01 · E-mail: dbi@brandogsikring.dk · www.brandogsikring.dk

Authors
Thomas Hulin – Project Manager
Konrad Wilkens
Aqqalu Ruge
Carsten Møller
Darko Perovic
Nicklas S. Koch
Asgrimur Eiriksson
Alexander B. Kleiman

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Carsten Damgaard - DBI
Poul Bjerre Toftild - DBI
The Danish Maritime Fund

DBI – Danish Institute of Fire and Security Technology
Jernholmen 12, 2650 Hvidovre, Denmark
www.brandogsikring.dk, +45 36 34 90 00

Contents

1 Executive summary

Containership fires remain significant events since the 1990s. They are one of the most costly type of accidents and can sadly claim lives. Containership fires have been recognized by marine insurers as a problem worthy of attention, and recent catastrophic events such as the MSC FLAMINIA and MÆRSK HONAM have elevated the debate around the topic.

Fire safety on board ships is traditionally covered by IMO regulations and class notations. In light of recent containership fires, DBI believes that fire safety engineering could be of assistance in this debate, and that the problem of containership fires itself is not well-defined.

The present CONTAIN project was thus formulated to depict the problem as accurately as possible with focus on the cargo hold, and show how fire safety engineering can benefit the maritime world.
DBI has carried out the project using its own transdisciplinary approach to fire safety engineering, merging the perspectives of engineering and social sciences to integrate technical, human, and organizational aspects in the problem definition, feeding each other for input and scope. The projects explored human and organizational challenges, the perspective of The Blue Denmark, and technical aspects of containership fires.

Our work on human and organizational challenges involved a series of interviews with stakeholders and mapping work. Our exploration of the problem definition highlighted the main issue of uncertainty, about the problem, its solutions, and its ownership in this highly complex value chain. The problem is socio-technical in nature, so technology alone will not solve it. Human and especially organizational aspects must be included, and the solution will not be a simple "quick fix". But should the problem be solved, some stakeholders ask. On the technology side, safety requirements in regulations and class notations were not scaled with the increase in ship size. The industry lacks agreement on technology effectiveness, and believes in different strategies with respect to technology. It shows the lack of technical knowledge of the problem and possible solutions. Lastly, situation awareness on board is questioned, together with decision making in fire situations. This leads to questioning the option of firefighting, as well as the need for an evacuation threshold to ensure safety of the crew.

As a complement, our work on The Blue Denmark focused on the logistics chain, Denmark's role in container shipping, and the opportunities for Danish companies to contribute to the definition and solving of the containership fire problem. As risks accumulate along the logistics chain transporting containers, fire becomes a structural problem set in the value chain, not just a question of technology. Today, Denmark is the world's second largest container owner, with several large shipping companies sailing under Danish flag. As The Blue Denmark provides technological equipment and training for a major part of the world fleet, containership fires do affect the Danish container industry. Nevertheless, The Blue Denmark retains a strong worldwide position and reputation. The main discussions on technology concern detection, firefighting and extinction, communication and decision support, are each areas of strength in Denmark, which need to be comprehensively considered in the solution space once the problem definition reaches acceptable details. An obvious strategy is through collaboration between companies of varied fields of activities, involving ship owners, as the solution to the problem will not be unique and simple.

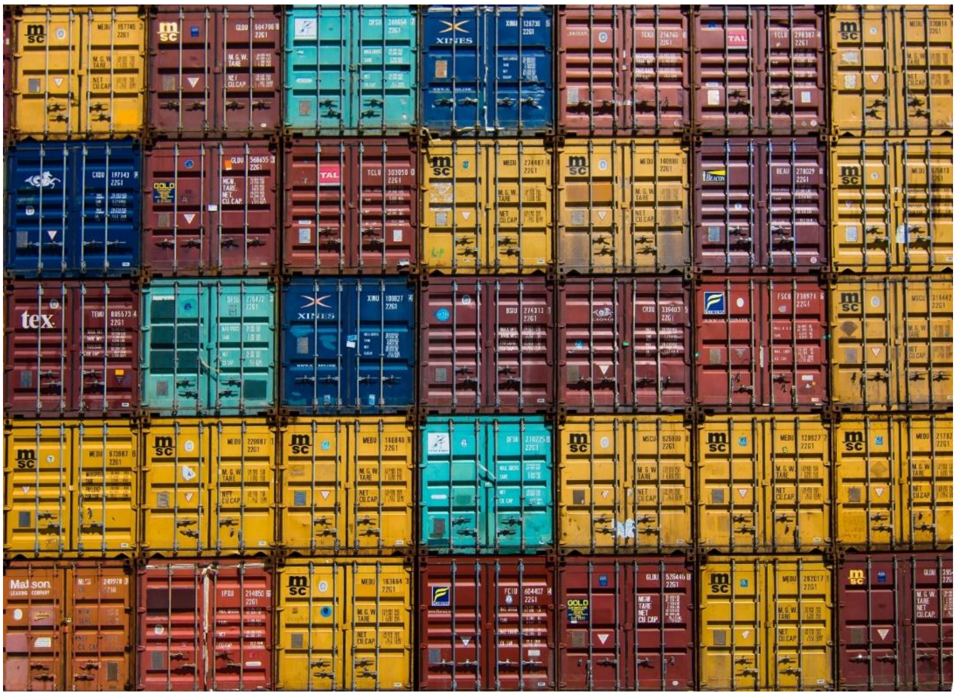
The engineering work proposed physical fire tests to verify fire spread hypotheses between containers. Our work showed that fire could spread vertically through ignition of the plywood floor, especially with new floors. The container door also promotes fire spread through radiation and combustion of the sealing material. Horizontal fire spread would be promoted through radiation via the walls of the containers. Beyond general understanding of the problem, this work served as input for numerical simulations of fires in cargo holds using Computational Fluid Dynamics. Our models reproduced both the behavior of a single container, and of a section of a cargo hold. The work on the single container showed that the three tested fire spread mechanisms may act in combination, and challenges previous findings that the fire chokes and does not propagate. Models at the cargo hold level, although preliminary, show the predominance of vertical spread, the sensitivity of detection on device location due to the stacking, and the influence of stacking on flame behavior, which seems to promote fire spread. The technical review highlights challenges related to the use of CO_2 in the cargo hold, and suggests important considerations for solution design.

In addition to the above summaries, we support the view that the problem of containership fires should be solved. We showed that the problem is socio-technical, and will require working on technical, social, and organizational levels to identify a solution. We would therefore argue that there is no easy solution, no "quick fix" to the problem.

This work proposes a first collection of insights into the problem of containership fires. We recommend to expand it along several lines. The understanding of the social and organizational contexts would benefit from additional interviews with stakeholders that could not be reach during the project period. Additionally, long-term participant observation would provide unparalleled insight on life on board, in turn relating to solution design. In a technical perspective, remaining fire spread mechanisms should be explored, as well as the combined effect of these mechanisms, through large or "real" scale testing. The simulation work primarily needs validation data, which in turns requires a comprehensive test program.

In relation to these lines for future work, DBI intends to investigate possibilities for follow-up projects. To this end, we would like to extend an invitation to all interested stakeholders to contact us for discussion of mutual interests, conflicting impressions, and potential collaboration, so that a solution could one day be found to the problem of containership fires.

2 Introduction to the CONTAIN project



2.1 Background and scope

The CONTAIN project ran from October 1st, 2019 until December 23rd, 2020. It was made possible thanks to the financial support of the Danish Maritime Fund.

The idea of the CONTAIN project originated in early 2019, after several catastrophic fires on board container ships[1,2]. These fires sometimes claimed lives. These fires often resulted in considerable financial losses, due to loss of cargo and the need for salvage operations, but also damage to the ships and subsequently reduced operations for the ship owners.

[1] Mærsk press release "Statement on the investigation of the tragic fire on the Mærsk Honam", October 20th, 2020 https://www.maersk.com/news/articles/2020/10/20/statement-maersk-honam, last accessed December 16th, 2020

[2] Burgoynes "MSC Flaminia – a brief account of an investigation", February 26th, 2019 https://www.burgoynes.com/articles/2019/02/msc-flaminia-a-brief-account-of-an-investigation, last accessed December 16th, 2020

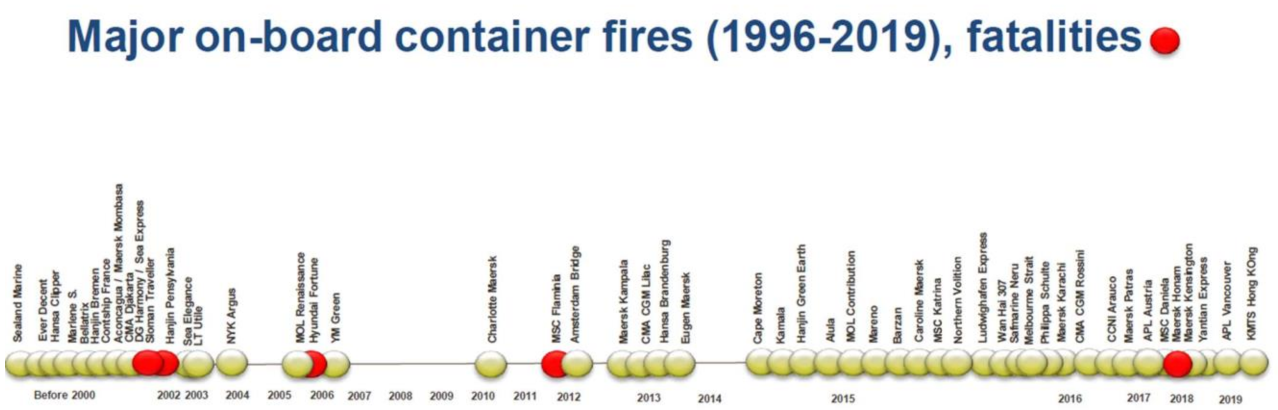


Figure 1

Source: - Presentation at Gard conference on containership fires, Arendal, Norway, 17-18 October 2019

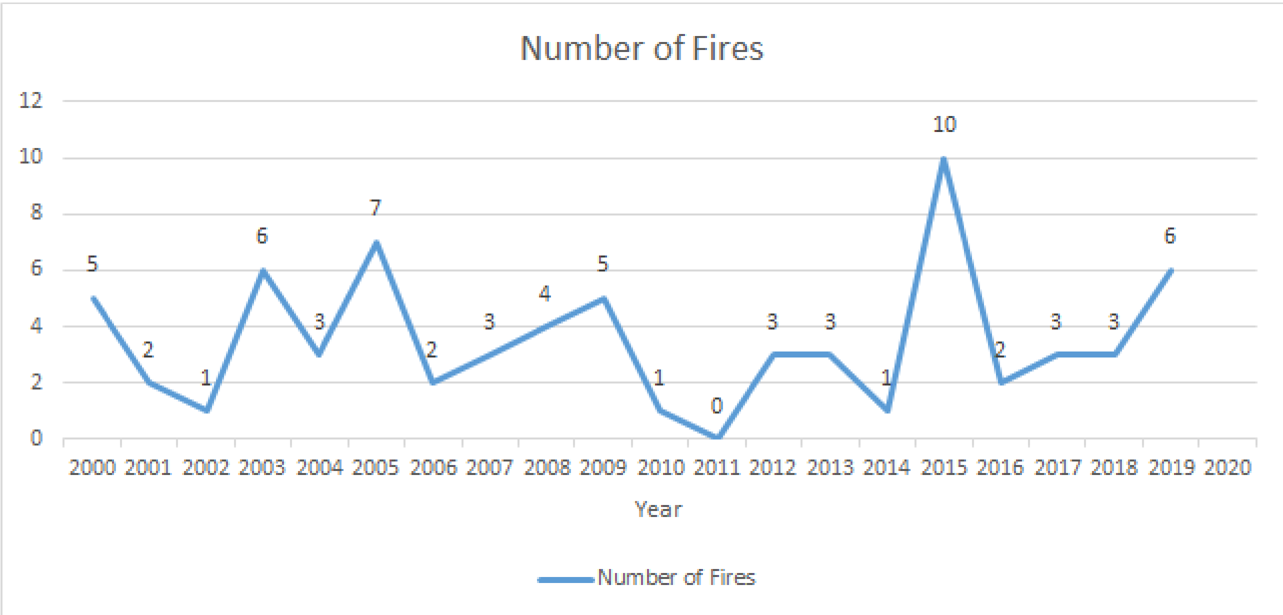


Figure 2

Data Source: Capt. Uwe-Peter Schieder, presentation at Gard conference on containership fires, Arendal, Norway, 17-18 Oct. 2019

At the time, the marine insurance world concluded that there is indeed a problem in this area, and that this problem deserves attention[3].

Many efforts from ship owners, ship designers, insurance companies, flag states, class societies, and the International Maritime Organization (IMO) were pursued, intending to help solving this strong issue.

These efforts have usually been solution-oriented, and much publicized. New notations were formulated by

[3] International Union of Marine Insurance press release "Containership fires: it is time to take action, says IUMI", October 18th, 2019 https://iumi.com/news/press-releases/containership-fires-it-is-time-to-take-action-says-iumi , last accessed December 16th, 2020

class societies[4], and new firefighting measures implemented on board (additional fire monitors on the weather deck, inclusion of new firefighting equipment to reach highly stacked containers)[5]. These efforts followed the traditional prescriptive system with a top-down approach, requiring compliance with rules formulated at higher levels. However, the decision basis for formulating these requirements does not appear rooted in evidence, or validated through a scientific approach. These requirements do serve the general idea that the stakeholders recognize the issue at hand and try to mitigate it; however, the concrete impact and efficiency of these requirements with respect to increasing safety remains unclear.

As a comparison, a single accident such as the Grenfell tower fire has shaken the prescriptive system in land-based fire safety engineering for building facades[6], sparking research efforts around the globe and leading the European Union to require and harmonize testing standards for such applications. It is true that the death toll of the Grenfell accident is outstanding compared to that of a containership fire. Nevertheless, the general attitude of the maritime world towards fire issues differs from that of the land-based world, as is exemplified by the need in Denmark to involve a fire safety engineer in any building project. In given projects, this engineer must be able to document that he/she is certified for the appropriate level of complexity required[7].

Another inspiring example comes from the fire on board CCNI ARAUCO[8]. This 9000 TEU caught fire in the port of Hamburg on September 1st, 2016. Efforts to control the fire required 150 firefighters, 4 fire engines, tugs and firefighting boats at work for 4 days. This event casts light on the possibilities to manage a fire event on even larger ships, far away from land-based resources, and highlights the difficulty of the task.

In the light of recent containership fire accidents, and of the attention given to them, DBI has formulated the hypothesis that fire safety engineering, in part inspired by the practice from the land-based environment, could be of assistance in the containership fire debate. DBI is a private, non-profit company operating in the field of fire safety, and covering all aspects of this broad issue. This includes material and structure testing, fire safety design for buildings and industrial facilities, fire inspection, fire investigation, fire safety training, and risk analysis. As a GTS institute (Approved Technological Service), DBI has a mission to assist Danish industry in solving challenges and bringing technologies to the market. In this perspective, our take on the problem of containership fires assumes a Danish angle, and explores possibilities for The Blue Denmark.

When we started defining the project, it appeared that much of the attention from academia and industry focused on the weather deck levels, but cargo holds received limited consideration. As a result, we decided to limit the scope of the CONTAIN project to study cargo holds specifically.

We therefore set out to look at containership fires in cargo holds. Soon after the beginning of the projects, we understood that the problem itself was neither well defined nor understood.

At early stages, it became clear that some points of consensus could be identified:

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[4] American Bureau of Shipping "Fire-fighting on containerships (FOC) – increased fire protection for container carriers", https://ww2.eagle.org/en/Products-and-Services/marine/containerships/foc.html, last accessed December 16th, 2020; and American Bureau of Shipping "Fighting fires on Containerships", brochure, last accessed December 16th, 2020.

[5] DNV GL Maritime News "DNV GL awards MSC new containership fire safety notation", February 25th, 2020 https://www.dnvgl.com/news/dnv-gl-awards-msc-new-container-ship-fire-safety-notation-168423, last accessed December 16th, 2020

[6] Mark Rice "Building regulations: The Grenfell Tower fire and its consequences", Timms Solicitors, January 2019 https://www.timms-law.com/building-regulations-the-grenfell-tower-fire-and-its-consequences/, last accessed December 16th, 2020

[7] Building Regulations 2018 (BR18) - Danish Building Act (Consolidated Act No. 1178 of 23 September 2016)

[8] Maritime Herald "Major fire on container ship CCNI Arauco in Hamburg", September 1st, 2016 https://www.maritimeherald.com/2016/major-fire-on-container-ship-ccni-arauco-in-hamburg/, last accessed December 16th, 2020

- The issue is of increased relevance
- The issue concerns the entire value chain
- Existing rules are not correlated to the reality of the situation and focus only on technical questions
- Incorrectly declared goods are here to stay – it is not possible to be certain about what is in the cargo
- Container ships are not designed for CO2 to work optimally
- When crew gets close to the fire, they get hurt
- Is safety taken over by financial concerns?

These points, though appearing broadly accepted, remain vague and subject to interpretation. A certain degree of description of the problem therefore exists, but it is not detailed enough to discuss technical solutions or amendments to existing rules, let alone new rules.

We wish to ask the question: Why talk about solutions without having defined the problem, let alone understood it?

2.2 Objectives

The CONTAIN project aims at gathering knowledge and painting a picture of the problem of containership fires as accurately as possible.

We defined two research questions to serve this aim:

- How is fire spreading from one container to the next?
- How are stakeholders seeing the problem?

The project intends to achieve the following objectives, focused on fire in the cargo holds:

- Increase the knowledge foundation and understanding of the issue of containership fires,
- Include a merged perspective between engineering considerations, life on board, and organizational challenges, including bringing the industry together in a workshop,
- Explore how fire safety engineering can benefit the maritime world,
- Propose insights for The Blue Denmark and its potential role relating to the problem.

2.3 Methodology

For several years now, DBI has been developing a risk-based methodology to analyze fire issues in more comprehensive ways, by integrating together the perspectives of engineering and social sciences into a transdisciplinary process[9].

Such events as fire events are not solely technical in nature, since people are always a part of the event, whether as skilled professionals or general public. In this respect, they influence the fire situation and the fire situation influences them, before the onset of the event and during the event itself. This is exemplified by the new sources of risk introduced by people (bringing combustible clothing with them, operating technology, being distracted...), their reaction times in the fire situation, the creative thinking displayed when managing the situation, or the relation to the equipment at hand.

Fires also take place within a given space, involving property and processes linked to organizations belonging to a certain field of operation, which in turn influence the fire. In the specific context of the CONTAIN project, this point relates to the value chain of shipping, the power relations at play, or the role of rules and

[9] Karsten MMV, Ruge AT, Hulin T, Closing the gap: Merging engineering and anthropology in holistic fire safety assessments in the maritime and offshore industries, Safety Science 122, 2020

regulations.

We at DBI believe that it is necessary to include the human factor perspective in the analysis of (potential) fire events to obtain applicable results. We have applied this methodology to maritime research projects[10][11] and commercial consultancy assignments.

As a result, the team working on the CONTAIN project consisted of engineers, fire scientists, anthropologists, firefighters, business developers, and maritime experts. Each of these professionals have their respective area of expertise and though we have all worked closely together, it seemed rather obvious that each of us should write the part of the report falling in our respective area of expertise. We have also acted as reviewers for each other. This methodological choice explains tone variations through the report. We believe it emphasizes the trans-disciplinarily concept and highlights the socio-technical nature of the containership fire issue in a more efficient way than the publication of separate reports.

The CONTAIN project is primarily about definition of the problem involving a large campaign of information gathering. The main methods used were literature review, fire testing, numerical modelling, semi-structured stakeholder interviews, and stakeholder mapping. In order to ensure trans-disciplinarily in an information-gathering project, the team members were meeting and discussing regularly to ensure that the respective findings from the various methods were used when seeking information using the other methods.

Two main elements relate to our research questions, namely containers themselves (“*the box*”), and containers included in the value chain of shipping (“*the concept*”).

The part on “*the box*” explores fire spread between containers by studying specific mechanisms through a fire testing program carried out in the laboratory at DBI, as described in Chapter 6 of this report. It also looks at the fire situation and its evolution inside the cargo hold through numerical modelling (see Section 6.7.1). A last point of interest is the existing technology for detection and suppression, as available today (see Section 6.8).

The part on “*the concept*” explores the perspectives that stakeholders have of the problem, according to their respective fields of operation (see Chapter 4). The intention is to highlight complexity and challenges, to later explore how the issue can be solved. “*The concept*” also looks at the role The Blue Denmark can play concerning the issue of containership fires (see Chapter 5).

2.4 Participation in conferences and external events

For the purpose and during the course of this project, DBI has attended the following conferences:

- ***Gard conference on containership fires*,** Arendal, Norway, 17-18 October 2019
- ***Salvage & Wreck Removal conference***, special day on Management and Prevention of Containership Fires, London, United Kingdom, 6 December 2019

DBI has presented the project at the following events:

[10] Danish Institute of Fire and Security Technology and OSK Shiptech “New fire strategies in the wake of Umoe Ventus – Concluding report”, https://brandogsikring.dk/files/Pdf/FogU/UMOE/New%20Fire%20Strategies%20in%20the%20Wake%20of%20UMOE%20VENTUS.pdf, last accessed December 16th, 2020

[11] Danish Institute of Fire and Security Technology and Danish Technological Institute “Project Blue Battery” https://brandogsikring.dk/en/research-and-development/maritime/blue-battery/, last accessed December 16th, 2020

- ***CEFOR Technical Forum***, Hamburg, Germany, 21 November 2019
- ***Salvage & Wreck Removal conference***, London, United Kingdom, 2-4 December 2020 (online)

DBI has submitted contributions to, or considers participation in, the following events:

- ***World Maritime Technology Conference*** (WMTC) **2022**, Copenhagen, Denmark, 26-28 April 2022
- ***Danish Society of Engineers (IDA)*** Maritime Group presentation in 2021

2.5 Limitations

The project is framed by a selection of limitations.

First, the available scientific and technical literature on the topic is limited. Few scientific publications covering the issue are available, which in turn supports the need to describe the problem more accurately. This lack of material also implies that test data are scarce, and much needs to be created. Similarly, numerical models for containers or cargo holds are few, and means of validation limited. This means that the present research effort should be considered as a feasibility study into how numerical models may be of service to the issues and industry as a whole.

Next, open-top or hatchless containerships are not included in the scope of this project. An "*Open-top containership*" means a containership that is especially designed so that one or more of the cargo holds need not be fitted with hatch covers. While similar to that of traditional vessel, the fire protection system for open-top container holds shall be based on the philosophy of containing the fire in the bay of origin and to cool adjacent areas to prevent structural damage. Open-top container holds shall be protected by a fixed water spray system, which shall be capable of spraying water into the cargo hold from deck level downward. The system shall be designed and arranged to take account of the specific hold and container configuration. [12]

The value chain of shipping is wide and complex. Ideally, the development of solutions should rest on an analysis in depth and in breadth of any issue, which could only be partially achieved with the resources of the project.

2.6 Disclaimer

The project was carried out during a challenging year. The COVID-19 pandemic affects many processes around the world and, unfortunately, has affected this project as well. As a result, the process was disturbed several times, many stakeholders were unavailable and some of their interviews will take place after completion of the project, in 2021.

[12] NSI - 608/Rev.1 Interim guidelines for open-top container ships - https://puc.overheid.nl/doc/PUC_2132_14/1/#20459

3 Technical Literature Review - Containership Fires –

CAUSES OF FIRES ON CONTAINERSHIPS AND A REVIEW OF PAST INCIDENTS

HYUNDAI FORTUNE was severely damaged in a 2006 fire in the Gulf of Aden. (Source: Wikimedia)

3.1 Introduction

This chapter presents an overview of the data found in the literature on the topic of containership fires. It is based on scientific literature, accident reports, industry reports, and maritime codes. Despite our belief and insistence on the need to work in a transdisciplinary manner with engineering and social sciences, as presented in Chapter 1, this literature review focuses mainly on technical topics since the issue lacks coverage from a social science perspective.

In 2019, it was estimated that 90 % of global trade is carried by international shipping. The International Cargo Handling Coordination Association has estimated that 6 million containers contain dangerous goods, and almost 1.3 million of these are either improperly packed or incorrectly identified[13].

The severity of recent blazes has made some shipping lines shy away from carrying particular kinds of hazardous goods. However, "*when a shipping line bans a particular cargo because of the cargo's history, shippers may misdeclare the cargo just to get it on board*" says Ian Lennard, of the non-profit National Cargo Bureau (NCB), a marine surveying organization that assists the US Coast Guard. In this way, dangerous materials make their way aboard illegally, and as a result are most likely to be stowed improperly—such as near other flammable cargo, or in vulnerable sections of the vessel.

The issue of containership fires is multifaceted. This review explores such themes as cargo fires, their causes and historical events, dangerous goods, on board response, and maritime regulations.

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[13] Safety and Shipping Review 2019 – An annual review of trends and developments in shipping losses and safety. Allianz Global Corporate and Specialty.

3.2 Main causes of cargo fire

Fires in cargo ships are commonly caused by self-heating of the certain transported goods.

3.2.1 Self-heating

Many marine cargo fires and explosions are due to self-heating in some form. In general, self-heating occurs when an exothermic (heat-producing) chemical or biochemical reaction happens within a body of cargo. The heat produced can only escape to the direct surroundings, i.e. cargo, packaging, dunnage, containers etc. Due to restricted heat loss, the temperature within the cargo tends to increase, which can ultimately lead to a fire in the cargo and surrounding materials.[14]

The most common and most hazardous types of cargoes prone to self-heating are: Bulk coal self-heating, bulk coal self-heating and emitting methane, bulk direct reduced iron, charcoal, metal powder or metal turnings, seed cake, reactive solids, calcium hypochlorite, biomass in bulk, fertilizers, batteries, and reactive liquid cargo.

Selected literature sources provide more details for each of the mentioned cargoes, including case studies for some of them[15].

A brief summary of each of the hazards is given here:

- Bulk coal self-heating
  Self-heating of coal depends on the reactivity of the particular coal (oxidation), starting temperature of the coal, and availability of oxygen. Coal that can self-heat produces carbon monoxide gas (CO); if coal oxidation develops to the point of problematic self-heating or burning, then some of the coal will decompose to produce flammable/explosive gas or vapor.

- Bulk coal self-heating and emitting methane
  In rare cases, coal cargoes can self-heat and emit methane at the same time. Methane is a flammable/explosive gas and so it can present an explosion risk in cargo holds.

  Methane-emitting coal therefore needs ventilation and the International Maritime Solid Bulk Cargoes (IMSBC) Code[16] advises adequate surface ventilation of holds if methane exceeds 20% LEL (As 100 % LEL is 5 % by volume this corresponds to roughly 1 % by volume in air). The Lower Explosive Limit, LEL is the lowest concentration of flammables that will burn in air.

  Bulk coal self-heating and emitting methane is especially problematic since the remedial actions for each occurrence are conflicting (excluding air/oxygen to tackle self-heating, vs. ventilation to reduce methane concentration).

[14] Swedish Club, with Niel Sanders from Burgoynes. *Fire ! A guide to the causes and prevention of cargo fires – Charcoal fire – case study 1*, November 30th, 2017. Available at: https://www.swedishclub.com/media_upload/files/Loss%20Prevention/Fire/TSC%20Fire%20Guide%20%28web%29.pdf, last accessed December 18th, 2020
[15] Paul Hockenos. Fire at Sea " *More than just bad luck is behind increasingly frequent and lethal container ship fires*. ", February 7th, 2019. Available at: https://www.hakaimagazine.com/news/fire-at-sea/, last accessed December 18th, 2020
[16] International Maritime Organization, International Maritime Solid Bulk Cargoes Code, 2020 Edition

- <u>Bulk direct reduced iron</u>
  Direct reduced iron (DRI) is made from iron ore through direct contact with a hot reducing gas. The resulting iron pellets are porous and can therefore be highly reactive with water, or oxygen in air, due to the large surface area present within the pores.

  Water ingress to holds, e.g. in heavy weather, can start problematic self-heating. Seawater tends to be more reactive than fresh water. When reacting with water, direct reduced iron releases hydrogen, which is a highly flammable/explosive gas that is colorless, odorless, easily ignited, and presents a serious explosion risk.

- <u>Charcoal</u>
  Charcoal is shipped for various uses, including shisha pipes (water bubble pipes) and for barbecues. Charcoal is porous and so it provides a large surface area for reaction with air/oxygen. Self-heating is therefore possible in charcoal. Some charcoal tablets for shisha pipes are not pure charcoal but contain impurities e.g. metal filings and hydrocarbon liquid, which may make them more likely to self-heat.

  It is prone to self-ignition if kept in large densely packed quantities at elevated ambient temperatures. This may produce a situation in which thermal runaway occurs. Thermal runaway is a condition in which more heat is generated inside the system than lost to the surroundings, causing elevated temperature inside the system and may lead to self-ignition of the charcoal.

- <u>Metal powder or metal turnings</u>
  Finely divided metals have a large surface area. If the surfaces have not previously oxidized, then they may react with oxygen in air or water, in a similar way to direct reduced iron. Oxidation with water can produce hydrogen and consequently a serious explosion risk. Other examples of this problem involve oxidation of metal by oxygen in air, which can lead to self-heating and sometimes ignition of the metal.

- <u>Seed cake</u>
  Seed cake is a residue left after extracting oil from plant seeds. Residual plant oil in seed cake can oxidize with oxygen in the air and the oxidation reaction evolves heat. Therefore, seed cake may self-heat, depending on factors such as the concentration of oil and the type of seed/oil involved. In addition, some plant oils are extracted using volatile, flammable/explosive solvents and residues of these solvents may remain in the seed cake. This can lead to the presence of solvent vapors in or around containers, or in bulk cargo holds, and consequently a risk of explosion.

- <u>Reactive solids</u>
  Cargoes that fall into this category include calcium hypochlorite (CHIO) and other oxidizing solids. They are often used for swimming pool sterilization and fabric treatment (bleaching or washing). These materials do not oxidize but they can be relatively unstable chemicals that decompose slowly over time, evolving oxygen. This self-decomposition can evolve heat, in turn leading to ‘thermal runaway’ increasing the speed of self-decomposition, and evolving heat and gases, sometimes including further oxygen. In a cargo hold, this sequence of events leads to effects similar to an explosion. The heat and oxygen produced can lead to fire spreading.
  Contaminants, higher than normal ambient temperatures, packaging sizes and moisture can all influence the stability of these products.

Of the discovered fire accidents, which initiated because of the decomposition of CHIO, resulted in major damage to the ship and containerized cargo. This strongly indicates to that CHIO is a high-consequence hazard with regard to the fire safety aboard container ships

- Biomass in bulk
  Biomass is shipped in bulk to provide fuel for ‘green’ power stations. Examples of biomass include wood chips and husks of oil seeds. These types of biomass do not contain significant amounts of oil, limiting the risk of self-heating from oxidation of oil. Nevertheless, biomass can naturally evolve carbon monoxide, even if it is not self-heating. This can lead to incorrect assumptions about whether there is a fire or self-heating in the biomass.

  Recent experience has shown that biomass can undergo a rotting process in which microbes (bacteria and mold) break it down. This can produce some heating, but the heating is not usually severe enough to cause fire. Microbial action can continue where oxygen concentrations are low, however, and that type of ‘anaerobic’ rotting can produce dangerous concentrations of methane. In some situations, rotting biomass has produced methane concentrations of about 40% by volume in the ullage space.

- Fertilizers
  Fertilizers, which are often shipped in bulk, may have some of the same characteristics as the aforementioned reactive solids. If some fertilizers become hot enough they may be able to decompose rapidly with evolution of heat and, often, toxic gases. Precautions for fertilizers include avoiding sources of heat, e.g. cargo lights and heated fuel tanks.

- Batteries
  There are several possible causes of rechargeable battery incidents including incorrect packaging, damage in transit (e.g. puncturing batteries), water ingress, and manufacturing defects. All of these issues can lead to short circuits and fire. Analyzing fire accidents resulting from lithium-ion batteries, the critical event identified as most likely to occur was a thermal runaway reaction. The causes of such event vary, but essentially, it occurs when the anode and cathode come in direct physical contact with each other. Besides those listed above, errors in design or assembly and insufficient packaging material can also be a cause of thermal runaway events. External heat sources also need to be considered. Lithium-ion batteries may vent with flame if heated and may require less external oxygen.

  Moreover, many rechargeable batteries naturally lose their charge slowly over time (‘self-discharge’). This means that self-heating can occur as the natural slow discharge releases electrical energy as heat. If that heat cannot dissipate fast enough, then batteries may become so hot that faults occur, such as failure of internal insulation. This can then spread rapidly to other batteries, leading to ignition and fire.

- Reactive liquid cargo
  Some chemicals are shipped as liquid monomers that have a tendency to polymerize. Polymerization means that the individual monomer molecules join together to make larger molecules. Polymerization often evolves heat. Inhibitors may be added to monomers, to stop or slow down polymerization.

  If the concentration of inhibitor or oxygen falls too much, the rate of polymerization may increase to a point at which heat is produced very quickly and the temperature becomes very high. This can cause boiling and release of flammable monomers and polymers via relief valves on a tank or tank container, which gives rise to an explosion risk.

Divinylbenzene (DVB)
A fault tree diagram is given in a 1999 Master thesis at the World Maritime University[21], analyzing all the potential scenarios that could lead to a fire caused by DVB. Explanation of failure modes of DVB are given in the section discussing the fire incident that occurred on board MSC FLAMINIA (refer section 3.4.3).

3.3 Other causes of cargo fires and explosions

Self-heating is one of the main common causes for fires on board containerships. It is however not the only one. The following list details other important causes.

- Cargo hold lights
  Many bulk carrier/general cargo holds have fixed cargo lights. These can easily ignite combustible cargoes such as grain, animal feed, wood chips, pulp and paper if they are too close to the light. Self-decomposition of fertilizer has been initiated in this manner. [17]

- Smoking and hot work
  Cigarettes and/or hot work can ignite many cargoes, including a wide range of bulk and general cargoes. Smoking and hot work therefore need to be properly controlled. Control of smoking can be difficult where stevedores are working. Hot work permits need to be properly considered, not just a 'tick box' exercise. Previous research by BMT [18] showed that in fact containers do not protect against sparks from hot works entering into the container itself.

- Vehicles and refrigeration units
  Cars and other vehicles carried on board ships present some risk of fire, as does the carriage of refrigeration units. There are a number of risks:
    - Cargo shifting in heavy weather can lead to ignition e.g. by rupturing gasoline tanks, damaging electrical cables and causing friction.
    - Vehicles being driven can lead to fire, if they are faulty. Working on vehicles to try to start them can lead to ignition, e.g. using petrol to top up tanks and using jump leads to start vehicles that have flat batteries. These risks are higher when dealing with used vehicles that may be in poor condition.
    - Electrical faults. Many vehicles have electrical circuits that remain energized even when the ignition is switched off. Electrical faults do not commonly cause fires in cars that are not being driven, but large numbers of cars are transported by ship and occasionally a fault can develop to cause ignition during shipment. Refrigeration units are also subject to electrical faults.

- Fumigation
  Agricultural products in bulk may be fumigated in cargo holds to prevent insect infestation. Solid aluminum phosphide (or similar) is often used for fumigation.

[17] Callesen, F. G. & Blinkenberg-thrane, M. Container ships Fire related risk. (2017)
[18] Container ship fires - Overview from a casualty investigator point of view. Jeroen de Haas, Gard Conference, Arendal 17 October 2019

Aluminum phosphide reacts with water vapor (humidity) in air to produce phosphine, a toxic and flammable/explosive gas, which kills insects. The reaction also produces heat. If there is an excessive amount of fumigant in one place, or if the fumigant is contacted by liquid water e.g. from sweating or condensation, then the fumigant can react quickly. This can evolve excessive heat and lead to ignition of cargo and/or packaging such as bags or paper placed over the top of the cargo. Under certain conditions, the fumigant gas itself may ignite, producing an explosion.

- Flammable liquid cargo
  Flammable liquid cargoes present risks of explosions in cargo tanks and other compartments. These explosions are often followed by fire.

3.4 Previous Fires Onboard Containerships

3.4.1 Overview

The authors conducted a fire scenario and hazard identification study to describe and understand the causes and development of fires.

3.4.2 Review of Container Ship Fires

Through the fire scenario study the authors in [19] were able to identify 39 container ship fires between 1996 - 2017. The summary is presented in Table 1.

[19] Callesen F.G, Blinkenberg-Thrane M, Taylor JR, Kozin I. Container ships: Fire-related risks. Journal of Marine Engineering and Technology 2019 DOI: 10.1080/20464177.2019.1571672

Table 1 - Major cargo container related fires aboard container ships from 1996 - 2017

Year	Ship(s)	Incident / cargo
1996	HANSA CLIPPER	Cargo fire (charcoal)
1996	MARLENE S.	Cargo fire (charcoal)
1997	BELLATRIX	Cargo fire (charcoal)
1997	CONTSHIP FRANCE	Cargo fire / explosion (calcium hypochlorite)
1998	ACONCAGUA	Cargo fire / explosion (calcium hypochlorite)
1998	DG HARMONY	Cargo fire / explosion (calcium hypochlorite). Total loss
1998	SEA-LAND MARINER	Cargo fire (pentane and isopentane)
1999	CMA DJAKARTA	Cargo fire / explosion (calcium hypochlorite)
2002	HANJIN PENSYLVANIA	Cargo fire /explosion (calcium hypochlorite)
2003	SEA ELEGANCE	Cargo fire /explosion (calcium hypochlorite)
2004	NYK ARGUS	Cargo fire (hot stow)
2004	CSAV ITAJAI	Cargo fire / Thiourea Dioxide
2005	CMV PUNJAB SENATOR	Cargo fire (NiMH Rechargeable Batteries)
2006	HYUNDAI FORTUNE	Cargo fire /explosion (petroleum based cleaning fluid)
2006	YM GREEN	Cargo fire /explosion (unknown)
2009	MOL PROSPERITY	Cargo fire /fire (unknown)
2010	CHARLOTTE MAERSK	Cargo fire (methyl ethyl ketone)
2012	MSC FLAMINIA	Cargo fire / explosion. Loss of life (divinylbenzene)
2012	AMSTERDAM BRIDGE	Cargo fire (calcium hypochlorite)
2013	MAERSK KAMPALA	Cargo fire (unknown)
2013	CMA CGM LILAC	Cargo fire (unknown)
2013	HANSA BRANDENBURG	Cargo fire (calcium hypochlorite)
2013	EUGEN MAERSK	Cargo fire (textiles)
2014	NOTHERN GUARD	Cargo fire (calcium hypochlorite)
2014	HANJIN ATHENS	Cargo fire (calcium hypochlorite)
2015	CAROLINE MAERSK	Cargo fire (charcoal)
2015	MAERSK LONDRINA	Cargo fire (calcium hypochlorite)
2015	CAPE MORETON	Cargo fire (sodium hydroxide)
2015	KAMALA	Cargo fire (unknown)
2015	HANJIN GREEN EARTH	Cargo fire (calcium hypochlorite)
2015	ALULA	Cargo fire (cardboard bales)
2015	MARENO	Cargo fire (charcoal)
2015	BARZAN	Cargo fire (unknown)
2015	PURPLE BEACH	Cargo fire (fertilizer)
2015	MSC KATRINA	Cargo fire (charcoal)
2015	MAERSK SEOUL	Cargo fire (calcium hypochlorite)
2016	LUDWIGSHAFEN EXPRESS	Cargo fire (charcoal)
2016	CMA CGM ROSSINI	Cargo fire (lithium-ion batteries)
2017	MSC DANIELA	Cargo fire (unknown)

The findings from the hazard identification study led the authors to conclude, calcium hypochlorite, compressed charcoal briquette products, rechargeable batteries and divinylbenzene, to constitute the main hazards to the cargo related fire safety aboard container ships.

From the consequence part of the study it was possible to discover an event line from the initiation process of a critical fire event to the final event, for all of the identified hazards and the development process of the fires during these chains of events.

3.4.3 Analysis of several fire incidents on board containerships

This section proposes a more detailed overview of the causes for selected containership fires.

2003 - mv SEA ELEGANCE - Calcium hypochlorite

Cause of the fire:

The fire supposedly originated from a container stored below deck containing 20 t of calcium hypochlorite, UN 1748. The cargo had been stored below deck, as it had not been declared as dangerous good. Remaining containers in the cargo hold carried plastic, rubber and paper goods.

Ambient temperature in cargo hold and the container itself was 35 °C on average, but the container had been placed up against the HFO storage tanks, which provided a source of heat. As calcium hypochlorite becomes unstable at temperatures exceeding 35 °C when carried in such quantities, experts agreed that it was the cause of the explosion and subsequent fire.

2012 - MSC FLAMINIA – Divinylbenzene

Cause of the fire:

In this case, 149 out of 2879 containers were carrying dangerous goods, which could all be fire sources. The Fire Investigations concluded that the fire had been caused by divinylbenzene (DVB). DVB is a monomer used in polymerization reactions, which may polymerize and produce heat. The reaction is accelerated with increasing temperature and may cause a thermal runaway reaction.

The potential causes of such an event have been established as external heating, contamination and limited amounts of available tertiary-butyl-catechol (TBC), the polymerization inhibitor used for stabilizing the product. TBC relies on available oxygen to limit the amount of DVB polymerizing spontaneously. The depletion rate of TBC increases with temperature, i.e. higher than normal ambient temperatures cause TBC to deplete quicker.

Considering this, a series of trajectories lead to the critical event, i.e. polymerization of DVB. These include polymerization of DVB due to external heat sources, unfortunate batch with insufficient TBC and/or oxygen and contaminants.

Low inhibitor levels may occur if the product has not been stored properly or improper quality control at the producer causing a bad batch to leave the factory. As TBC relies on available oxygen to inhibit polymerization, if aeration has not been performed prior to shipment the TBC will be rendered useless.

Lastly, the possibility of contaminants is considered. As DVB is transported in tank containers, entry of contaminant into the cargo while it is in transit seems unlikely. However, if DVB were to be contaminated by catalysts, acids or oxidizers this could cause the DVB to polymerize violently.

2015 - CAROLINE MAERSK – Charcoal

Cause of the fire:

The cargo that initiated the container fire on CAROLINE MAERSK was later identified as shisha charcoal. The cause of ignition was allegedly due to self-heating of the charcoal.

The container manifest provided by the shipper of the cargo, described the content of the container as "tablet for water pipe". However, the cargo had not been declared as dangerous goods, even though the IMDG code states that charcoal is a Class 4.2 cargo, which covers substances liable to spontaneous combustion.

2016 - CMA CGM ROSSINI - Lithium-ion batteries

Cause of the fire:

It was established that the fire originated from one of two containers carrying lithium-ion batteries destined for recycling. As the ambient temperatures were about 32°C, it was assumed that this was not the cause of the fire. Alternative causes were considered, the most likely being a short-circuit of the positive and negative terminal of a battery. This would have caused a runaway reaction and subsequent igniting of the battery.

However, the batteries had prior to shipping received individual pieces of polyethylene adhesive tape covering the terminals to mitigate this issue. Whether the tape failed or was not there in the first place could not be established, as any evidence had been lost in the fire. The shipper proposed that rough handling of the shipment might have been a factor in causing this. The French marine investigation office BEAmer (Bureau d'enquêtes sur les événements de mer) points out that such cargo should preferably be packed with sand in between the layers of batteries, to act as an electrically insulating layer.

2018 – MÆRSK HONAM – probably Sodium Dichloroisocyanurate Dihydrater (SDID)

Cause of the fire:

As most of the evidence was destroyed by fire, the investigation team was not able to conclusively determine the cause of the fire.

However, there was evidence that the integrity of Sodium Dichloroisocyanurate Dihydrater (SDID) in No.3 cargo hold had been compromised such as the chlorine-smell smoke, the irritating and uncomfortable feeling, including breathlessness experienced by the crew at the onset of the event. The heat generated by spontaneous self-decomposition of the SDID worsened, as it was carried in block stowage.

Apart from looking at the cause of the fire, the investigation also questions the appropriateness of emergency responses of the crew, the emergency response plan and the design of the fire containment and firefighting equipment on board the ship.

Despite the good efforts demonstrated by the crew in taking care of each other and saving lives during the emergency, it was noted that the fire alarm was not raised at the onset of the event causing a delay in the closure of the magnetic fire doors of the accommodation, and non-closure of exterior ventilation vents. These had resulted in toxic smoke entering and spreading within the accommodation areas.

The Muster List did not clearly identify the roles of everyone on board, which resulted in some of the crew waiting to be given instructions. The investigation also revealed that the firefighting flow charts under the ship emergency response plan did not ensure that all the ventilator flaps/ dampers on board were closed as one of the primary firefighting actions, regardless of the location of fire. The investigation team also noted that due to the intense heat and smoke all ventilator flaps on the sides of No.3 cargo hold hatch covers had proven to be challenging to close.

In addition, the investigation revealed that the secondary hazards of chemical decomposition/ instability of SDID had not been identified in the IMDG Code. This is because SDID was classified under Class 9 in the IMDG Code, instead of the more stringent Class 5.1 (oxidizing substances), despite having similar chemical properties as those in Class 5.1.

2019 – KMTC Hong Kong - Calcium hypochlorite
Origin and cause of the fire:
The fire broke out on board the ship while berthed at Thailand's eastern Laem Chabang port. The cause of the fire was due to improperly declared chemical cargoes of calcium hypochlorite and chlorinated paraffin wax.

3.5 Maritime fire and explosion accidents – analysis and statistics

This section proposes an analysis of fire and explosion accidents for various types of ships, including cargo ships.

3.5.1 Causal Analysis

A paper titled "*Analysis of Maritime Fire and Explosion Accidents*" was published by University of Lisboa[20]. The aim of the paper was the analysis of accidents involving fires and explosions in ships. To achieve this goal, 20 accident investigation reports classified as fire and explosion are collected from which detailed information related to the accidental events is obtained. The accidental events are coded using CASMET (Casualty Analysis Methodology for Maritime Operations) methodology and a detailed analysis of the results of the codification process is conducted.

From the 20 accidents selected, a total of 138 accidental events are identified and coded according to the CASMET taxonomy that addresses adequately the contribution of the human and organizational factors to the accidents. The sample of accidents under analysis consists of 18 cases of fires and 2 fires and explosions, in 6 fishing vessels, 1 container, 5 general cargo vessels, 2 passenger ships and 6 Ro-Ro vessels.

The results obtained show that human error is the leading cause of accidental events (57.2% of the cases). Besides human factors, no-detection of technical failures is the main cause of accidents. Another accidental event with lower incidence than human error, but still relevant, is equipment failure (32.6%), the fire-fighting system being the most frequent one and the engine room the most likely location.
The author gathered the 75 coded casual factors by causal groups. She found that the types of causal factors with higher incidence in the coded accidents are lack of knowledge (44%), inadequate operation and emergency procedures (40.0 %) and fire-fighting equipment (30.7%).

3.5.2 Statistics

The statistics presented here focus on cargo damage, which are covered by P&I (Protection and Indemnity) insurance, and include incidents on bulk carriers, container vessels, dry cargo, and Ro-Ro vessels. All these claims are after the deductible and have generated a claims cost of USD 5,000 or above. Looking at the statistics from P&I cargo claims in the period 2007-2016 it can be concluded that fire related claims account only for 0.76% of all the claims. Even though they are among the least common incidents to happen, they are the leader when it comes to cost of cargo claims, accounting for 28% of total costs for all cargo claims.

Figure 3. presents an overview of the most common causes of fires on board cargo ships, demonstrating that calcium hypochlorite, charcoal, and batteries are responsible for most of the fire accidents on board these ships.

[20] Raquel, S. Analysis of Maritime Fire and Explosion Accidents. (2015)

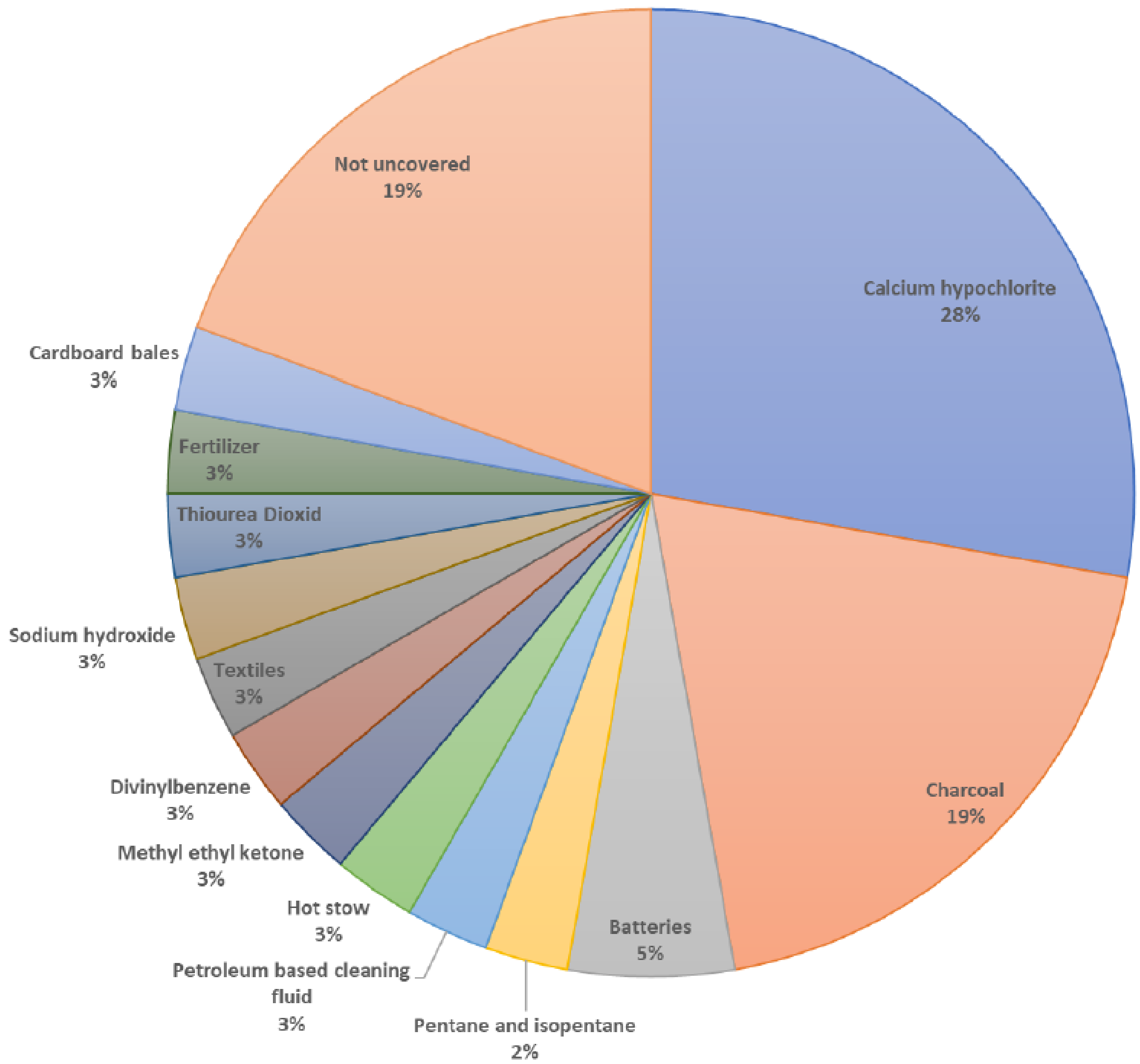

Figure 3 - Causes of fires on board cargo ships in %

3.5.3 Hazards

Four cause-consequence studies were conducted in order to analyze the risks associated with the containerized shipment of the cargoes which were identified as the main hazards to fire safety aboard containerships; calcium hypochlorite, charcoal, rechargeable batteries, and divinylbenzene.[21] The study allowed the authors to investigate the occurrence of critical events by analyzing potential causes for the realization of such events combined with the consequence chains arising from these hazardous events.

3.5.4 Frequency of fire accidents on board containerships

The frequency assessment period covers the time span 2011–2016, both years included. The major cargo fires occur between 4.56 and 9.94 times per 10,000 ship years. Such frequencies can be used in determining the justifiable investment or performing a risk evaluation towards the ALARP-principle (As Low As Reasonably Practicable) of risk acceptance. (A calculation of justifiable investment in preventing fires is presented in [20].) There are however organizational difficulties – primarily the questions of who should pay and the question of how the cargo types could be registered.

[21] Callesen, F. G. & Blinkenberg-thrane, M. Container ships Fire related risk. (2017)

It remains to be said that NORSOK's standard Z-013 on risk and preparedness analysis suggests an acceptability criterion of an annual frequency of 1.10^{-4} per accident 'load'. Meaning that a single type of accidents like cargo container fire may not occur more frequent than 1.10^{-4} per ship year.

3.6 Management of the fire situation

A thesis under the title "*Shipboard Fire Emergency Response Plan at Sea*" was published in 1999 at World Maritime University[22]. This dissertation shows the different circumstances that may take place and the responses that have to be carried out accordingly.

Summary of the major points covered in the Thesis are given hereafter. For detailed reading upon each of the points mentioned, please refer to footnote for this section.

Immediate Response

On the discovery of the fire:

- Locating the fire (Early detection, Location of the fire, Nature of the fire, Methods, Precautions, Equipment)
- Sounding the alarm (Early sounding, Effective alarm)
- Alarm response (Muster station - Emergency team station, Bridge team station, Engine room team station)
- Officer of Watch response (Appropriate course, Ventilation monitoring, Emergency equipment, General announcement)

Organizational Response

Emergency Teams (The Bridge Team, The Attack Team, The Support Team, The Engine Room Team)

The firefighting procedures:

- The captain's role (Establishing communication, Assessing the situation, Issuance of commands, Control and feedback)
- The team leader's role (Taking proper initiatives, Communications, Maintenance of resources, Directing the team)

Emergency Response Involving Fixed Fire-Fighting Systems

- Carbon dioxide system
  Fire in a cargo hold (On hearing the alarm, Confining the fire, Release of CO_2, Cooling the surrounding area, Precautionary measures)
  Fire in the engine room (Evacuation, Confinement, Cooling and Internal Inspection)
- Halon 1301 system
- Sprinkler system

Equipment preparation for shipboard fire emergency response

- Portable fire extinguishers
- Semi portable fire extinguishers
- Fixed fire extinguishers
- Fireman's outfit

Training and Fire drills

- Training (Theory of fire, Fire extinguishing agents, Firefighting equipment, Fighting a fire, Firefighting organization)
- Shipboard fire drills (Full application of the plan, Proper equipment, Record and feedback)

Conclusion and recommendations

This paper explains how in theory the fire situation should be managed and gives examples of why some tragedies have happened when some of these procedures were not followed.

3.7 Regulations for Transport of Dangerous Goods

Carriage of dangerous goods by sea is regulated in order reasonably to prevent injury to persons or damage to ships and their cargoes. Carriage of marine pollutants is primarily regulated to prevent harm to the marine environment. Both dangerous goods and marine pollutants are covered in the **The International Maritime Dangerous Goods (IMDG) Code** – see Appendix G – which has an objective to enhance the safe carriage of dangerous goods while facilitating the free unrestricted movement of such goods.

3.8 Summary

In this chapter, we presented a technical literature review based on published accident reports, material from industry conferences and publications, and published scientific literature. We explored a selection of important historical containership fires and their causes, together with general statistics from the industry on containership fires. We have also presented the current available knowledge on sensitive cargoes which can act as ignition sources, especially discussing their ignition mechanisms and precautions for their handling.

From this review, it is quite evident that knowledge from fire investigations is paramount to understand the development of fires on board, catalog relevant cargo acting as ignition source, and learn about effectiveness of current fire situation management and organizational challenges.

Knowledge about ignition sources remains critical, but it can be stated that improperly declared and improperly packaged goods are here to stay, emphasizing the pressing need to understand better the development of fires in containers. Literature treating fires in containers is noticeably arduous to find, confirming our assessment that technical knowledge on the problem of containership fires remains low.

Understanding this problem requires understanding ignition but also fire growth and fire spread in and from containers, in the cargo hold and the weather deck. Eventually, technical knowledge only provides one perspective on these accidents, which must be complemented by insights on human and organizational factors.

The next chapters of this report build on the experience gathered in this literature review. They cover both technical aspects investigating containers and containers in cargo holds, and human and organizational factors.

[22] Philippe RP. Shipboard Fire Emergency Response Plan at Sea. Master thesis, World Maritime University, 1999

4 Industry Insights

4.1 Introduction

The following chapter describes and discusses the insights gained from a number of interviews and workshop discussions with various industry stakeholders. The interviews and discussions are supplemented by a literature review of past accidents, peer-reviewed literature on human- and organizational factors in the maritime industry, and popular articles on container fires. The objective of this task is to include knowledge and insights from actors in industry and provide a highlight of these to create the foundation of knowledge for a future solution to the problem of container fires. In this pre-project however, the insights serve mainly to identify the issues as seen by the industry and identify future topics of study.

As described earlier in this report, the team at DBI is working with merging technical knowledge, typically gained through fire tests, fire simulations, codes and engineering practice, and knowledge based in the social sciences, often obtained through qualitative fieldwork.

The following chapter is focused on organizational and human factors, which DBI believes plays a major role in understanding, addressing, and in the future, hopefully solving the issue of container fires. The purpose of the original work package was to gain insights from various industry stakeholders in order to explore their respective views and understanding of the issue, and knowledge based in the social sciences, often obtained through qualitative fieldwork.

The insights described in this chapter mostly comes from the industry actors and stakeholders themselves during via qualitative interviews and a workshop (see methodology section below), while others are extrapolations from the subsequent analysis performed after the literature study, interviews, and workshop.

Finally, the chapter describes an example of DBI's acquisition of a *seaworthy* container to be used for fire testing and how this led to a discussion of the general state of seaworthy containers.

4.2 Methodology

The following section describes the methodologies applied throughout the research and data acquisition, as well as and key events, which shaped the insights of this work package.

Generally, the work package consists of data and insights gathered and obtained through qualitative fieldwork and subsequent anthropological analysis carried out throughout the project period. In addition, a literature review was conducted with a focus on human factors in maritime accidents and maritime risk studies.

4.2.1 Literature review

A literature review was conducted at the beginning of the project period. This literature review took place simultaneously with the technical literature review described in detail in Chapter 3 of this report. The review was a typical desk research setup and consisted of two focus areas.

(1) Studying human factors in maritime accidents with a focus on Danish accident reports. The entire back-catalog of DMAIB (Danish Maritime Accident Investigation Board) accident reports[23] were studied to obtain a solid foundation and understanding for the qualitative fieldwork with industry stakeholders. The reports were prioritized in the following order: Cargo fires on board container ships; fires onboard container ships not seated in the cargo area; other types of accidents on board container ships; fires onboard other types of vessels; and lastly other types of incidents onboard other vessels. In addition, the recently published final report [24]on the MÆRSK HONAM incident was likewise included in this section of the review.

(2) The second focus area consisted of studying peer-reviewed and popular articles focused on human factors in maritime accidents and maritime risk- assessment and control. Literature about the topic of container fires and the human and organizational matters surrounding these events were likewise included in this study.

4.2.2 Qualitative interviews

A large portion of the data and insights gathered and described in this chapter, as well as Chapter 5, stems from a series of interviews carried out with various industry stakeholders. The interviews were carried out throughout the entire project period, from the initial phase of writing the application and the efforts will continue after this report has been published. Although this work appears quite extensive, this part of the project did suffer somewhat from the global health crisis in late 2019 and through 2020. As is well known, the COVID-19 outbreak caused great global disturbances including within the maritime industry, which meant that a large portion of the scheduled interviews either had to be canceled or postponed. Despite these challenges, a fair number of qualitative interviews were successfully carried out with industry stakeholders, including accident investigators, maritime lawyers and insurers, shippers, and container industry experts. As previously mentioned, the efforts of reaching out and including more stakeholders in the industry do not end with this initial project, as several meetings and interviews have already been scheduled for 2021. These will provide further insights and continue building the foundation for future projects on the topic.

The data and insights gathered through these qualitative interviews formed part of the foundations for DBI hosting a workshop on the topic of container fires, which included several of the prior interviewees, as is described in the next section.

4.2.3 Workshop

On November 12th, 2020, DBI hosted a closed forum workshop, totaling 31 participants, focused on the topic of container fires onboard container carrying vessels. The workshop saw four keynotes from various industry stakeholders, including Ashok Srinivasan (Manager, Maritime Safety & Security at BIMCO), Helle Hammer (Managing director of CEFOR), Øssur Jarleivson Hilduberg (Head of the Board of DMAIB), and David Handley (Senior Associate and Master Mariner (representing Watson Farley & Williams LLP).

Along with the guest speakers the core team of the CONTAIN project presented the project scope and preliminary findings. These presentations sparked fruitful discussions among the participants in the workshop fora. Unfortunately, much like the qualitative interviews, due to the global health crisis, the workshop had to be hosted online. This was however, received positively with much support from the participants.

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[23] https://dmaib.com/reports/?Go%20to%20archive

[24] TSIB Final Report – Fire On Board MAERSK HONAM at Arabian Sea on 6 March 2018 - https://www.mot.gov.sg/docs/default-source/default-document-library/final-report_mib-mai-cas-035---fire-on-board-srs-maersk-honam-on-6-march-2018.pdf

Participants at the DBI CONTAIN workshop included; ship-owners and operators, ship designers and consultants, classification societies, surveyor and ship-owner associations, maritime authorities, marine insurance and law firm, and a research institution. All of these workshop participants play an important role as part of the container shipping value-chain. Their participation provided many interesting insights into the discussion concerning the best approach in tackling the challenges of container ship fire safety.

Following the workshop, several participants have shown great support for the current project as well as interest in any future endeavors concerning the container fire issue headed by DBI.

4.3 Insights

The following sections describe the insights gained through the methodologies described in the previous section.

Through the interviews and subsequent analysis, it has become evident that the problem of container fires is not just a technical problem but rather a socio-technical problem. This might seem trivial and obvious when considering the complex nature of the shipping chain and all of the actors involved in this. There is plenty of room for organizational and human factors to play a major role in creating the conditions for disastrous fire incidents on board container vessels. However, what is important to realize by defining the problem to be socio-technical rather than just technical - is that the potential solution will not come from a quick technical fix.

The issues that have led the industry to the place it is at today and facing these incidents ever more often - run deep in the shipping chain. These issues must be realized and subsequently addressed and dealt with cohesively in order to satisfactorily address the overall problem. Unfortunately, this study is not in a position to claim solutions to the problem, but it is an important step to take to realize that quick technological fixes probably will not solve the overall problem alone.

Lastly, a major question, which warrants mentioning here was raised several times during the interviews, by multiple interviewees, and at the workshop – namely, should the problem of container fires even be solved? Unsurprisingly, a question like this is very delicate to answer, however, DBI support that this be addressed.

Nevertheless, several stakeholders posed the question as a theoretical consideration. Even going as far as asking if the number of fires compared to the number of containers shipped yearly, and the number of vessels in operation - is statistically significant enough to warrant major investments? At the workshop hosted by DBI, the question was likewise posed and answered by a resounding yes by the participants. What is interesting about this question is probably not whether it should be solved or not. The loss of life in these incidents are enough of a driver to warrant a collective response to the problem. However, had there been no risk to life during these events, it might actually be a viable option to not address the issue and “just” deal with the consequences of lost cargo and damaged vessels when they occur. This point can be highly controversial to bring up but it warrants at least a mention since it is actually posed as a serious consideration in the industry and was brought up by several stakeholders during the interviews.

4.3.1 Shipping chain and vessel size

One major element, which most interviewees kept returning to, is the complexity of the transport chain of goods and the close ties with the business model. The argument being that the sheer complexity of the transport chain makes knowledge sharing increasingly more difficult while the probability for errors increases. Specifically, knowledge about the transported goods becomes harder to keep track of, and the potential for unwanted and undocumented interaction with the container or the goods increases.

Concretely, this means that e.g., tracking a container's journey at any given point in time is extremely difficult, nigh on impossible. Additionally, knowing what the container actually carries and how it is packaged inside is also impossible to know for certain without inspecting it. These issues coupled with the sheer quantity of containers in transit at all times make it very difficult to address issues regarding stowage and packaging of various goods e.g., dangerous goods. This specific problem and the complexities of it is covered more in-depth in chapter 5.

Maersk is employing new technological measures i.e., Artificial Intelligence solutions to address the issues of incorrectly declared cargo[25]. This, along with new IoT standards for containers[26], and potential new digital bill of lading [27]solutions might be steps in the right direction to begin addressing these issues. However, whether these new methods are economically feasible and if they will have a significant impact on safety is yet to be seen.

Another key point that is routed in the historic development of the shipping chain is the dramatic increase in vessel size in recent years. This notion has been described and pointed out by many industry stakeholders and in multiple recent media and articles. The issue here is not necessarily in the size increase of the ships alone. The increase in ship size makes it probabilistically more likely that the ship carries something dangerous and potentially incorrectly declared, which naturally increases the risk for a fire.

This is logically a problem, but the systemic issue rather lies in the fact that the safety requirements have not kept up with evolution of the Container Ship, as they have often been up-scaled with the vessels, but not in a manner befitting the new challenges faced by the crew on board (linear scaling vs non-linear behavior, as discussed later on in Chapter 6). This means that oftentimes the crew will not be able to fight the fire in a feasible manner, due to insufficiencies in a number of areas; including lack of both appropriate equipment and personnel for fighting of these fires.

Here it is important to say that this issue is not highlighted to point a finger at the ship-owners, as they are following the international safety standards as prescribed in SOLAS - and some even go beyond these through their own initiative, or via their Classification Society. However, the fact of the matter is that the sheer number of containers carried onboard and the size of the ship is not matched by firefighting equipment and crew sizes meant to feasibly fight a large container fire.

The crew sizes are determined to safely carry out daily operations - not deal with large-scale fire incidents on board. This raises the question of whether firefighting should even be attempted by the crew during a fire incident onboard the vessel. This topic will be discussed more in-depth later in this chapter.

[25]https://www.soefart.dk/article/view/751680/brandfarligt_gods_i_containeren_maersk_udfordrer_kunderne_ved_hjaelp_af_algoritmer

[26] https://dcsa.org/dcsa-establishes-iot-standards-for-container-connectivity/

[27] (Container majors agree on digital bill of lading Standards - shippingwatch.com Dec 8, 2020 — https://shippingwatch.com/carriers/article12613820.ece , Container association wants to digitize the bill of lading: "the Holy Grail of global trade"-- https://shippingwatch.com/carriers/Container/article12153846.ece)

The fact is that there are basically no IMO Regulations specifically for container ships. With only a very few exceptions (e.g., *Interim guidelines for open-top containerships (*MSC/Circ.608/Rev.1) and for *on deck container stowage areas on ships designed to carry containers on or above the weather deck, constructed on or after 1 January 2016*,)[28] requirements for container ships fall under the generic designation of '*Cargo Ship*' in SOLAS. Also, it should be noted that a container ship is the only vessel type where we do not know with a high level of certainty, the actual content of the cargo being transported. One could argue that Ro-Ro vessels are in a similar situation, however, the sheer quantity of unknowns onboard a modern container-vessel is unmatched.

4.3.2 Disagreements on the problem

One striking issue that became evident through the interviews and the workshop is that there is very little agreement on what the problem actually is. Of course, the concept of incorrectly declared cargo is often highlighted as the main culprit and most stakeholders seem to agree with this. However, when it comes to other factors such as rules and regulations, firefighting capabilities, the efficiency of the CO2 system, the efficiency of the current detection solutions, etc. there is very little agreement.

Some stakeholders highlighted that the current detection capabilities onboard the vessels are insufficient and by improving these, the risk would be greatly diminished and early firefighting would be easier accomplished. Others deemed the current detection solutions sufficient, not ideal, but rather *good enough* since according to them, the problem lies in the actual firefighting capabilities. Here, both the CO2 system was highlighted as overall inefficient and faulty by design, as well as the portable means of firefighting deemed insufficient.

Whether who is wrong or right does not necessarily matter for this discussion, as the point is not to place blame or define a potential solution. Rather, it is important to notice that the industry does not agree with what the actual problem is and therefore not on how to solve it either. As mentioned earlier in this chapter, the answer probably lies somewhere in between and a potential solution likewise.

Another aspect, which became clear through these discussions, is that there is very little technical knowledge about the problem of container fires. Many stakeholders hope for a technical solution that can easily address the issue and still fit the current business model i.e., quite low cost and thus being economically viable. However, with little agreement among the stakeholders and little technical knowledge about containership fires present in the industry or the published literature, it is difficult to imagine a feasible and economically reasonable technical solution being developed in the near future without addressing this lack of fundamental knowledge.

4.3.3 During the fire

The following section addresses a number of issues that all fall under the category of the *ongoing fire*. Where most of the other sections in the chapter deals with the organization around the concept of container freight, these issues are all centered on the fire event itself. These issues are as the others routed in the organizational set-up around container freight – but they become very evident when discussing and researching the fire event itself. Some of the elements highlighted in this section are naturally also evident in other types of emergencies on board ships since they are not all specific to fire.

The entry point for this section is the concept of an *evacuation threshold.* The dilemma here is that when a fire event is ongoing, the crew and master needs to constantly make decisions about their next actions and mainly ask themselves – do we fight the fire or evacuate the ship? Both strategies have been successfully applied throughout past fire incidents, however, lives have also been lost during evacuation where the

[28] SOLAS, Chp. II-2, Reg. 10.1.2

decision to leave was potentially taken too late. This topic leads to several other themes within the fire event that are relevant to explore.

It is relevant to investigate how the decision is made whether to evacuate or fight the fire and whether the crew and master have sufficient *situational awareness* to make such a call confidently. In addition, the fact that locating the burning container can be extremely difficult, coupled with the lack of knowledge about the content of a given container makes assessing the initial risk of the situation very difficult. Here the improperly declared of cargo poses an additional risk since it adds another variable to the uncertainty of the container content. Understanding the decision-making process better to determine recommended actions for these large-scale fire events on containerships would be highly relevant in order to answer the next question.

This next question was raised on several occasions and pointed out to DBI by multiple stakeholders, including professional firefighting instructors. Given their lack of firefighting experience and equipment, should seafarers attempt to fight the fire at all? The marine industry is not currently in a place to take such a decision let alone collectively, but hypothetically, it is a very relevant and interesting topic to explore. The firefighting training for seafarers is quite limited compared to a professional firefighter on land. Additionally, most of the training is focused on engine room fires or other fire sources e.g., galley or accommodation – not cargo fires in containers stored in the hold. So being relatively few people with limited skills and equipment seems like a very disadvantageous starting point for fighting and controlling a fire. Whether it should even be attempted or if immediate evacuation is the preferred or correct way going forward is not for this report to decide, but it is relevant to have the discussion and at least include these factors in discussions about potential future solutions.

These issues concerning decision-making during the fire event and the situational awareness on board the ship needed to make the correct decisions spark another topic of debate. Namely, the authority of the master and the new role of the landside of the organization. This dynamic is not new per se since the landside of the organization have always played a role and any company policy and the power this has over the master and crew has played a role in decision making in case of an emergency. The relatively new facet to the dynamic is the use of modern communication. This development has enabled the landside of the organization to take an active role in the decision-making process in real-time - while the fire event is ongoing. An example anecdote of this noted from conference discussions being; "*a captain ringing their insurance company contact up in the middle of the night, checking to see what their coverage is before making their next decision*". It is important to notice here, that this is not necessarily a negative thing in and of itself nor a critic of the ship-owners – but rather that these new means of communication alter the decision-making process during the event, and the complications this might bring is worth exploring. For further studies on this topic, Ø. Hilduberg's *The Decision To Evacuate A Passenger Ship - An Assessment of the Normative View of the Shipmaster*[29] is an interesting and relevant case study in the domain of passenger ships, although still very relevant and

Furthermore, the topics of crew morality, culture, and adaptability were highlighted as key factors to the development of the fire events. The maritime business is global and crew oftentimes consist of multiple nationalities. How this influences the decision-making and crew dynamic internally can play a major role in the outcomes of a given scenario. Moreover, the nationality of the captain and officers can likewise play a major role in how communication is performed, how power is understood and negotiated in the context, and which moral obligations are in play e.g., to save the ship or save yourself. This topic is not just relevant to fire or for emergencies for that matter, but also for troubleshooting daily operations and ensuring well-being on board.

[29] Hilduberg, Øssur J. THE DECISION TO EVACUATE A PASSENGER SHIP – AN ASSESSMENT OF THE NORMATIVE VIEW OF THE SHIPMASTER

Lastly, the topic of *communication*. Always a critical element in any emergency, but here again it has been highlighted as a critical, and in some past accidents potentially a deciding factor in lives lost. Ensuring clear, consistent, and functional communication between crew members is paramount to positively handling the situation. Again, a point that might seem trivial, albeit always critical in any emergency situation.

4.3.4 The Aftermath

The final section addresses the issues highlighted by the interviewees as being central after the fire incident. Several elements will be central and can cause further issues after the fire has happened, many more than will be addressed here. Naturally, it must be mentioned that container fires happen on a global scale, so these post-fire issues will be very dependent on the concrete context of a given fire. Some issues might be more severe while others might be non-existent depending on the geographic location of the incident, the damage sustained, the companies and flag-states involved, and how well the firefighting and salvage operation has gone.

Firstly, the increase in vessel size again plays a major role in the issue of container fires. Especially the interviewees from the insurance industry pointed out that the sheer size of the vessels makes it difficult to deal with the post-fire scenario. These enormous ships (not just container vessels but also LNG carriers etc.) make it difficult when events happen that take them out of the prescribed routes and operations. E.g., events like groundings are increasingly problematic because the tugboats and cranes needed to assist in these incidents are not readily available and are often booked long into the future.

The same types of issues become evident following a severe fire on board a container vessel. The size of the ship makes it difficult to find a suitable port, both willing and able to handle a damaged ship of this size.

First, the ship must be able to enter the port and secondly, there has to be a willingness from the port's side to accommodate. It is not unheard of to have ships stranded at sea for weeks or months waiting to find a suitable safe port to assess the damage and potentially conduct repairs.

In addition to the port having to be physically able to accommodate a vessel of this size, there is also a time factor. The ship will have to stay for an extended period taking up large amounts of valuable quay space.

Lastly, there is the whole cleaning up and handling of a vessel that has seen a severe fire. Depending on the salvage and firefighting situation for the given vessel there might be large quantities of sludge water and damaged goods. The sludge and damaged goods must be removed following proper routine and procedures and will in most cases be considered hazardous and toxic. Besides being economically very costly to handle, it requires that the port and the country in which the port resides are willing and able to assist in handling these dangerous and toxic substances.

The few points highlighted here are by no means exhaustive for the issues concerning a large container vessel after a large fire. Nonetheless, they do help highlight that the issue does not end with the flames being extinguished - but rather continues far into the aftermath at a very high price.

4.4 Container acquisition – Seaworthiness and condition

The following experience is described in full in Appendix F.

DBI needed a full, representative and seaworthy container for fire testing purposes. Through discussions and meetings with a Danish sales representative on maintenance and classification scales of containers it was decided to choose a container in the middle of its lifetime as a seaworthy container. DBI provided drawings for cutting up the container in order to fit with furnaces.
When delivered, parts of the container were missing and the manufacturer claimed that the container had severe damage. DBI decided to require a third party Container Consultant to assess the container and it turned out that the parts delivered to DBI did not derive from the same container. On top of this, the container – however still seaworthy – was in poor shape.
The experience illustrates that even a fairly simple process such as purchasing a container and assessing seaworthiness is potentially confusing and adds to the uncertainty and complexity of the container shipping.

4.4.1 The context of the example and the greater issues of container condition

The above-stated example should be viewed in a greater context since the ambiguity of a container's condition is a part of the complex challenges concerning fire safety onboard container carrying vessels.

As part of the project, DBI interviewed an employee in a Danish shipping company. The employee said that the company routinely carries out randomized tests of the commissioned containers, in order to assess their seaworthiness. The seaworthiness i.e., condition can be especially critical to assess in cases of shipping extra heavy freight or dangerous goods. Therefore, it is the container's condition that is the most important factor in what makes a shipping container seaworthy and this is the responsibility of the container's owner.

Through the randomized tests, experience shows that approximately 40% of the received containers are more or less damaged. The damages range from small dents, corrosion, small holes in the metal or wooden floor, dissolved plywood, or damaged seals. The company rejects roughly 5% of the containers but damages are mostly accepted. The damages are not documented nor photographed. Therefore, there is currently no knowledge about the potential causalities between container condition and fire spread in the event of ignition. The employee believes that *seaworthiness* is a broad term and mentioned that e.g., holes in the plywood floor the size of a Danish 20 kr coin is normally accepted (approximately 25-30mm). According to the employee, the average condition of containers is worse the further eastward one goes, whereas requirements are stricter in Denmark and Europe.

DBI believes that it would be relevant to study the potential causalities between the development of fires in cargo holds and the aging and condition of containers in future work. The occurrence of holes, damages to the load-bearing structures, the fire properties of the plywood floor, damaged seals, etc. can all play a role in fiercer fires developing quicker and faster fire spread between containers. This risk warrants future studies to be assessed.

Additionally, it might be worth considering whether there is a basis for common and objective criteria for the age and condition of containers concerning fire safety.

Unfortunately, the economically feasible limit to address fire safety for a single container is rather low. Various stakeholders throughout the project have pointed to different figures, but anything from $10-$30 per container is considered unacceptable and not economically feasible. This will naturally make it very difficult to make significant changes even if it is proven that container condition has a noteworthy impact on fire safety.

4.5 Summary of insights

The following section is a brief summary of the insights presented in the chapter.

- The challenge of container fires is underlined by the whole problem being complex, which leads to a feeling of uncertainty about the issue and potential solutions in the business.
- The problem is not just technical but rather socio-technical. This means that it will most probably take socio-technical action and solutions to solve the issue.
- The question is raised whether the problem should even be addressed. There seems to be agreement that it should, which DBI supports, mainly due to the fact that lives are lost in these fires. However, it is important to notice that seriously raising the question, no matter how controversial, is actually founded in it being a potentially feasible way forward.
- The complexity of the shipping chain and the current issues of improperly declared of cargo are highlighted as primary causes of the issue. However, new technological developments currently being implemented might be important steps in addressing this issue.
- The dramatic increase in vessel size seen is recent years is likewise highlighted as a primary driver for the catastrophic fires. The ships have inflated in size and thus probabilistically increased the risk of fire but the safety measures currently in place does not match the new size of the vessels. As per current regulations there is neither enough crew nor suitable firefighting equipment on board to fight fires onboard modern container vessels, especially below deck.
- There is no real agreement of the nature of the problem outside improper declaration of cargo and the increase in vessel size. Whether the current detection systems are sufficient enough, or if the of the CO_2 system is suitable is not agreed upon. This chapter does not address this issue further, it is merely important to highlight that there is a disagreement.
- There is very little technical knowledge in the industry as to the nature of the issue. Additionally, peer-reviewed literature is also severely lacking on the topic. This will make it difficult to develop suitable technical solutions in the near future.
- There is no established evacuation threshold to aid in determining when to fight the fire and when to evacuate. This can be impossible to pre-determine, but the concept helps highlight other aspects of the emergency situation as is descried below.
- The question is raised of whether there is sufficient situational awareness during a cargo hold fire to feasible make the decision of firefighting vs. evacuation.
- It should be determined if attempting to control or fight the fire is the best option given the crew's lack of firefighting experience and training and the current state of firefighting equipment onboard. These problems coupled with the lack of situational awareness in the fire event might suggest that the best solution for crew is to wait for help from firefighting ships or evacuate immediately.
- Modern modes of communication have brought a new dynamic into the emergency event. The shore-side of the organization can now actively contribute to decision making during the actual emergency. This might influence the master's decision making. This is not necessarily negative, but should be investigated and included as an additional factor.
- Crew and officer nationality, culture, and morality plays a major role in the handling and outcome of emergency situations. The influence of these aspects on daily operations and emergencies should be investigated further and be included in future decision-making.
- Communication during the emergency situation is extremely critical. Poor, incomplete or total loss of communication between the fire-fighters (crew) and Operational Command has resulted in loss of life.
- The aftermath of the fire is equally problematic. The size of the ships makes it difficult to find a suitable and capable port for safe refuge.

- The concept of a container's seaworthiness is widely defined. The state and conditions of container on board the world's ships vary greatly and some are severely damaged. The effects on fire safety due to aging and poor condition of containers should be investigated further.

4.6 Recommendations for future work

The following section focuses on recommendations for future work within the realm of human and organizational factors and their respective roles in container fire incidents.

- Interview more and a wider range of stakeholders – this is already ongoing and will continue after the end of the CONTAIN project, but should also be a feature of any future projects. The recommendation here would be to broaden the scope and include an even more global pool and not be limited in the selection.
- Future work and collaboration with selected industry partners, including ship-owners – this is also ongoing and will continue after the project. This will help with a greater understanding of the problem, getting more concrete with certain issues and solutions with selected partners.
- Long-term fieldwork to understand the ship and crew situation better. This includes qualitative interviews with crew, officers, manning companies, shipping companies, etc. Participant observation on board a container vessel for an extended period. This is the opportunity to gather significant qualitative data on daily life on board a container vessel. Crew relations, the effects on various cultures within the crew, the relationship between management, land, the officers, and the crew. Building significant rapport with crewmembers. Gain a deeper understanding of the issues they face and their take on the fire incident.
- Investigate the concept of container aging. What is the influence of damaged containers on fire spread?
- Investigate whether it is possible to feasibly fight a developed fire aboard a container ship with the personnel and equipment available as stated by the rules.

5 The Blue Denmark's Challenges and Development Opportunities in Connection with Container Fires

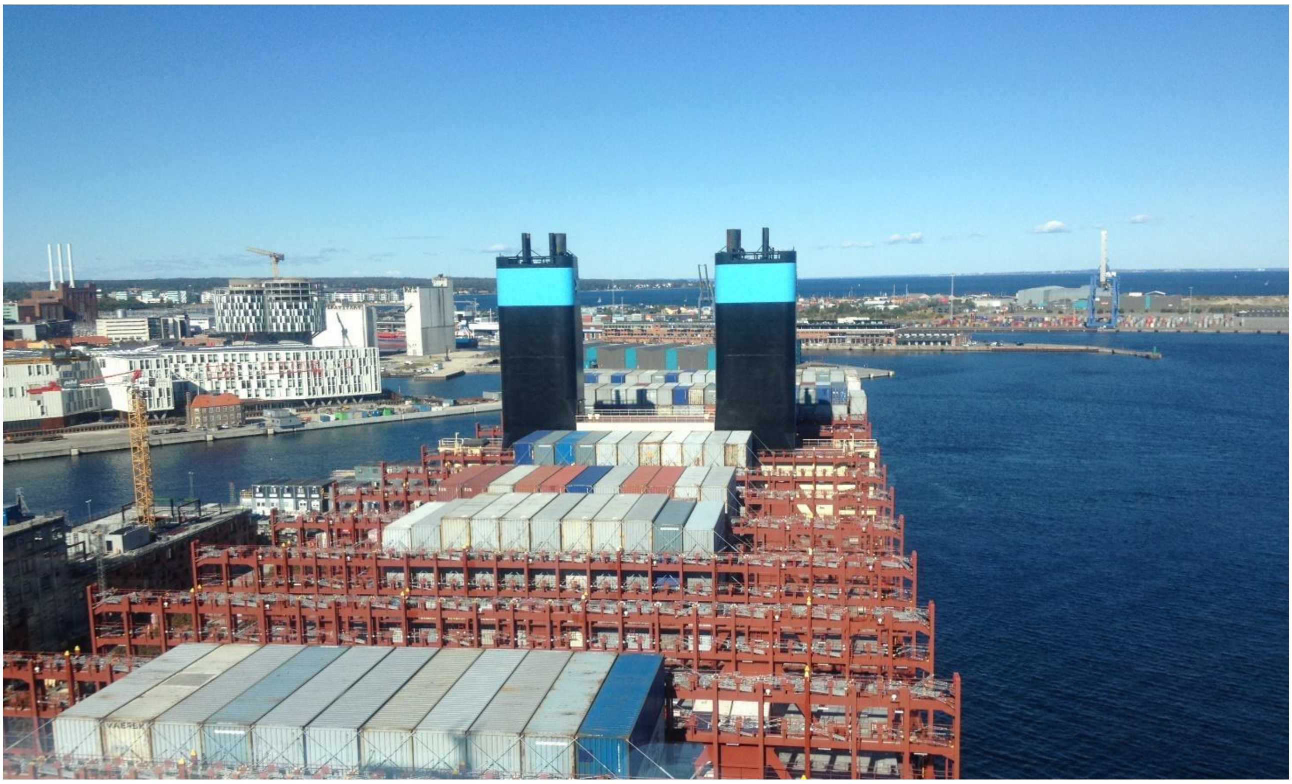

Photo: **Triple-E Containership at Copenhagen Harbor** - 2013 (A.Kleiman)

The Blue Denmark's
Challenges and Development Opportunities
in Connection with Container Fires

5.1 Introduction: The Blue Denmark's Role in the Container Shipping Value Chain

Since Viking times, Danes have played a crucial role in the transportation of goods over the seas and oceans from all over the world. Likely due to the natural geography of the Kingdom of Denmark, with close access to water along its 8,750 km of tidal shoreline and the 1,419 offshore islands. No location in Denmark is further from the coast than 52 km.

Through the middle of the 20th Century, Denmark became the world leader in the innovative new means of commercial intermodal freight transport, and today containers carry most of the world's seagoing non-bulk cargo (about 90% of non-bulk cargo worldwide is transported by container ships.) The largest modern container ships, which include many Danish flagged vessels, can carry over 23,000 TEU.

Fires onboard container vessels are an increasing problem for shipping companies on a global scale. Historically, the fires have shown to be complex and difficult to handle, often leading to substantial economic losses and sadly also with the loss of human lives.

Since their inception, container ships have significantly increased in size and the trend seems to continue towards ever-larger vessels. While economically impactful, this size increase leads to even greater risks of fire. Container fires are often difficult to detect in the early stages and fight, and therefore lead to economic losses in the scale of hundreds of millions of dollars. IUMI estimates, that the fire on the ms MAERSK HONAM in March 2018 is likely to be the largest General Average loss in history.

Denmark is the world's second largest container owner, with several large shipping companies sailing under the Danish flag. Therefore, the problem is naturally of great significance to the blue Denmark and the future of Danish shipping. However, Denmark is also in a unique position to address the issue with several key actors, such as technology suppliers, fire experts, and shipping companies located within our relatively small borders. Through this unique position, Denmark has the possibility to gain a vantage position for both shipping companies and technology suppliers alike. The complexity of the issue is however, a hindrance for a swift solution.

Container fires are a multifaceted problem, and solely focusing on technical aspects is not sufficient. Human aspects such as safety culture, training, manning, and maintenance, must also be investigated and addressed, to create a holistic solution to the problem. Early detection means little if the crew cannot operate the active firefighting system to combat the fire.

The maritime industry has special factors to consider when it comes to crew and workforce. Living- and workspaces are often interchangeable and shifts are long. In addition, the industry has a primarily multinational workforce. This additional factor means that besides long shifts, elements such as cultural differences, language barriers, travel times for crew, and training all play a significant role in how daily operations are carried out. Specifically, daily operations play a significant role as input for designing robust holistic fire safety strategies.

In addition to these aspects, there are complex issues within the complete systemic supply chain of container shipping. Although container fires constitute the biggest problem for the shipping companies themselves, the responsibility to solve the issue should not lie solely here. Port authorities, freight owners, logistical handlers, and the shipping companies all share the responsibility and all play a vital role in the chain.

Incorrectly declared dangerous cargo is shown to be a major cause of container fires. However, the problem cannot be solved globally if all countries' customs and port authorities do not share the responsibility of checking and penalizing mis-declarations.

By addressing these aspects systematically, using a variety of experts and disciplines, the goal of a significant reduction in number and scale of container fires may be achievable. Such a reduction would greatly benefit the whole container supply chain, not only just the shipping companies. In addition, the multitude of innovative Danish technology and marine equipment suppliers could get a lead in the industry, both within detection and fire-fighting equipment.

5.2 The Container Shipping Revolution in Denmark?

Since 1951, when the first purpose-built container vessels began operating in Denmark[30], the Blue Denmark has had a very strong presence in the container industry and a significant role to play. Over the years, this has involved every element of the container shipping value chain, from import/export of goods to and from Denmark, containership owners and operators, which at one time also included Danish shipbuilding activities as well as manufacturing of the actual container boxes, to ship design of container ship and marine insurance.

In 1966, the first standardized American 20-foot containers (Twenty-foot equivalent units (TEUs) are the shipping industry's standard unit of measure, denoting the capacity of a standard freight container) arrived in Europe, and radical changes in the transport of goods were about to happen.

The Danish company Maersk Line's fleet consisted at that time of 44 break-bulk cargo vessels. The impact of the container revolution included the rule of thumb figure, that one container ship replaced five conventional break-bulk cargo vessels. This unprecedented efficiency was first introduced on the main markets (between the USA, Asia & Europe) and Maersk Line had to adapt. A-P Møller Mærsk made the decision to invest in building in Denmark, a fleet of cellular containerships, containers and equipment starting in 1973, and their first fully containerized service started operations in 1975. A-P Møller Mærsk soon gained market share and by 1993, Maersk Line established itself as the world's largest container carrier[31].

By Slawos - Own work, CC BY-SA 3.0, *https://commons.wikimedia.org/w/index.php?curid=27885888*

" When you look at the inventions or innovation of the last 100 years…the really low-tech invention of the container has done more for global trade than anything else."

Søren Skou, CEO of Maersk Line, 2012 [31]

Today, Mærsk Line operates a fleet of more than 690 ships and has a total capacity of 4 million TEU.

[30] From Wikipedia (https://en.wikipedia.org/wiki/Container_ship)
[31] Source: Maersk Line (https://www.maersk.com/news/articles/2019/02/21/maersk-line-from-one-route-to-a-global-network)

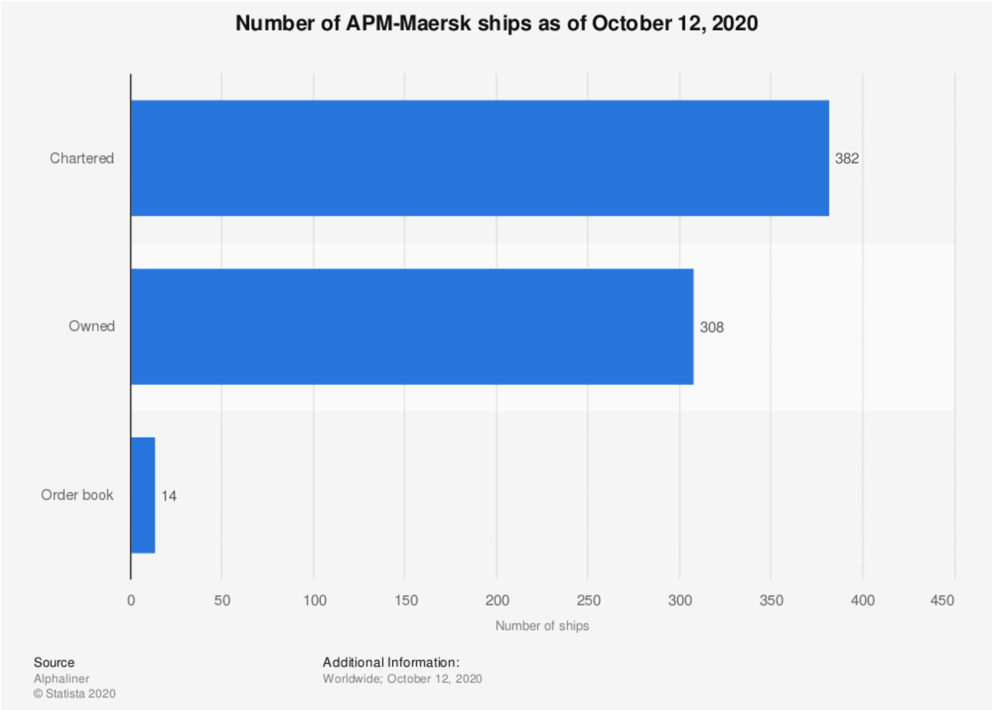

Figure 4

Denmark is also home to several logistics companies[32] , including Damco, DFDS Logistics, DSV, Frode Laursen, Scan Global, offering container shipping services, as well as intermodal Container Terminals in Aarhus, Copenhagen and Frederica, offering road, rail and sea transportation of Containers.

5.3 The BLUE DENMARK

WHAT IS BLUE DENMARK? [33]

The Danish Maritime cluster comprises of all maritime related companies and operations in Denmark, which includes shipping companies, shipyards, suppliers and designers of ships, maritime equipment, products and services, as well as higher educational and training institutions.

The cluster of maritime activities is often referred to as the ***Blue Denmark***, and accounts for approximately 25 pct. of total Danish exports. The Blue Denmark employs approx. 100,000 persons directly or indirectly.

The maritime industry is a storied and traditional industry, but one that has shown that it is adaptable to change when there is a shift in the global economy. It has succeeded in maintaining a leading position, not least due to continuous research, development and innovation.

[32] https://www.logisticsdenmark.com/Logistics_Denmark/
[33] Danish Shipping – Facts and Figures (June 2018)

The Danish Maritime Industry

Despite a drastic reduction in shipbuilding activities over the past several decades in Denmark, the main reason why the major part of the Danish maritime industry has survived and flourished is that it is still very innovative and research intensive. With over 40,000 employees, the maritime industry represents the major part of the total number of persons employed by the Blue Denmark.[34]

Denmark has long ranked in the top ten of global maritime nations, and as a seafaring nation with cutting-edge innovation and an excellent regulatory framework, favorable conditions exist for marine companies to succeed.

The Danish maritime industry, including both shipping companies and manufacturers, offer very environmentally and climate friendly solutions such as design of wind farm installation and service vessels, exhaust gas scrubbers, and shore-power technology. In many cases, these products and solutions do not only meet with the applied legislation; often they are a step ahead to be ready for future demands.

The Danish maritime cluster joins companies, universities, GTS Institutes, SMEs and authorities in a close-knit hub. Together, they create successful blue networks and partnerships, for pursing new, innovative solutions based on the latest technological advances.

The world's fleet consists of more than 100,000 ships, and a major portion of these ships have Danish equipment onboard such as Hydro-pen, DASPOS, and Viking Lifesaving Equipment. Two-thirds of the total activity of the shipping industry takes place outside the borders of the EU, and as a result, shipping is one of the most global Danish industries.

The container industry has a significant position in the Blue Denmark. Both domestically and internationally. Whether it be by the containers being transported with a Danish container logistics company, onboard Danish flagged and Danish owned Container Ships, which are designed by Danish Naval Architects, fitted with Danish marine equipment and manned by Danish educated officers and crew.

Danish Maritime Training

An important element that makes up part of the Blue Denmark, are the many world-renowned maritime Training and Educational Institutions. These include the seafarer schools such as SIMAC, Marstal, MARTEC and Maersk Training center, RelyOn Nutec and VIKING Safety Academy, Force Technology, Fire-fighting Academies and School of Marine and Technical Engineering.

With a long history of supplying qualified mariners to the Danish fleet, these institutions provide both the IMO mandated STCW (The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers) courses as well as advanced training in risk management and decision support.

These Danish Maritime Training institutions can offer tailor made courses, which go beyond the standards, which are based on the actual situations and risks encountered, and provide the opportunity to craft the decision makers to make better and more informed decisions at Sea.

Appendix E illustrates an overview of a selection of Danish stakeholders relevant to container shipping.

[34] From Danske Maritime (https://danskemaritime.dk/presentation-of-the-danish-maritime-industry/)

Danish Shipping Companies [35]

The Kingdom of Denmark is home to world-renowned shipping companies such as A.P. Møller-Mærsk, Royal Artic Line and DFDS, which provides a strong foundation for setting maritime industry standards. [36]

With a dominant first position, is the A-P Møller Mærsk (APMM) owned **Maersk Line**, offering worldwide transportation solutions utilizing Containers. As described earlier, Danish Mærsk is one of the originators of the entire container industry and still is the most significant player in both the Blue Denmark and on the global Container shipping scene.

Royal Arctic Line (RAL) exclusively operates cargo routes between Nuuk and Aalborg in Denmark and among the Greenland settlements. RAL manages 13 harbors in Greenland as well as the Greenlandic base harbor in Aalborg, which serves as the source for all European shipping to Greenland. RAL operates a fleet of ten container ships – six container ships in Liner service and four "*settlement ships*" for feeder service around Greenland.[37]

DFDS (Det Forenede Dampskibs-Selskab) has a long history in the Blue Denmark, with origins dating back to 1866, when four Danish steamship companies merged to form DFDS. The new company enabled trade that was growing exponentially in the wake of the industrialization, creating growth for all. Products such as coal from the UK, the world's industrial locomotive at that time, were transported to the textile and energy demanding markets in Scandinavia and other countries.[38] Over the years, DFDS has grown and developed from one of the world's leading steamship companies to become one of the largest forwarding and logistics companies in Northern Europe. Connecting people and businesses cargo, from door-to-door, DFDS has transformed itself to become a unique European Shipping and Logistics Group providing vital infrastructure services in Europe. While primarily operating a fleet of both passenger and Ro-Ro ferries with over 50 vessels, DFDS' fleet also includes 14 container and side-port ships, as well as four cruise ferries.

Danish Shipping employment

In 2019, Danish Shipping companies employ 24,437 persons. 6,788 persons are land-based employees in Denmark while 17,649 persons are employed at sea. Figure 5 shows a breakdown of employment in Danish Shipping over the past 6 years, as reported by the approximately 100 member companies of the Danish Shipowners Association, DANISH SHIPPING.

[35] Danish Shipping – Ultraflash – Danish Shipping Employment (June 2019)
[36] Source: Ministry of Foreign Affairs of Denmark
[37] From Wikipedia (https://en.wikipedia.org/wiki/ Royal_Arctic_Line)
[38] Source: DFDS homepage (https://www.dfds.com/en/about/group/our-history)

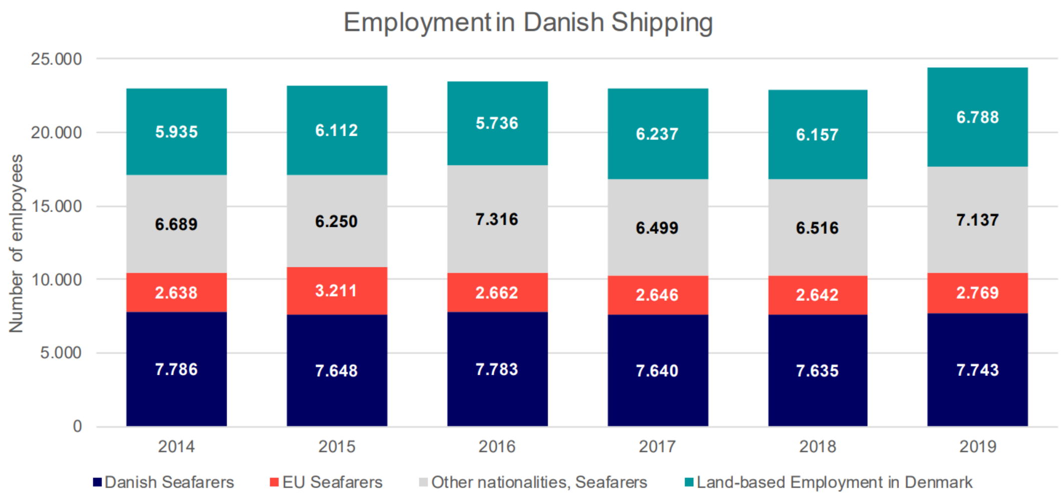

Figure 5

Source: Annual member survey by Danish Shipping, regarding employment in each of the approx. 100 member companies.

More ships under the Danish flag [39]

The merchant fleet sailing under the Danish flag has grown over the last 10 years. At the end of 2019, a total of 731 vessels with a gross tonnage (GT) of 21.3 million were flying the Danish flag. This positive development means that Denmark has now passed the United States as the world's fifth largest shipping nation in terms of gross tonnage of Danish-operated ships, both Danish- and foreign-flagged.

Looking at the merchant fleet under the Danish flag alone, Denmark is 12th in the world ranking and holds a 4th place of the largest EU-flagged merchant fleets (GT). Containerships flying the Danish flag account for approximately 20% of the total Danish flag fleet in terms of number of vessels, while the large size of these vessels account for 75% of the fleet when measured in gross tonnage (See figure 6.)

[39] Danish Shipping – Ultraflash – Growth in the Danish Flagged Merchant Fleet 2019 (January 2020)

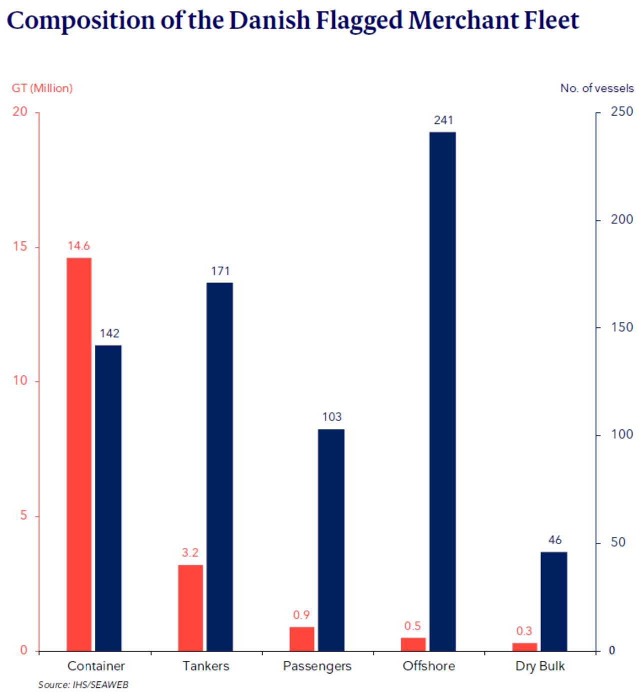

Figure 7

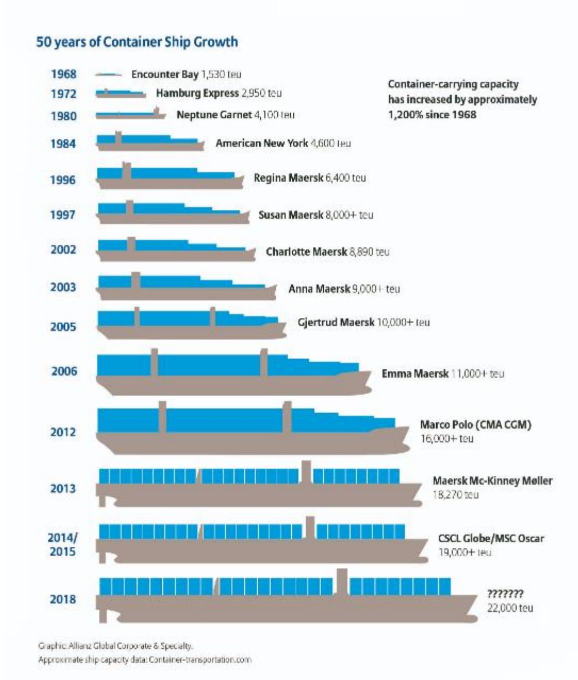

Figure 6

This indicates that vessel size has increased, along with the number of containers carried per vessel (see figure 7.) More containers on board equates to a greater chance of a vessel being exposed to an undeclared or improperly declared DG cargo. Thus, larger ships carrying more cargo represent a greater accumulation of risk. [40]

Many Challenges and Opportunities for the Blue Denmark

Blue Denmark is part of the global maritime industry. More than 95 pct. of Danish shipping activities take place outside of Danish waters. It is an extremely competitive market, which is sensitive to national regulation. Therefore, it should continue to be a clear objective for Danish legislators through the Danish Maritime Authority, to regulate the Blue Denmark through the International Maritime Organization. [41]

Additionally, the Blue Denmark should take advantage of the many commercial opportunities created by a green transition of the global shipping industry. With the innovative climate that exists in Denmark, led by the strong blue industry trade organizations such as Danish Shipping and Danish Maritime, together with a leading role on ship safety and environmental compliance that the Danish Maritime Authority plays, the Blue Denmark can promote Danish companies' influence on future technology for fire safety on container ships.

History of the Intermodal Shipping Container

A monumental development since the success of cargo containers in the mainstream shipping sector, intermodal cargo shipping containers have set really high operational standards in the global maritime industry.

[40] National Cargo Bureau - white paper - A comprehensive holistic approach to enhance safety and address the carriage of undeclared, miss-declared and other non-compliant dangerous goods

[41] Source: THE CLIMATE PARTNERSHIP FOR BLUE DENMARK

Shipping containers as we know them today were first introduced in the 1950's. After their first decade of use, in 1961 the International Standards Organization (ISO) Technical Committee introduced "*ISO / TC 104 Freight containers*" standard, defining the dimensions, materials, stacking, maintenance etc. of containers. The purpose was to standardize and pave the way for increased use of containers as a means of freight, which was fully successful. [42]

By 1972, the IMO published *The Convention for Safe Containers (CSC 1972)*, which has two goals: "*one is to maintain a high level of safety of human life in the transport and handling of containers by providing generally acceptable test procedures and related strength requirements which have proven adequate over the years; the other is to facilitate the international transport of containers by providing uniform international safety regulations, equally applicable to all modes of surface transport. In this way, proliferation of divergent national safety regulations can be avoided*." [43]

At the same time, BIC (The Bureau International des Containers) developed a well-structured, reliable alphanumeric system for marking containers known as the 'BIC-CODE' system. ISO adopted this system in 1972, and entrusted BIC with the exclusive management of the allocation of the BIC-CODES for international container transport, and the publication of its official Register of owners 'codes."[44]

Back then, as now, newly built containers were approved by a Classification Society, while other third-party companies with qualified surveyors could also carry out the required 5-year Periodic Examination Scheme (PES) of the containers. At this time, containers used in shipping were predominantly owned by a ship owner / the shipper, so the entire logistics chain was simpler and the responsibility more clearly placed.

Since then, a number of changes have made the logistics chain significantly more complex and perhaps vulnerable:

- In 2010, it became possible for container owners to carry out periodic self-inspections by virtue of ACEP (Approved Continuous Examination Program)
- The ownership of containers has been expanded, so that both shippers, logistics companies, manufacturers and more today are responsible for the operation and maintenance of their own containers.
- The number of container boxes has grown rapidly, and it is estimated that today there are approx. 17 million intermodal shipping containers in the world, out of a total of approx. 530 million containers worldwide.
- The price competition for containers has meant that 97% of the world's containers today are produced in China. [45]
- It has become more common today, with Less than a Container Load (LCL) shipment, where the contents of the containers are shared together by several shippers.

Container Shipment

Intermodal shipping containers are typically found in several different sizes. The two most common are the 20-ft (TEU) and 40-ft (FEU) sizes, allowing them to be stacked on top of each other, often up to 11 boxes high onboard ships.

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[42] ISO News Boxing Clever - How Standardization built a Global Economy, Barnaby Lewis on 11 September 2017. (https://www.iso.org/news/ref2215.html)
[43] Source: https://www.imo.org/en/OurWork/Safety/Pages/Containers-Default.aspx
[44] Source: https://www.bic-code.org/about-us/history/
[45] Source: https://www.porttechnology.org/news/10_unknown_facts_about_shipping_containers/

Full Container Load (FCL) - FCL means that the whole container is utilized for one shipment. A shipper may not necessarily have enough volume of cargo to completely fill the container; however, the entire box is exclusive to the one shipper. This is the most secure and reliable form of shipment.

Less than a Container Load (LCL) – Part load transport is when the shipper does not have enough to fill a standard container. Thus, the container may be loaded with cargo from several different origins and shippers, and therefore may not always be compatible. This introduces additional risks which can affect the safety chain.

Hundreds of containers enter Denmark each and every day, transported by tractor trailers over roadways and by rail, as well as through the network of seaports along the vast Danish coastline, by regular Liner and by Feeder Container Ship service. While it cannot simply be concluded that these factors are linked to the high level of fires on container ships, it may still be appropriate to examine the link between the condition of the individual containers and the history of fires.

5.4 Actors and Risks in the Container Shipping Logistics Chain

Introduction

In the following section, two main hypotheses are presented in order to describe the relevant connection between the logistics chain of dry intermodal containers and the amounts of fires in cargo holds, which also has severe implications for the actors in The Blue Denmark.

Hypothesis 1:

> *The many actors of the Container Shipping Logistics Chain are in themselves a source of many errors, which makes it difficult to find a common solution.* In addition, fires on container ships can be seen as a *"structural challenge".* The stricter the requirements, the more people will try to find less expensive (= less safe) modes of transport for, e.g., chlorine. The many players in the Container Shipping Logistics Chain make ownership difficult and thus place a responsibility, which both complicates and delays a solution.

Hypothesis 2:

> *There are a number of risk factors along the way, which overall increase the probability of fire and the danger of the fire.* This is an accumulated risk, which is not least due to unintended actions related to the structural dysfunction. The risk is not quantified in this report, but is based on observations from reading through a number of accident reports from container ship fires as well as interviews with stakeholders.

Actors along the Logistics Chain

The table below reviews which actors are involved in a typical transport of a container, from sending customer to receiving customer. In addition, it states what responsibility each actor typically has through this journey. The purpose is to illustrate the complexity of the process, as well as the complicated division of responsibilities, which also plays a role in relation to the prevention of fires on container ships and the subsequent damages.

Process Steps and Actors	**Role / Responsibility**
Before ordering and shipping	

Customer / cargo owner	Responsibility for declaring the goods correctly in relation to danger (*The International Maritime Dangerous Goods (IMDG) Code*). Does not necessarily fill an entire container.
Container owner	Responsibility for containers being seaworthy and functional in relation to "*Industry Guidance for Shippers and Container Stuffers", 2009*.
Classification society	Responsibility for approving / certifying new containers.
Freight forwarder	- Book and plan the customer's transport from A-to-Z, or to a specific port, including a plan for lay days and lay time in ports (schedule). The transport can go via several ports and with several shipping companies. - Inspects containers randomly before shipping and can reject damaged containers, which is estimated to be approx. 5% of containers (oral notice). Responsibility for discovering any DG.
Approving Competent Authorities	Companies selected by National Administrations, as being competent to conduct audits and to deliver Approved Continuous Examination Program. They have a technical profile, listing among their services the survey of containers, and typically are Classification Societies.
The container ship	
Ship designers - Naval architects	Responsible for ensuring that ships are designed to comply with all requirements of the IMO (SOLAS, MARPOL, etc.), Flag state and the Classification society rules, for newbuilds and retrofits.
Shipyard	Responsibility for building the ship according to the ship-owner's / customer's requirements, including all Flag state and the Classification society rules according to the contracted specification.
Classification Society	Responsibility for ensuring that the ship complies with IMO and flag State regulations and with Class rules. Responsible for conducting periodic surveys of ships on behalf of the owner, and certifying the vessel as a Recognized Organization (RO) on behalf of the Flag State. Had there been common class rules for container vessels, the classification society would also have complied with these.
Flag State	Overall responsibility for ensuring that the Flag State's fleet of registered vessels complies with all applicable IMO conventions, national regulations, etc. for ship design and operation.
Shipping	
Freight forwarder (owner of trucks / trains)	Responsibility for proper handling of the containers on truck, train, at storage depts. etc.
Terminal Operators	Responsibility for correct handling of the containers on trucks, trains, etc. Responsibility for goods for filling containers being packed and declared correctly.
Harbor + Longshoremen	Responsibility for proper handling of the containers upon receipt, storage, relocation, loading (including clamping) and unloading. Both for feeder vessels and ocean-going vessels. Responsibility for complying with port security requirements, cf. IMO's International Ship and Port Facility Security *(ISPS)* Code.
Customs Authorities	Responsibility for ensuring that goods are declared correctly, also in accordance with IMDG.

Shipment	
Shipping company / ship management	Responsibility for ensuring that the ship and the ship's operations comply with the rules of the IMO and flag states, the classification society's rules, rules for safe manning and that the crew has the required training in relation to STCW (*International Convention on Standards of Training, Certification and Watchkeeping for Seafarers, 1978*).
Ship owner	Depending on the Ownership structure of the vessel (Shipping company or Charterer) similar to the above. In the case of a '*Bare-boat*' charter, the charterer obtains possession and full control of the vessel along with the legal and financial responsibility for it. The charterer pays for all operating expenses, including fuel, crew, port expenses and P&I and hull insurance.
Manning agencies	Responsibility for delivering crews to ships by order of ship owner. Responsibility for crew members completing training according to STCW and any class rules.
Cargo owners	*No additional requirements as the cargo is on the ship*
Charter	A Charterers' Liability includes a type of insurance meant to protect shipping businesses from certain risk or liabilities, including fire. Coverage of a Charterers' Liability Insurance can vary based on the charter-party type and additional inclusions or exclusions arranged prior to the purchase of the insurance.
Crew	Responsibility for carrying out required inspection, maintenance tasks and exercises.
Captain / management	Chief Officer of the ship is responsible for safe and secure stowage of the cargo on ships. Responsibility for carrying out required inspection, maintenance tasks and exercises.
In case of fire and post-fire	
Cargo owner	Responsibility for ensuring that the cargo was insured.
Shipping line / ship management	Responsibility for ensuring that the ship and crew are properly maintained, equipped and training to tackle such Fire incurred.
Ship owner	Financially responsible for the ship, Responsibility for protecting the environment, life and property carried onboard, and for recovery and salvage of the ship.
Crew	Responsibility for carrying out fire extinguishing, according to the Captain's instructions.
Captain / management	Responsibility for deciding on and coordinating extinguishing the fire and ultimately deciding to leave the ship.
Search & Rescue service	Responsibility for extinguishing the fire, if the ship's crew are unsuccessful.
Salvage	Responsibility for bringing the ship to port and / or saving as much of the ship's cargo as possible in the event of an accident. Responsibility for the least possible environmental impact during rescue.
MAIBs	Responsibility for conducting an accident investigation on behalf of the flag state under which the ship is registered.

Insurance - Hull & Indemnity	Responsibility for covering the value of the cargo. Each customer / cargo owner can in principle each have their own insurance company.
Insurance - P&I clubs	Responsibility for covering the value of the ship / hull. Reinsurance for Hull & Indemnity. Some insurance companies consist of both H&I and P&I. After a fire, the insurance burden must be distributed, which can take up to several years to clarify.
Surveyors	Responsibility for conducting an accident investigation on behalf of the owner.
Flag state	Responsibility for conducting an accident investigation
IMO	Consider revision of existing Regulations or establishment of new requirements

Risks Along the Transport & Safety Chain

The purpose of the following overview is to illustrate that an accumulated risk arises in the complex logistics chain.

In 2020, The National Cargo Bureau (NCB) published findings from the "*Container Inspection Safety Initiative* (CISI) involving the inspection of 500 containers from participating carriers.[46] The study investigates the potential gap between routine and in-depth inspections and it reveals a number of serious problems in the supply chain of containers.

It points out, amongst other things, that switching of containers between many carriers, and the resulting complexity and lack of coordination, leads to an increased incidence of Dangerous Goods.

In addition, it appears that language, cultural and organizational barriers during transport have a major impact on the overlooking of DG 55% of the containers examined did not comply with the rules, including 43% due to poor securing of cargo within the container.

In the context of the review above, it can therefore be said that the seed for a fire in the cargo hold is already laid long before the first flame breaks out, solely by virtue of a complex and opaque transport chain. The following table provides a review of the safety chain, with the known risks that may arise along the way.

Process Steps	**Risks Incurred**
Before ordering & shipping	
	– The container is damaged despite approval - potentially dangerous containers are sent away (see below). – Inadequate sample control by the freight forwarder - the damaged container is sent away. – Misunderstandings in the categorization of goods – resulting in potentially unintentionally dangerous mixing of goods means that goods are packed inappropriately or together with incorrect goods in the container and placed incorrectly on the ship.

[46](http://www.natcargo.org/Holistic_Approach)

	– Deliberate incorrect declaration of goods - the container is handled incorrectly throughout the logistics chain (when packing and location at port and ship). Improper placement on the ship, e.g. in the hold instead of on the open deck, with a high probability that the fire is detected later and develops more seriously, e.g. because the content is unknown and combat is hampered. – Damage to the container is incorrectly assessed - can lead to the container contributing to an unforeseen and serious development of a fire. Structural defects can lead to early collapse and thus more powerful development of fire. Defective rubber gaskets, holes in the sides of the container or floor can cause early fire spread due to increased oxygen supply to the burning contents of the container. – Goods are packed incorrectly (e.g. poor fastening), - goods are damaged, e.g. if cardboard boxes collapse and high-pressure gas bottles collide with each other or with the other goods in the container. This can start a fire or cause the contents of a container to catch fire earlier than with proper storage.
Shipping	
	– Misunderstandings in the categorization of goods – (see above). – Improperly-declared goods - intentional and unintentional – (see above). – Goods are packed incorrectly (e.g. poor fastening) – (see above). – Accidentally dangerous mixing of goods – (see above.) – Delay carries the risk of degradation and self-ignition. There may be a delay of the ship, if the port does not have the capacity to handle the goods, or at the port if the container arrives late or the port lacks capacity. There are examples of self-ignition of chlorine compounds and other chemicals, cable debris, batteries, charcoal and cotton, which may well be due to delays. However, this is not documented in this report. According to oral information from a Danish shipping company, delays are more the rule than the exception. Once a container experiences its first delay, it is normal for the delay to extend on during further transport, – Damage occurring in transport, – Unaccounted environmental fluxes
Shipment	
	– Goods are packed incorrectly (e.g. poor fastening) – (see above). – Delay carries the risk of degradation and self-ignition – (see above). – Incorrect reading (e.g. shock, incorrect placement, overlooking incipient self-ignition) or lack of attention from the port staff can lead to containers, where the contents are already in self-ignition and therefore radiate heat, being overlooked in the rush, and be loaded on the ship anyway.
In case of fire and post-fire	
	– Inadequate or late detection of fire - Most common detection systems for cargo holds are smoke detection associated with the

	ventilation system. In most fires, it has been found that this detection is uncertain, both in terms of time and location of the fire. This has meant that the fires have time to develop to a size where it is difficult and extremely dangerous for the crew to fight the fire once the burning cargo hold has been located. – Defective fire extinguishing equipment. There is also agreement among all actors with whom the project has been in contact that the requirements for fire-fighting equipment have not kept pace with developments and that CO2 extinguishing is no longer sufficient to deal with the fires on the ever-larger ships. The CO_2 extinguishing equipment originally became a requirement for cargo ships from before the time of container ships, and the international community has not yet agreed on common requirements for more modern systems. However, new forms of firefighting have been developed, e.g., the Danish Hydro-Pen, just as several classification societies (including DNV-GL, BV and ABS) have launched new notations for enhanced fire safety on container vessels. – Inadequate training – Ship's officers and crew hold the mandatory STCW required Fire-fighter training, however this may not be adequate for all types of fires which can occur. – Inadequate communication – Communications may be hampered during an incident due to equipment inadequacy or malfunction, or cultural differences between nationalities. – Too dangerous extinguishing - Access to the container ship's cargo hold is only available via cargo hatches from the deck.

5.5 Outlook and Forecast

The Danish government's aggressive ambitions for CO_2 neutrality exceed both the global and European Union's goals, with targets of 70% emissions reduction of 1990 levels by 2030 and with full carbon neutrality achieved by 2050 at the latest. This strong green environmental policy will also impact shipping and the global container fleet.

The IMO is currently developing a Carbon Intensity Code, which will provide the framework for the Rating of ships (using a scale from A - E) based on several Carbon Intensity Indicators, including a new Energy Efficiency Existing Ship Index (EEXI) for the current fleet and the Energy Efficiency Design Index (EEDI). The Carbon Intensity Code is anticipated to become mandatory for all contracting governments by 2026.

The demand for Zero-carbon fuel supply is anticipated to have a great impact on the future demand for new vessels, and help drive technological development in greener technologies. This development must include safety consideration assessments made outside of the current rules and regulations, considering the hazards that new fuel types and systems introduce, following a Risk-based design approach.

Danish maritime companies, including; ship designers, shipyards, ship-owners and operators, equipment manufacturers, research institutions and Classification societies, all play an important role in this development as part of the Container Shipping value-chain. The Blue Denmark's high level of cooperation on innovative and environmentally friendly solutions, through project collaborative networks such as Green Ship of the Future and Shipping Lab, and in the technical committees of both the Danish Ship-owners and Danish

Equipment Manufacturers associations, provide the right milieu for sharing best practices and developing new innovative solutions in addressing Container fire safety.

Going Forward

The overall purpose of the DBI CONTAIN project is to highlight the issues connected to fires in the cargo holds of container ships, and thus reduce the loss of property and human life. This results in a derived effect in the form of greater credibility for the container industry in relation to taking fire safety seriously.

During the past 18 months, DBI has discussed the challenges of container ship fires with a number of Danish and international stakeholders, covering most of the supply chain (logistics, ship owners, insurance companies, manufacturers etc.). The pilot CONTAIN project has developed new knowledge and increased awareness on the complexity of container ship fires in cargo holds. It also helps paving the way for the Blue Denmark to take a major lead in, and have influence on, technical solutions of the future and their applicability in the whole container shipping supply chain.

While it was beyond the framework of this pilot project to examine the economic impact on Blue Denmark of fires on container ships, this is a very relevant aspect to understand when considering this challenge and warrants further work. In addition, it could be a potential future task for Blue Denmark's innovative cooperation, to investigate the business case by promoting logistical and technological solutions for greater safety and thus result in fewer and smaller fires.

To go further in addressing this, DBI recommends creating a strong consortium of Danish maritime companies, including; ship designers, shipyards, ship-owners and operators, research institutions, insurance underwriters and Classification societies, to address the challenges on fire safety facing the global Container industry. DBI seeks support for a number of future activities that will partly expand and disseminate the available knowledge on fires in cargo holdings on container ships, and will also contribute to a central Danish position in an consortia that develops new solutions to strengthen fire safety on container ships globally.

Given the many companies across the Blue Denmark who have important roles to play in the Container value chain, DBI believe there exists a great potential here in Denmark, to impact and improve the fire safety of containers and the ships which carry them all around the world.

5.6 Summary and Conclusions

This chapter describes the Blue Denmark's role and importance in the global container shipping logistics chain and including the opportunities to contribute solutions.

The Blue Denmark is widely represented in container shipping with the representation of shipping companies with a significant fleet, freight forwarders, designers, equipment manufacturers, manning with Danish trained ship officers, the operation of ships as well as a maritime strong flag state, and this includes opportunities to focus on fire safety and to make bids for new technology, safer logistics and a new mindset that can help break the chain of diffused responsibility that characterizes the logistics chain. The Blue Denmark has a strong innovation environment, which through projects and partnerships can make this happen.

The size of container ships has grown dramatically (22,000 + TEU, in 2018), but the IMO regulations & codes, rules from Class, as well as standards for design, container construction, fire safety and fire training in relation to the types of fires we know today have been followed. All stakeholders with whom DBI have been in contact with, in connection with the CONTAIN project agree that the current rules are inadequate and some even outdated. At the same time, however, this situation also presents a fantastic opportunity to influence future standards and rules.

The logistic path of a container from A – Z in the global shipping market is a complex process, and the complexity of the supply chain is in itself a major fire risk due to many links and diluted responsibilities.

Delays of the container along the way also have a major impact on the fire risk, partly because an early delay typically leads to further delays, which can lead to the initiating self-ignition of both organic and inorganic materials as well as chemicals. The long supply chain creates an accumulated risk of fire, as the many links in the chain can contribute new risks.

The physical condition of each container, both when newly produced and throughout its lifetime, and the link between damage to containers and the emergence and spread of the fire has not been adequately investigated. This may be a result of both the low price for a single container and the low freight rates, which make it unattractive to strengthen the fire safety characteristics on the container itself. Here there is potentially an area for innovative Danish companies to explore.

6 Technical Fire Scenario Research

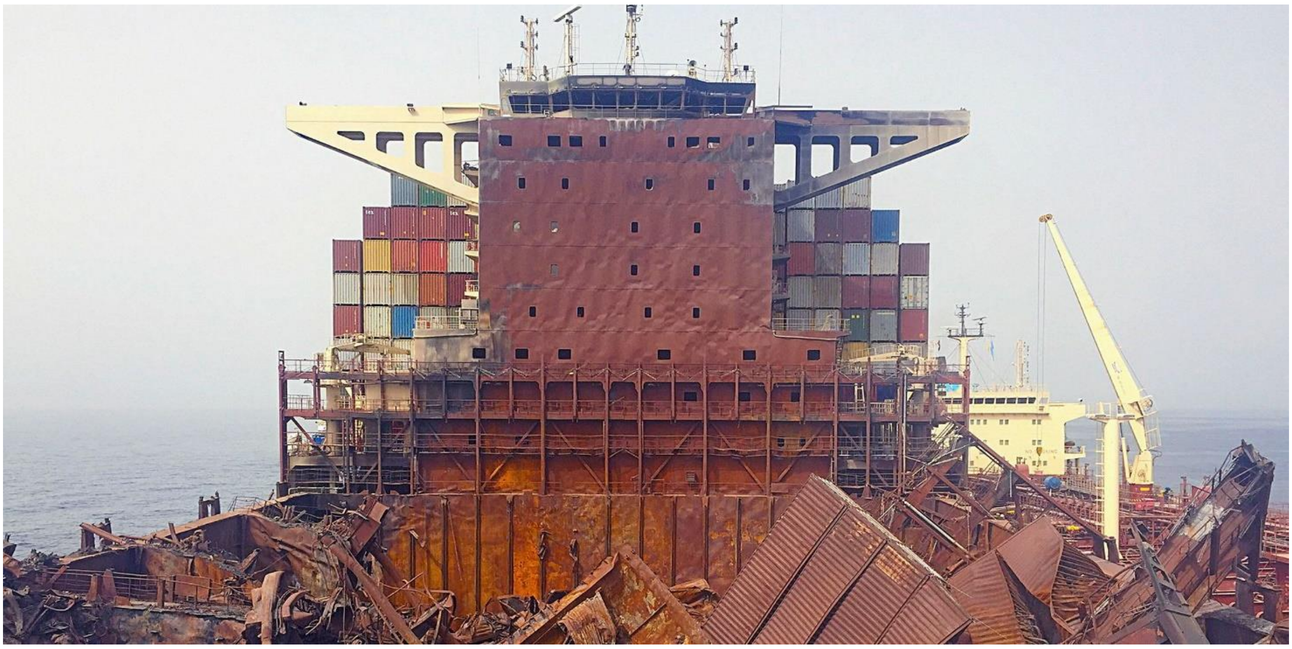


Photo from the accident report into the MAERSK HONAM fire. (Photo credit: Smit)

6.1 Introduction

As described earlier in this report, the team at DBI is working with merging technical knowledge, typically gained through fire tests, fire simulations, codes and engineering practice, and knowledge based in the social sciences, often obtained through qualitative fieldwork.

This chapter outlines the technical investigations performed as part of this research project. During the investigatory phase of this project, it was observed that most work performed on this topic takes a “top-down” view on solving the underlying problems in the industry. In this section, we take a “bottom-up” approach, considering both technical and social point-of-view. First investigating “how a fire may spread from an initial container of origin”.

This approach was taken as through the literature research this question remained still largely open. It was therefore decided that more focus should be taken on understanding the mechanisms that form the conditions for a large fire event to occur, before posing potential solutions. Setting the foundation on “understanding” and highlighting methods that can take this knowledge and apply it to look for potential solutions is therefore the overall goal of this chapter. This is undertaken through a variety of approaches, including experimental investigations, investigating the feasibility of using simulation tools, and reviewing current requirements on fire protection systems within container ships.

6.2 Fire Spread Hypotheses

In this section, the hypotheses that were developed on 'how a fire can spread from one container to another' are outlined. These were based on the knowledge obtained from the literature review, background expertise within DBI and interviews with experts. Hypotheses outlined in this section are based on the assumption that a fire occurs inside a container. Previous research (e.g. SAFEDOR[47] - EU-FP6, 2010) showed that fires can be hard to sustain within a container due to e.g. lack of oxygen, however experience shows that they can still occur via whatever means (refer Chapter 3), thus how an initial fire occurs is ignored, and rather the focus here is on what happens next i.e. spread to neighboring containers.

Developing a set of hypotheses on fire spread mechanisms is the first step in obtaining answers that are quantitative, and that can provide insight not only into how these fires spread, they can also showcase weak points in the environment (e.g. the container itself and the cargo hold it is kept in), and highlight potential prevention opportunities. In addition, they provide valuable information for the subsequent modelling that may be performed – "*A model is only as good as the data that it uses as input*".

One important issue to note is that spread due to explosion was considered out of scope for this investigation, the focus instead has been on assuming a fire occurs in a container and if this occurs, what the subsequent spread mechanisms may be. Explosion is however a very probable cause of container integrity failure which will accelerate potential spread to other containers, however spread mechanisms after such an event means that the below investigations are also relevant for this type of scenario.

6.2.1 Hypothesis 1: the plywood floors are a source/mechanism that allows fire spread between containers.

The basis for this hypothesis took inspiration from the article in "ship technology research VOL. 57 pg. 40-55" – Fire investigation in a container.
Hypothesis 1 timeline:

- Fire starts in a container
- Begins to heat steel roof
- Heat transfer from the steel roof to the above plywood floor results in fire spread with ignition of the plywood due to radiation;
- Burn-through and heat transfer from the plywood floor ignites materials inside container
- Fire growth in this container is accelerated due to openings in floor
- Process continues

Taking this hypothesis as a basis, a list of more detailed questions is then outlined below. These are questions that can provide us with the answers required in order to confirm or deny the likelihood of the hypothesis.

- What is the ignition temperature/critical heat flux/auto-ignition temperature for the plywood used in the containers?
- What is the required temperature of the steel roof of one container to provide the critical heat flux require to ignite the containers plywood floor above?
- Burn through time of wooden floor?

[47] http://www.safedor.org/index.htm

6.2.2 Hypothesis 2: Fire Spread is likely to occur through the door of the container.

This hypothesis is based on a discussion with staff at the fire school in Helsingør.
Hypothesis 2 timeline:

- Internal fire
- doors heat up and begin to radiate heat
- any combustible material on the door decomposes
- doors lose their integrity, warp and then lets fire and heat out to a larger extent, thus making the spread of fire more likely both horizontally via radiation or vertically via flame impingement.

6.2.3 Hypothesis 3: Fire spread is likely to occur horizontally through the wall sections of the container via radiation.

This hypothesis is formulated from knowledge of heat transfer in steel.
Hypothesis 3 timeline:

- Internal fire
- Walls heat up
- Walls radiate energy to neighboring containers
- Ignites combustible contents of neighboring containers
- Process then continues the transfer of energy to its neighbors.

6.2.4 Hypothesis 4: Plastic vents on the side of containers contribute to the fire spread.

This hypothesis is based on a discussion with staff at the fire school in Helsingør.
Notes:

- Vents are made of plastic thus combustible
- Vents are in the same positions, thus align with each other, potential giving a "weak" point for spread between containers

6.2.5 Hypothesis 5: Structural collapse/deformation from internal heating is the cause of fire spread.

This hypothesis is based on the question: If a closed container cannot spread fire through radiation/leakage, maybe only a damaged one can?
Notes:

- In all the previous research no fire got hot enough to damage the structural integrity of the container significantly. How hot must the container get before it loses its structural integrity?

6.2.6 Hypothesis 6: External fire in the cargo hold may be the cause of fire spread.

Based on conclusions from research article: "Fire performance of intermodal shipping containers"[48]
Notes:

- In this article the authors make a statement that "in an interior fire within an undamaged, sealed container will self-extinguish due to oxygen depletion" thus is unlikely to cause fire spread. Can we confirm this?
- If only an external fire is needed to spread fire to neighboring containers and their contents, thus plywood floors do not contribute to the spread of fire,
- An external fire can cause fire spread and structural collapse after as short as 5 minutes,
- Is there any other combustible material in the cargo hold that can burn?

[48] Fire Performance of Intermodal Shipping Containers, Eberly R, Merchant Marine Technical Division , US Coast Guard, Washington DC, 1977

6.2.7 Summary

From these 6 hypotheses, the first 3 (H1, H2 and H3) were deemed the most significant, and thus it was chosen to investigate these experimentally. Hypotheses 4,5 and 6 could be looked at by other methods initially (e.g. simulation – refer section 6.7), and a decision from there could be made if they also required experimental methods.

6.3 Experimental approach

6.3.1 Summary of test methods

Three different testing methods were chosen/designed to investigate H1, H2 and H3. Below provides a brief summary of each. More details, are provided in subsequent sections or in the relevant appendices.

- The cone calorimeter; this is considered a small-scale test, and an efficient way to investigate the fire behavior of the plywood flooring, as samples required for testing are small in size, thus, the tests are relatively easy and inexpensive, which allows for a large number of individual tests to be performed. The reader is referred to Appendix A for the full test report.
- The second test method involved performing a larger scale (50 cm X 50 cm) test, on the so-called "mobile furnace"[49]. In this apparatus, a more realistic setup can be tested, in which the steel sheet from the roof of the container below is placed on an electric furnace and heated to a set temperature. A piece of the sub-structure of the purchased container was then placed on top of this to replicate the actual spacing between the roof of the container below and the plywood floor of the container above. The plywood floor section was then place on top of the steel sub-structure as it would be in an actual container setup. The reader is referred to Appendix A for the full test report.
- The third method - the full-scale fire resistance furnace; this is a furnace with dimensions of 3 m X 3 m X 3 m, this is primarily used for large scale fire tests of construction systems, e.g. doors, walls. The size of this furnace allowed the testing of the full door section of a container. This test simulates a full-scale fire event occurring inside a container, in order to test the ability of the door to withstand/enable fire spread for such an event. Measurements of door temperature and radiative heat flux taken in this test can also be applied for investigating H3, hence it is also included here. The reader is referred to Appendix B for the full test report.

[49] DBI

6.3.2 H1 Experimental Methodology

In this section the testing methodologies for both test series are briefly described. The reader is referred to the appendices for a more complete description of each test series.

6.3.2.1 Cone calorimeter tests

All tests were carried out in the cone calorimeter (Figure 8 – Schematic of cone calorimeter apparatus). In this apparatus a conical shaped heater emits radiant heat to a specimen which is positioned 25 mm below. The heat exposure is defined at the start of a test and remains constant throughout its duration. A spark ignitor is positioned above the sample to ignite any flammable gases, at which point the time to ignition is recorded. The post-combustion gases are collected and measured in the exhaust above to enable calculation of the amount of heat released by a material. The mass loss rate of a specimen is also recorded using a scale.

Specimens of dimensions 100 x 100 mm were placed under the cone heater in the horizontal orientation. Three different radiant heat levels were initially chosen – 50, 25 and 15 kW/m2 – which correspond to high, medium and low levels of heat exposure respectively. And additional heat flux level of 35kW/m2 was later added to due to the uncertainty in ignition times recorded at 15kW/m2. Tests were otherwise performed according to the standardized procedure given in ISO 5660.

In order to assess the performance of the plywood, there are a number of parameters which are evaluated. These are described in Table 2.

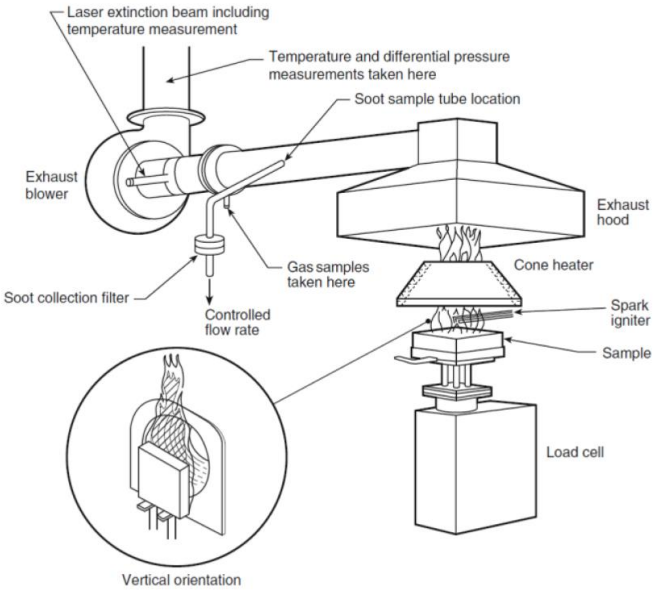


Figure 8 – Schematic of cone calorimeter apparatus

Table 2 – List of key parameters obtained from the cone calorimeter

Key parameters	**Description**
Heat Release rate (kW/m2), HRR	The HRR is the time dependent measured release of energy from the specimen as combustion takes place
Peak heat release rate (kW/m2), PHRR	The peak heat release rate is a measurement of the greatest amount of heat release from a sample, which typically occurs shortly after ignition. It is often considered one of the most critical parameters since it can affect whether a room will develop from a small fire into whole room burning.
Time to ignition (s), tig	This gives a measure of the ignitability of a material. It is also critical in evaluating whether a material is capable of supporting flame spread, and whether a room will develop into whole room burning.
Total energy (heat) released (kJ), THR	A summation of the heat released over the full duration of burning. This gives an indication of how much the lining contributes to the fuel loading in a compartment.
Mass Loss Rate (kg/s), MLR	The rate at which mass is lost from the sample as it goes through the pyrolysis/combustion process.
Other terminology	
Incident heat flux (kW/m2), IHF Also heat exposure, radiant heat flux, heat flux, heat level, radiation	Amount of heat transferred from the cone heater to the surface of the sample.

Materials

It was discovered when purchasing a container for experimental purposes, that the floor was not a single material, but was made up of a patchwork of various plywood sections – varying in age, condition, materials, and surface treatments as shown in Figure 9 – floor of purchased container below.

The reader is referred to Section 4.11 on container purchasing experience, Appendix F - Container Acquisition – Seaworthiness and condition and Appendix C – Damage Mapping report

Figure 9 – floor of purchased container

Figure 10 illustrates where the various samples used for cone testing (blue numbered squares) and mobile furnace testing (white squares) were taken from the floor.

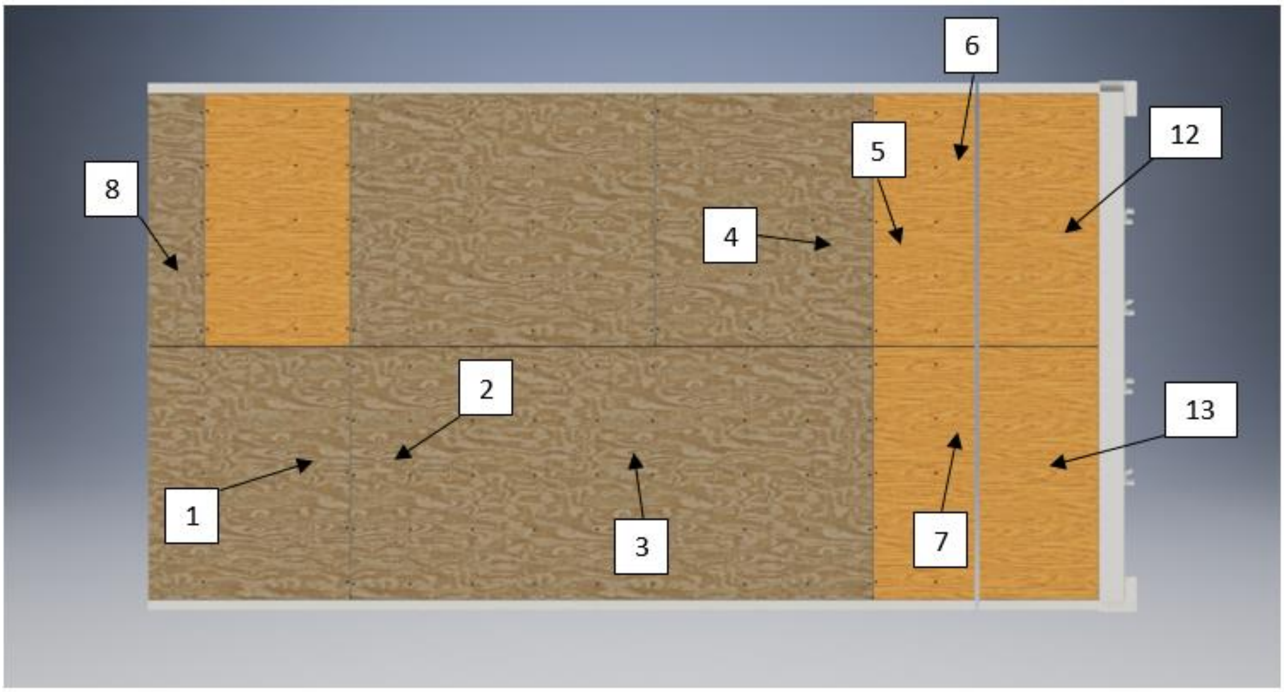


Figure 10 – sampling location on the container floor

Figure 11 – examples for plywood samples illustrates some examples of the differences in plywood materials extracted from the floor of the purchased container. Differences were not only visually observable, i.e. in appearance or having surface treatment (e.g. asphalt layer for water proofing) or not, densities were also recorded as varying significantly with values ranging between approximately 600 and 900 kg/m3.

Figure 11 – examples for plywood samples

Experimental design

A total of 41 experiments were performed in the cone calorimeter. Table 3 outlines the scenario tested (pilot or non-pilot ignition or damaged sample), the heat flux applied (in kW/m2) and the sample ID (X—Y) where 'X' indicates where the sample was taken from (refer Figure 10). 'Y' is the sample number i.e. 6—2 indicates a sample taken from position 6, and is the 2nd sample tested from this location. Mass in grams is also included.

Table 3 – Experimental Design

Scenario	heat flux	sample ID	Mass (g)
Piloted ignition			
	15	6—2	194.9
	15	3—4	245.5
	15	12—4	210
	15	13—3	231.1
	15	5—3	192.3
	15	8—5	194.7
	25	3—2	258.9
	25	2—3	268.2
	25	3—3	263.9
	25	13—2	221.3
	25	4—1	258
	25	8—2*	201.9
	25	12—2*	218
	25	8—3	199.2
	25	6—1	208.6
	25	8—4	196.2
	25	12—3	226.6

Scenario	heat flux	sample ID	Mass (g)
	35	6—3	197.9
	35	4—2	247.4
	35	13—4	224.1
	35	3—5	244.3
	35	8—6	184.7
	35	12—5	219.4
	50	8—1	198.3
	50	3—1	260.2
	50	2--1	255
	50	2—2	260.5
	50	5—1	213
	50	12—1	222.1
	50	5—2	210.5
	50	1—1	239.8
	50	13—1	227.1
damaged samples			
	50	8-D-1	181
	50	12-D-1	216.9
	50	4-D-1	258.6
self-ignition (non-piloted)			
	50	12-S-1	200
	50	13-S-1	213.3
	50	8-S-1	188.1
	25	12-S-2*	228.9
	35	12-S-3	215.4
	35	8-S-2	181.5

* Some data was lost, or measurements malfunctioned in these tests, thus they are not included in the results section.

Mobile Furnace

This small scale test's primary focus is to investigate a part of a container flooring exposed to radiation from a steel plate. This setup aims to simulate a section of a container standing on top of another. The Mobile Furnace is designed for conducting small scale resistance to fire type experiments. It is electrical heated and equipped for continuous sampling of surface temperatures, furnace temperature and running heating programs using automatic furnace controls. Temperatures are sampled with approximately 0:8 Hz.

Test sample design

An ISO container is designed to carry all weight at the corner posts, and the corner castings are the only contact surfaces of stacked containers. A 50 mm gap is allowed between one container's top and the lowest part of an adjacent container's bottom structure. The bottom flooring structure is made of a steel frame and steel crossbeams boarded with 28 mm plywood plates.

A section of the floor structure from the purchased container was cut out to match the size of the furnace chamber, and a section of steel plate was added underneath this to simulate the roof of the container below, this configuration (as shown in Figure 12was then placed on top of the furnace and insulated with mineral wool on the sides to avoid excessive heat loss as in Figure 13 (full details are provided in APPENDIX A.

Figure 12 – test sample design

Figure 13 – test sample in place on the furnace

Measurement equipment

Instead of using the main thermocouples inside the furnace for heat control, three thermocouples were welded on the top plate's unexposed side as a control instrument, such that the top plate could act as the heat exposure. The controlling temperature was set to 620C with a warm-up time of 20 minutes.

A total of 8 thermocouples were using to measure temperature of the sample and environment in the test. As shown in Figure 14, 5 of these were mounted on the unexposed side of the sample and 3 additional thermocouples were positioned in the cavity between the plywood floor and the steel plate, one through a drilled hole, one hanging, and one placed between the mid beam and the plywood

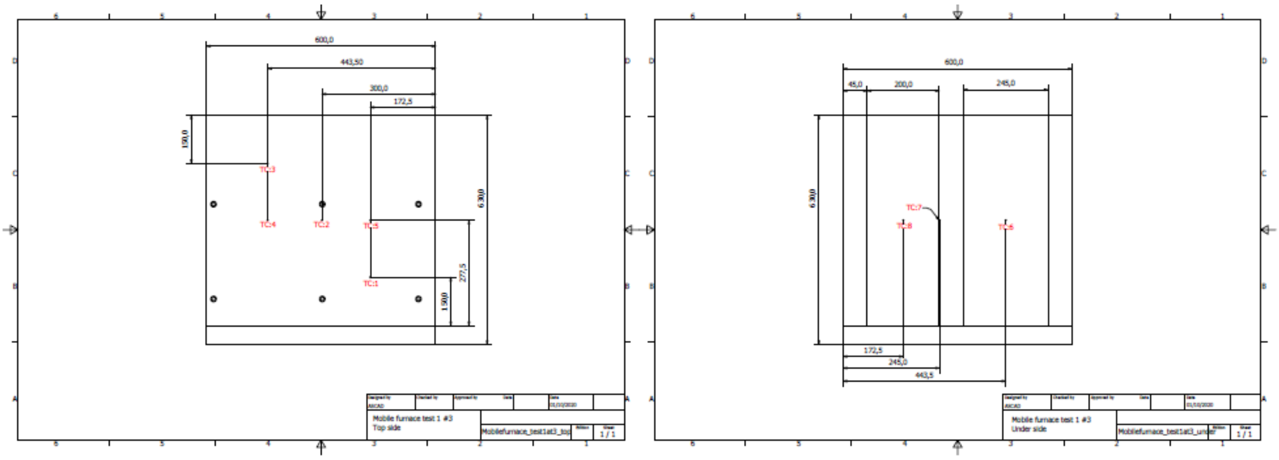


Figure 14 – Thermocouple placement

A thermal camera was used for recording the heat distribution on the plywood unexposed side (the camera was mounted with a delay of 5 minutes, with respect to the test start).

6.3.3 H2 & H3 Experimental Methodology

Full scale furnace test

The full scale fire resistance furnace; is a large furnace with dimensions of 3m X 3m X 3m, this is primarily used for large scale fire tests of construction systems, e.g. doors, walls. The size of this furnace allows testing of the full door section of a container. This test simulates a full scale fire event occurring inside a container, in order to test the ability of the door to withstand/enable fire spread for such an event. A Full detailed test report is provided in APPENDIX B.

Sample preparation

For this test the end section, including the door leaves and frame, were cut off from a 20-foot seaworthy container and placed in a designed test frame as shown in Figure 15. The test frame was constructed with aerated concrete with a hole slightly larger than the dimensions of the door section.

Figure 15 – door and testing frame

The door section was mounted in the test frame and the surrounding gaps between the container and the concrete was isolated with mineral wool and ceramic wool. The remaining plywood flooring was removed and gaps between the steel cross members isolated to avoid heat loss. The test frame was then mounted vertically on front of a fire test furnace as shown in Figure 16.

Figure 16 – Door mounted on furnace

Test procedure

The test was run for approximately 90 minutes and the furnace temperature set to follow the ISO 834 standard fire curve as shown in Figure 17.

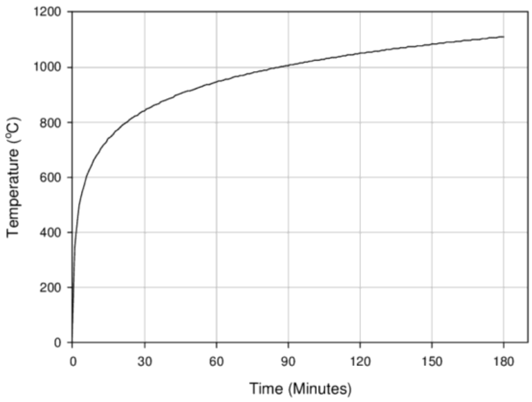


Figure 17 – ISO 834 standard fire curve

Measurement equipment

Temperature measurement:
Equipment to monitor temperatures of the unexposed side of the door and various specific door elements included both thermocouples as well as a thermal camera.

A total of 31 thermocouples were attached to various locations on the door and door frame as per Figure 18. Thermocouples were split into 5 groups, located similarly as for standard test of a double door except the thermocouple group number 4 which was placed on the sides of the door frame. Group 1 was mounted on the panel of each door leaf, Group 2 on the external container structural frame, Groups A3 and B3 where located at the left and right door frame respectively.

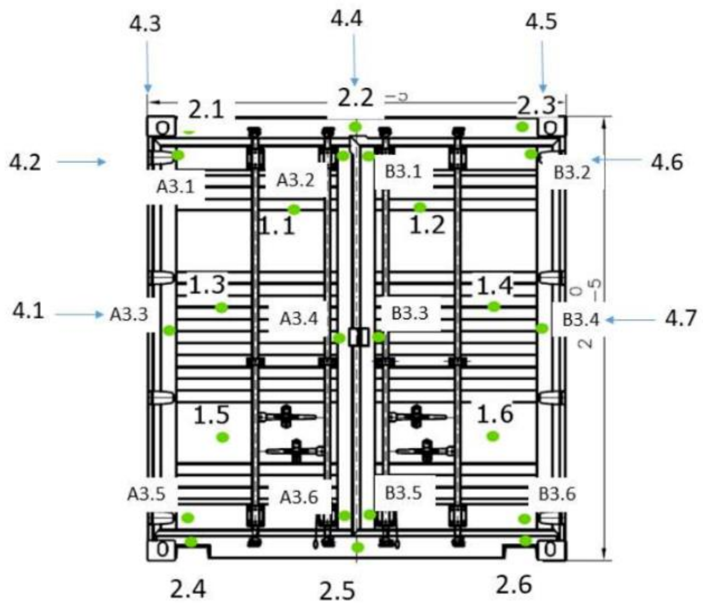


Figure 18 – Thermocouple placement on door

Other measurements:

- Deflection measurements (i.e. how much the door bends or warps during the test) was monitored via a specialized deflection camera, which measures specifically designed nodes that are attached to the unexposed side of the door at locations shown in Figure 19

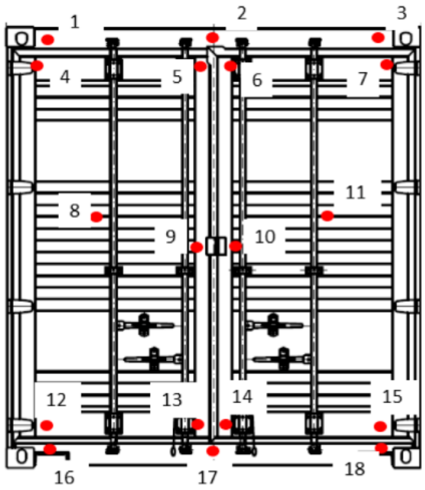


Figure 19 – deflection measurement point placement

- Heat flux (predominately radiative heat flux) was measured via 2 heat flux meters; R1 and R2 which were located centrally, at a distance of 1m from the unexposed side of the door at heights of 185cm and 102cm above the container floor level.

6.4 Results

This section briefly summaries the results from the experiments described in the previous sections. More detailed results may be found in the APPENDICES A, B and C.

6.4.1 Cone calorimeter

Generally, based on the test data, there are two distinct phases of burning for each specimen, as exemplified in Figure 20**Fejl! Henvisningskilde ikke fundet.** and in the report in APPENDIX A. Upon ignition, there is a large amount of heat release (initial peak). Following this, a char layer forms and the rate of heat release drops significantly. Once the char reaches a certain thickness, there is a second phase where the burning is relatively constant or steady.

Tests were run for between 20-30mins and not run until all of the materials was burned, this was mainly due to time constraints, and the observation of steady burning after the initial peak, which is expected to extend until close to material completion. Also, due to the test setup, it is generally considered that towards the end of a test, results are less reliable as artefacts from the test setup (i.e. the sample holder) begin to effect the results.

Figure 20 below shows the test results for samples tested at 50kW/m2. The legend can be read as follows: Test X-Y-Z, where X is the incident heat flux tested at (e.g. 50kW/m2), Y is the sample location, according to Figure 10 and Z is the test number e.g. “3” indicate this is the 3rd sample tested from this location. For full report refer APPENDIX A.

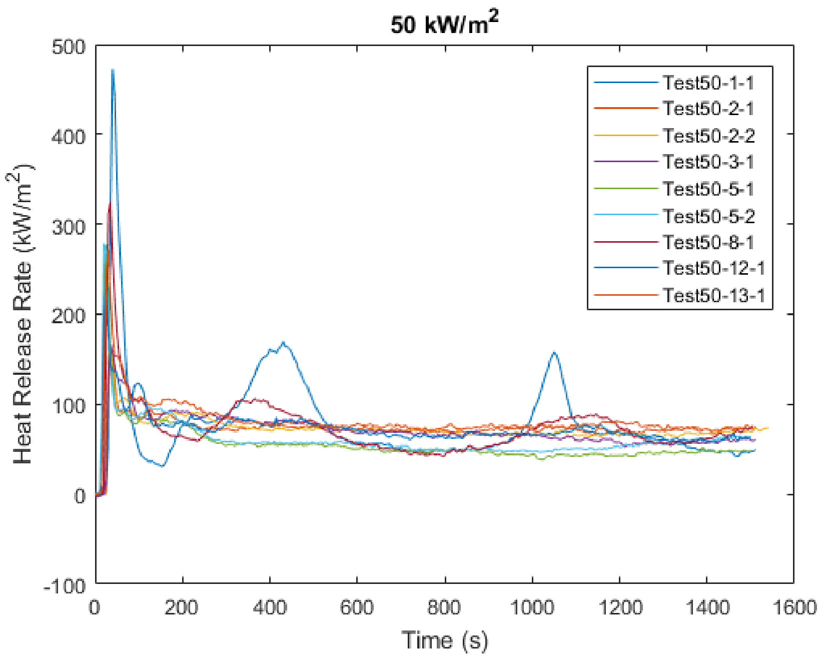


Figure 20 – heat release rates for all samples tested at 50kW/m2 incident heat flux.

6.4.2 Mobile Furnace results

The test ran for 100 minutes at the temperature of 620 °C with 20 minutes warm-up time. As shown by the sharp increase in temperature values in Figure 21 – Temperature reading from the mobile furnace test, ignition occurred after 23 minutes at temperature around 350 - 400 °C starting with green blue colored flames at the surfaces closest to the exposure.

Soon after ignition flames were detected in the whole cavity as can be seen by the fluctuation of thermocouples 6,7 and 8. flames were noticed at the steel members where tare was also dripping down. The fire maintained during the test, smoke was coming from junctions of the steel frame and plywood and increased when the rubber seal was melted away.

The temperatures at the unexposed side of the plywood showed uniform increment for the test period up to 75 °C. For full report refer APPENDIX A.

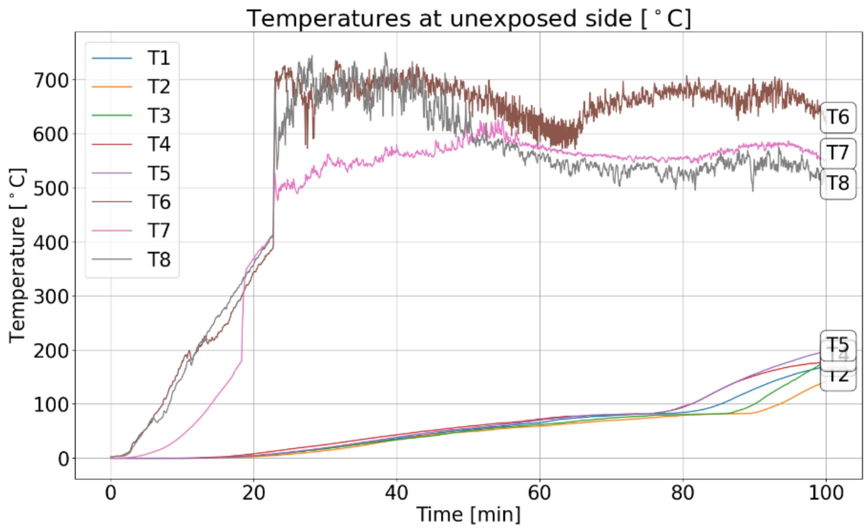


Figure 21 – Temperature reading from the mobile furnace test

6.4.3 Full scale Furnace results

The results show that deflection of the steel structure occurs mostly during the temperature increment at the beginning of the test, the door section tends to bend in to the furnace at the middle with a convex form. The EPDM rubber door gasket caught fire (refer Figure 23 – Ignition of rubbers seal around doors at 17minutes) after approximately 17 minutes around the temperature of 300 °C, with visual flames for approximately 20 minutes.

After the flames had gone out the temperature increased uniformly until the test was stopped after 90 minutes. The highest temperature reading is found to be at ”TC 1.6” placed on the panel of the right door leaf. The lowest maximum temperature is at ”TC 2.2” placed in the middle of the upper structural frame. The paint delaminated from the steel during the test period. The radiation was measured at two different heights one meter away from the furnace in front of the door leaf junction, with the maximum radiation values of 19.66 kW and 17.74kW.

Examination of the remain door structure showed no major deformations or damages, other than an approximately 2 cm gap was around the door leafs where the door gasket was, functioning parts as door hinges and locking bars were in functional shape. For full report refer APPENDIX B.

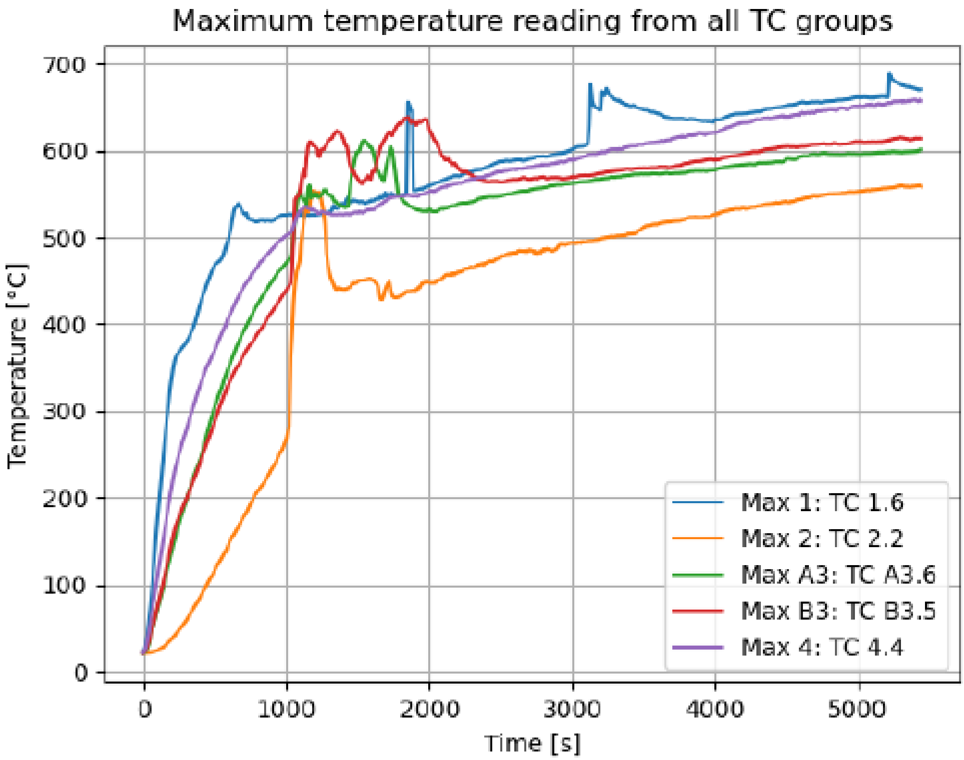


Figure 22 – Max temperature curves for each thermocouple group

Figure 23 – Ignition of rubbers seal around doors at 17minutes

6.5 Discussion / Summary of findings

In this section the outcomes of the experiments are discussed and what they mean with relation to the original hypotheses.

6.5.1 Cone Calorimeter tests

Cone calorimeter testing was undertaken to investigate hypothesis 1 (H1), which was to determine whether the plywood floors of a standard type container could be a method of fire spread between containers. Tests were made to examine what the "minimum requirements" for this spread mechanism to occur could be, and how the floor behaves when it is exposed to various level of heat exposure.

Material Variation

Material variation observed in the samples obtained from the purchased container is an important consideration, as described previously, the container floor was not made from a uniform material, but was rather a patchwork of old and new pieces of plywood, with varying degrees of wear, bitumen coating, damage etc. Because of this, a large number of Cone calorimeter tests were performed in order to get an idea of how this variation also affected the fire behavior of the floor. As represented in the results from the testing, this variation visually observed also translated to a large variation in the fire performance. To highlight this, an example is taken for tests performed at 50kW/m2: peak HRR; which is the measure of maximum heat output during the test was shown to vary approximately between 150 and 500 kW/m2, which equates to over a 200% increase in peak output from minimum to the maximum results. The same is true, although decreasing in overall variation, for all the tested incident heat fluxes.

Another interesting metric to examine is the "time to ignition" (tig), here we see the opposite trend, with variation increasing as the incident heat flux goes from high to low. At 50kW/m2 tig varies from 17 to 34 seconds, at 25kW/m2 we see variation from 93 to 203 seconds, and at 15kW/m2 only half the samples actually ignited within the test period. However, taken as a %increase from lowest to high values within a given incident heat flux level we see similar increases of around 100% for samples tested at both 50 and 25kW/m2.

These results and more outlined in the APPENDIX A, highlight that the floor of these containers, really cannot be considered as one material, with a certain fire performance. It illustrates that the level of risk that these floors pose as a spread mechanism can be significantly varied, depending on the plywood it is composed from. The following points are highlighted as important observations from this:

- "Newer" plywood samples were less dense than older samples
- The "newer" plywood replacement sections were in general significantly worse, in regards to their fire performance than older sections tested. In both energy output i.e. peak HRR and in ignition times i.e. they ignited faster.
- Samples with the bitumen waterproofing coating in general gave higher peakHRR, and ignited quicker (although the newest samples without a coating also ignited fast)
- Damaged samples i.e. with impact damage, or some form of surface layer penetration/hole etc., did not act significantly different, however more testing would be required to fully confirm this.

Piloted vs non-piloted (self-ignition) tests

In the standard testing method, a pilot ignition source is presented just above the surface of the sample to ignite the combustible pyrolysis products that are volatilizing as the sample begins to thermal decompose. However, for this case it was considered prudent to also test the materials propensity to self-ignite, i.e. no pilot ignition source.

A piloted ignition cannot be ruled out, however this hypothesis relies heavily on radiation transport as the heat transfer mechanism between the steel roof and the plywood floor of the container above, therefore in order to test if ignition could still occur even without a piloting source, additional cone tests were also performed.

Self-ignition tests were performed at 50, 35 and 25kW/m2.

Results confirmed the following:

- at 50kW/m2 self-ignition would occur for both old and new samples tested.
- At 35kW/m2 self-ignition occurred in the new samples, but not the old
- At 25kW/m2 self-ignition did not occur
- Ignition times were no different to ignition times with a pilot. i.e. they ignited just as quickly.

This shows that again, the “newer” boards proved to be worse in terms of fire performance, however self-ignition tests were not comprehensive, only 1 old and 1 new type of sample that had given the worst results in the previous tests were tested in this way.

More comprehensive testing is recommended before more could be concluded.

Critical heat flux

One of the main purposes of doing the cone tests was to determine the “minimum requirement” for ignition of the plywood to take place, this can be translated to the determination of ‘critical heat flux’ (CHF) which is defined as the minimum heat flux to the surface of the sample required to get ignition.

The optimal way of determining this is to test samples at lower and lower heat fluxes until no ignition occurs, however the time requirement for this, means that tests are required to run for very long periods, which is not always feasible. Another method is to plot the inverse square root of the ignition time vs heat flux, and plot a trend line down to the intersection of the x-axis (heat flux axis) as in Figure 24.

Classical ignition theory states a the should be a linear correlation, however due to the processes occurring in the plywood, e.g. charring, a linear correlation may not be expected at lower heat fluxes, hence in Figure 24, a polynomial fit is used. Intersection with the x-axis is shown to occur approximately at 12kW/m2, based on this and that fact that ignition occurred only for some of the tested specimens at 15kW/m2, a CHF of approximately 10-12kW/m2 seems reasonable, this is also backed by previous research on similar materials[50].

[50] Gratkowski, M. & Dembsey, N.A. & Beyler, Craig. (2006). Radiant smoldering ignition of plywood. Fire Safety Journal. 41. 427-443. 10.1016/j.firesaf.2006.03.006.

This is a general conclusion using all the results together. However differences can be seen when samples are separated out, with results showing that "new" samples (e.g. sample ID: 12) will likely ignite at lower heat fluxes.

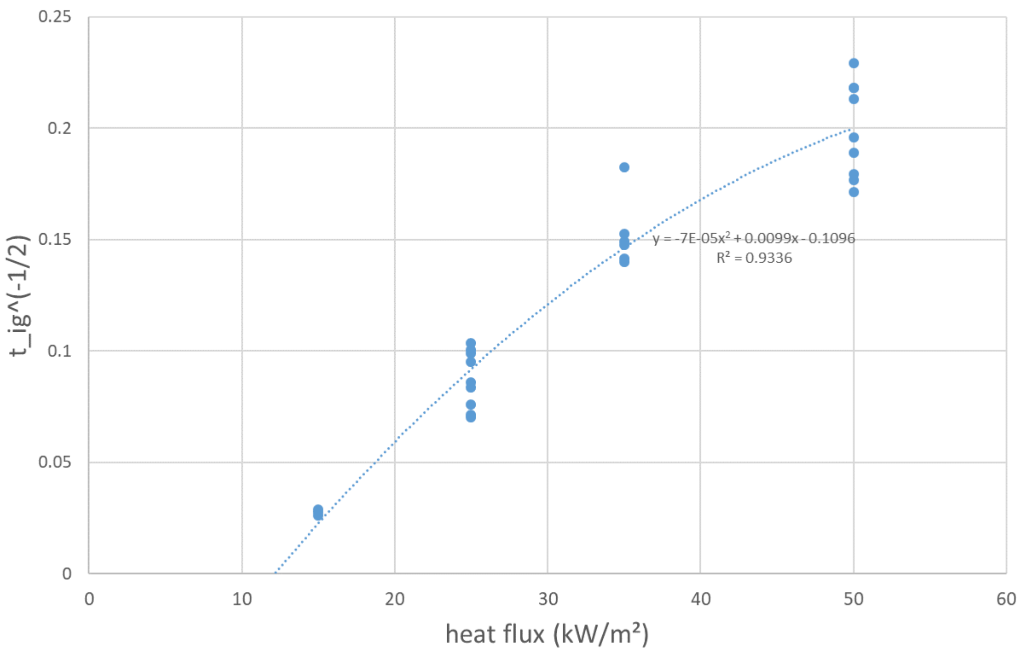


Figure 24 – Determination of Critical Heat Flux

6.5.2 Mobile Furnace test

The mobile furnace test was undertaken to confirm results obtained from the cone calorimeter testing, in a more realistic scenario. A steel plate was placed on top of the furnace, to simulate the roof of one container, and a portion of an actual container floor was cut to size and placed on top of this, with the prescribed spacing.

Given the distance between the plywood and the heated steel plate, using a basic radiation hand calculation, the chosen temperature of 620C equates to approximately 20kW/m2, this temperature was chosen as 20kW/m2 represents the lower side of the cone test results, however still above the CHF, thus ignition should have (and did) occur. 620C also represented a temperature within reason for the roof, given a fire inside.
This test confirmed that the hypothesis [H1] posed is definitely plausible. It showed that fire could spread from a hot roof to the container above, even without a specific ignition source being required. In addition, given the calculated CHF, it may be supposed that ignition may occur in this scenario down to temperatures as low as 500C for the steel plate ceiling.

Temperatures required may even be lower, as due to the steel support structure, hot convected air is pressed/trapped on the bottom surface of the plywood floor, thus providing more heat that has not been accounted for in these calculations (which only account for radiation). Indeed, ignition occurred in this test with measured cavity temperatures 350-400C.

6.5.3 Full scale furnace test

The door test was made in order to investigate the susceptibility of the door, when a fire inside the container occurs, this was posed in H2 as the question: is the door a plausible means of fire spread? What the results from the test showed was that the answer to this question is, yes. The reasoning behind this is due mainly to the data gathered from the test that indicates fire may spread from the door potentially via multiple mechanisms.

The term "*multiple mechanisms*" here can be broken down as the following:

- The radiation coming from the door got up to almost 20kW at 1m from the door. This alone may be sufficient to heat its neighboring containers enough to put them at risk.
- At 17 minutes into the test, the rubber seals went into almost spontaneous flaming, this constitutes as loss of barrier integrity, as flames from these burning rubber seals, not only add more heat, but may impinge on the container above, and even act as an ignition source for that containers plywood, as this floor is also likely to be heating up to a potential dangerous levels as shown in the mobile furnace test.
- Flaming droplets were also observed from either the burning rubber seals or the paint on the outside of the container, these can act as an additional spread mechanism, in this case to the lower containers.

Other results, such as the deflection measurements, showed that the door is relatively robust, deflection/warping was minimal, and after the test the door could still function as a door, including all the locking mechanisms.

Initially it was thought that the door may deform much more, leading to a big "escape route" for flames to come from, however this was not observed in this test, even though the door rose to temperatures above 600C in some locations.

6.5.4 Conclusions

Hypothesis 1: Based on all the results obtained from this test series, looking at the original hypothesis, it seems highly probable that the plywood floor could act as a mechanism to spread fire from one container to another in the vertical direction. The CHF has been determined as approximately 12kW/m2 on average, however this may be slightly higher or lower depending on the specific sample tested. Ignition was shown to increase in likelihood (i.e. be more easily ignitable), if the newer types of plywood were used, or if the bitumen layer was still present. These factor were also shown to increase the energy output from the plywood floor.

Hypothesis 2: Based on the door tests, it was shown that; assuming a fire develops within a container, the door is also potential method of fire spread, this is both due to the radiation it can transfer to the container opposite it, but also due to the external combustion of the combustible materials surrounding the door and the flaming droplets may help to spread the fire further.

Hypothesis 3: In addition to the findings above which address H2, data gathered from this test can also be applied to consider the scenario posed in H3. H3 – "fire spread is likely to occur through the walls via radiation". If it is assumed the walls will likely heat up similar to what was observed in the door test, this would mean that even higher heat fluxes may be radiating to the neighboring containers via the wall.

The reason for this is simply that they are closer to the walls, with gaps between walls of neighboring container being approximately 100mm (although this can vary ship to ship).

This distance is so close that you may even consider that the wall temperatures of neighboring container could simply follow those of the wall in which the fire is, simply with a slight time delay. Knowing that the walls can heat up like this, means that goods within these containers will quickly follow and reach their ignition temperatures leading to fire spread.

6.6 Future experimental work

The experimental work described in the above sections have been exploring 3 of the hypothesis first outlined at the beginning of this chapter. That work produced some worthy results, and has provided new insight that are not only important from a stand-alone point, but were a necessary step to allow further investigation from an experimental side, and also importantly, from a numerical/simulation side. The data created gives input for how to set up models that can be used to investigate further both fire spread mechanisms and associated risks, but also evaluate and improve fire protection systems and give input for more strategic topics, e.g. firefighting, life safety and decision support.

Looking further, many interesting and essential questions remain to be investigated. Further hypothesis testing, investigating the other potential spread mechanisms outlined at the beginning of the chapter is required to assess how they may contribute to the overall picture.

However, on top of this, the next big important phase is to investigate how all these mechanisms interact in a larger more realistic test environment. Fire spread has so far been investigated in a piece-wise manner, looking at individual mechanisms and evaluating their potential to be a cause of fire spread. In a “real” scenario, with a multitude of containers, within a cargo hold, these mechanisms will work together, and as discussed in the previous section, will likely feed, and/or feed on each other. Fire is generally a non-linear process, thus simply “adding” these mechanisms together will not be sufficient, chain reactions can occur, where one process feeds another, which then gives more back to the first accelerating this, and so on. This interaction between mechanisms is very important to understand, as it can have a significant impact e.g. how quickly fire can spread through a cargo hold, as spread between containers is likely to be an accelerating process, not a constant one.

Investigating this interaction between mechanisms, is not a small undertaking, and can really only be performed at a “real scale”, this means at a minimum; a multi-container test scenario, like that pictured in Figure 25, preferably within an environment that can also replicate that of a cargo-hold is considered highly relevant. Previous research on container fires, was often done in an open setting, which does not replicate these environmental conditions. Testing in an actual cargo hold would of course be the most ideal to investigate fire spread behavior on this scale. This type of real situation testing (i.e. in a cargo hold) can have a number of other advantages, rather than performing experiments with one goal e.g. fire spread, other sub categories of tests can be performed simultaneously.

This includes; producing validation data for simulation tools – which is very important to increase the confidence in the outcomes produced by simulation, and gauge its performance. It also would allow tests of various detection, and potentially suppression systems to be undertaken simultaneously, which can be very valuable in terms of better understanding the real world performance of these systems, and testing new technology. Earlier detection has been cited in many forms[51] as part of the pathway to reducing the consequences of fire on board container ships, thus having the ability to test new systems in a very realistic scenario could bring much added input to this debate.

[51] Addressing the regulatory deficiencies - Helle Hammer, Chair IUMI Policy Forum, Gard conference on container ship fires - Arendal, 18 October2019

In terms of data capture, the learning obtained from these experimental series means that for future larger scale testing, tracking temperature evolution through the container stack should be sufficient as a means to track the fire spread. Temperature criteria can be set according to critical temperature for various relevant materials in order to track ignition and spread, similar to principles followed in other fire research areas to do with fire spread[52].

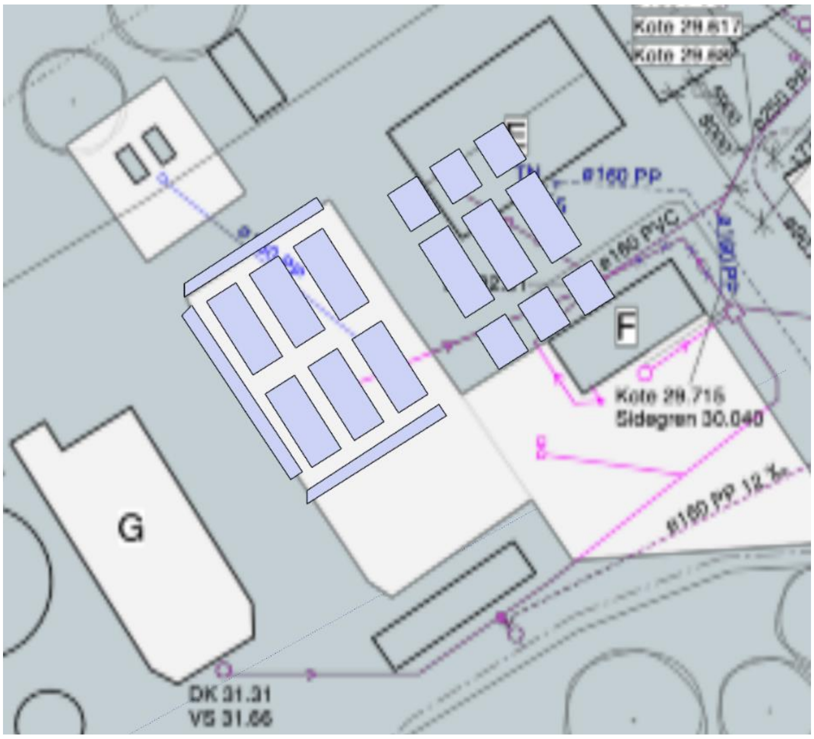


Figure 25 – possible alternatives (using 40ft, or 20 & 10ft containers) for minimum requirements to investigate interactions between mechanisms and rate of spread from container of origin
[note: container stacks should be at least 3 high].

6.7 Modelling and Simulation approach

One of the original purposes of this project was to investigate how fire simulation can give insights into how fire and smoke can spread within a cargo hold, and how current fire protection methods e.g. detection and suppression, perform given different simulated scenarios. The advantages of using simulation tools, is that it allows large, "*real*" scenarios to be investigated without having to test in an actual ship. Within the world Fire Safety Engineering (FSE), there are specifically design computational tools that allow FSEs to run fire scenarios and investigate the potential risks, consequences and life and property safety. The use of these tools is common practice in the '*built environment'*.

However, this type of fire and life safety analysis seems to have found little traction in the maritime industry, even though these tools, typically implementing a form of computational fluid dynamics, would be applicable to e.g. ships just as much as they are used for buildings. One possible explanation for this is the general "*conservatism*" within the maritime industry. The aim within this project was to investigate the feasibility of these tools, and show how they can give insights that provide new knowledge and better quantify both potential risks in a cargo hold scenario, how current fire protection systems perform and illustrate how these systems can be better optimized or how other/new systems may work better.

6.7.1 Computational tools

COMSOL - Thermo-mechanical modelling of shipping container

This section presents an attempt to model thermomechanical behavior of a 20-foot container ship exposed to fire conditions. Ideally, this modeling work would allow for a better understanding of the behavior of shipping containers exposed to different fire scenarios, and would further allow for characterization of various failure modes. This modelling effort pursues the goal to represent such failures as door opening under heat, or container deformation under the combined action of heat and mechanical load, which is particularly representative for containers located at the bottom of a stack.

The knowledge and understanding which can be gathered through this exercise could subsequently be used to describe fire spread mechanisms between containers in a Computational Fluid Dynamics (CFD) model. CFD models are used to describe the evolution of a fire in a given space, in terms of flames, smoke, and heat among others. Understanding the evolution of fire in a cargo hold requires obtaining the right way to simplify fire spread between containers.

The software chosen for this purpose was COMSOL multiphysics. This Finite Element Modelling (FEM) software is well suited to modelling tasks involving different types of physics, in the present case heat transfer and structural mechanics. The idea was to test and compare two approaches in solving this issue:

- Creating the geometry using only the solid 3D elements – computationally very expensive, most realistic
- Creating the geometry using the combination of solid elements for load-carrying parts and shell elements for the corrugated panels – computationally less expensive, however insufficiently validated

Unfortunately, the work could not be concluded due to meshing difficulties related to the software.

Solid 3D elements approach

A geometry using the 3D solid elements is shown in Figure 26. The issue arose when meshing. The full container geometry contains too many very thin domains and small details, making it impossible to create the mesh. COMSOL support was contacted regarding this issue, and it had been jointly concluded that using 3D solid elements does not seem to be appropriate for this type of problem. Instead, using shell elements for simulating most of the geometry was suggested.

[52] Wilkens Flecknoe-Brown, K & van Hees, P 2020, 'Experimental investigation into the influence of ignition location on flame spread and heat release rates of polyurethane foam slabs', Fire and Materials. https://doi.org/10.1002/fam.2921

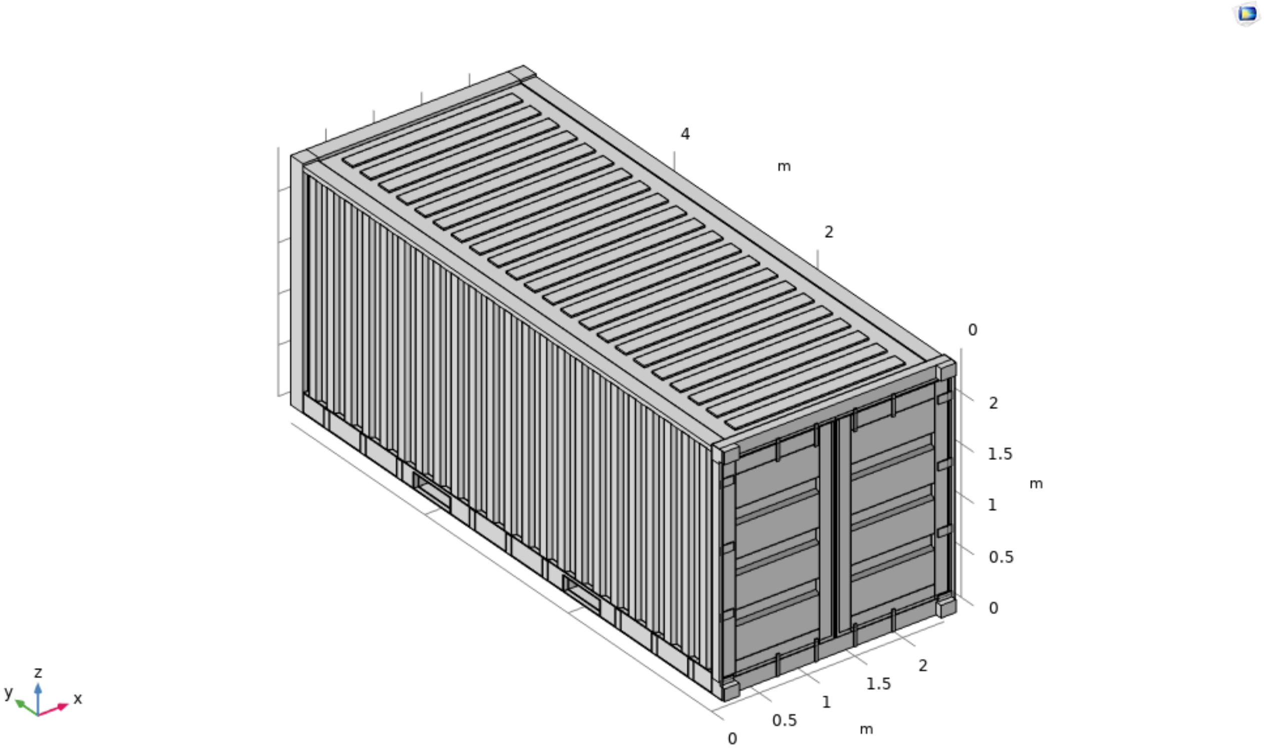


Figure 26 - Geometry of a 20 foot container (snapshot from DBIs model in COMSOL multiphysics)

Solid 3D + shell elements approach

Following COMSOL support's advice, it had been decided to try and combine the 3D solid elements with the shell elements, in particular the new "layered shell" functionality. Shell elements are a type of structural elements, which have a dimension in one direction being much smaller than the dimensions in the other two directions. In this case shell elements have been used for making most of the walls (corrugated plates on sides, back, bottom and top), and the door parts. Using shell elements allows for having simplified mesh, which further results in having shorter computation times. The meshed geometry is shown in Figure 27 - Meshed container using shell and solid 3D elements:

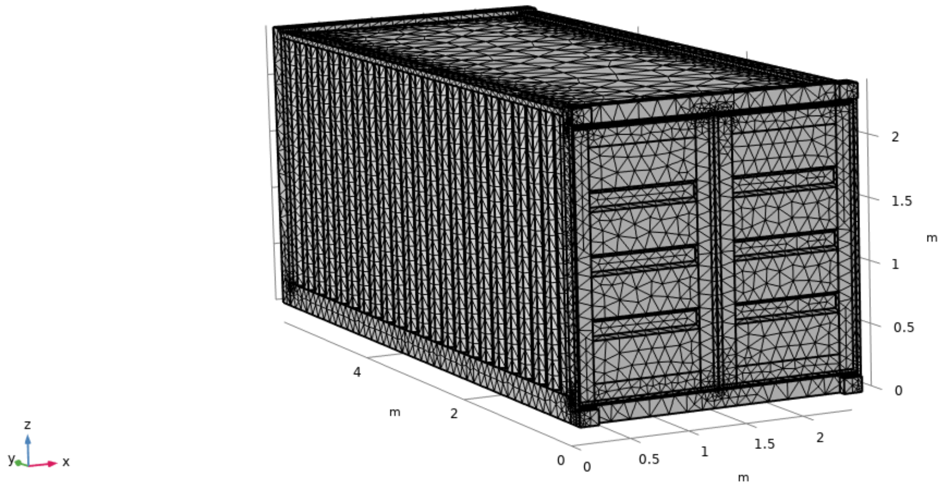


Figure 27 - Meshed container using shell and solid 3D elements

When running the initial simulations new errors occurred, and it was pointed out by COMSOL support that Layered Material is quite a new functionality in COMSOL Multiphysics, and that there are still questions that need to be addressed by developers to make sure the physics behave as expected.

It had been observed by COMSOL support that there is not a simple way to connect thermal shell elements (with different temperatures on the different sides) with each other through some kind of bifurcation.
This case made COMSOL developers ”realize that we need a simple way to handle connections like this in future versions of the program, even though it is unclear when it might be included.“

It is fair pointing out that COMSOL support offered a way to tackle this issue, but it included many simplifications and still many uncertainties related to using it. The project decided to pause the task until further notice, as the outcome of the analysis would be uncertain, especially within the available project resources.

All the communication with COMSOL support is saved, and can be provided upon request.

The promises of this exercise and its potential to help understand spread mechanisms between containers are important. The current efforts had to be halted to allow completion of other parts of the project. However, we consider it relevant and important to further this work. A simplified model could be used in a first time, which could be further completed by a refined meshing strategy to decrease simplifications and increase the accuracy of the results, especially with regards to the role of this FEM model towards subsequent CFD simulations.

Fire Dynamics Simulator

Fire Dynamics Simulator (FDS), is a computational fluid dynamics (CFD) model of fire-driven fluid flow. FDS solves numerically a form of the Navier-Stokes equations appropriate for low-speed (Ma < 0.3), thermally-driven flow with an emphasis on smoke and heat transport from fires. The formulation of the equations and the numerical algorithm are contained in the FDS Technical Reference Guide. Verification and Validation of the model are discussed in the FDS Verification and Validation Guides. (Guide Reference: K. McGrattan, S. Hostikka, R. McDermott, J. Floyd, C. Weinschenk, and K. Overholt. Fire Dynamics Simulator, Technical Reference Guide & User Guide. National Institute of Standards and Technology, Gaithersburg, Maryland, USA, and VTT Technical Research Centre of Finland, Espoo, Finland, sixth edition, September 2013.)

The most common applications of the model have been for design of smoke handling systems and sprinkler/detector activation studies. Other applications consist mainly of residential and industrial fire reconstructions. Throughout its development, FDS has been aimed at solving practical fire problems in fire protection engineering, while at the same time providing a tool to study fundamental fire dynamics and combustion.

FDS Models

The purpose of the simulation work in the report, was to highlight through example, how models can be a useful tool to investigate issues that are often very hard to quantitatively document using other methods. Once a model is setup correctly, a multitude of different scenarios can be simulated and examined, that would not be feasible/possible by any other means.

Two different types of model are investigated in this report; a detailed model of a single container, which aims to further investigate fire spread mechanisms on top of and in comparison to the experiments performed. This model takes a specific case of fuel burning inside a container and investigates how this develops.

The second model is that of an entire section of a cargo hold, here no specific results that are targeted at specific questions are presented as this requires much more extensive work than was feasible within this project, with large sets of simulations needing to be run in order to properly analysis the outcomes.

Models of this size (cargo hold model) are computationally very expensive and time consuming to run, which is still a limitation at this point in their more widespread usage. However, given this, some results of the initial simulation runs are presented below to further illustrate their potential usefulness, specifically for investigating performance of fire detection and suppression systems.

Container model

In order to approach the mechanism of the fire spreading inside the cargo hold, a model for one container was derived and the experimental data was used in the pre-processing of the simulation.

To fit the mesh size, the model container external dimensions where set to L = 6.2m, B = 2.4m and H = 2.6m and the material defined as steel properties. The model of the container was defined with two ventilation openings one at each size in the opposite corners.

Two cell sizes were used to describe the computational domain, inside and around the container, the cell size was refined to 0.1 m to replicate the fire, and everywhere else the cell size was set to 0.2 m. To speed up the computational time the domain was split up in eight meshes and each domain assigned to single MPI parallel process.

Figure 28 below shows the mesh structure around one container and the computational domain.

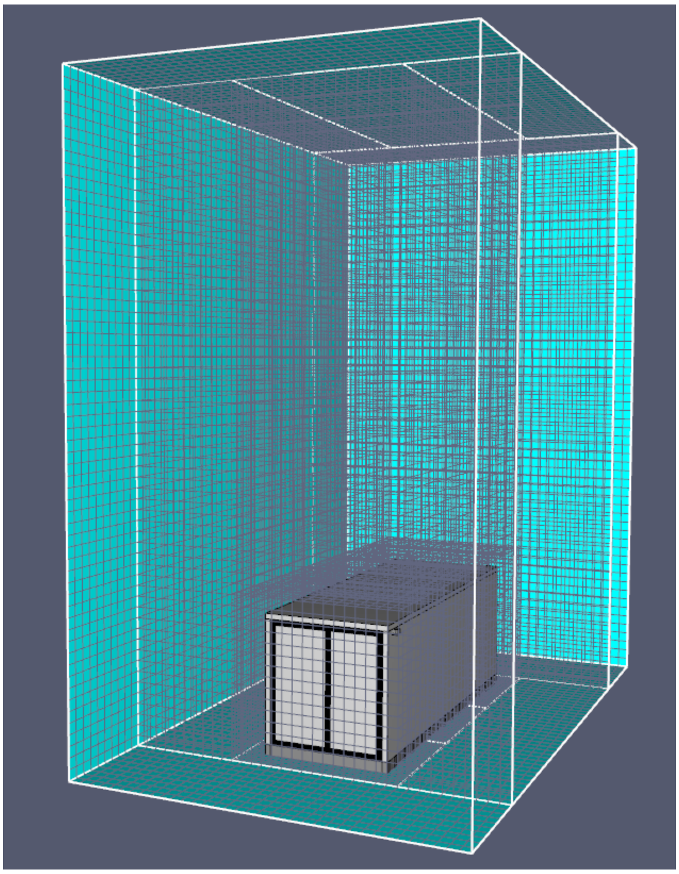


Figure 28: Container and the computational domain

Figure 29 shows the door section of the container and the door gasket.

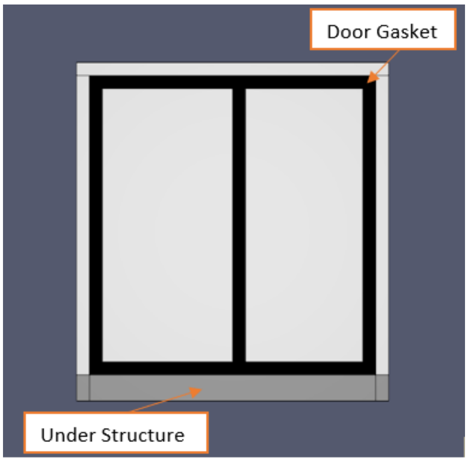


Figure 29: Container front, door section

Figure 30 shows the under-structure of the container and the plywood flooring seen from beneath. Parts such as the forklift sockets where ignored. Because of stress while loading and unloading the container there is less distance between the cross members in the bottom framing close to the door section and increased distance between those at the other end. For the FDS model the cross members were evenly distributed with respect to the cell size.

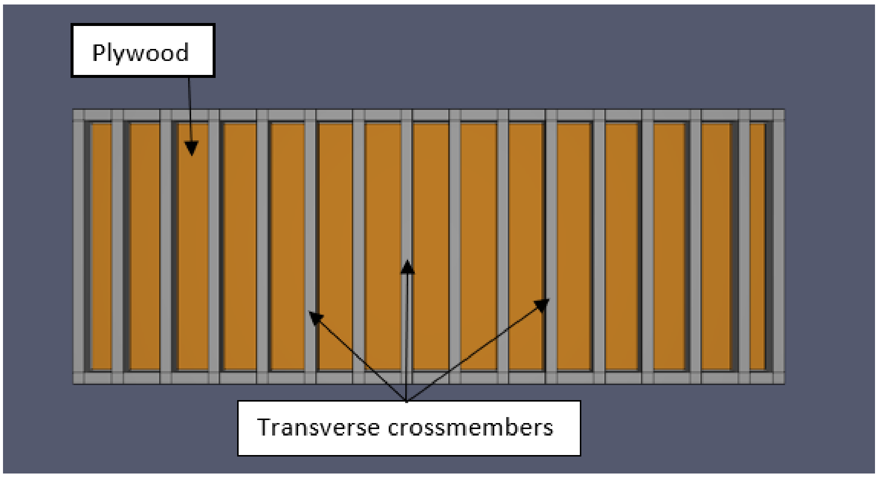


Figure 30: Container understructure

To replicate a realistic fire scenario inside the container the burning material content was defined as cube of charcoal with the volume of 17.5 m^3, which is approximately 60 % of the internal domain of the modelled container, the initialized material properties for charcoal are listed in Table 4 below.

Table 4 – material properties of charcoal

Material Properties		Charcoals
Density	kg/m^3	25.00
Specific heat	kJ/(kg·K)	1.00
Conductivity	W/(m·K)	0.04
Emissivity		0.9

The cube of charcoal was defined as a reaction fuel with a simple chemistry model, heat of combustion was set to 38 MJ/kg, which is rather high value. Table 5 below shows the reaction properties for charcoal.

Table 5 – reaction properties of charcoal

Reaction Properties		Charcoals
Carbon atoms		25.00
Hydrogen atoms		1.00
Oxygen atoms		1.00
CO yield	Y_{CO}	0.006
Soot yield	Y_S	0.005
Hydrogen fraction		0.1
Specific heat of combustion	kJ/kg	38000
Critical flame temperature	°C	1427

For initial ignition of the charcoals a heptane igniter with the dimensions 0.2*0.2*0.2 m was defined and placed behind the charcoal at the inner end of the container as Figure 31 illustrates. The igniter was defined with simple ramp function such that after 10 seconds of simulation the heptane igniter goes off for 20 seconds. The HRRPUA (heat release rate per unit area) for the heptane igniter was set to 250 kW to create sufficient combustion of the charcoals.

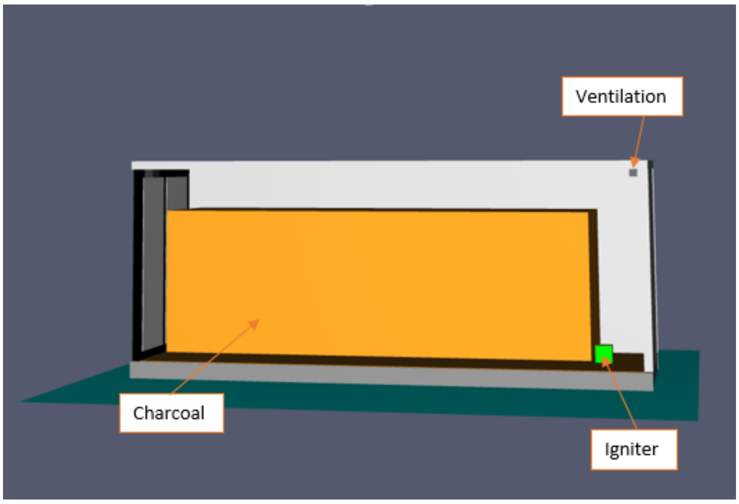


Figure 31: Container content and igniter

To describe the pyrolysis of the materials that are suspected to influence parts of the containers integrity under high temperature, the built-in FDS function BURN_AWAY was used. The function allows FDS to remove cells after they have reached the prescribed criteria such as HRRPUA and ignition temperature. The charcoals, EPDM rubber seal used as the door gasket and the 28 mm thick plywood flooring where defined with the burn away function. The material properties for the EPDM rubber and plywood are listed in Table 6 below.

Table 6 – material properties of other materials

Material Properties		Plywood	EPDM
Specific heat	kJ/(kg·K)	1.20	1.80
Conductivity	W/(m·K)	0.12	0.15
Density	kg/m^3	400	80
Emissivity	-	1	0.90
HRRPUA	kW/m^2	250	500
Ignition temperature	°C	350	300

The run time of the simulation was set 1200 seconds. Instruments used as measuring devices were defined as slice profiles of temperature and velocity, and thermocouples located at focus areas such as door section and ceiling as shown in Figure 32.

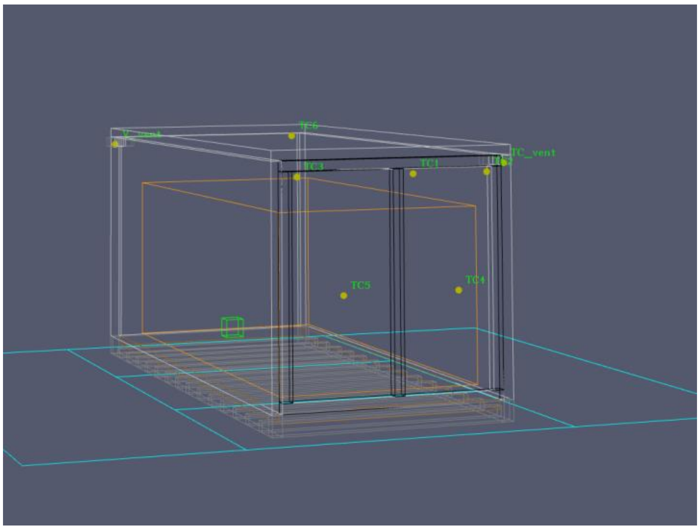


Figure 32: thermocouple locations

The model derived with respect to coarse mesh to decrease the computational time, this done to approach realistic solution before refining the mesh, which is common way to do. The run time of the simulation was approximately 15 hours but refining the mesh will results with results that are more realistic.

Cargo hold section model

A mid-section of a container ship with the capacity of 11.400 TEU's as shown in Figure 33, was utilized as template to draw the three dimensional model in Autodesk Inventor and the FDS graphical user interface PyroSim was used to importing and render the model to create the offset points.

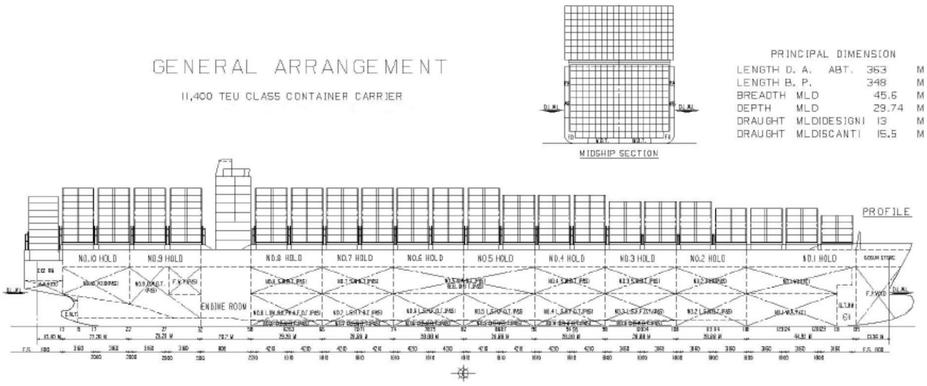


Figure 33 – Mid ship section and characteristics of the container ship used for the modelling work

Generally, ship hulls split up in watertight sections with watertight transverse bulkheads, for general container ships one watertight section includes two cargo holds at each side of so called transverse pillar bulkhead or non-watertight bulkhead. Each hold can store two rows of 20 foot containers or one row of 40 foot, the number of containers in bay and tire depend on the hulls size as Figure 34 illustrates.

Figure 34 – Orientations of bays, tiers and row

Ventilation of the cargo holds can be either natural or mechanical and the ventilation ducts are located inside the pillar bulkhead with inlets located at the deck between the hatch covers. Accessibility is through openings at the deck down the watertight bulkhead and the pillar bulkhead such that access is to the end of the containers stored in the hold. Figure 35 shows a general configuration of a cargo hold.

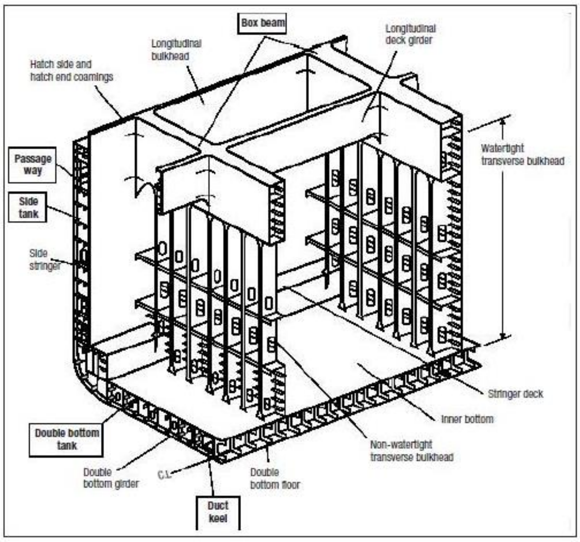


Figure 35 – Usual cargo hold configuration for container ship

Figure 36 shows the model of the cargo hold viewed in PyroSim, the bulkheads and hatch covers are not physically drawn in the model for a simplification purpose in order to reduce computational time and gain clearer view of fire and smoke spreading.

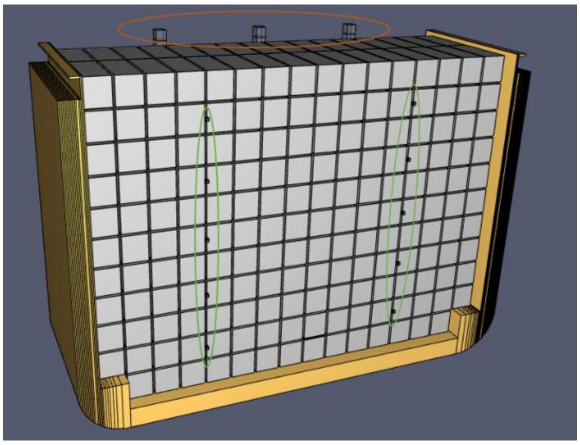


Figure 36 – FDS model of the cargo hold, showing ventilation inlet and outlet

The computational domain was set as the boundaries representing the bulkheads and the hatch covers. Ventilation inlets where defined on the boundary sides of the computational domain marked with green circle in Figure 36 with the volumetric flow rate equivalent to six air changes per hour of the cargo hold. The exhaust outlet where defined at the top of the domain as three ventilation openings marked with orange circle in Figure 36. The computational domain was split up to 46 domains with similar number of cells. The vertical and horizontal mesh between the containers was refined to the number of four cells in order to gain the realistic mechanism of the fire and smoke spreading.

In the initial simulation runs presented in this report, a large fire was set to ignite in the bottom central section of the cargo hold. This fire started already large which is not necessarily are realistic scenario, nevertheless this was chosen as it would reduce the run time required in order to see some of the potential impacts such a fire could have in terms of spread and smoke movement throughout the cargo hold.

6.7.2 Results

Container simulation results

The maximum HRR during the ignition occurred at 55 seconds and then the fire started to decay as Figure 37 shows, this can be explained by the enclosure of the container and an insufficient circulation of fresh air via the ventilation openings.

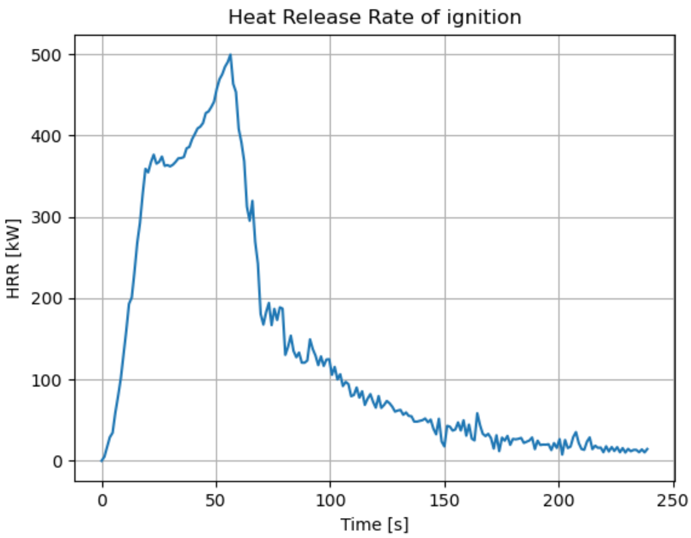


Figure 37: Graph of the HRR during ignition in container

Figure 38 shows the model outlines and a temperature profile taken at the middle of the container, it can be seen that the temperatures inside the container quickly reach high values under the ceiling.

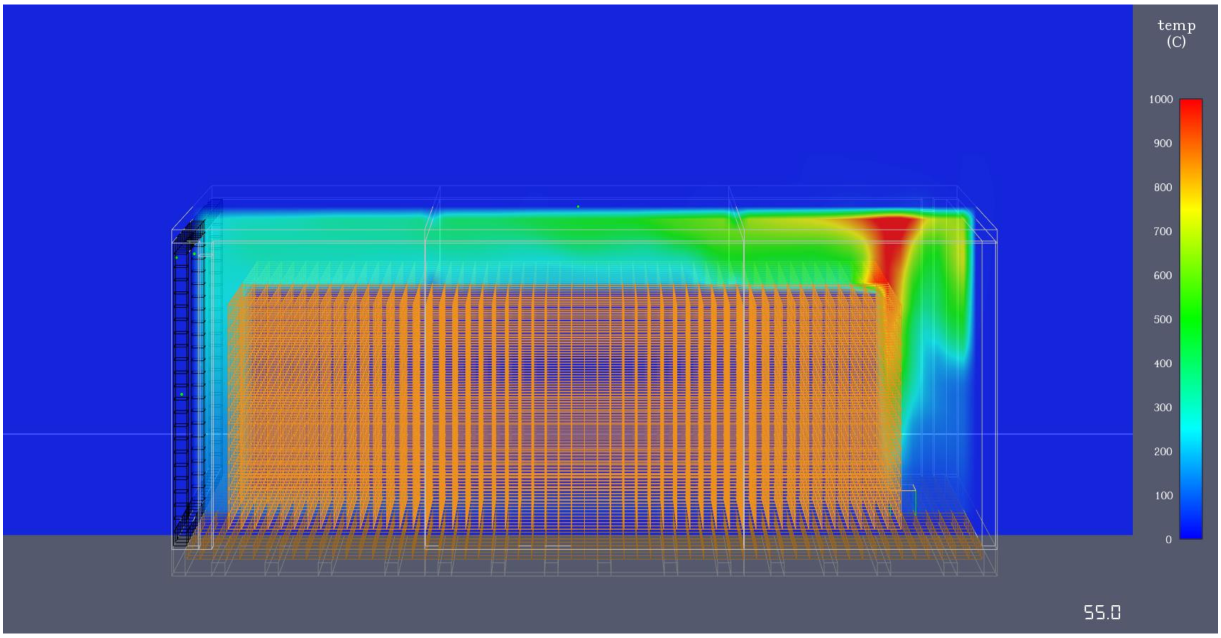


Figure 38: Temperatures along the middle of the container during ignition

Figure 39 is taken after 200 seconds and shows that the temperatures have decreased significantly. Some cells representing the charcoals have been burned away around where the ignition started. Flames are only visible at the ventilation openings where air is mixing with the hot gases and influencing the combustion as Figure 40 shows.

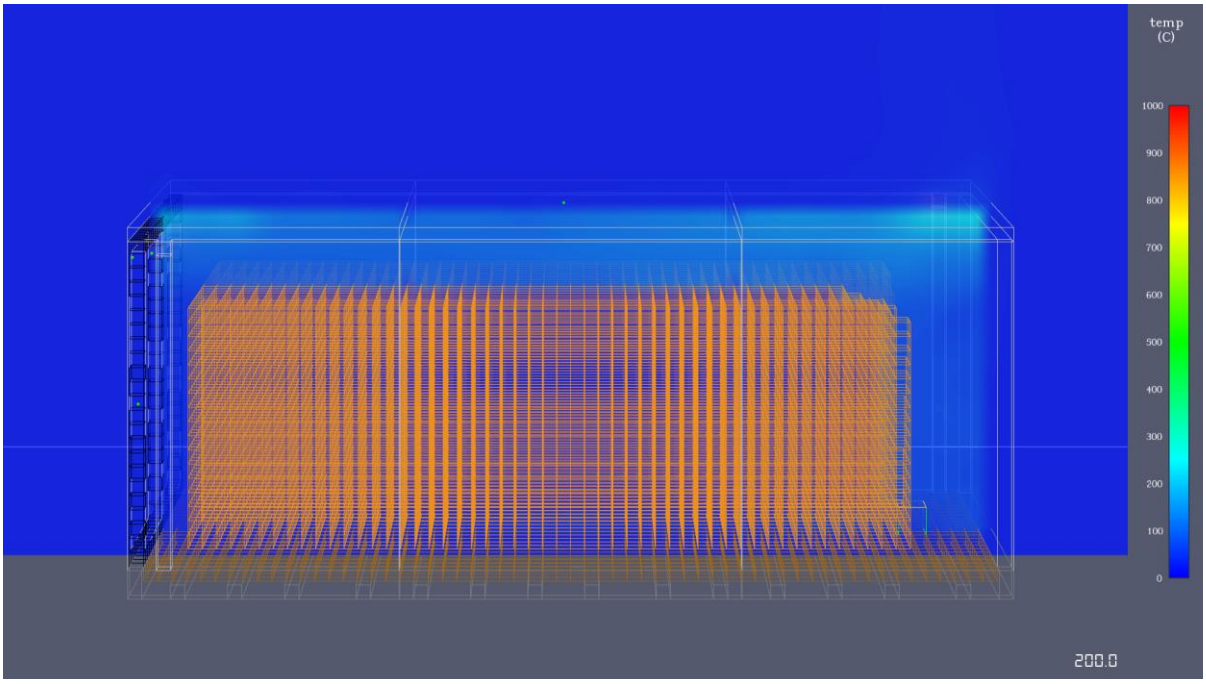


Figure 39: smoldering fire

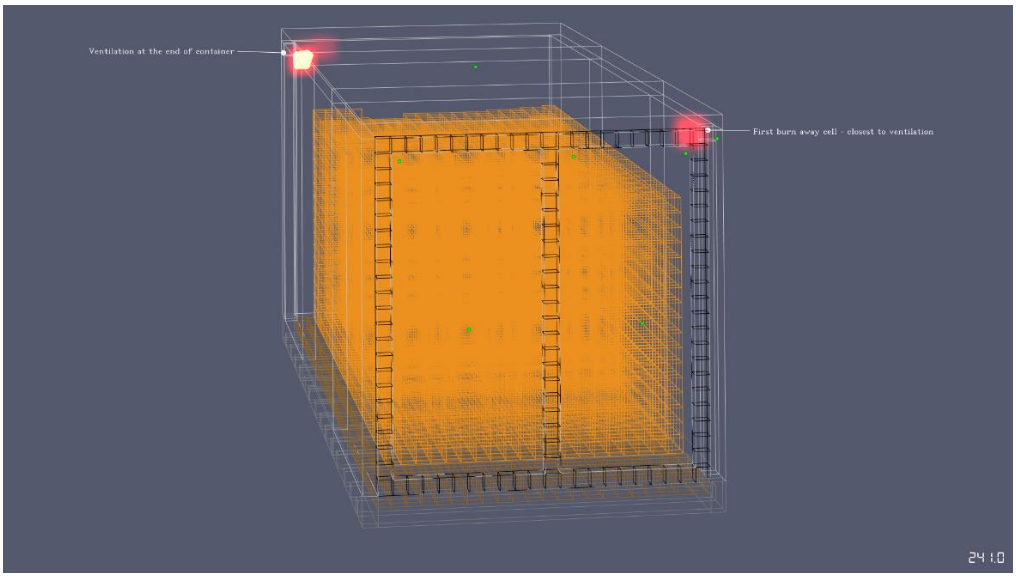


Figure 40: Fire at the ventilation holes

Because of the flames at the ventilation close to the door gasket the “burn away” criteria is reached for the EPDM rubber and the first cell is burned away at the time of 250 seconds as illustrated in Figure 41, and after that chain reactions to the neighboring cells causes an increasing airflow that influences the combustion. At the time of 620 seconds approximately 50 % of the door gasket is burned away and the HRR rate is around 2500 kW.

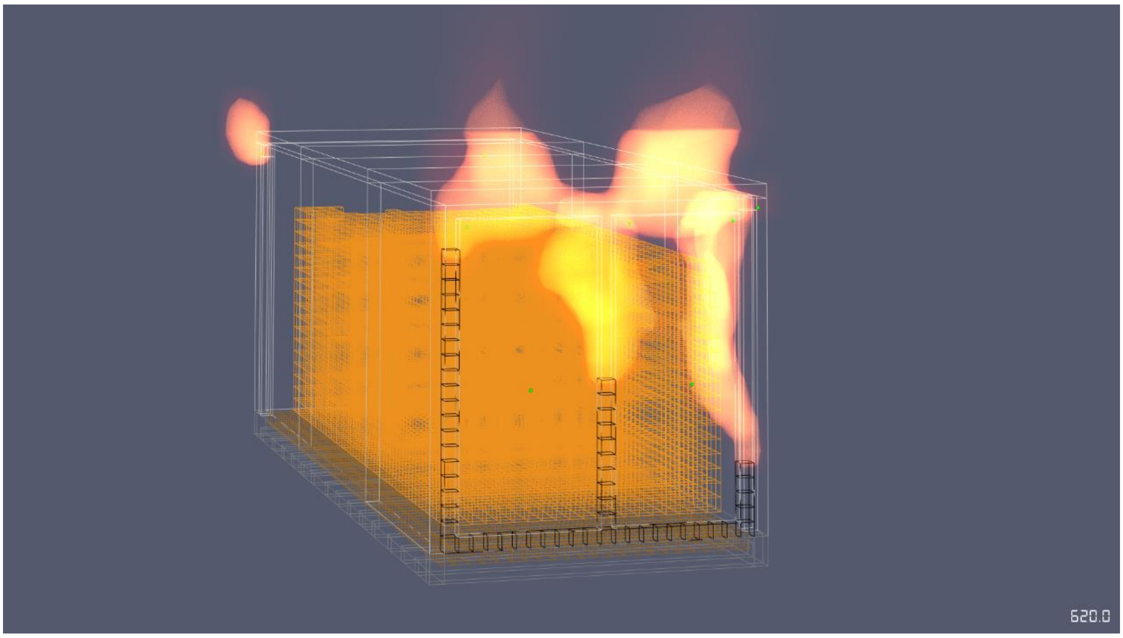


Figure 41: Burn away of the door gasket

The surface temperatures of the unexposed side are shown in Figure 42.

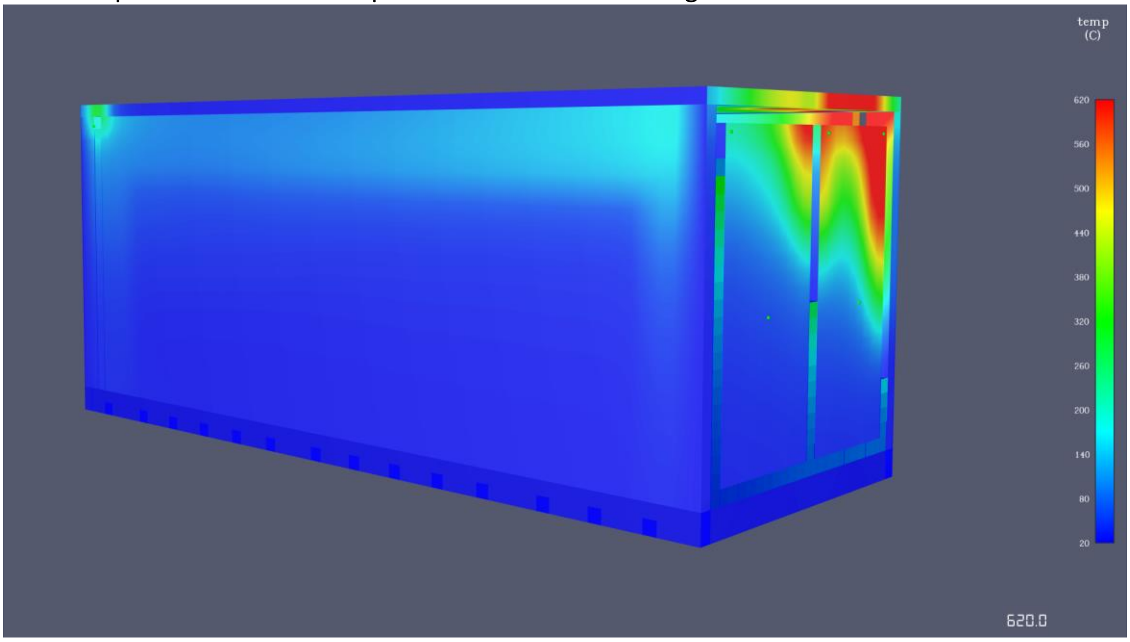


Figure 42: Surface temperatures at 620 seconds

After the burn away of the door gasket more ventilating air is allowed to flow into the container which gives rise to a faster burn of the charcoals inside the container, as Figure 43 indicates, pyrolysis of the charcoal is predominately occurring closest to the door section.

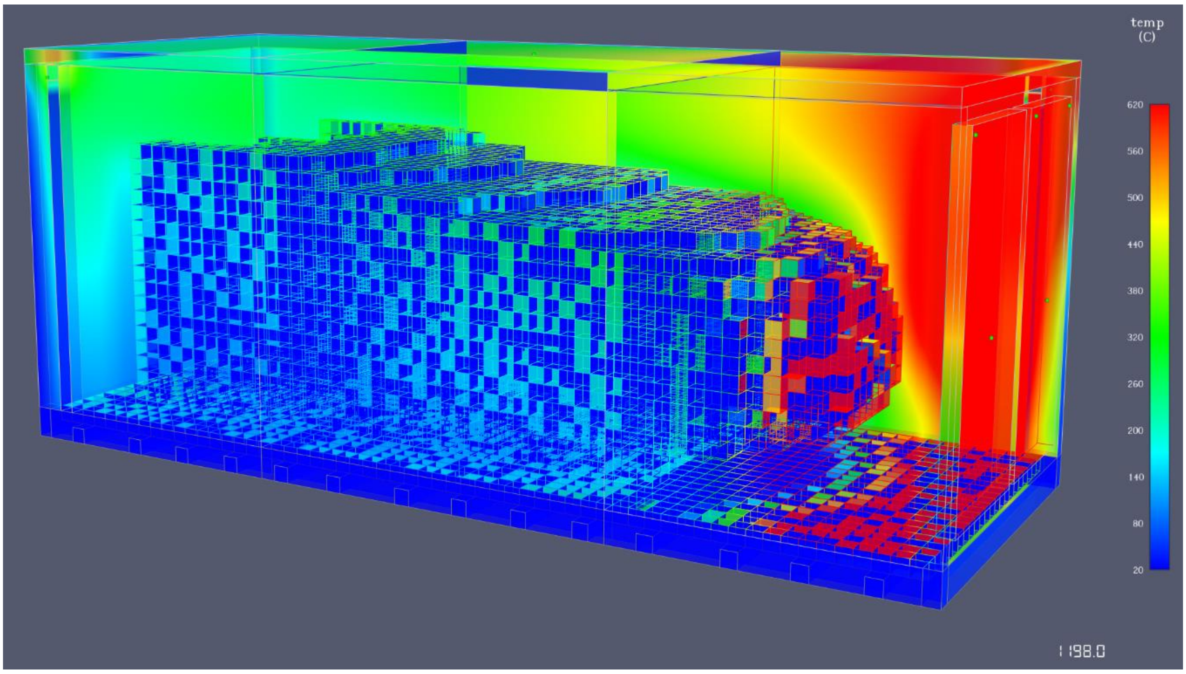


Figure 43: Pyrolysis of the charcoals

Figure 44 shows the mass loss rate of the burning fuel, it can be observed that the combustion process is reaching a fully developed stage with almost constant mass release after approximately 900 seconds.

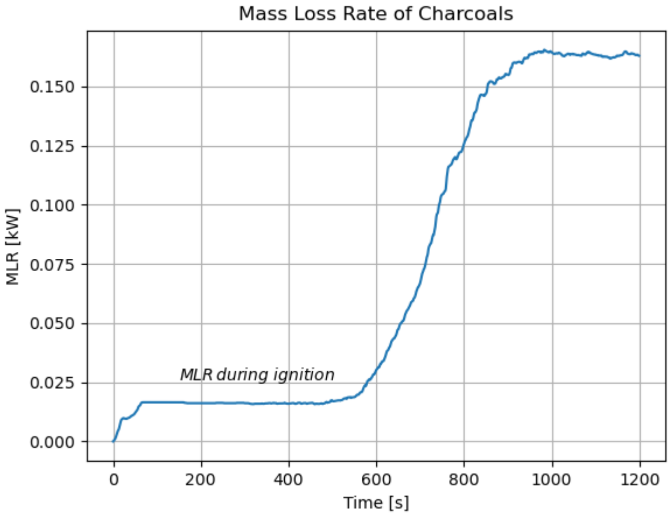


Figure 44: Mass loss rate of the fuel

Figure 45 shows the flame height coming from the gap of the door gasket is reaching 1/3 to 1/2 of its own height.

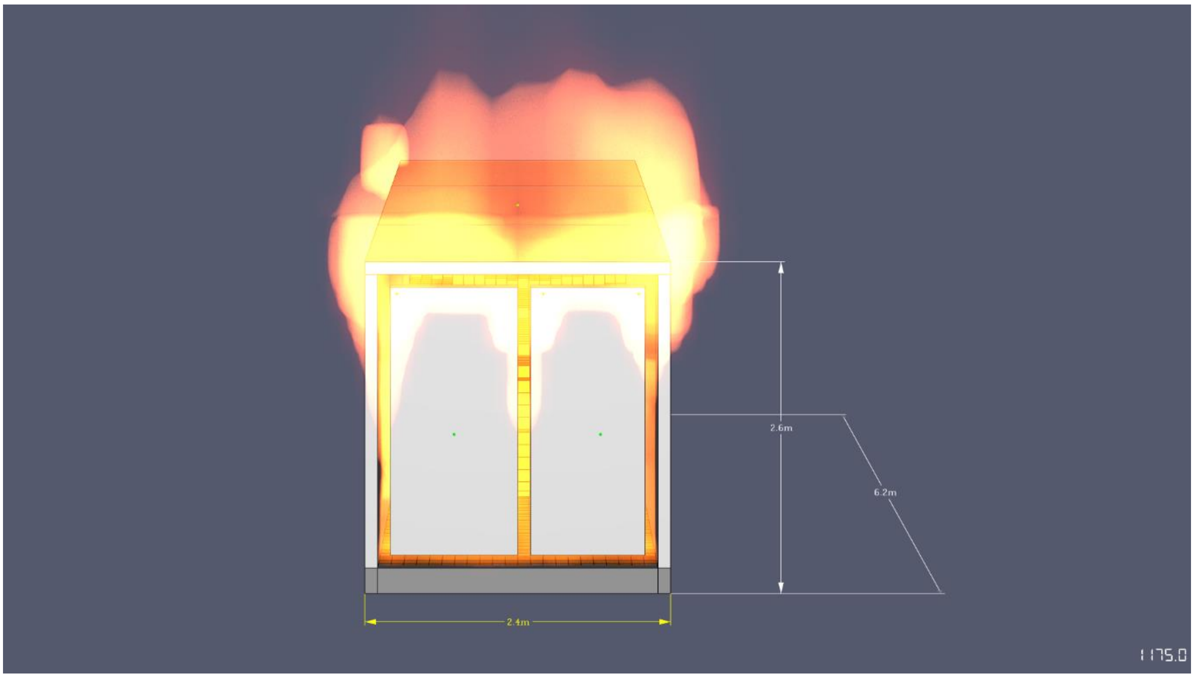


Figure 45: flame height

Figure 46 shows the plot of the total heat release rate during the simulation and it can be seen that the fire appears to be in a smoldering condition after the decay of the ignition until approximately 250 seconds then the HRR starts increase again. The maximum HRR is found at one peaking point to be 7241 kW, because the simulation was run only for 20 minutes, complete burning of the charcoal fuel is not achieved within this period, thus the average HRR may not realistic. However, based on this period, the average HRR may be assumed to be around 5 MW during the whole process.

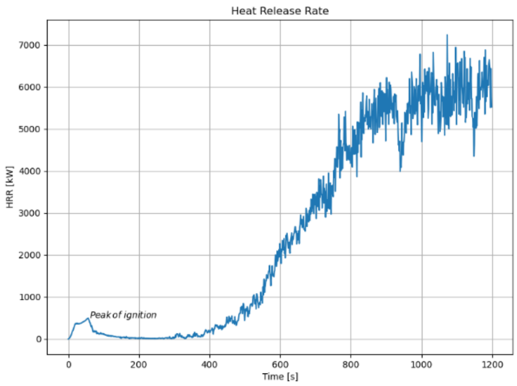


Figure 46: Total HRR during the simulation time

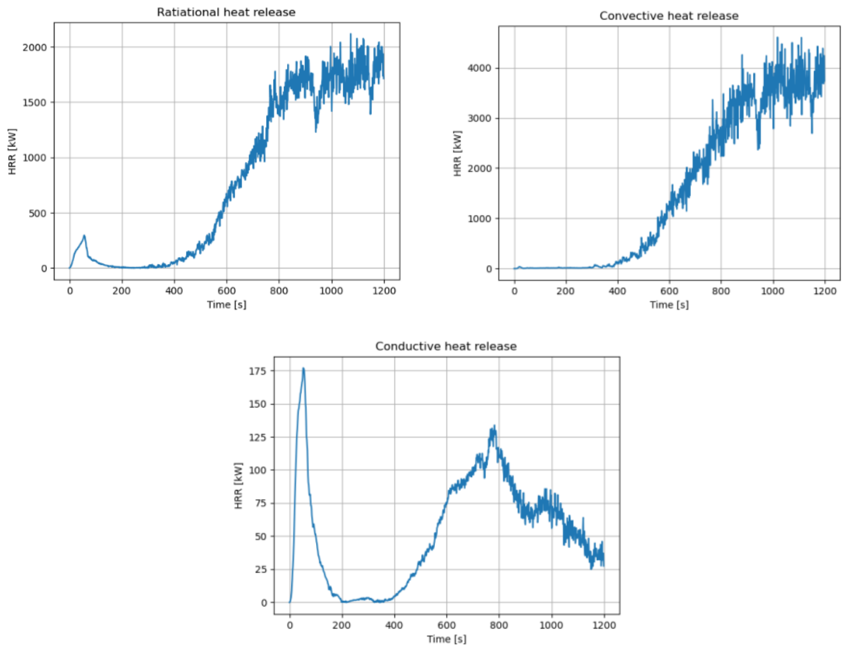


Figure 47: Composition of HRR from the three main elements

6.7.3 Discussion and further work

After ignition and after the heptane reaction is shut off the fire decays, this can be related to the enclosure of the container and a lack of air flow, providing oxygen for combustion. During the period of the decay the temperatures inside the container drops and only visible fire is at the ventilation holes at the sides, however, this is still sufficient to ignite the door gasket. The results show that the burn away of the door gasket is the main turning point where the fire goes from smoldering to fully defined burning. The maximum temperatures on the unexposed side reaches the critical of 620 degrees which was also used in the mobile furnace tests and showed that the plywood floor of the container about could ignite in this condition. flames out of the door gap reach significant height such that the integrity of the door section of above container can possibly be threatened.

The next phase in this work is two-fold;

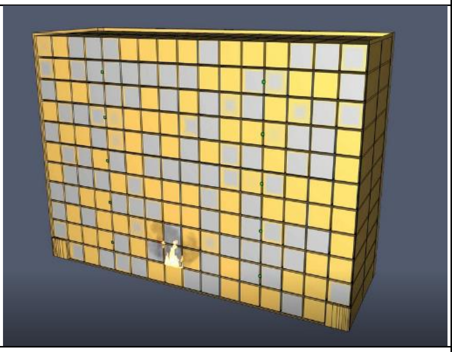
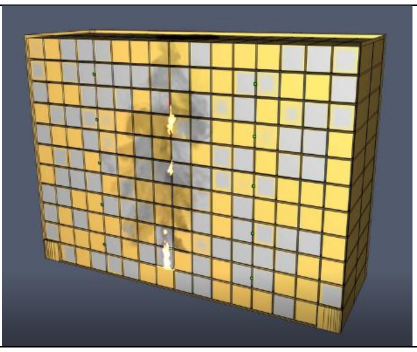
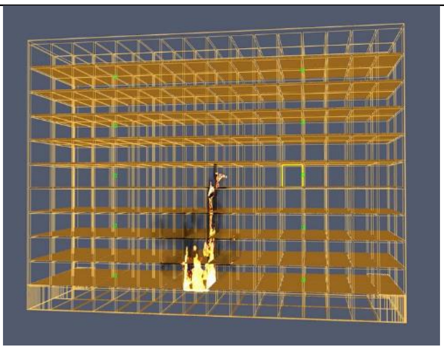
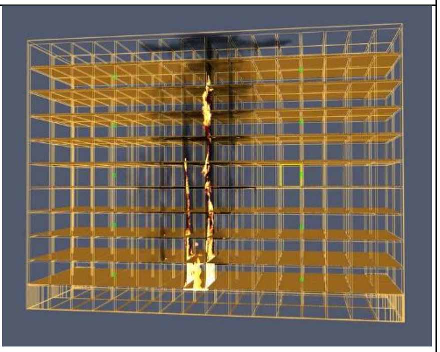
- Simulate the door test that was performed – this will act as a good validation step for the model, to show that it is simulating the physics and chemistry at play in this scenario correctly.
- Add additional containers to this simulation – this will then allow further investigation into the impacts on neighboring containers, and may help to investigate the interaction between the various fire spread mechanisms examined in the testing phases of this research (refer experimental section of this report to review).
- Impact of various cargo/fuel types – this simulation used charcoal to demonstrate its usefulness as an investigation tool, but many other fuels may also now be investigated, this can help determine which fuels are more hazardous in terms of contributing to fire spread.

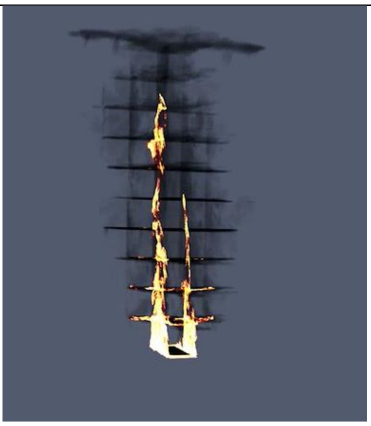
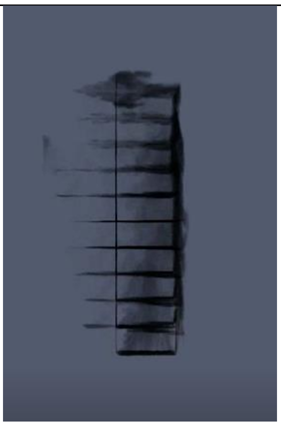
Cargo hold simulation

Table 8 provides snapshots from an initial simulation. Images at different time points are outlined to highlight how the fire and smoke travels within the cargo hold environment.

Images are split into different visualization approaches and provided with some commentary.

Table 8 – Cargo Hold Simulation Snapshots

Observation / comments		**Observation / comments**	
Fire starts in the middle container of the bottom row		Fire quickly accends vertically	
Same as above, with containers made to be see-through		Here the fire spread vertically is much more easily seen, note the strong vertical movement compared to the little horizontal movement	

Observation/ comments		Observation/ comments	
Same as above, with containers completely hidden so that only fire a smoke is observed		Different view of the same time period as image to the left. Most interesting here is how the smoke is also very restricted to vertical movement	
side view of same time period as above, showing only the smoke, note the high proportion of smoke collecting between the container row next to the bulk head, rather than travelling in between containers		Front view	

6.7.4 Discussion and future work

Due to the size of simulation domain, simulations at this level have only been feasible for illustrative purposes. Computational resources required to undertake a full analysis of this domain, and analyze these in terms of fire and smoke spread, effectiveness of detection and suppression systems is not within the scope of such a project as this, rather it is an undertaking that can be considered "the next step" in this research, after the conclusion of this project phase. Investigating these is also a task that requires "ship specific" information to be as valuable as possible, this requires collaboration with other invested parties that can provide as many details as possible, as finding detailed, relevant and specific information such as locations of detectors proved difficult based on general information that can be found on places like the internet.

However, even from these initial simulations, some interesting observations can be made;

- Rate of spread vertically is much higher than horizontally, as shown in Tabe 8 horizontal spread only reaches in total 2 containers either side of the origin along the short side and less than 1 on along the long side – this is useful for two reasons;
    - 1 – impact on future simulations: knowing this means that in future simulations, the domain (the area simulated) may be reduced, this will have a significant impact on the computational requirements and allow for greater productivity in running various scenarios.
    - 2 – knowing this can already inform on how detectors may be more optimally placed for earlier detection, it also illustrates that detection times may be very dependent on where the fire originates.
    - This may be an obvious conclusion, however more detailed analysis from these simulations, may result in further simplifications that could be useful in future ship design and development.
- Smoke spread seems to be much denser and faster in the space between the container stacks and the bulkhead compared to between the container stacks. Flow between containers appears to be quite restricted due to the minimal spacing. This means that smoke tends to accumulate in the spaces that are less restrictive – i.e. area between container and bulkhead.
- Flame extension vertically up gaps could increase spread rates to other containers, as heat fluxes these other containers may experience could be higher[53], this suggests that a fire from one container could effect not just its direct neighbors, but many more simultaneously. Also to note is that this is not something that can be examined without simulation or full scale testing of full height container stacks. This is significant, as information based on any other methods, may completely miss this phenomena, which may not only effect fire spread rates, but also life safety of sailors, especially if firefighting is a consideration.

It should be noted that these conclusions, are based only on preliminary simulation results, and further work is really required before any of these observed effects can be confirmed.

In future work, the flexibility of this developed model would allow a whole suite of potential scenarios to be examined, and the results analyzed. Issues such as; locational impact, fire growth rates, fire sizes, fuel types, ventilation conditions, positioning of detector systems, types of detectors, even effectiveness of suppression systems, and life safety hazards can all be investigated through this type of simulation.

[53] Livkiss, K., Svensson, S., Husted, B. et al. Flame Heights and Heat Transfer in Façade System Ventilation Cavities. Fire Technol 54, 689–713 (2018). https://doi.org/10.1007/s10694-018-0706-2

6.8 Review of technical fire protection solutions

6.8.1 Current systems

According to SOLAS II-2 (Safety of Life at Sea) there are different fixed fire extinguishing systems used for different spaces in ships all depending on the purpose, characteristics and ship types. For cargo holds aboard container vessels, the requirements are to have installed *fixed gas fire-extinguishing systems*. Due to risk of pollution only few gases are allowed, and the most used gas is Carbon dioxide (CO_2.)

The system requires a gas storage either in form of storage tank or gas cylinders and must be stored in separated compartment usually called the CO_2 room. The room must be located above the freeboard deck with effective ventilation and external entrance. Most common is to locate the CO_2 room in the ships superstructure. The minimum required amount of CO_2 capacity is 30 percent of the gross volume of the largest cargo space, the discharge requirements are at least 50% of CO_2 discharge in 1 minute, and at least 85% discharge in 2 minutes. However, the cargo in the hold can be at such nature that further CO_2 release is required in order to extinguish or control the situation. Two main types are fixed gas systems are available those that are low pressure gas systems, mainly used for smaller compartments and less hazard, and high pressure gas systems suitable for larger bulk flooding of CO_2.

Figure 48 shows a diagram of a typical CO_2 flooding system.

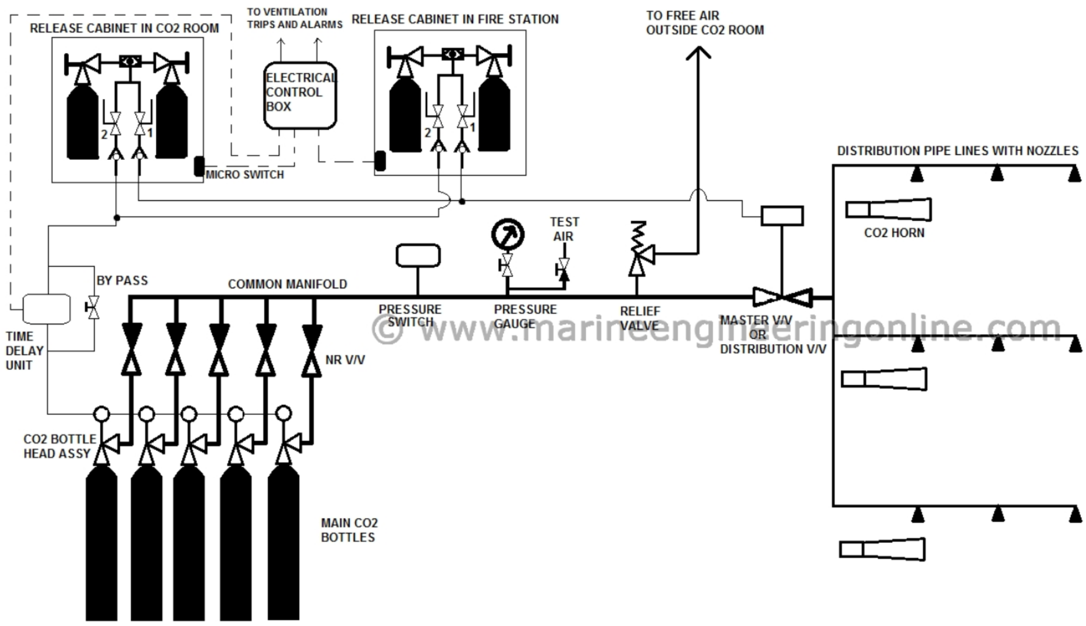


Figure 48: showing diagram of a CO_2 flooding system

The main system mechanisms consist of pipeline from a fire station to each cargo hold, this pipeline has two functionalities; as a detection sample line, and as a CO_2 supplier. The pipe enters the cargo hold with a multiple discharge nozzle located at the top of the pillar bulkhead (non-watertight bulkhead) as shown in Figure 49 showing the pillar bulkhead of cargo hold no 3 aboard MAERSK HOMAN. Where the green pipe represents the discharge line, the smoke detection sampling points are marked red on the discharge line.

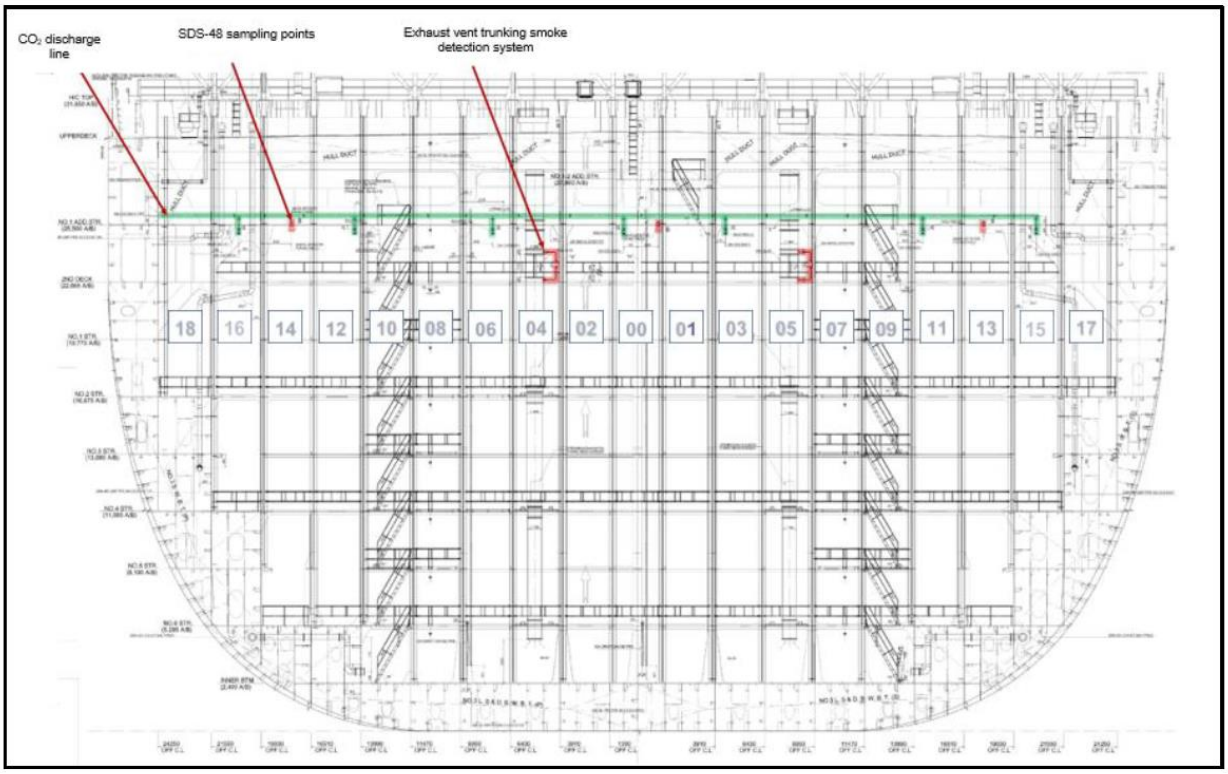


Figure 49: Showing the pillar bulkhead of cargo hold 3 in MAERSK HONAM (picture taken final incident report)

Those systems are designed to be continuously absorbing air and passing it through the distribution station where the air is analyzed for smoke particles. If smoke is detected a signal is given either to the control room or the bridge where decision is taken for further actions, e.g. over-flooding the cargo hold. Before the cargo hold can be over-flooded fire needs to be verified and ventilation must be turned off and all flaps and hatches needs to be closed in order to reduce the air going in and/or gas going out. Both requires human involvement.

Scaling effects

Due to the enormous upscaling of container ships concerns are waking that the design of the fixed gas fire-extinguishing systems has not kept pace with the size enlargement (refer footnotes for references), issues such as detection timing and efficiency of the CO_2 flooding are being raised. One main cause of this is due to a presumed assumption of linear scaling for both the fire and thus the detection and suppression systems; however, this is an incorrect assumption, as fire is generally a non-linear process, and thus scaling up fire protection systems linearly may not make sense from scientific point of view, especially considering CO2 does nothing to lower residual heat, which could lead to re-ignition issues.

As a fire increases in potential size, so too does the thermal feedback to the environment and the fire 'seat', which in turn accelerates the thermal degradation and combustion processes, which in turn accelerates the spread and growth of the fire, something that is not accounted for in simply "sizing up" fire protection systems according to the space.

In addition, the enlargement of the ships has caused the increase of the distances from the cargo hold to the distribution station and enlargement of the cargo hold volume, which can cause delay of detection and inefficiency in the CO_2 flooding.

It can be seen in Figure 49 that the distance from the tank top to the sampling points is around eight container tiers. Meaning that for smoke detection, the smoke has to travel from the fire origin e.g. inside a container on the tank top, through the vents of the container up eight container tires to the sample nozzle and from there through the pipe line which can be hundreds of meters long, to the distribution station. This also assumes that smoke will be passing the sampling points. In addition, it is worth to mention the increasing number of ventilation ducts and natural ventilation flabs that require manual closing due to the enlarging of the cargo hold volume and capacity, these can all potentially cause delays in interventions and increases the risk of injures and death.

6.8.2 Looking forward

Earlier detection is seen by many in the industry[54,55,56] and in related maritime projects such as the "LASHFIRE" project[57] as a means to rectify the issues of fire on board ships. Experience obtained through this project highlights that a purely technical solution such as simply improving detection is unlikely to address all the issues within the industry. However, this is not to say that improving fire detection is meaningless, it can be a part of the way forward to improving the situation and thus should (and is) be seriously considered.

The previous section highlighted some of the perceived issues with the current fire protection systems, and superficially, issues with detection may be easily addressed by simply changing the detection system. This is of course easier said than done. Simulation tools as discussed in previous section could prove as an excellent tool to test and assess different concepts/systems, compare their performance under many different conditions to help find an optimal solution. When discussing detection concepts, two main options should be discussed:

1. Individual container detection
2. Cargo hold detection

1. From a purely detection angle, with the aim of improving detection times, an individual container detection system is the obvious choice, as this type of system monitors individual containers, and therefore will have a much higher resolution than an entire cargo hold solution (as is currently implemented). However, the implantation of such a system introduces a large number of complexities that make it much less feasible. These include:
    - Cost (huge number of containers to cover),
    - Ownership (who is going to pay?),
    - Implementation (how can these be retrofitted to existing containers easily?),
    - Integration with ship systems (e.g. wireless communication),
    - Life span (battery systems need to be changed),
    - Etc.

[54] Addressing the regulatory deficiencies - Helle Hammer, Chair IUMI Policy Forum, Gard conference on container ship fires - Arendal, 18 October2019

[55] CHALLENGING THE SOLAS REGULATIONS – Alf Martin Sandberg, Special advisor, Gard AS, Gard conference on container ship fires - Arendal, 18 October2019

[56] FIRE ON CONTAINERVESSELS - Does size of vessel matter? – Ardent, Gard conference on container ship fires - Arendal, 18 October2019

[57] https://lashfire.eu/project-info/work-packages/wp9/

Any of these issues, may be a "*deal breaker*" in terms of feasibility/possibility of implementing such a system. However, that is not to say it's an impossibility – new wireless communication networks make communication in such harsh environments more possible, low cost sensors and battery consumption are all improving. There are also some innovative companies that are offering possible solutions to many of these issues, by offering container-wise detection but not requiring sensors to be attached to the containers themselves[58]. "Smart containers" are also a possible solution in the future, as these would already be monitoring themselves for various purposes, and thus this information could also be re-purposed for use in detection systems.

2. Cargo hold detection may be viewed as the much less complicated, more viable option. However, there is always going to be a trade-off in regards to responsiveness of such a system, when compared to individual container monitoring. As discussed in the previous sections, the current systems are likely not appropriate for the current situation and scale of container ships, and thus improvements could most definitely be made, this may be done by things such as:

- Changing the detection methods – using a different technology that has shown to give faster response to fire.
- Changing the location of detection points – a thorough evaluation of optimal detection location may also improve detection times significantly, this may be achieved through the use of simulation tools like those described in the previous sections.
- Increasing sampling points/detectors – adding more detector locations may be a simple solution to reduce detection times.
- Including multiple systems – having multiple systems that are optimized for different scenarios or what they detect, can also be a way to improve both detection times, and also issues with false alarms.

There are many innovative companies (refer to Chapter 5 – Blue Denmark) that offers systems that could potentially improve results dramatically. However, all of the above suggestions require extensive work to determine which potential solutions give the best outcomes.

Performance is also not the only prerequisite on which these systems should be judged, however simulation tools as described in the previous section do offer a way forward as an investigation tool for this area.

Different types of systems e.g. gas or photoelectric or other can be trialed virtually, optimizing location and number of detection points is also a perfect task for such tools.

One final note: as stated previously, although improving detection systems will offer an improvement in detection times and thus some consequences may be avoided, this will not fix all the issues that result in fires on container ships, and should not be viewed as the "final solution". Issues related to operations e.g. what happens after an alarm is initiated (refer Chapters 3 and 4 of this report) may have a more significant impact, and thus should also be seriously considered when looking at the issue of fires on container ships holistically, rather than looking simply for a quick fix.

[58] Early Detection of Container Fires on Containerships – Radicos, Gard conference on container ship fires - Arendal, 18 October2019

6.9 Conclusions

Conclusions from the experimental work investigated three potential spread mechanisms;

- H1 – via the plywood floor,
- H2 – through the door and
- H3 – through the walls.

These 3 hypothesis were tested through small and large scale experiments with the following conclusions:

Hypothesis 1 – seems highly probable that the plywood floor could act as a mechanism to spread fire from one container to another in the vertical direction. The critical heat flux was determined as approximately 10-12kW/m2 on average; however this may be slightly higher or lower depending on the specific sample tested. Ignition was shown to increase in likelihood (i.e. be more easily ignitable), if the newer types of plywood were used, or if the bitumen layer was still present. These factors were also shown to increase the energy output from the plywood floor.

Hypothesis 2: Assuming a fire develops within a container, the door is also potential method of fire spread, this is both due to the radiation it can transfer to the container opposite it, but also due to the external combustion of the combustible materials surrounding the door and the flaming droplets may help to spread the fire further.

Hypothesis 3: If it is assumed the walls will likely heat up similar to what was observed in the door test, this would mean that even higher heat fluxes might be radiating to the neighboring containers via the wall. The reason for this is simply that they are closer to the walls, with gaps between walls of neighboring container being approximately 100mm (although this can vary ship to ship). This distance is so close that you may even consider that the wall temperatures of neighboring container could simply follow those of the wall in which the fire is, simply with a slight time delay. Knowing that the walls can heat up like this, means that goods within these containers will quickly follow and reach their ignition temperatures leading to fire spread.

Data obtained from these experiments, gave some quantitative insights in to what the minimum requirements for fire spread to occur may be, and provides data that can be used for both risk assessment and simulation work to be developed further.

The simulation work showed through example how in a more detailed container simulation, fuel and ventilation effects can be investigated. These simulations also highlighted how much of an effect the burning away of the rubber seals around the door could impact the fire growth inside. Initial simulations of the cargo hold, also demonstrated some interesting observations on the rate of spread horizontally and vertically, how smoke accumulated in certain areas within the cargo hold and how flame extension could increase the exposure rates not only to the direct neighboring containers, but to many more sitting above the container of origin.

In future work, the flexibility of this developed model would allow a whole suite of potential scenarios to be examined, and the results analyzed. Issues such as; locational impact, fire growth rates, fire sizes, fuel types, ventilation conditions, positioning of detector systems, types of detectors, even effectiveness of suppression systems, and life safety hazards can all be investigated through this type of simulation. Finally, issues with the current fire protection systems were highlighted, then two main detection concepts were outlined, and the strengths and weakness of each were discussed, these being:

- Individual container detection
- Cargo hold detection

It was also noted that as previously stated through other work in this report that, although improving detection systems will offer an improvement in detection times and thus some consequences may be avoided, this will not fix all the issues that result in fires on container ships, and should not be viewed as the "final solution". Issues related to operations e.g. what happens after an alarm is initiated (refer Chapters 3 and 4 of this report) may have a more significant impact, and thus should also be seriously considered when looking at the issue of fires on container ships holistically, rather than looking simply for a quick fix.

7 Conclusions

This chapter summarizes the findings of the CONTAIN project, giving the overall perspective of the problem of fires on board containerships as gathered during this year of study. The reader is referred to the respective sections of the full report for comprehensive insights concerning these conclusions.

The project set out to answer two research questions:

- How is fire spreading from one container to the next?
- How are stakeholders seeing the problem?

These two questions are closely linked, one affecting the other. However, they are answered in their respective parts "the box" and "the concept" as described in the introduction of the project.

7.1 Conclusion of the CONTAIN project

The main conclusion of this project is that there is indeed a problem of fire on board containerships, and we support the view from several stakeholders that this problem should be solved. The work presented herein shows that the problem is not solely technical, but socio-technical in nature; this indicates that the solution(s) would most likely be socio-technical as well. This body of work also highlights the complexity of the issue, both on a technical, social, and organizational level; we therefore would argue that there is no easy solution, no "quick fix" to this comprehensive problem.

7.2 "*The Box*"

The part on "*the box*" explores fire spread between containers by studying specific mechanisms through a fire testing program carried out in the laboratory at DBI, as described in Chapter 6 of this report. It also looks at the fire situation and its evolution inside the cargo hold through numerical modelling (see Section 6.7.1). A last point of interest is the existing technology for detection and suppression, as available today (see Section 6.8).

Results from the experiments confirmed that some of the hypothesized spread mechanisms are possible;

- H1 – spread vertically through the floor,
- H2 – spread through the door and
- H3 – spread through the walls

These experiment also provided quantitative information on what exposures to surrounding containers may be, and also what the minimum requirements to enable these mechanisms to take place are. Simulations illustrated the using these tools is a feasible method to further investigate container fire issues, and that they can be used not only for investigating the causes and consequences of fires, but they can also give insights on how to better design fire protection systems e.g. detection and suppression systems, that no other methods can feasible do to the same level of detail.

The review and analysis of the current fire protection systems concluded that there is deficiencies in the current systems and thus room for improvement. However, although improving detection systems will offer an improvement in detection times and thus some consequences may be avoided, this will not fix all the issues that result in and from fires on container ships, and should not be viewed as the "final solution". Issues related to operations e.g. what happens after an alarm is initiated may have a more significant impact, and thus should also be seriously considered when looking at the issue of fires on container ships holistically, rather than looking simply for a quick fix.

7.3 "*The Concept*"

The inclusion of containers in the value chain of shipping gives rise to a multifaceted understanding of the fire issues. The main findings of the study in this regard can be categorized as follows.

The Definition of the Problem

- The issue of container fires is characterized by a feeling of uncertainty about it, about solutions, and about ownership.
- The problem is not just technical, but rather socio-technical. In turn it will probably take solutions of socio-technical nature.
- Should the problem be solved? This point is being discussed in the industry, without consensus regarding the answer.
- The value chain is extremely complex.
- Improperly declared cargo is considered as a main cause of the issue, but this is the only consensus.
- The aftermath of a fire is also problematic. The size of the ships makes it difficult to find a suitable and capable port of refuge.
- The concept of a container's seaworthiness is widely defined. Effects on fire safety due to ageing and poor conditions of containers should be investigated further.

Technology and Rules

- "The inflated ship" – safety measures in place do not match the dramatic increase in size and capacity of containerships. As per current regulations, there is neither enough crew nor firefighting equipment on board.
- There is no agreement on technology – are current detection and suppression methods efficient? Which track should be pursued further as a solution?
- There is very little technical knowledge in the industry as to the nature of the issue. Peer-reviewed literature also lacks dramatically, which could question the possibility to solve the issue in the near future.

Situation on board

- Evacuation threshold does not exist, as an aid in determining when to fight the fire.
- Situational awareness is questioned, which in turns questions the current ability to make valid decisions regarding firefighting.
- Is firefighting the best option, regarding current levels of training and on-board resources to tackle a fire situation?
- The chain of command and role both master and shore in decision-making is a factor to be investigated further.
- Cultural origin, nationality, and morality are critical factors for handling an emergency situation.
- Communication is critical, and lives have been lost due to poor or total loss of communication on board.

7.4 The Blue Denmark

The CONTAIN project aimed at providing perspectives for the Danish maritime industry relating to containerships, in the debate covering the fire issues. This point has been addressed through a study of The Blue Denmark and detailed in Chapter 5.

The Blue Denmark is widely represented in container shipping with the representation of shipping companies with a significant fleet, freight forwarders, designers, equipment manufacturers, manning with Danish trained ship officers, the operation of ships as well as a maritime strong flag state, and this includes opportunities to focus on fire safety and to make bids for new technology, safer logistics and a new mindset that can help break the chain of diffused responsibility that characterizes the logistics chain. The Blue Denmark has a strong innovation environment, which through projects and partnerships can make this happen.

The size of container ships has grown dramatically (22,000 + TEU, in 2018), but the IMO regulations & codes, rules from Class, as well as standards for design, container construction, fire safety and fire training in relation to the types of fires we know today have been followed. All stakeholders with whom DBI have been in contact with, in connection with the CONTAIN project agree that the current rules are inadequate and some even outdated. At the same time, however, this situation also presents a fantastic opportunity to influence future standards and rules.

The logistic path of a container from A – Z in the global shipping market is a complex process, and the complexity of the supply chain is in itself a major fire risk due to many links and diluted responsibilities.

Delays of the container along the way also have a major impact on the fire risk, partly because an early delay typically leads to further delays, which can lead to the initiating self-ignition of both organic and inorganic materials as well as chemicals. The long supply chain creates an accumulated risk of fire, as the many links in the chain can contribute new risks.

The physical condition of each container, both when newly produced and throughout its life time, and the link between damage to containers and the emergence and spread of the fire has not been adequately investigated until now. This may be a result of both the low price for a single container and the low freight rates, which make it unattractive to strengthen the fire safety characteristics on the container itself. Here there is potentially an area for innovative Danish companies to explore.

Going Forward

The overall purpose of the DBI CONTAIN project is to highlight the issues connected to fires in the cargo holds of container ships, and thus reduce the loss of property and human life. This results in a derived effect in the form of greater credibility for the container industry in relation to taking fire safety seriously.

To go further in addressing this, DBI recommends creating a strong consortium of Danish maritime companies, including; ship designers, shipyards, ship-owners and operators, research institutions, insurance underwriters and Classification societies, to address the challenges on fire safety facing the global Container industry. DBI seeks support for a number of future activities that will partly expand and disseminate the available knowledge on fires in cargo holdings on container ships, and will also contribute to a central Danish position in an consortia that develops new solutions to strengthen fire safety on container ships globally.

While it was beyond the framework of this pilot project to examine the economic impact on Blue Denmark of fires on container ships, this is a very relevant aspect to understand when considering this challenge and warrants further work. In addition, it could a potential future task for Blue Denmark's innovative cooperation, to investigate the business case by promoting logistical and technological solutions for greater safety and thus result in fewer and smaller fires.

DBI is willing and interested in taking the initiative, to create a strong consortium of Danish maritime companies, including; ship designers, shipyards, ship-owners and operators, research institutions, insurance underwriters and Classification societies, to address the challenges on fire safety facing the global Container industry.

Given the many companies across the Blue Denmark who have important roles to play in the Container value chain, DBI believe there exists a great potential here in Denmark, to impact and improve the fire safety of containers and the ships which carry them all around the world.

8 Future Work

This chapter presents recommendations for future work, based on the input from stakeholders and DBI's original work.

Our main recommendation is that the issue of fire on board containerships is treated as a problem which should be solved. Though some stakeholders challenge the necessity of solving the issue, on economical and statistical grounds, we believe that the consequences of this problem in terms of potential loss of lives, loss of assets, and financial losses are too high to remain unaddressed.

8.1 Recommendations for future work

The following section focuses on recommendations for future work of the same nature as has been conducted in the work package i.e. within the realm of human and organizational factors and their respective roles in container fire incidents.

- Interview more and a wider range of stakeholders – this is already ongoing and will continue after the end of CONTAIN, but should also be a feature of any future projects. The recommendation here would be to broaden the scope and include an even more global pool and do not be limited in the selection.
- Future work and collaboration with selected industry partners – this is also ongoing and will continue after the project. This will help with a greater understanding of the problem, getting more concrete with certain issues and solutions with selected partners.
- Long term fieldwork to understand the ship and crew situation better. This includes qualitative interviews with crew, officers, manning companies, shipping companies, etc. Participant observation on board a container vessel for an extended period. This is the opportunity to gather significant qualitative data on daily life on board a container vessel. Crew relations, the effects on various cultures within the crew, the relationship between management, land, the officers, and the crew. Building significant report with crew members. Gain a deeper understanding of the issues they face and their take on the fire incident.
- Investigate the concept of container aging. What is the influence of damaged containers on fire spread?
- Investigate whether it is possible to feasibly fight a developed fire onboard a container ship with the personnel and equipment available as stated by the rules.

8.2 Future experimental work

Looking further, many interesting and essential questions remain to be investigated. Further hypothesis testing, investigating the other potential spread mechanisms outlined at the beginning of the chapter is required to assess how they may contribute to the overall picture.

On top of this, the following are also important to consider:

- How all these mechanisms interact in a larger more realistic test environment. Fire spread has so far been investigated in a piece-wise manner, looking at individual mechanisms and evaluating their potential to be a cause of fire spread.
- Producing validation data for simulation tools
- Effects of explosive scenarios

Figure 25

8.3 Future simulation work

In future work, the flexibility of the developed model would allow a whole suite of potential scenarios to be examined. Issues such as;

- Locational impact,
- Fire growth rates, fire sizes, fuel types
- Ventilation conditions,
- Positioning of detector systems, types of detectors,
- Effectiveness of suppression systems,
- Life safety hazards.

All of these can be investigated through this type of simulation.

Finally, although improving detection systems will offer an improvement in detection times and thus some consequences may be avoided, this will not fix all the issues that result in fires on container ships, and should not be viewed as the “final solution”. Issues related to operations e.g. what happens after an alarm is initiated also have a significant impact, and thus these issues should be seriously considered together when looking at the issue of fires on container ships holistically, rather than looking simply for a quick fix.